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, have been experiencing a continuing and accelerating ice loss since 1959, although the snowfall here is abundant and evenly distributed over the year. As an attempt to reduce their melting, we carried out two artificial-snowfall experiments to the Muz Taw glacier during 19 – 22 Aug 2018. We measured the albedo and mass balance at different sites along the glacier before and after the experiments. Two automatic weather stations (AWS) were set up at the equilibrium line altitude (ELA) of the glacier as the target area and the forefield as the control area to record the precipitations, respectively. The comparison of the two precipitation records from the two AWSs suggests that natural precipitation could account for up to 21% of the snowfall received by the glacier during the experiments. Because of the snowfalls, the glacier's surface albedo significantly increased in the mid-upper part; the average mass loss decreased by between 32 and 41 mm w.e. after the experiments (Aug 18 – 24) comparing to that before (Aug 12 – 18); and the mass resulting from the snowfalls accounted for between 42% and 54% of the total melt during Aug 18 – 24. 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. The work in current status is primitive as a preliminary trial, the conclusions of which need more controlling experiments to validate in larger spatial and temporal scales in future.

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 technical 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).

Cloud-seeding over a glacier to generate and enhance snowfall for reducing mass loss has rarely been tested in previous study. There have always been controversial discussions on the virtual efficacy and positiveness of using AgI smoke to seed cloud and enhancing precipitations since the measure was introduced by Vonnegut (1947). The controversy mainly resides in two sides. One side claimed that no statistical or physical evidence had been provided to establish the scientific validity of the operations (Council, 2003; Silverman, 2001), while the other affirmed that the past operations conducted in Australia successfully increased precipitations by 5% up to 50% (Bowen, 1952; CSIRO, 1978; Smith, 1967). However, both sides agreed that the experiments of seeding clouds and producing more precipitation were promising and deserved more observations to understand the link of physical reactions leading to precipitation (Council, 2003). A peer review report on global artificial-snowfall activities by the World Meteorological Organization suggests that the toxicity of the seeding material (majorly silver iodine, i.e. 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.

As an attempt, we select the Muz Tau glacier in the Sawir Mountains as the projected glacier. During the glacier's ablation period in 2018, we tried to induce artificial precipitations by using the ground AgI smoke generators to seed clouds over the glacier. 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).

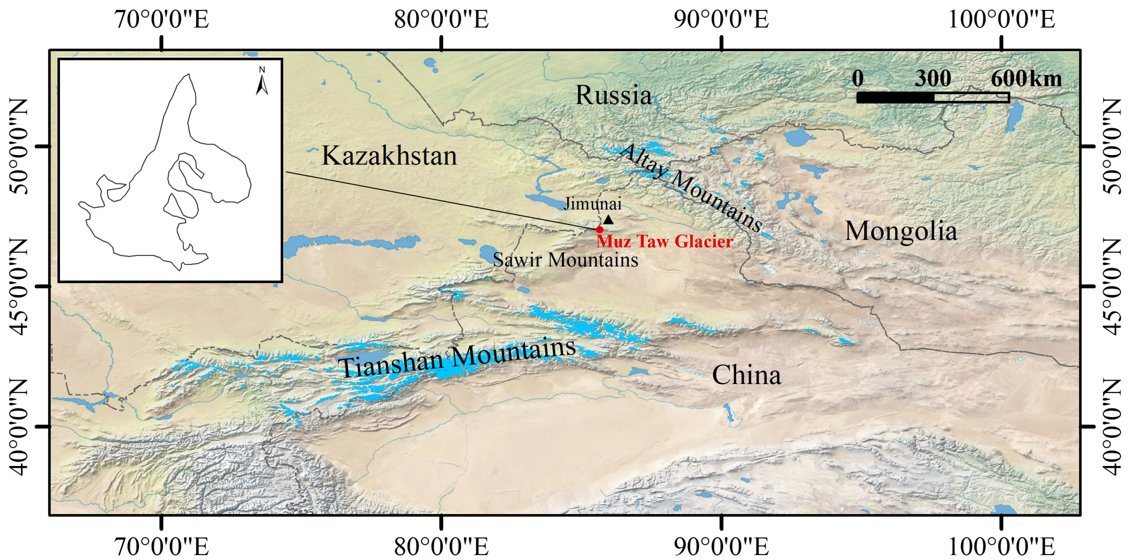

Figure 1 Location of the Muz Taw glacier and the Sawir Mountains, where the map in the background is downloaded from the website https://www.naturalearthdata.com/ and the outline of the glacier is sourced in Guo et al. (2015).

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 Meteorological radar observations

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).

3.2 Artificial-precipitation experiment

The Muz Taw glacier is developing along the valley, and the terminal is the heading source of the Ulequin Urastu River and Ulast River. Fourteen silver-iodide (AgI) smog generators have been distributed along the rivers for artificial-precipitation tasks by the local meteorological service. 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).

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.

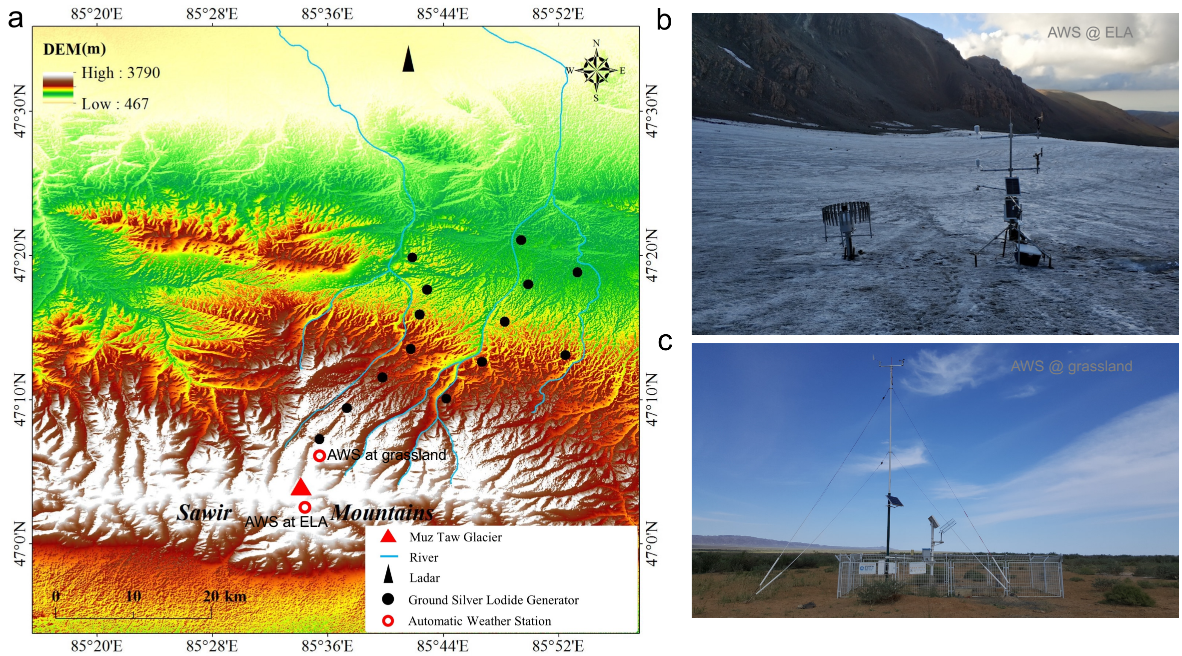

Figure 2 a) The map of the study area, including the Muz Taw glacier, the two automatic weather stations (AWS) set up at the equilibrium line elevation (ELA) and the forefield of the glacier and the distribution of the silver-iodide-smog generators along the Ulequin Urastu River and Ulast River in the Sawir Mountains for seeding artificial precipitations, b) the AWS set up at ELA and c) the AWS set up at grassland with a straight distance of ~5 km north to the AWS at ELA.

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.

3.3 Measurement by the automatic weather stations (AWS)

We set up an automatic weather station (AWS at ELA) on a relatively flat surface near the equilibrium line altitude (ELA) of the Muz Taw glacier since 8 Aug 2018 (47° 03′36″N, 85°33′43″E, 3430 m a. s. l.; Figure 2a&b and 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. In the forefield of the glacier around five kilometers north of the AWS at the ELA, another AWS on the grassland (AWS at grassland) was set up by the local meteorological service to monitor conventional meteorology (Figure 2a&c).

Table 1 The sensors mounted on the AWS at ELA 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

3.4 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.

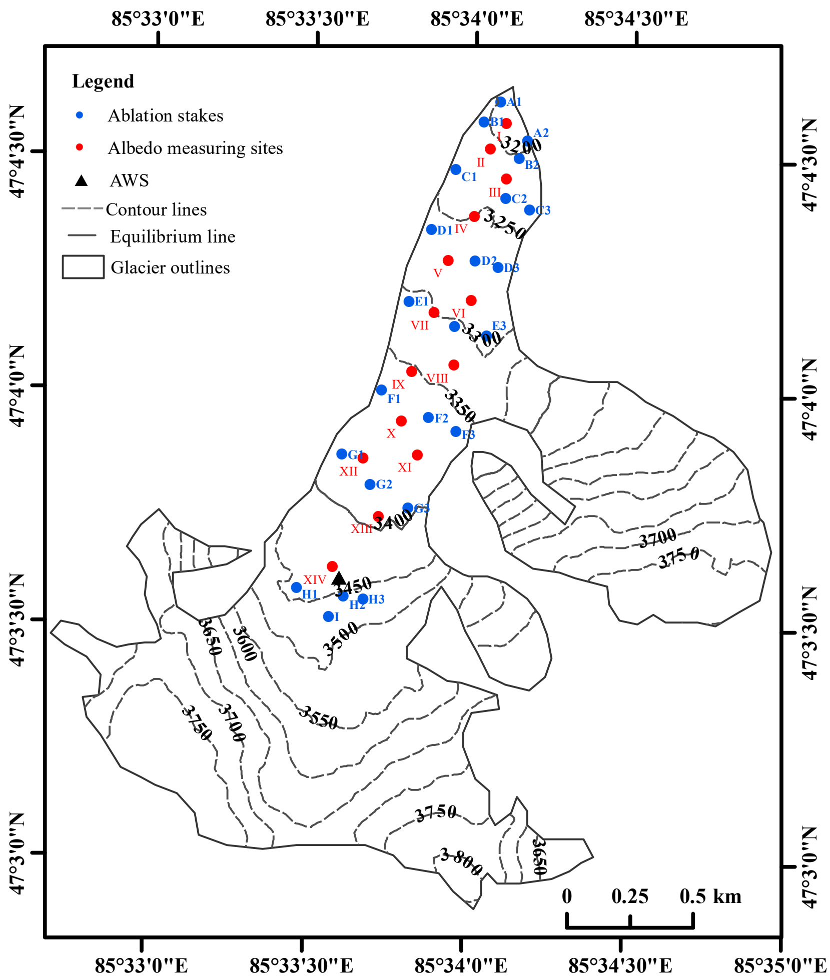

Figure 4 The location of the AWS at ELA and the measuring sites for surface albedo and mass balance on the Muz Taw glacier.

3.5 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 Natural or artificial precipitations and their amounts and forms

Figure 5a shows the hourly temperature and precipitations recorded by the AWS at ELA 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. It seems not likely to distinguish the artificial precipitations from the natural ones if they were simultaneously mixed in all these events.

Previous weather modification experiments using the same method as ours concluded that it was challenging to tell that how much artificial precipitation mixed in the whole amount directly came after conducting the cloud seeding (CSIRO, 1978; Qiu and Cressey, 2008; Ryan and King, 1997). The results from the measurements by Marcolli et al. (2016) and (Fisher et al., 2018) suggested the efficacy and success of using AgI on growing ice nuclei in clouds and promoting snowfall. In our study, there were significant precipitation amounts recorded by the AWS at ELA every single time after we ignited the smoke generators, associated with a highly significant linear relationship (n = 10, $r^2 = 0.9999$) between the timings of igniting AgI and recording snowfalls (Figure 5b). The co-occurring of the significant snow falling using the AgI smoke to seed cloud (Figure 3 and Figure 5b) allows supposing that we were producing artificial precipitations.

The AWS at grassland in the forefield of the Muz Taw glacier was clear from the AgI smoke during the AP experiments. This allows us to use the precipitation data recorded by it as a control to distinguish natural precipitation from the artificial recorded by the AWS at ELA. We lost the precipitation data from the AWS at grassland during the first AP experiment on Aug 19 for the rain gauge was full and overflowed. While for the second experiment, the precipitation data were successfully collected from the AWS at grassland for a comparison.

Figure 6 shows the precipitations recorded by both AWSs and the record ratio of grassland to ELA during the second AP experiment (Aug 22 to 23). The precipitations recorded by the two AWSs were not synchronized. The AWS at ELA did not record any precipitations when that at grassland recorded at 19:00 and 20:00 on Aug 22; while there were records after 6:00 by the AWS at ELA but none for at grassland. The correlation between the two precipitation records is fairly weak ($r^2 = 0.05$) when they were both recorded by the AWSs, implying that the cause of precipitation (i.e. natural or artificial) might be distinctly different or likely mixed on the target area.

We presume two possibilities of whether there was natural precipitation joined the artificial process targeted on the glacier. The first was none natural precipitation took part in conceiving artificial snow on the target area, and the second, if any, was a part of this. The ratios of precipitations by the AWS at grassland to that at ELA were smaller than 0.35 with a mean of 0.21 ± 0.03 (Figure 6), which could be used for estimating how much naturally induced precipitation taking part in the AP experiment based on the second presumption.

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.

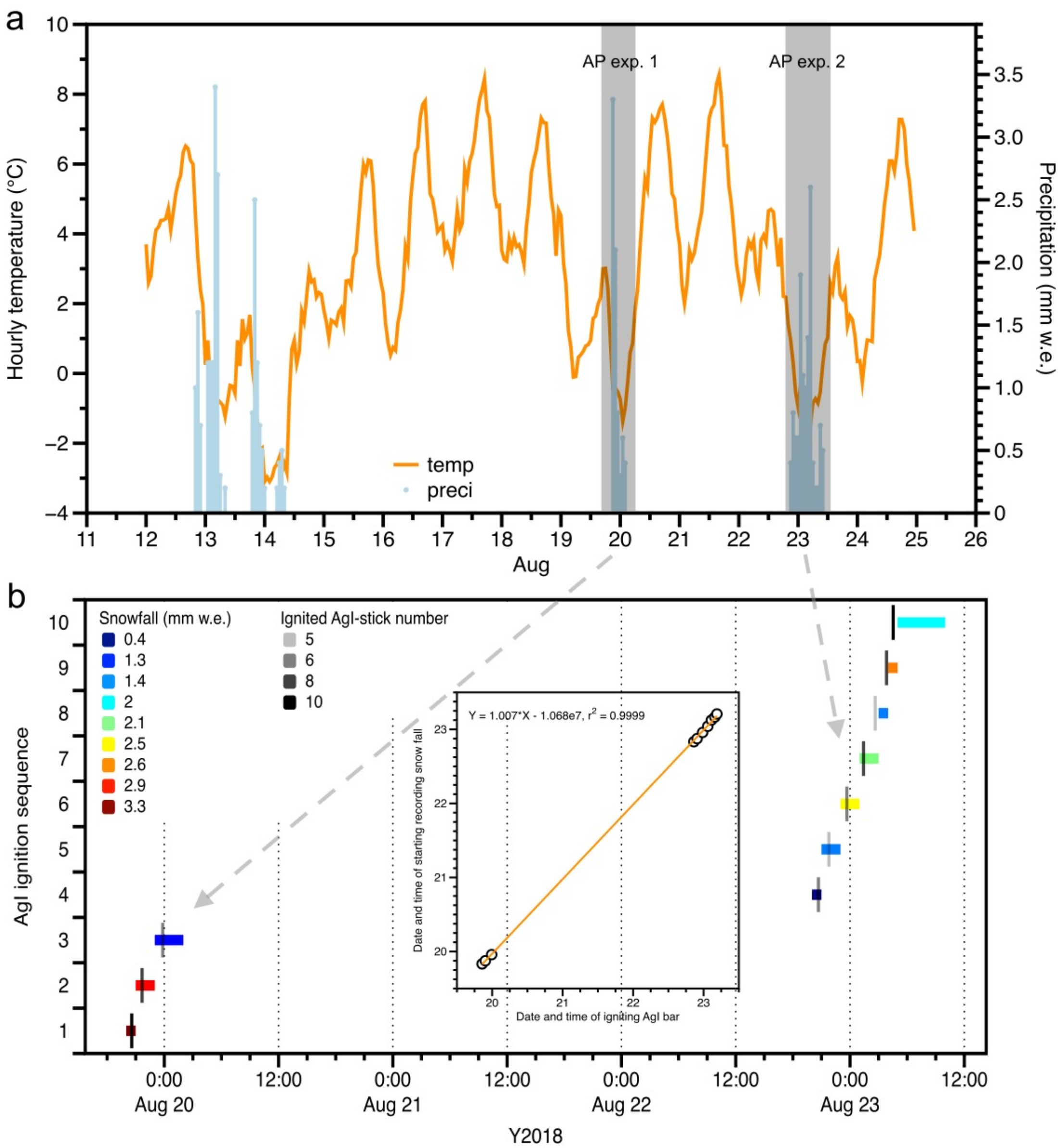

Figure 5 a) The daily snowfalls and hourly averaged temperature recorded by the AWS at ELA from 12 to 24 Aug 2018, where the two artificial-precipitation experiments (AP exp. 1 and 2) are marked, and b) the hourly snowfall amounts (indicated by color) and time periods (indicated by length) *recorded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

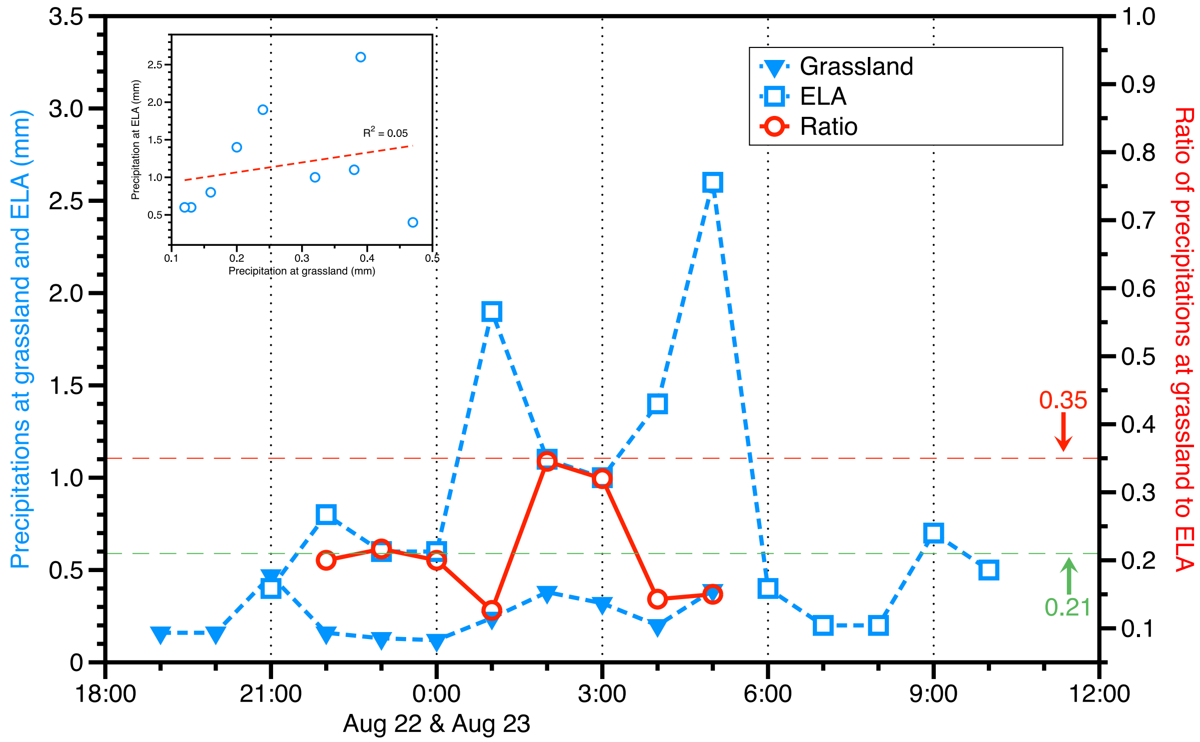

Figure 6 The precipitations recorded by the AWSs at grassland (inversed blue solid triangles) and ELA (hollow blue squares) and the precipitation-record ratio of grassland to ELA (hollow red circles) during Aug 22 to 23, in which the scatter plot of the precipitations by both AWSs is included and the green and red dashed lines indicate the upper limit and mean of the ratios.

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 7 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.

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 7. 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.

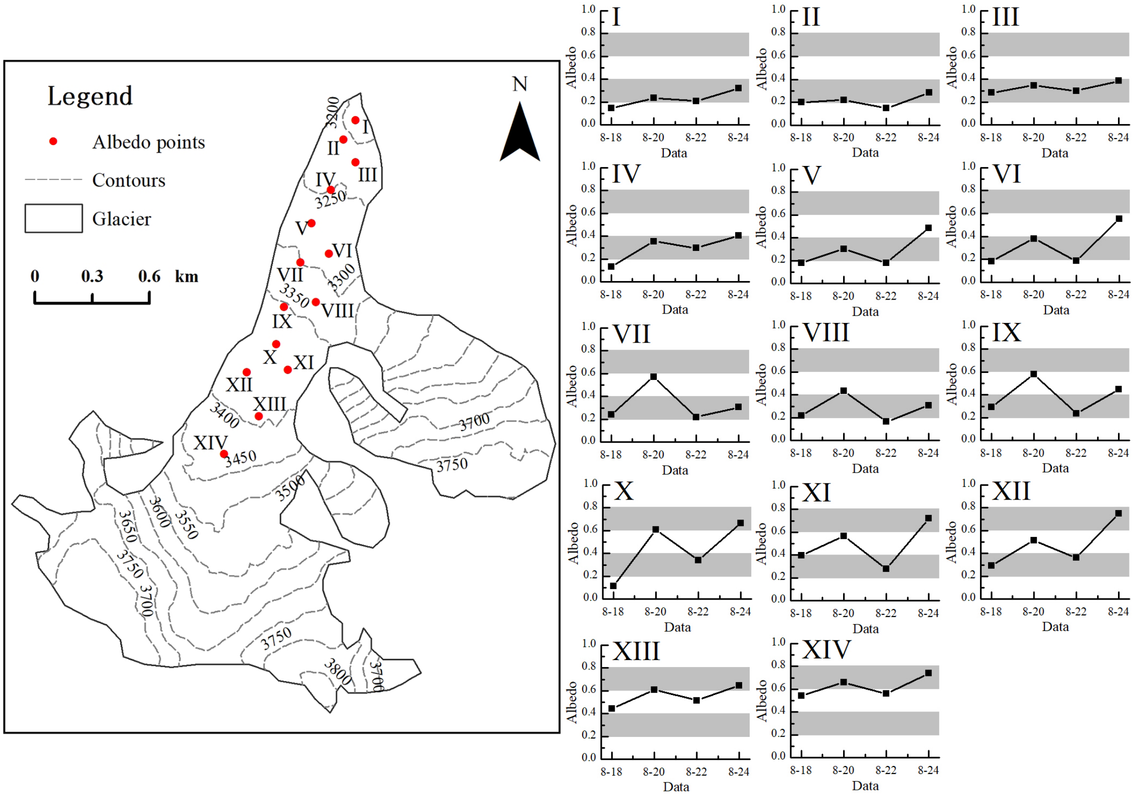

Figure 7 The surface albedo at the fourteen sites (I - XIV) of the Muz Taw Glacier, where the red points denote the sites and the top-left chart as the reference of the fourteen charts (site I to XIV) marks the albedo scale and date with the highlighted grey shades.

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

8). 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. averaged on the stake measurements for the Muz Taw Glacier, considering the difference was completely due to artificial precipitation. If we take 21% of the difference was due to natural precipitation (Figure 6), the difference would be 32 mm w.e. Therefore, the difference resulting from the artificial snowfalls accounted for between 14% (with 21% natural) and 17% (without natural) of the mass balance before the artificial snowfalls (- 237 mm w.e.).

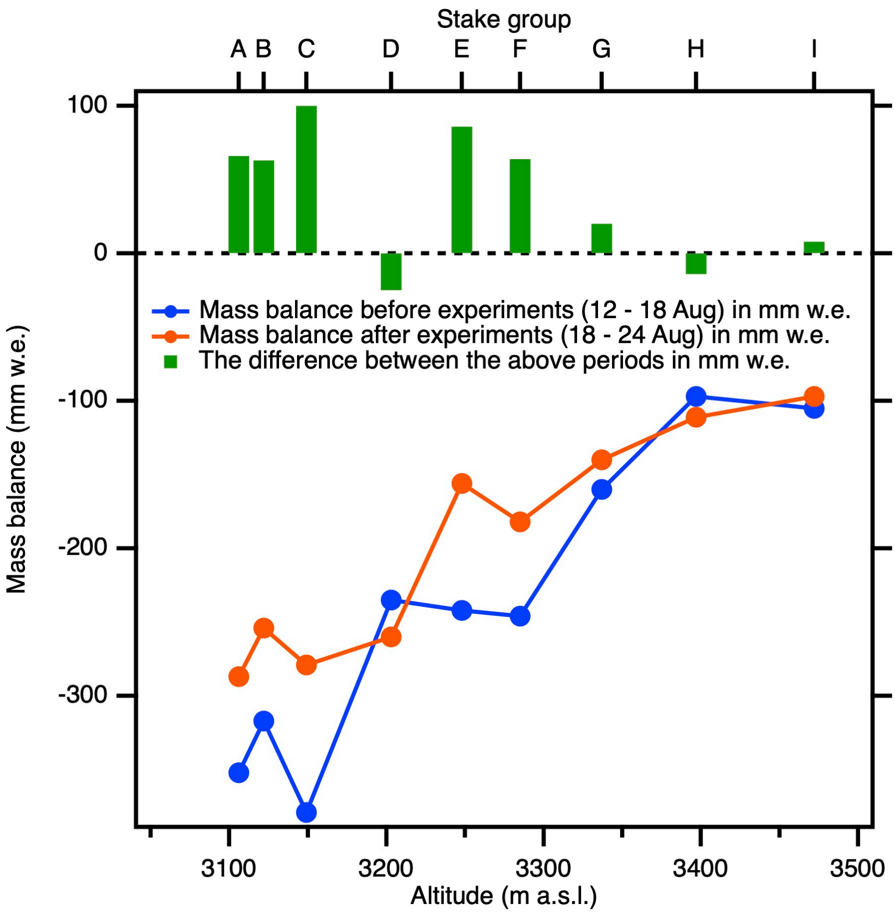

Figure 8 The averaged mass balance measured at the sites (Stake A - I) before (blue) and after (orange) the artificial snowfalls on 18 and 20 Aug compared with that on 12 Aug (The zero line), and the gained mass (green = orange - blue) due to the artificial snowfalls.

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 at ELA. 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 lower mass loss during t_2.

Table 2 The positive accumulated temperatures, snowfalls and albedo measured by the instruments on the AWS at ELA, 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 at ELA of the Muz Taw glacier during t_2 was the average received mass of the whole glacier after implementing the AP experiments. The extra melt amount from the glacier besides the gained mass during t_2 would be the difference between the calculated mass loss (37.2 mm w.e.) and the snow mass measured by the AWS at ELA (19.9 mm. w.e.), and that would be 17.3 mm w.e. The artificial snowfalls may significantly save the melt of the glacier by 54% during t_2, calculated as the percentage of the snowfall divided by the estimated mass balance. Excluding 21% of the mass measured by the AWS at ELA presumably as the contribution of natural precipitations, we conclude that the artificial precipitations buffered the total melting during t_2 by 42%.

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 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 and the partition of natural and artificial precipitations need to be quantified more confidently, for which more controlling experiments are needed in future.

5 Conclusions

We used AgI-smoke generators to induce artificial snow on the Muz Taw Glacier in Sawir Mountains on 19 and 22 Aug 2018. Two AWSs were set up on the target glacier and control area, respectively. 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 experiments, which increased the surface albedo of the glacier. Larger fluctuations in albedo were measured at the higher sites than lower.

By comparing the precipitations measured by the two AWSs, we conclude that artificially induced snow could account for at least 79% of the total snow measured by the AWS at ELA. After interpolating the mass balance measured 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 snow reduced the mass loss of the glacier by ~ 40% due to more snowfall and higher albedo, nevertheless the positively accumulated temperature during the latter period was higher than the former.

We compared the mass balances directly calculated from the measurements of the stakes before the experiments (12 – 18 Aug) with that after (18 – 24 Aug). The difference between the two periods was between 32 and 41 mm w.e., taking possible natural snow into account. This suggests that artificial snow does add mass to the glacier, which is consistent with the result by interpolating stake measurements to the whole glacier. We also compared the total melt of the glacier during 18 – 24 Aug with the artificial snow received by the glacier, implying that artificial snow significantly saved the mass loss by between 42% and 54% after the experiments.

We 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 dramatic in the Central-Asian glaciers, applying the approach suggested by our study on a much broader scale might reduce the melting significantly. This study is preliminary and short in operating time and needs more sophisticated experiments at control and target areas to partition natural and artificial precipitations. The approach would sophisticate itself when being implemented more regularly in future repeated and longer-term, or scaled-up experiments.

Code/Data availability

It is currently shared by communities that the dataset would be publicly available upon acceptance of publication. Please directly contact the corresponding author F. Wang (wangfeiteng@lzb.ac.cn) or the coordinating author J. Ming (petermingjing@hotmail.com) for the data repository and the authors will response accordingly.

Author contributions

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. reanalyzed the data and plots, edit and sophisticated the manuscript. Z.L. helped with the final revision.

Competing interests

All contributors declare no competing interests in this work.

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References

Bojinski, S., Verstraete, M., Peterson, T. C., Richter, C., Simmons, A., and Zemp, M.: The Concept of Essential Climate Variables in Support of Climate Research, Applications, and Policy, B Am Meteorol Soc, 95, 1431-1443, 2014.

Bowen, E. G.: AUSTRALIAN EXPERIMENTS ON ARTIFICIAL STIMULATION OF RAINFALL, Weather, 7, 204-209, 1952.

Braithwaite, R. J.: Temperature and precipitation climate at the equilibrium-line altitude of glaciers expressed by the degree-day factor for melting snow, Journal of Glaciology, 54, 437-444, 2008.

Council, N. R.: Critical Issues in Weather Modification Research, The National Academies Press, Washington, DC, 2003.

CSIRO: Rainmaking; the state of the art. In: ECOS, 1978.

Dyer, C.: Now THAT'S a wrap! Swiss glacier is shrouded in UV-resistant blankets to stop it melting in the summer heat. In: Daily Mail, Daily Mail, Online, 2019.

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.

Fisher, J. M., Lytle, M. L., Kunkel, M. L., Blestrud, D. R., Dawson, N. W., Parkinson, S. K., Edwards, R., and Benner, S. G.: Assessment of Ground-Based and Aerial Cloud Seeding Using Trace Chemistry, Advances in Meteorology, 2018, 1-15, 2018.

Flossmann, A. I., Manton, M. J., Abshaev, A., Bruintjet, R., Murakami, M., Prabhakaran, T., and Yao, Z.: Peer Review Report on Global Precipitation Enhancement Activities, 2018. 2018.

Fujita, K. and Ageta, Y.: Effect of summer accumulation on glacier mass balance on the Tibetan Plateau revealed by mass-balance model, Journal of Glaciology, 46, 244-252, 2000.

Guo, W., Liu, S., Xu, J., Wu, L., Shangguan, D., Yao, X., Wei, J., Bao, W., Yu, P., and Liu, Q.: The second Chinese glacier inventory: data, methods and results, Journal of Glaciology, 61, 357-372, 2015.

Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääb, A., Kang, S., Kutuzov, S., Milner, A., Molau, U., Morin, S., Orlove, B., and Steltzer, H.: High Mountain Areas. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, IPCC, New York, 2019.

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B. J., Elmore, A. C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J. S., Koppes, M., Kraaijenbrink, P. D. A., Kulkarni, A. V., Mayewski, P., Nepal, S., Pacheco, P., Painter, T. H., Pellicciotti, F., Rajaram, H., Rupper, S., Sinisalo, A., Shrestha, A. B., Viviroli, D., Wada, Y., Xiao, C., Yao, T., and Baillie, J. E. M.: Importance and vulnerability of the world’s water towers, Nature, doi: 10.1038/s41586-019-1822-y, 2019. 2019.

Immerzeel, W. W., van Beek, L. P. H., and Bierkens, M. F. P.: Climate Change Will Affect the Asian Water Towers, Science, 328, 1382-1385, 2010.

Kong, J., Wang, G., Fang, W., and Su, Z.: Laboratory study on nucleating properties and microstructure of AgI pyrotechnics, Meteorological Monthly, 42, 74-79, 2016.

Marcolli, C., Nagare, B., Welti, A., and Lohmann, U.: Ice nucleation efficiency of AgI: review and new insights, Atmos Chem Phys, 16, 8915-8937, 2016.

Ming, J., Xiao, C., Wang, F., Li, Z., and Li, Y.: Grey Tienshan Urumqi Glacier No.1 and light-absorbing impurities, Environmental science and pollution research international, 23, 9549-9558, 2016.

Mölg, T., Maussion, F., Yang, W., and Scherer, D.: The footprint of Asian monsoon dynamics in the mass and energy balance of a Tibetan glacier, The Cryosphere, 6, 1445-1461, 2012.

Möller, M., Schneider, C., and Kilian, R.: Glacier change and climate forcing in recent decades at Gran Campo Nevado, southernmost Patagonia, Annals of Glaciology, 46, 136-144, 2007.

Moustafa, S., Rennermalm, A., Smith, L., Miller, M., Mioduszewski, J., Koenig, L., Hom, M., and Shuman, C.: Multi-modal albedo distributions in the ablation area of the southwestern Greenland Ice Sheet, The Cryosphere, 9, 905-923, 2015.

Oerlemans, J., Haag, M., and Keller, F.: Slowing down the retreat of the Morteratsch glacier, Switzerland, by artificially produced summer snow: a feasibility study, Climatic Change, 145, 189-203, 2017.

Østrem, G. and Brugman, M.: Glacier mass-balance measurements: a manual for field and office work, National Hydrology Research Institute, Inland Waters Directorate Conservation and Protection Environment Canada, Saskatoon, Sask, Canada, 224 pp., 1991.

Panagiotopoulos, F., Shahgedanova, M., Hannachi, A., and Stephenson, D. B.: Observed Trends and Teleconnections of the Siberian High: A Recently Declining Center of Action, J Climate, 18, 1411-1422, 2005.

Qiu, J. and Cressey, D.: Meteorology: Taming the sky, Nature, 453, 970-974, 2008.

Ryan, B. F. and King, W. D.: A Critical Review of the Australian Experience in Cloud Seeding, B Am Meteorol Soc, 78, 239-254, 1997.

Silverman, B. A.: A Critical Assessment of Glaciogenic Seeding of Convective Clouds for Rainfall Enhancement, B Am Meteorol Soc, 82, 903-924, 2001.

Smith, E. L.: Cloud seeding experiments in Australia, 1967.

Song, L.: Blue book on climate change in China, Center on Climate Change Press, 2019.

Vonnegut, B.: The Nucleation of Ice Formation by Silver Iodide, Journal of Applied Physics, 18, 593-595, 1947.

Wang, F., Xu, C., Li, Z., Anjum, M. N., and Wang, L.: Applicability of an ultra-long-range terrestrial laser scanner to monitor the mass balance of Muz Taw Glacier, Sawir Mountains, China, Sciences in Cold and Arid Regions, 10, 0047-0054, 2018.

Wang, P., Li, Z., Li, H., Wang, W., and Yao, H.: Comparison of glaciological and geodetic mass balance at Urumqi Glacier No. 1, Tian Shan, Central Asia, Global Planet Change, 114, 14-22, 2014.

Wang, Y. Q., Zhao, J., Li, Z. Q., and Zhang, M. J.: Glacier changes in the Sawuer Mountain during 1977-2017 and their response to climate change, Journal of Natural Resources (in Chinese), 34, 802-814, 2019.

Wright, P., Bergin, M., Dibb, J., Lefer, B., Domine, F., Carman, T., Carmagnola, C., Dumont, M., Courville, Z., and Schaaf, C.: Comparing MODIS daily snow albedo to spectral albedo field measurements in Central Greenland, Remote Sens Environ, 140, 118-129, 2014.

Xu, Z., Jing, H., Zou, L., and Li, Y.: Application research of type WR-08X digital radar on artificial precipitation in Saur Mountains area, Jiangxi Science (in Chinese), 35, 727-730, 2017.

Yue, X., Zhao, J. U. N., Li, Z., Zhang, M., Fan, J. I. N., Wang, L. I. N., and Wang, P.: Spatial and temporal variations of the surface albedo and other factors influencing Urumqi Glacier No. 1 in Tien Shan, China, Journal of Glaciology, 63, 899-911, 2017.

Zemp, M., Huss, M., Thibert, E., Eckert, N., McNabb, R., Huber, J., Barandun, M., Machguth, H., Nussbaumer, S. U., Gartner-Roer, I., Thomson, L., Paul, F., Maussion, F., Kutuzov, S., and Cogley, J. G.: Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016, Nature, 568, 382-386, 2019.