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Applying artificial precipitations to mitigate 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. Influenced by the westerly circulation and the polar air mass, the precipitation is abundant and evenly distributed over the year in this area. However, a continuing and accelerating mass loss of glaciers has been in presence since 1959. To study the role of precipitation in mitigating the glacier's melting, we carried out two artificial-precipitation experiments on the Muz Taw Glacier of the Sawir Mountains on 19 and 22 August 2018, respectively. We measured the albedo and MB at different sites along the glacier before and after the individual experiment. According to the records of the automatic weather station (AWS) set up at the equilibrium line (EL, 3400 m), the amount of precipitation was 6.2 mm and 12.4 mm water equivalent in solid form by the two experiments, respectively. Due to the artificial solid precipitations, the glacier's surface albedo significantly increased in the mid-upper area, and the amounts of the mass loss decreased by 17%. We also propose a possible mechanism describing the role of precipitation in mitigating the melting of the glacier.

Keywords

artificial precipitation, Muz Taw Glacier, Sawir Mountains, MB, melting mitigation

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1 Introduction

Mountain glaciers are an essential part of the cryosphere. As high-altitude reservoirs, they are vital solid-water resources (Immerzeel et al., 2010). Glacier fluctuations represent an integration of changes in the 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., 2015). For the Sawir Mountains, the ablation of the glaciers is more intense, and the total area of the glaciers reduced by 10.51 km^2 and the total length retreated by 45.72% from 1977 to 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.

For mitigating the melting of glaciers, governments and scientists have taken various measures, including energy conservation, temperature-increase control and establishing glacial reserves. Current research on glacial ablation focuses more on physical mechanisms and future-change projection, while less on taking geoengineering measures to mitigate glacial ablation. 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, scientists plan to use artificial snow to slow down the glacier melting (Oerlemans et al., 2017).

We select the Muz Tau glacier in the Sawir Mountains as the investigated glacier. During the glacier's ablation period, we introduced artificial precipitations (APs) by the ground silver-iodide-smog generators set at the glacial area. We also combined the snowfall amounts, time and frequency recorded by the rainfall gauge and the mass balance (MB) and albedo of the glacier measured to study the role of artificial precipitation in mitigating the mass loss of the glacier.

2 The Sawir Mountains and the Muz Taw Glacier

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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).

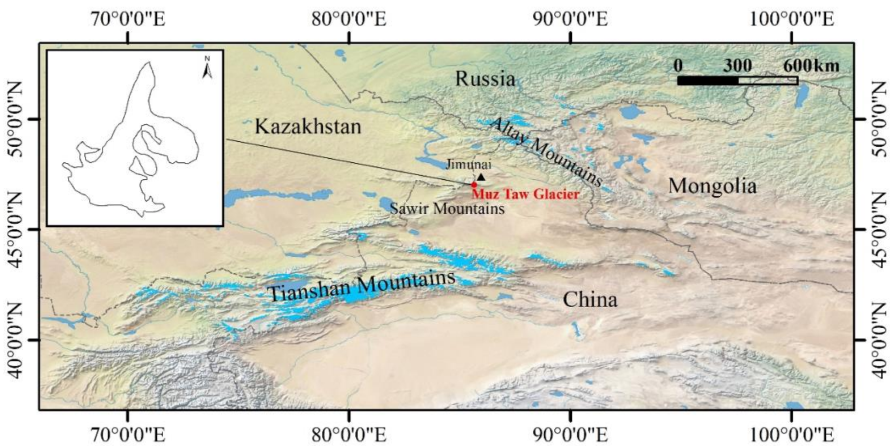

Figure 1 Location of the Muz Taw glacier and the Sawir Mountains, where the map in the background is downloaded from the website https://www.naturalearthdata.com/ and the outline of the glacier is sourced in Guo et al. (2015).

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. 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 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 MBs of the

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Muz Taw Glacier was -975 ~ -1286 mm w.e., 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). When we realized the possibility is high enough to potentially form precipitation, we ignited the 14 silver-iodide smog generators distributed along the glacier's two terminal rivers (i.e., Ulequin Urastu River and Ulast River) in the Sawir Mountains for seeding AP (Figure 2).

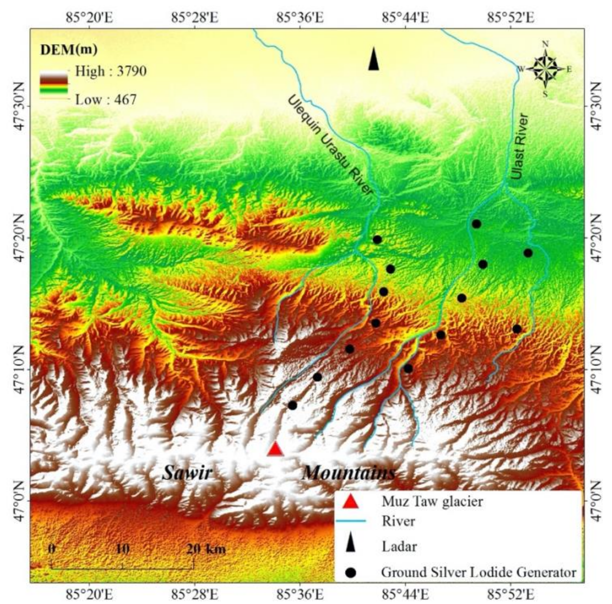

Figure 2 The distribution of the silver-iodide-smog generators along the Ulequin Urastu River and Ulast River in the Sawir Mountains for seeding APs.

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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 AP 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 August 2018 (47°03′36″N, 85°33′43″

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E, 3430 m a. s. l.; Figure 4). The AWS has a thermometer (Pt100 RTD, ± 0.1 K) 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 the accuracy of about ± 0.1%. All sensors were connected to a data logger (CR6) working in low temperature (-55 °C) and recording the hourly means every ten seconds.

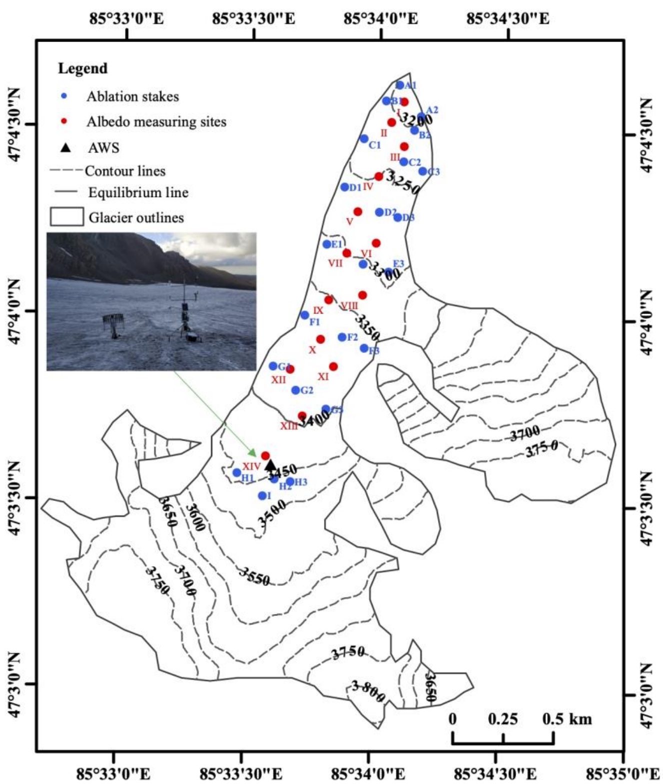

Figure 4 The location of the AWS and the measuring sites for surface albedo and MB on the Muz Taw glacier, where a photo of the AWS is in the up left.

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

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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 August 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). We excluded the apparent outliers (greater than 0.98) of the albedo data which are physically unrealistic.

3.4 Measurement of the MB

We have measured the MB 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 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 MB at the stake sites. The MB was obtained on 1 May and 31 August annually. For verifying the effect of APs on the MB of the glacier, in particular, we conducted three additional measurements for the MB on 12, 18 and 24 August 2018, respectively. The baseline of all the MB data in this study is the MB measured by the stakes on 12 August. The calculation of the MB of the whole glacier is following an

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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 AP

Figure 5 shows the hourly temperature and precipitations recorded by the AWS from 12 to 24 August 2018. Artificial-precipitation experiments were carried out on 19 and 22 August. The amounts of precipitations were 6.2 mm on 19th, 1.8 mm on 22nd and 10.6 mm on 23rd, respectively. Most precipitations were observed during mid nights and early mornings.

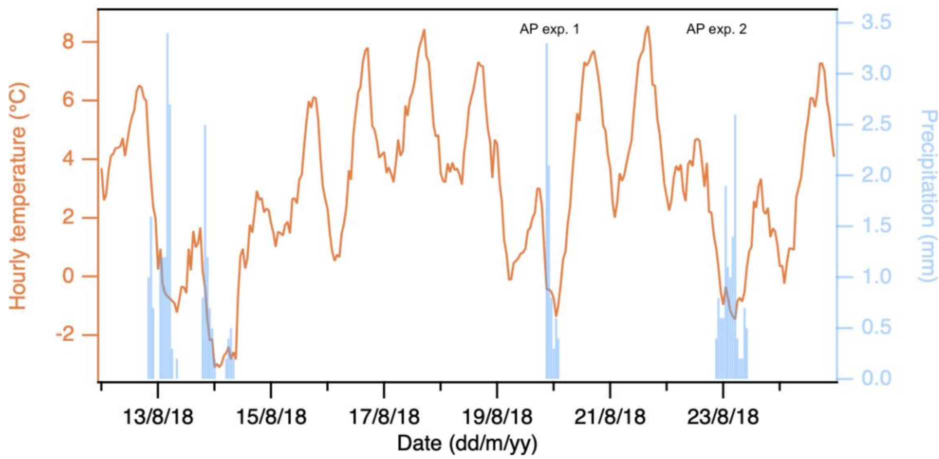

Figure 5 The daily precipitations and hourly-averaged temperature recorded by the AWS from 12 to 24 August 2018, where the two AP experiments are marked.

To determine the amount of solid precipitation 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 (snowfall) will occur, and between 2 – 4 °C rain would fall with snow. During our experiments, the air temperatures were below 2 °C when the precipitations occur, implying that the precipitations in the two experiments were solid. While liquid precipitations might occur in the lower altitudes of the ablation zone since the temperature was measured by the AWS located near the equilibrium line.

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4.2 The effects of AP 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-precipitation 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 August.

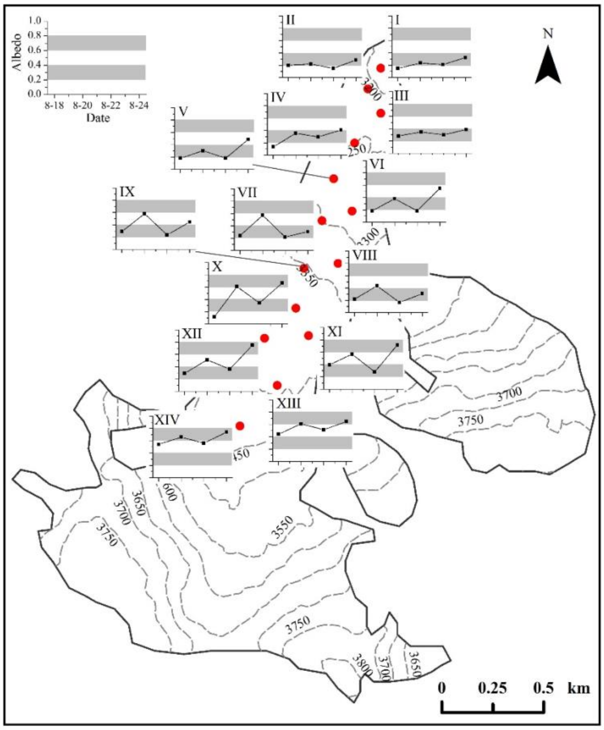

Figure 6 The surface albedo at the fourteen sites (I - XIV) of the Muz Taw Glacier, where the red points denote the sites and the top-left chart as the reference of the fourteen charts (site I to XIV) marks the albedo scale and date with the highlighted grey shades.

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

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this area was located near the equilibrium line (EL), it was highly sensitive to air temperature and precipitation. Artificial precipitation 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 EL, 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 APs.

4.3 The varying MBs responding to the APs

To study the effects of the APs on the MB of the glacier, we calculated the MBs measured by the stakes. The stakes in a group (A to I) were roughly along the altitude contour (Figure 4), and the correspondingly measure MBs of the same group were averaged (Figure 7). The negative MBs decrease with the altitudes from ~ – 400 mm w.e. at 3100 m to ~ – 100 mm w.e. around the EL measured by the stakes before the APs, and from ~ – 300 mm w.e. to ~ – 100 mm w.e. after the APs. The APs gained the mass of 41 ± 15 mm w.e. on average for the Muz Taw Glacier. The average mass gain after the APs (18 Aug – 24 Aug) accounted for 17% of the average loss before the APs (12 Aug – 18 Aug). The mass gain is more significant in the part lower than the EL while less around and above the EL.

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), the amounts of precipitations, and the surface albedo of the measurements from 12 to 18 August (t_1) and from 18 to 24 August (t_2) (Table 1), respectively. The two periods represent the time before and after the APs, respectively. The estimated MBs after interpolating the stake MBs 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, the mass loss of the glacier was 40% lower than t_1. More precipitation and higher albedo resulting from the APs during t_2 can explain the less mass loss. Therefore, artificial precipitations may significantly mitigate the melting of the glacier.

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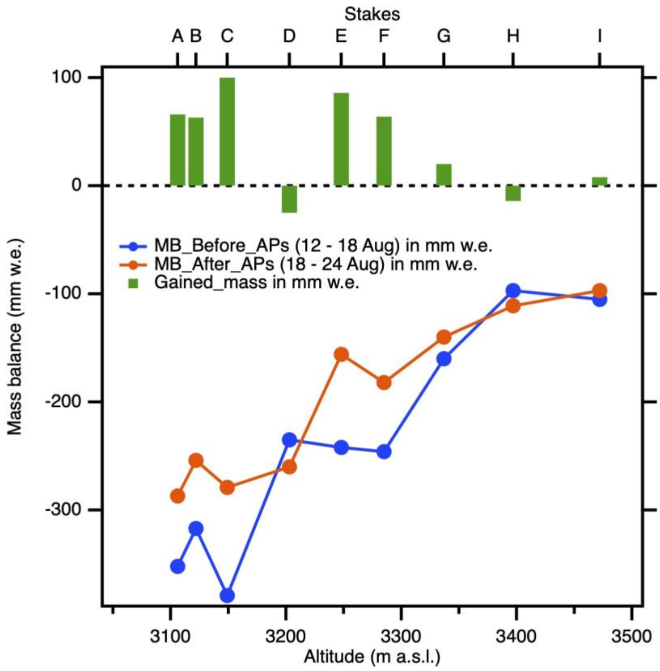

Figure 7 The averaged MBs measured at the sites (Stake A - I) before (blue) and after (orange) the APs on 18 and 20 August compared with that on 12 August (The zero line), and the gained mass (green = orange - blue) due to the APs.

Table 1 The positive accumulated temperatures, precipitations, albedo and MBs of the glacier during the two AP experiments

Period	Positively accumulated temperature (°C)	Precipitation (mm)	Albedo	MB (mm)
t_1	17.0	17.4	0.24	-61.4
t_2	18.2	19.3	0.33	-37.2

4.4 The mechanism: how the APs mitigate the melting of glacier

Here we hypothesize a mechanism by which APs mitigate a glacier’s melting. The APs influence a glacier’s MB in three possible aspects, by snow (1), rainfall (2) and forming clouds (3), respectively (Figure 8).

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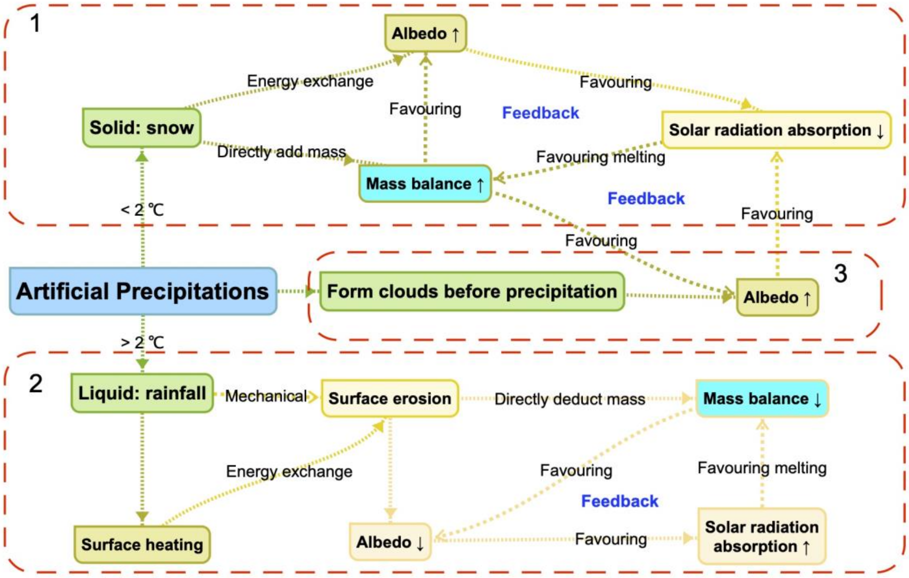

Figure 8 The hypothesized mechanism of the AP mitigating the melting of glacier in three aspects (marked in number 1, 2 and 3).

In the air temperature lower than 2 °C, the AP promotes the form of snow which directly adds mass onto the glacier and increases the MB of the glacier and thereby albedo; the snow cools the surface by energy exchange and increases the surface albedo; the increased albedo will decrease the solar radiation absorption in the surface and favour retaining the MB which will, in turn, save the albedo; and eventually the whole process forms a positive feedback (Aspect 1 in Figure 8).

When the air temperature is higher than 2 °C during the AP experiment, rain will fall onto the surface, warm the surface by energy exchange and cause its erosion physically and thermal-dynamically, leading the mass loss (Schneider et al., 2007); the eroded surface decreases its albedo, which increases the solar radiation absorption, favours the melting and trends the negative MB; the albedo of the losing-mass glacier will decrease; and therefore the complete process forms a positive feedback too (Aspect 2 in Figure 8).

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The AP experiment will favour the forming of clouds over the glacier. The surface albedo of a glacier under clouds would be 5% - 15% higher than in clear sky (Grenfell and Perovich, 2008; Jonsell et al., 2003). The increased albedo will help to form another positive feedback (Aspect 3 in Figure 8).

5 Conclusions

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

The AP experiments gained the mass of 41 ± 15 mm w.e. on average for the Muz Taw Glacier, accounting for 17% of the total loss before the APs (12 Aug – 18 Aug). The mass gain was more significant in the area below the EL; while around and above the EL, it was not apparent. By interpolating the measurements of MB 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 AP experiments reduced the mass loss of the glacier by ~ 40%, although the PAT during the latter period was higher than the former.

We also propose a possible mechanism describing the role of precipitation in mitigating the melting of the glacier. The mechanism determines that the environmental temperature and the form of precipitation, 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 in future.

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