Characteristics of mountain glaciers in the northern Japanese Alps

Kenshiro Arie[1], Chiyuki Narama[2], Ryohei Yamamoto[1,3], Kotaro Fukui[4], Hajime Iida[4]

[1]Graduate School of Science and Technology, Niigata University,8050 Igarashi2-Cho, Nishi-Ku, Niigata, 950-2181
[2]Program of Field Research in the Environmental Sciences, Niigata University,8050 Igarashi2-Cho, Nishi-Ku, Niigata, 950-2181
[3]Aero Asahi Corporation Spatial Information Infrastructure, 350-1165
[4]Tateyama Caldera Sabo Museum, 68 Ashikuraji-bunazaka, Tateyama-machi, Toyama, 930-1405

Correspondence to: Kenshiro Arie (kenshiroarie@gmail.com)

Abstract. In 2012, three perennial snow patches in the northern Japanese Alps were determined to be very small glaciers (VSGs: <0.5km^2). These were soon followed by four more nearby. However, it had not been determined how such glaciers could be maintained in such a warm climate. In this study, we calculate the annual mass balance, accumulation depth, and ablation depth ~~annual and seasonal mass balances~~ of five of these VSGs, covering 2015–2019 for four of them (2017–2019 for the fifth) using multi-period digital surface models (DSMs) based on structure from motion–multi-view stereo (SfM–MVS) technology and images taken from a small airplane.

The results indicate that, due to snow ~~mass~~ acquired from avalanches and snowdrifts, these VSGs are maintained by the accumulation in winter ~~acquiring an winter balance~~ that is more than double that from the snowfall ~~amount~~, thereby exceeding the ablation in summer ~~balance~~. Therefore, we classify them as topographically controlled VSGs. We find very small yearly ~~almost no annual~~ fluctuations in their ablation depth ~~summer balance~~; however, their annual mass balance and accumulation depth ~~winter balance,~~ have large annual fluctuations. The annual mass balance, which mainly depends on the accumulation depth ~~winter balance~~, showed accumulation throughout each glacier during heavy snow years and ablation throughout each glacier during light snow years. This characteristic differs from the upper accumulation area and lower ablation area that exists on most glaciers. These VSGs had a lack of positive annual mass balance gradient ~~negative annual balance gradients~~, which suggests that they are not divided by a distinct glacier ELA into an upstream accumulation area and a downstream ablation area ~~they did not have an equilibrium line during the observation period~~. Moreover, comparing to other glaciers worldwide, we find the mass balance amplitude of glaciers in the northern Japanese Alps to be the highest measured to date.

1 Introduction

More than 100 perennial snow patches are distributed throughout the northern Japanese Alps (Higuchi and Iozawa et al., 1971~~80~~), with some containing glacial ice as determined by the density (at least 830 kg m^{-3}) (Sakita, 1931; Ogasahara, 1964; Tsuchiya, 1978; Kawashima et al., 1993; Kawashima, 1997). Since the 1960s, researchers have tried to determine which ones are glaciers, but the difficulty of measuring flow stymied the earlier efforts (Fukui et al., 2018). However, recently smaller, more accurate surveying instruments have been developed that allow the measurement of ice thickness using groundpenetrating radar ~~(GPR)~~. Using these instruments together with the cm-scale accuracy of global navigation satellite system (GNSS) surveys, several groups measured the ice thickness and horizontal flow velocity of seven perennial snow patches in the region, finding them to be active glaciers, subsequently named Gozenzawa, Sannomado, Komado, Kakunezato, Karamatsuzawa, Kuranosuke, and Ikenotan (Fukui and Iida, 2012; Fukui et al., 2018; Arie et al., 2019). As they are less than 0.5 km^2 in area, they are classified as very small glaciers (VSGs) (Huss, 2010; Huss and Fischer, 2016).

In general, glaciers form and change in response to their mass balance, which is determined by the accumulation of primary snowfall and ablation of primary snow. Therefore, to understand the factors contributing to glacier formation and persistence, one must measure accumulation and ablation (Ohmura, 2010). Accumulation and ablation can be substituted by winter and summer balances~~, also called the seasonal balance~~ (Ohmura, 2011). This approach should also apply to VSGs.

The accumulation and ablation ~~seasonal balance~~ incorporate~~s~~ the geographical characteristics of glaciers, and are ~~is~~ crucial for assessing the relationship between the climatic environment and glacier mass balance (Dyurgerov and Meier, 1999; Huss et al., 2008; Ohmura, 2011; Pelto et al., 2019). A related quantity is the mass balance amplitude, which Meier (1984; 1993) defines as half of the sum of the absolute values of the winter and summer mass balances. In the Glossary of Mass Balance and Related Terms (Cogley et al., 2011), the mass balance amplitude tends to be higher for glaciers in maritime climates than those in continental climates due to the former having higher accumulation.

In the northern Japanese Alps, Fukui et al. (2018) measured the mass balance of the Gozenzawa G~~g~~lacier using the stake, or glaciological, method. Their study indicated that the mass balance in 2012−2015 had accumulation throughout, whereas in 2015−2016, it had ablation throughout. The characteristic of accumulation or ablation throughout has also been reported in the VSGs in the European Alps (Colucci et al., 2021). In addition, they showed that avalanches contributed significantly to the accumulation of Gozenzawa Glacier. However, the stakes were measured only twice, in the autumns of 2012 and 2016, the accumulation and ablation ~~seasonal balance~~ not being determined. For measuring accumulation and ablation ~~winter and summer balances~~, the stake method is not reliable in the northern Japanese Alps because the stakes are buried under heavy snowfall during winter. In some years, they remain buried even at the end of the snowmelt season.

Although some characteristics of VSGs that persist in warm environments at middle latitudes (here: 36.57°–36.69°N) and low altitudes (here: 1,750–2,770 m) have been explored, the mechanisms by which the VSGs in the northern Japanese Alps are formed and maintained remain unclear. To clarify the mass balance characteristics of these VSGs, we measured the annual mass balance, accumulation depth, and ablation depth ~~annual and seasonal mass balance~~ of five VSGs in the northern Japanese Alps using a geodetic method. The geodetic method obtains the change in volume ~~mass~~ by evaluating the elevation change of the entire glacier surface between two dates (Ohmura, 2010, 2011). This method has been used in recent years to measure the mass balance of many glaciers because it can obtain data for parts of the glacier that are difficult to access and observe on-site (Brun et al., 2016; Dussaillant et al., 2019; Vincent et al., 2021).

Here, we calculate the annual mass balance, accumulation depth, and ablation depth ~~annual and seasonal mass balance~~ of four VSGs in 2015–2019 and for one VSG in 2017–2019 by comparing multi-period digital surface models (DSMs) created using structure from motion–multi-view stereo (SfM–MVS) software and aerial images taken from a small airplane. We also compare the mass balance amplitude and mass balance profile of VSGs in the northern Japanese Alps with those of other glaciers worldwide. In addition, we discuss the characteristics of the mass balance profile of VSGs based on the profile of the altitude changes.

2 Study area

The climate of the northern Japanese Alps is greatly influenced by the winter monsoon and Tsushima warm current in the Sea of Japan. During the winter monsoon, a dry cold air mass from the continent passes over the Tsushima warm current, gaining heat and water vapor, then undergoes topographic updraft, producing some of the heaviest snowfall worldwide over the northern Japanese Alps (Nosaka et al., 2019; Kawase et al., 2020). In addition, the winter eastwesterly winds supply much snow to the east side of the mountain ridge due to snowdrifts deposits (Suzuki and Sasaki, 2019). Over 80% of perennial snow patches are also distributed on the east side of the mountain ridge (Asahi, 2013). Based on the wind speed data at the near Mt. Hakubadake (2740 m) observed during December in 2010, January, February, March in 2011 by the Research Center for Mountain Environment of Shinshu University, monthly average data of a maximum wind speed are 23.5, 34.9, 23.3, and 25.9 m s^{-1} respectively. Wind directions are mainly west and northwest during the observation period. Moreover, an average monthly temperature in January 2011 observed at the same place is -18.0 ℃; an average temperature in July 2011 is 11.9 ℃; an average annual temperature in 2011 is -2.3 ℃. For example, t The average snow depth at Tateyama Murododaira (~2,450 m; Fig. 1), located at the west side of the mountain ridge, in March during 1996–2018 was about 6.8 m (Iida et al., 2018).

In this study, we focus on five VSGs in the northern Japanese Alps (Fig. 1). Briefly, their characteristics and environments are as follows. The Gozenzawa Glacier (Fig. 2a) lies on the eastern side of Mt. Oyama (3,003 m), at the bottom of the north-eastern curve in the Gozenzawa valley. The Sannomado Glacier (Fig. 2b) lies sits at the bottom of the glacial trough erosion valley between the Sannomado and Hachimine ridges, and trends east–southeast. The Komado Glacier (Fig. 2b) lies at the bottom of the glacial trough erosion valley between the southeast side of Mt. Ikenotaira (2,561 m) and the Sannomado ridge, and trends east–southeast. The Kakunezato Glacier (Fig. 2c) is at the head of the glacial trough erosion valley extending northeast from the northern peak of Mt. Kashima-Yarigatake (2,842 m). The Karamatsuzawa Glacier (Fig. 2d) lies at the head of the glacial trough erosion valley extending northeast from the northern peak of Mt. Karamatsu (2,696 m). These glaciers are located at trough bottom surrounded by steep bedrock in the east part of the mountain ridge. This means snow avalanches and snowdrifts contribute largely to the accumulation of the entire glacier.

The bedrock surrounding the Sannomado and Komado Glaciers is diorite, whereas that for the Gozenzawa and Kakunezato Glaciers is granite and that for the Karamatsuzawa Glacier is serpentine. These geological differences influence the differing amounts of sediment on the glacier surfaces. In particular, the Sannomado and Komado Glaciers are clean-type glaciers with little few debris, whereas the Gozenzawa, Kakunezato, and Karamatsuzawa Glaciers have a debris-covered area in their middle and terminal regions during ablation years.

For further details about these glaciers, see Table 1 (also, Fukui and Iida 2012; Fukui et al. 2018; Arie et al. 2019).

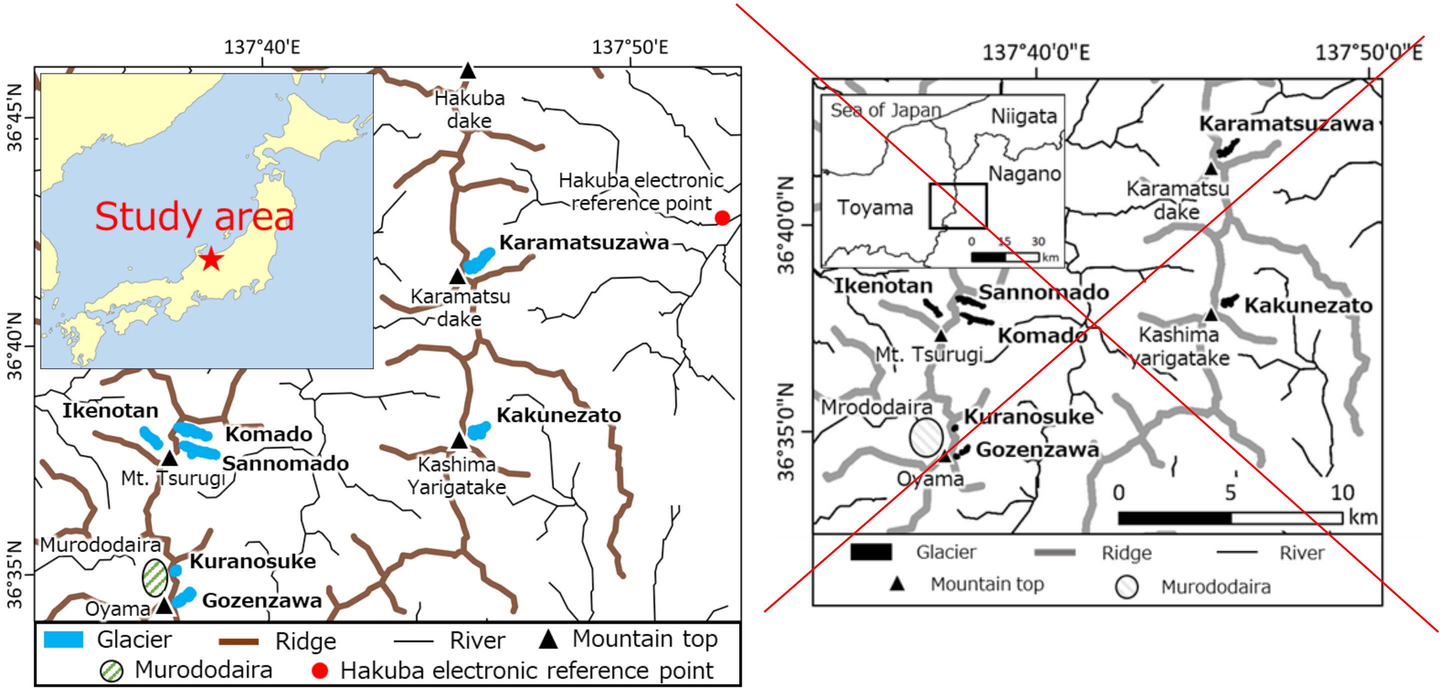


Figure 1 Seven glaciers in the northern Japanese Alps (names in bold font).

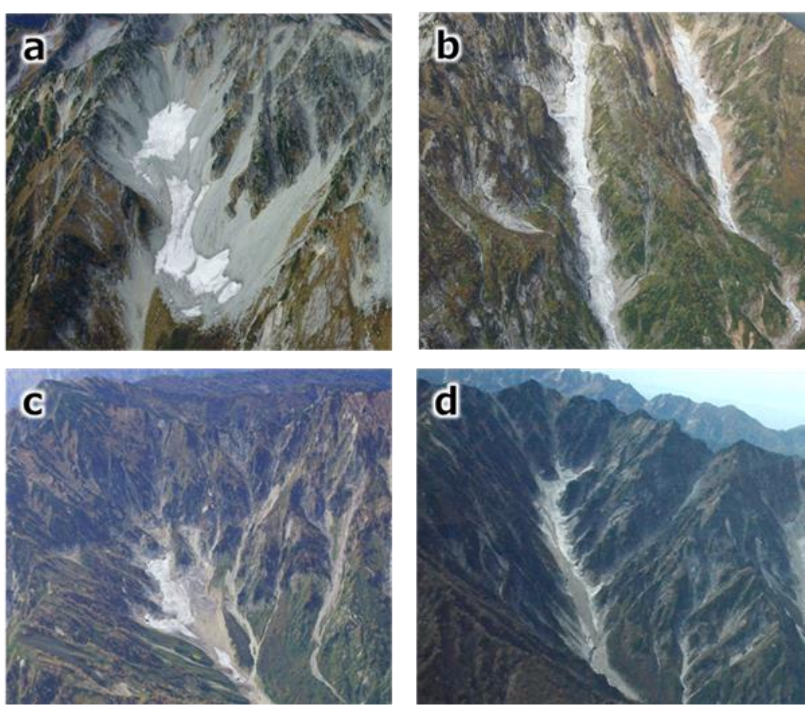


Figure 2 The five very small glaciers (VSGs) in this study at the end of snowmelt season in 2016. a) Gozenzawa. b) Sannomado (left), Komado (right). c) Kakunezato (left). d) Karamatsuzawa. All taken on Sep. 30.

Table 1 Physical properties of the glaciers. Maximum depth and maximum horizontal velocity at Gozenzawa, Sannomado, Komado, Kakunezato Glacier were showed in Fukui et al. (2018).

Glacier	Gozenzawa	Sannomado	Komado	Kakunezato	Karamatsuzawa
Length (m)	760	1420	1270	740	1080
maximum width (m)	200	110	210	250	150
Area (km²)	0.074	0.101	0.109	0.087	1.034
Altitude range (m)	2510-2770	1760-2500	1910-2300	1800-2150	1750-2350
Average inclination (°)	19.9	27.7	20.4	25.6	26.4
maximum depth (m)	27	48	30>	30>	35
maximum horizontal velocity (m a^{-1})	0.63	3.65	3.77	2.39	3.15

Glacier	Gozenzawa	Sannomado	Komado	Kakunezato	Karamatsuzawa
Length (m)	760	1420	1270	740	1080
Maximum width (m)	200	110	210	250	150
Area (km²)	0.074	0.101	0.109	0.087	0.103
Altitude range (m)	2510-2770	1760-2500	1910-2300	1800-2150	1750-2350
Average inclination (°)	18.9	27.5	17.1	25.3	26.1
Maximum depth (m)	27	48	30>	30>	35
Maximum horizontal velocity (m a^{-1})	0.63	3.65	3.77	2.39	3.15

3.1 Methods

3.1 Data acquisition

We determine the altitude changes (annual, winter, summer) ~~seasonal and annual mass balances~~ of the five glaciers by comparing multi-period DSMs created using aerial images and SfM-MVS software. The images were taken under clear weather with few clouds from a small Cessna aircraft at the end of the snowmelt season (late September to early October) and during the maximum snow depth season (late March to early April) from 2015 to 2019. These shooting days were 9 Oct. 2015, 16 Mar. and 30 Sep. 2016, 5 Apr. and 30 Sep. 2017, 10 Apr. and 3 Oct. 2018, 18 Mar., and 16 Oct. 2019.

The cameras were a Sony α7II (24.3 million pixels) from 2015 (end of snowmelt season) to 2018 (maximum snow depth season) and a Sony α7RII (42.4 million pixels) from 2018 (end of snowmelt season) to 2019 (end of snowmelt season). Images were taken every 2 s to obtain a complete view of the entire glacier and surrounding terrain from an ~~at the~~ altitude range of 3,500–3,800 m. The AUTO mode was used from 2015 (end of snowmelt season) to 2017 (maximum snow depth season). From 2017 (end of snowmelt season) to 2019 (end of snowmelt season), we used a shutter setting of less than 1/1600 s, and an ISO of 100–200, with the F value set to automatic. The flight route first visits Gozenzawa, then Sannomado, Komado, Karamatsuzawa (from 2017), and Kakunezato Glaciers.

The observation period included both light and heavy snow years. For 1996–2018, the measured snow depths at Tateyama Murododaira (2,450 m) were the lowest in 2016 and second-highest in 2017 (Iida et al., 2018).

3.2 SfM-MVS analysis

SfM is a calculation technique that allows automatic camera position determination in three-dimensional (3D) space. After estimating the camera positions, we use additional dense image-matching algorithms such as MVS to calculate the dense 3D point cloud of the surveyed object on an arbitrary relative scale (Piermattei et al., 2015). This relative scale must then be converted into an absolute scale to obtain geometric measurements using real-world coordinates or a known field distance (Dai et al., 2014).

Creating a DSM is as follows. First, high-density point cloud data are created from continuous aerial images using SfM-MVS. Next, multiple (three or more) ground control points (GCPs) are defined in the created point cloud data and geometrically corrected. Finally, these corrected data are used to create a DSM. Setting the GCPs is the only manual work in this process because PIX4Dmapper ~~Pix4dmapper~~ automates the first and last steps.

We set the GCPs using a DSM (resolution: 0.5 m) created from both aerial laser survey data (from the Ministry of Land, Infrastructure, Transport and Tourism) and orthophoto-corrected images of aerial images obtained at the time of the survey. The error in the height direction of the aerial laser survey data is 0.4–0.6 m in a region with large undulations (Sato et al., 2004). The aerial laser survey data are from the end of the snowmelt season in 2009 for the Sannomado and Komado Glaciers, in 2010 for the Kakunezato Glacier, in 2011 for the Gozenzawa Glacier, and in 2014 for the Karamatsuzawa Glacier. The GCPs were positioned to surround the glacier. At the end of the snowmelt season, the GCPs were set at long-term immovable and easy-to-read buildings and rocks. In the maximum snow depth season, GCPs were set at an exposed rock wall without snow at the same location for each image. Figure 3 shows the locations of GCPs for each glacier and period. The numbers of GCPs for each glacier at the end of the snowmelt season are 17 at Gozenzawa Glacier, 28 at Sannomado and Komado Glaciers, 17 at Kakunezato Glacier, and 17 at Karamatsuzawa Glacier. For the maximum snow depth season, these numbers are instead 5, 6, 5, and 7, respectively.

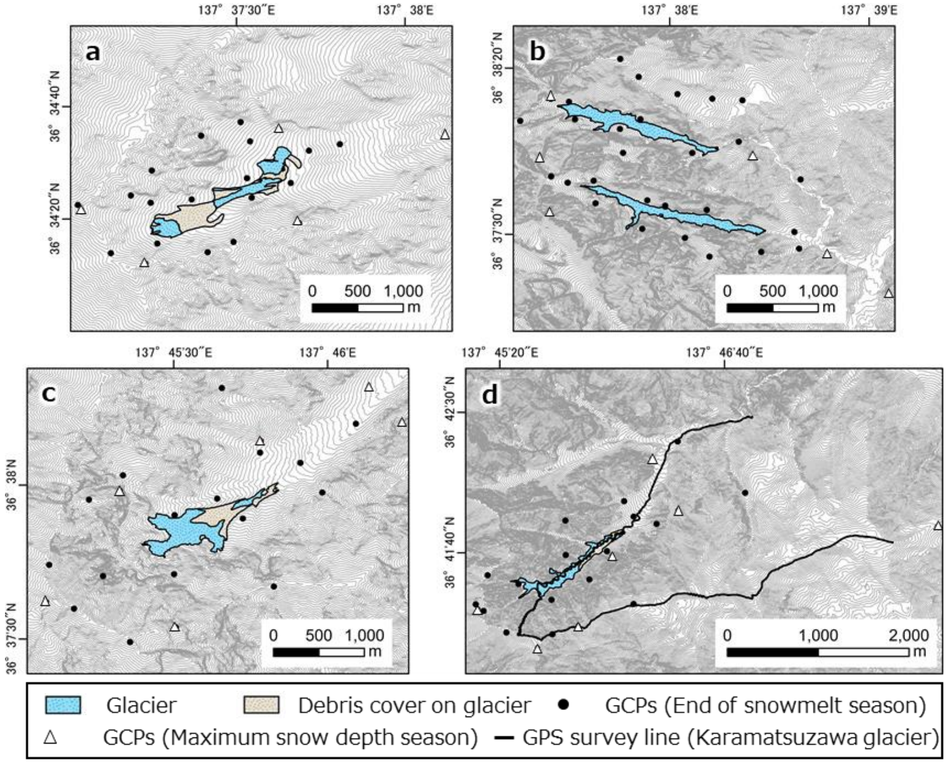


Figure 3 Glacier area and GCP locations for each glacier and season. a) Gozenzawa. b) Sannomado (lower), Komado (upper). c) Kakunezato. d) Karamatsuzawa. Black line of d is the GPS survey line ~~path~~. Contour interval is 10 m.

3.3 Geodetic mass balance determination

In the geodetic method, the mass balance of glaciers is estimated by the change in volume as judged by comparing the DSMs for two periods and multiplying the result by the estimated ice density (Huss, 2013; Piermattei et al., 2016). This estimated relative volume change equals the surface mass balance plus the vertical component of glacier flow (i.e., the emergence velocity). Therefore, to express the surface mass balance, one integrates the relative volume change for the entire glacier to remove the vertical flow component (Ohmura, 2010). The resulting mass balance B is

$$B = (\delta V \times \rho)/A \, , \qquad (1)$$

where B is expressed in m of water equivalent (m weq), δV is the relative volume change (m^3), ρ is the snow and ice density (kg m^{-3}), and A is the glacier area (m^2).

For the calculation of annual mass balance, ~~To determine δV,~~ we compare DSMs from the end of one snowmelt season to the end of the next to determine annual δV. The area A is determined at the end of the snowmelt season, an approach called a stratigraphic system (Cogley et al., 2011~~Unesco/IASH., 1970~~). The aerial images were taken just before the snow falls at the end of snowmelt season based on the stratigraphic system. However, the date has a gap of several days from a day before the snow falls, due to flight schedule and weather conditions.

Here, differences between DSMs were calculated using a geographic information system (GIS). For the ice density, the average value for Gozenawa was 695 kg m^{-3} in the top 0.7 m (570–740 kg m^{-3}) and 860 kg m^{-3} at depths below 0.7 m (824–907 kg m^{-3}) at the end of the snowmelt season (Fukui et al., 2018). In the perennial snow patches of Japan, snow transitions to glacier ice during a one-year period (Kawashima 1997); therefore, the layer between the snow surface and a depth of 0.7 m consists of residual snow from the previous winter, whereas the deeper layer consists of ice formed earlier. For annual mass balance calculations for all glaciers, we used a snow and ice density of 695 kg m^{-3} if the balance was positive and 860 kg m^{-3} if the balance was negative.

We also compared DSMs created for the maximum snow depth season with those for the end of the snowmelt season and calculated the change in relative volume during the accumulation and ablation seasons. The accumulation and ablation depth are calculated by one integrates the relative volume change for the entire glacier area. Due to the uncertainty of the winter snow density, including avalanche deposits, it is difficult to calculate the exact winter and summer balance. At Tateyama Murododaira, which is flat and not affected by the topographical influence of avalanches and snowdrifts, Iida et al. (2018) measured the density in the snow-cover cross-sections in late March 1996–2018, getting an average of 431 kg m^{-3}. In Japanese mountains, the snow density of avalanche deposits is larger than that of snowfall snow layers (Naruse et al., 1986; Abe et al., 2016). In the northern Japanese Alps, the density of avalanche deposits is 590 kg/m^3 (Shimizu et al., 1974). Therefore, we calculate the winter and summer balances using the winter snow density in the range of 431 to 590 kg/m^3 and change in relative volume during the accumulation and ablation seasons. ~~We calculate the winter and summer balances of the glaciers by~~

~~multiplying the snow density for the maximum snow depth season with the calculated volume change. At Tateyama Murododaira, Iida et al. (2018) measured the density in the snow-cover cross-sections in late March 1996–2018, getting an average of 431 kg m^{-3}, a value we use to calculate the seasonal mass balance.~~

We apply these calculations ~~densities to the annual and seasonal mass balances~~ for the Gozenzawa, Sannomado, Komado, and Kakunezato Glaciers in 2015−2016, 2016−2017, 2017−2018, and 2018−2019, as well as for the Karamatsuzawa Glacier in 2017−2018 and 2018−2019. For each glacier, the mass balance calculation uses the glacier area when this area was smallest for five years. This occurred on October 16, 2019, for Gozenzawa, Sannomado, Komado, and Karamatsuzawa Glaciers and on September 30, 2016, for Kakunezato Glacier.

3.4 Data accuracy

Following the method in Immerzeel et al. (2014), we estimate the error for the annual mass balance at the end of the snowmelt season by first creating a 10-m-wide buffer zone around the outside of the glacier area on the base area (Fig. 4). Then, we calculate the geodetic annual mass balance error as the mean and standard deviation (SD) of the altitude difference in ~~between~~ the buffer zone.

However, because the base area is covered with snow during winter, we must use a different method to estimate the accumulation and ablation depth ~~annual balance~~ error. For this estimate, we ran kinematic GPS surveys of Karamatsuzawa Glacier and the ridges of Mts. Karamatsu and Happoike-Sanso one day after the aerial photography (Fig. 3). We then equate the geodetic seasonal mass balance error as the SD of the altitude difference between the measured kinematic GPS data for March 19 and the DSM of Karamatsuzawa Glacier on March 18, both in 2019. The GPS surveying instrument was GEM-1 (Enabler; formerly GNSS Technologies), with calculated coordinates of the GPS antenna and post-processing using the open-source program RTKLIB (ver. 2.4.3) with the base station data of the 'Hakuba' electronic reference point of the Geospatial Information Authority of Japan (Fig. 1).

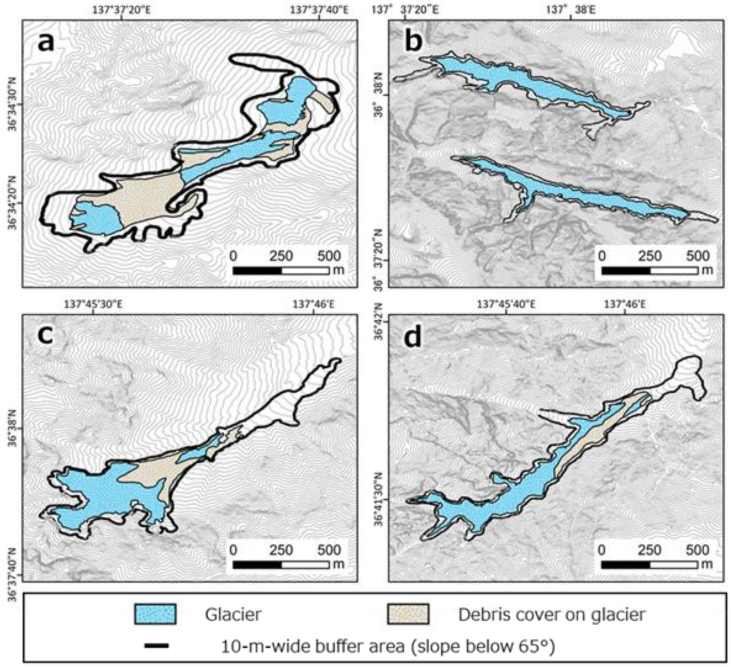


Figure 4 Glacier area and 10-m-wide buffer zone used for uncertainty estimate. a) Gozenzawa. b) Sannomado and Komado. c) Kakunezato. d) Karamatsuzawa. Contour interval is 10 m.

3.5 Mass balance amplitude

The mass balance amplitude (*α*) equals the average of the absolute values of the winter (B_w~~w~~) and summer (B_s~~s~~) balances:

$$\alpha = (|B_w| + |B_s|)/2. \quad (2)$$

Using this equation (2) with ~~these~~ winter and summer balances that calculated during 2015–2019, we estimate ~~We use this equation to determine~~ the mass balance amplitude for the Gozenzawa, Sannomado, Komado, and Kakunezato Glaciers~~, where the winter and summer balances were measured during 2015–2019~~. We then compare these four-year averages to the average mass balance amplitude of other glaciers worldwide. The worldwide glaciers were all glaciers observed for periods longer than 5 years according to the "fluctuations of glaciers" database of the World Glacier Monitoring Service (World Glacier Monitoring Service (WGMS), 2020). Glacier locations are shown in Fig. 5.

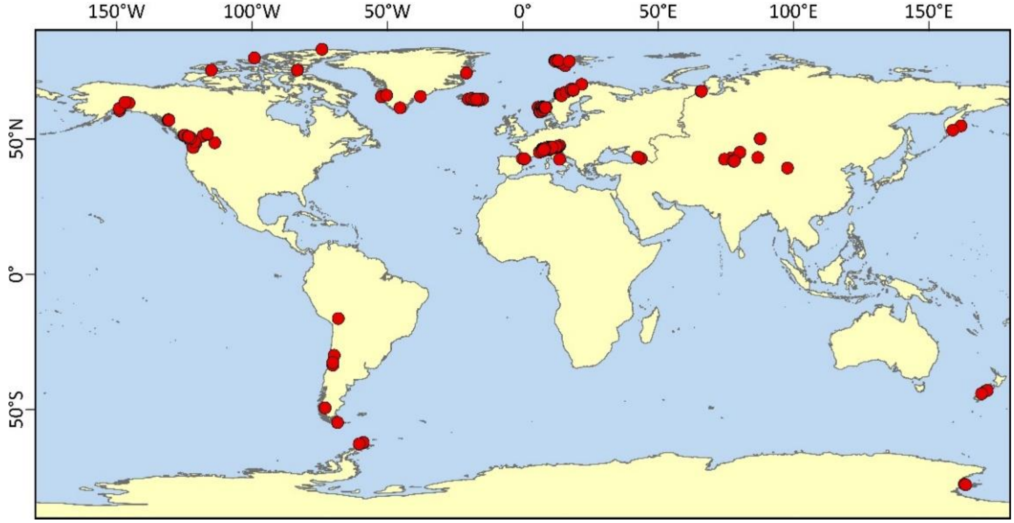


Figure 5 Glacier locations used for comparison of winter and summer balances (from WGMS, 2020). All glaciers had been observed for periods longer than 5 years~~ except those in Japan~~. ~~Each circle represents~~ The~~ following~~ numbers of glaciers in each region are: 51 in Alps,~~51 glaciers;~~ 7 in Andes, ~~7 glaciers;~~ 3 in Antarctic, ~~3 glaciers;~~ 3 in Arctic North America, ~~3 glaciers;~~ 3 in Caucasus, ~~3 glaciers;~~ 2 in Dry Valley, ~~2 glaciers;~~ 5 in Greenland, ~~5 glaciers;~~ 13 in high mountain Asia (HMA: Tien Shan, Altai, Qilian), ~~13 glaciers;~~ 12 in Iceland, ~~12 glaciers;~~ 2 in Kamchatka, ~~2 glaciers;~~3 in New Zealand, ~~3 glaciers;~~ 38 in Scandinavia, ~~38 glaciers;~~ 9 in Svalbard, ~~9 glaciers;~~ 2 in Urals, ~~2 glaciers;~~ 27 in western North America, ~~27 glaciers~~.

3.6 Mass balance profile ~~gradient~~ and emergence velocity

On many glaciers, the amounts of ablation and accumulation vary systematically with altitude and thus the mass balance has an altitude profile, and the rate at which mass balance changes with altitude is termed mass balance gradient (Benn and Evans, 2014). In general, the amount of ablation and accumulation ~~is~~ increases ~~ing~~ with altitude due to the decrease in temperature.

We divided each glacier region into 10-m altitude intervals and calculated the ~~mass balance~~ profile of altitude changes (annual, winter, summer) using the altitude changes ~~mass balance~~ of each interval. This was done for the Gozenzawa, Sannomado, Komado and Kakunezato Glaciers because they were observed for four years. ~~In addition,~~ However, due to altitudinal changes ~~differences~~ calculated by the geodetic method include both the surface mass balance and the emergence velocity (as explained at 3.3~~the vertical flow component~~). Thus, we assessed the profile including the influence of estimated emergence velocity. ~~calculating mass balance profile involves removing the influence of emergence velocity. After obtaining the mass balance profile, we derived the mass balance gradient based on mass balance profile.~~

The emergence velocity (*Ve*) is expressed using the flux method as

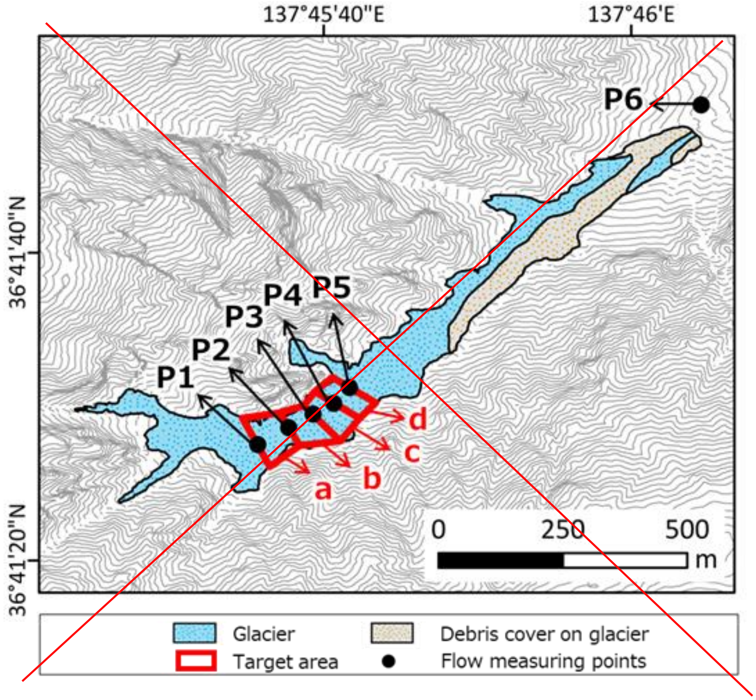
$$Ve = (Q\text{in} - Q\text{out})/(W \times x)\,, \qquad (3)$$

where Q is the ice flux into and out of the target area, W is the average glacier width, and x is the longitudinal length of the target area (Nuimura et al., 2011).

The ice flux at the boundaries of the target area is

$$Q = W \times h \times v, \tag{4}$$

where W, h, and v are the glacier width, depth, and flow velocity (Nuimura et al., 2011). For the Karamatsuzawa Glacier, we measured W and v, and use the depth measurement from an earlier study (Arie et al., 2019). For the flow v, we measured the stake locations on 22 October, 2019 using a GEM-3 GNSS surveying instrument (Enabler) and then calculated the annual flow by comparing to their locations in 2018 (Arie et al., 2019). The earlier study had inserted 4.6-m-long stakes at five points on the glacier (Fig. 6, P1–5) and used GNSS surveyors to measure the stake locations on 23 October 2018 (As a check, we also compared a base point located~~ion~~ near the glacier terminus (Fig. 6, P6) between 2018 and 2019). With the five flow measurements, we determine *Ve*. We then use the maximum value as the mass balance profile error for four glaciers.



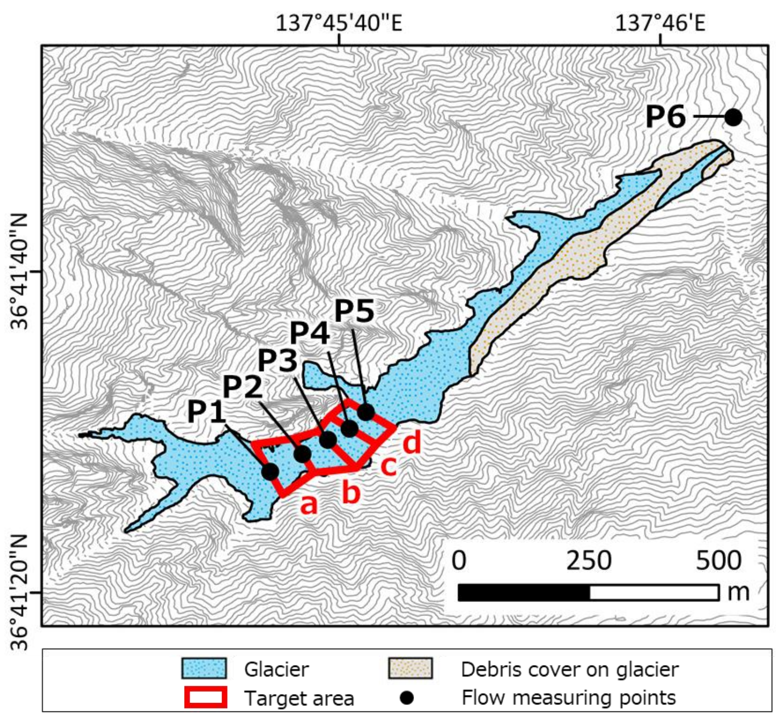


Figure 6 Target area for emergence velocity estimation and flow measurement point in the Karamatsuzawa glacier. Contour interval is 10 m.

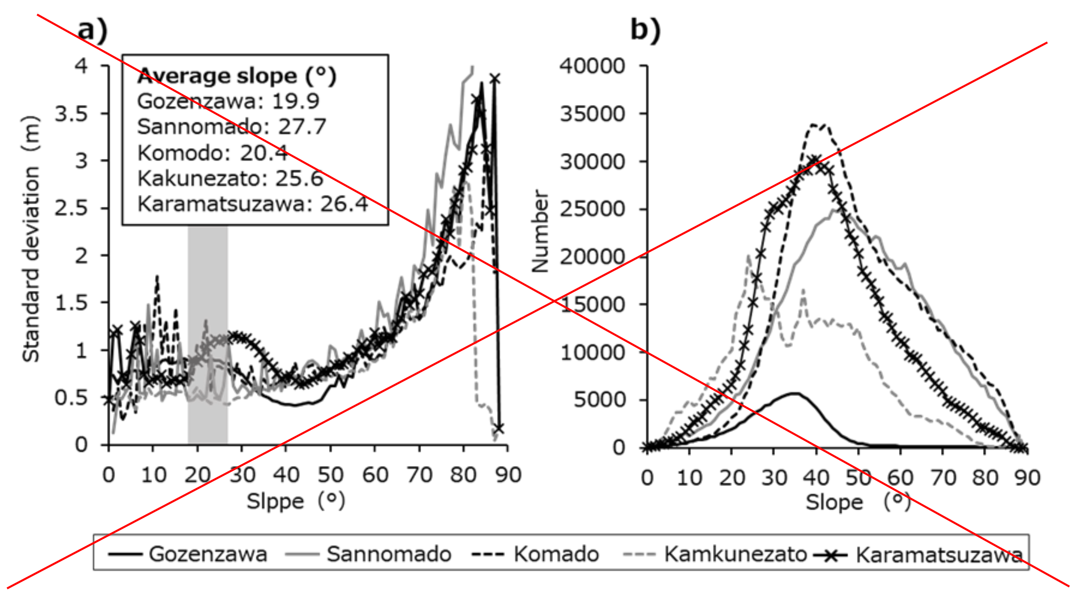
4 Results

4.1 Data accuracy

For the different DSMs, the SD of differences in slope within the 10 m buffer zone around the glacier area increases with the slope of the terrain, particularly above 60°, as shown in Fig. 7a. Such an increase is consistent with the finding of Piermattei et al. (2016). However, regions with a slope below 65° account for over 75% of the total buffer area (Fig. 7b).

Thus, we evaluated the value in the region of the polygon with an inclination of 65° or less. Table 2 shows that all mean and SD values are below 1 m, except for 2018-2019 on Komado Glacier where the SD is 1.11 m. As the glacier slopes and buffer regions sloped less than 65°, the annual mass balance calculation method has sufficient accuracy.

To evaluate DSM accuracy during the maximum snowfall season, the day after obtaining aerial images for this season, we obtained surface altitude data via a kinematic GPS survey. The survey was done when a researcher attached a GPS antenna to their pack, then walked the ridge between Karamatsudake and Happoike Sanso, then snowboarded down Karamatsuzawa Glacier. The mean and SD of the altitude differences between the Karamatsuzawa Glacier DSM (March 18, 2019) and that from the GPS data (March 19, 2019) are 1.89 and 1.73 m, respectively. Assuming an average height of 1.5 m from the ground to the antenna (on the pack), the mean and SD of the altitude difference between the DSM and GPS survey data are 0.39 and 1.73 m, respectively. We used this SD value as the altitude-difference error for the winter and summer seasons. ~~Then, using 431 kg m^{-3} as the mean ice density (late March value at Tateyama Murododaira), the calculated error between the winter and summer balances is ± 0.75 m weq.~~



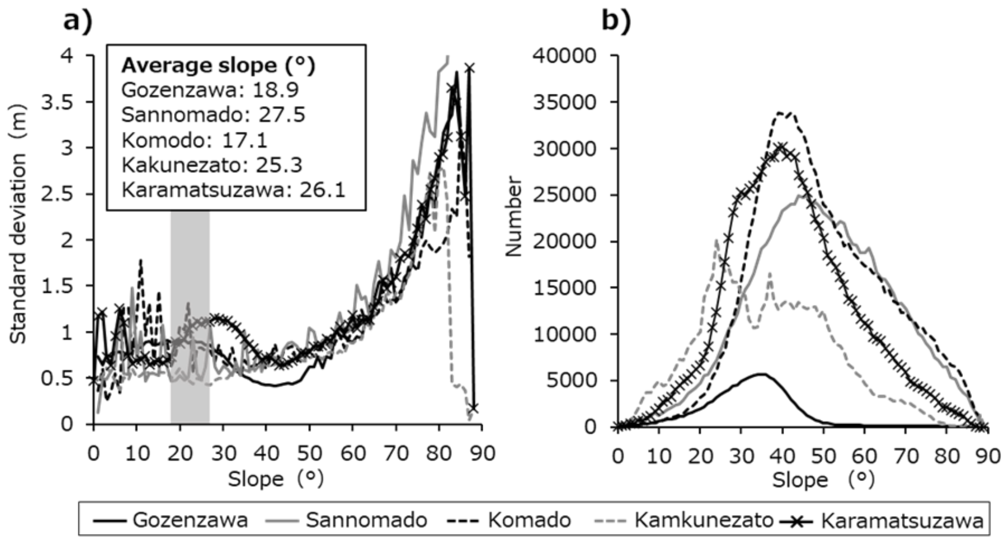


Figure 7 Comparison of the DSMs for the end of the 2017 and 2018 end of snowmelt seasons. a) The standard deviation SD of differences in slope between the different DSMs used. b) The number of pixels within the 10 m buffer around the glacier area. Shaded band along abscissa axis is the range of average slopes of the five glaciers.

Table 2 Mean and SD of the altitude differences (m) in the DSMs for the 10-meter-wide polygon around each glacier ~~glacier buffer regions~~ with an inclination of 65° or less in the given years. In parentheses are the mean slopes in the 10-meter-wide polygon around each glacier.

Year	Gozenzawa (31°)		Sannomado (44°)		Komado (43°)		Kakunezato (36°)		Karamatsuzawa (42°)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
2015-2016	0.1	0.55	-0.81	0.96	-0.66	0.87	-0.6	0.85		
2016-2017	-0.15	0.3	0.38	0.99	0.37	0.73	-0.12	0.79		
2017-2018	-0.04	0.33	-0.06	0.9	-0.01	0.81	-0.33	0.62	-0.07	0.92
2018-2019	0.2	0.29	-0.37	0.85	-0.08	1.11	-0.28	0.74	0.24	0.88
Average	0.03	0.37	-0.22	0.93	-0.10	0.88	-0.33	0.75	-0.07	0.92

year	Gozenzawa (31°)		Sannomado (44°)		Komado (43°)		Kakunezato (36°)		Karamatsuzawa (42°)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
2015-2016	0.10	0.55	-0.81	0.96	-0.66	0.87	-0.60	0.85		
2016-2017	-0.15	0.30	0.38	0.99	0.37	0.73	-0.12	0.79		
2017-2018	-0.04	0.33	-0.06	0.90	-0.01	0.81	-0.33	0.62	-0.06	0.89
2018-2019	0.20	0.29	-0.37	0.85	-0.08	1.11	-0.28	0.74	0.29	0.81
Average	0.03	0.37	-0.22	0.93	-0.10	0.88	-0.33	0.75	0.12	0.85

4.2 Mass balance

For all glaciers, the annual mass balance is negative in all years except 2016-2017 (Table 3), a heavy snow year. All glaciers are also consistent in all having their largest mass reduction in 2015-2016, a light snow year. In this year, the ablation area extends throughout each glacier (first column, Fig. 8), whereas in the heavy snow year that followed (2016-2017), each glacier is entirely an accumulation area (second column, Fig. 8). These characteristics agree with Fukui et al.'s (2018) findings for the Gozenzawa Glacier.

For the accumulation depth ~~winter and summer balances~~, the values for all glaciers are 13-30 m ~~-11 m weq~~, as shown in Table 4. We can compare this value to the average snow depth of 6.8 m on Tateyama Murododaira (1996–2018) (Iida et al., 2018). ~~Considering that the average value of the mean density here is 431 kg m^{-3}, this snow amount is 2.93 m weq.~~ Unlike the glaciers, the terrain at Tateyama Murododaira (2,450 m) is flat and not affected by the topographical influence of avalanches and snowdrifts. But in the northern Japanese Alps, the glaciers had an accumulation depth ~~a winter balance~~ of 13-30 m ~~5-11 m weq~~, or over 2-4 times as much as the snow depth ~~amount~~ at Tateyama Murododaira. Presumably, this additional accumulation ~~winter balance~~ is from avalanches and snowdrifts.

Between the light and heavy snow years, the accumulation depth ~~winter balance~~ increases by about 8-11 m ~~3-5 m weq~~ (Table 4), whereas their ablation depth ~~summer balance~~ remains about the same. This difference in behaviour between summer and winter can be seen to occur throughout the four-year period in the plots in Fig. 9. Namely, the ablation depth ~~summer balance~~ is much less variable ~~remains nearly constant~~ compared to the variations in the annual mass balance and accumulation depth ~~winter balances~~.

The cumulative mass balances are shown in Fig. 10. From 2015 to 2019, the trends show a significant mass loss, decreasing by 4-5 m weq for the Gozenzawa and Kakunezato Glaciers, which had debris cover. For the ~~for~~ Sannomado and Komado Glaciers, which did not have debris cover, the loss is larger, at 7-9 m weq. The Karamatsuzawa Glacier also has a significant mass loss, though the period covered is only three years (2017-2019). These balances are closely correlated between the five glaciers over this period (Figs. 9 and 10).

Table 3 Relative altitude change, and annual mass balance of each glacier ~~(surface area in parenthesis)~~ calculated from comparison of the DSMs at the end of snowmelt season. Corrected data were calculated using Mean and SD in Table 2. We subtract the mean value of the difference in the buffer zone from the value of the difference on the glaciers. The SD of buffer zone is used as the error (±).

Gozenzawa (74093m²)

Year	Relative altitude change (m)		Relative volume change (m³)		Annual mass balance (m weq)	
	Original	Correction	Original	Correction	Original	Correction
2015-2016	-3.46	-3.56±0.55	-256362	-263771±40751	-2.98	-3.06±0.47
2016-2017	1.88	2.03±0.30	139295	150408±22228	1.31	1.41±0.21
2017-2018	-1.80	-1.76±0.33	-133367	-130403±24451	-1.55	-1.51±0.28
2018-2019	-1.30	-1.50±0.29	-96321	-111139±21487	-1.12	-1.29±0.25

Sannomado (101040m²)

Year	Relative altitude change (m)		Relative volume change (m³)		Annual mass balance (m weq)	
	Original	Correction	Original	Correction	Original	Correction
2015-2016	-8.01	-7.2±0.96	-809330	-727488±96998	-6.89	-6.19±0.83
2016-2017	3.53	3.15±0.99	356671	318276±100030	2.45	2.19±0.69
2017-2018	-1.13	-1.07±0.90	-114175	-108113±90936	-0.97	-0.92±0.77
2018-2019	-3.72	-3.35±0.85	-375869	-338484±85884	-3.20	-2.88±0.73

Komado (109390m²)

Year	Relative altitude change (m)		Relative volume change (m³)		Annual mass balance (m weq)	
	Original	Correction	Original	Correction	Original	Correction
2015-2016	-7.85	-7.19+0.87	-858704	-786507±95169	-6.75	-6.18±0.75
2016-2017	2.67	2.3±0.73	292069	251595±79854	1.86	1.60±0.51
2017-2018	-0.82	-0.81±0.81	-89699	-88605±88606	-0.71	-0.70±0.70
2018-2019	-4.02	-3.94±1.11	-439744	-430993±121423	-3.46	-3.39±0.95

Kakunezato (86870m²)

Year	Relative altitude change (m)		Relative volume change (m³)		Annual mass balance (m weq)	
	Original	Correction	Original	Correction	Original	Correction
2015-2016	-5.71	-5.11±0.85	-496028	-443905±73836	-4.91	-4.39±0.73
2016-2017	3.54	3.54±0.79	307520	317944±68627	2.46	2.54±0.79
2017-2018	-2.19	-2.19±0.62	-190245	-161578±53859	-1.88	-1.59±0.53
2018-2019	-1.92	-1.64±0.74	-166790	-142466.8±64283	-1.65	-1.41±0.64

Karamatsuzawa (103400m²)

Year	Relative altitude change (m)		Relative volume change (m³)		Annual mass balance (m weq)	
	Original	Correction	Original	Correction	Original	Correction
2017-2018	-1.27	-1.01±0.92	-131318	-104434±95128	-1.09	-0.87±0.79
2018-2019	-2.08	-1.82±0.88	-215072	-188188±90992	-1.79	-1.57±0.76

Gozenzawa

Year	Relative altitude change (m)		Annual mass balance (m weq)	
	Original	Corrected	Original	Corrected
2015-2016	-3.45	-3.55 ± 0.55	-2.98	-3.06 ± 0.47
2016-2017	1.80	1.95 ± 0.30	1.31	1.41 ± 0.21
2017-2018	-1.80	-1.76 ± 0.33	-1.55	-1.51 ± 0.28
2018-2019	-1.30	-1.50 ± 0.29	-1.12	-1.29 ± 0.25

Sannomado

Year	Relative altitude change (m)		Annual mass balance (m weq)	
	Original	Corrected	Original	Corrected
2015-2016	-7.97	-7.16 ± 0.96	-6.89	-6.19 ± 0.83
2016-2017	3.58	3.20 ± 0.99	2.45	2.19 ± 0.69
2017-2018	-1.09	-1.03 ± 0.90	-0.97	-0.92 ± 0.77
2018-2019	-3.67	-3.30 ± 0.85	-3.20	-2.88 ± 0.73

Komado

Year	Relative altitude change (m)		Annual mass balance (m weq)	
	Original	Corrected	Original	Corrected
2015-2016	-7.82	-7.16+0.87	-6.75	-6.18 ± 0.75
2016-2017	2.71	2.34 ± 0.73	1.86	1.60 ± 0.51
2017-2018	-0.80	-0.79 ± 0.81	-0.71	-0.70 ± 0.70
2018-2019	-3.97	-3.89 ± 1.11	-3.46	-3.39 ± 0.95

Kakunezato

Year	Relative altitude change (m)		Annual mass balance (m weq)	
	Original	Corrected	Original	Corrected
2015-2016	-5.71	-5.11 ± 0.85	-4.91	-4.39 ± 0.73
2016-2017	3.54	3.54 ± 0.79	2.46	2.54 ± 0.79
2017-2018	-2.19	-2.19 ± 0.62	-1.88	-1.59 ± 0.53
2018-2019	-1.92	-1.64 ± 0.74	-1.65	-1.41 ± 0.64

Karamatsuzawa

Year	Relative altitude change (m)		Annual mass balance (m weq)	
	Original	Corrected	Original	Corrected
2017-2018	-1.27	-1.21±0.89	-1.09	-1.04±0.77
2018-2019	-2.08	-2.37±0.81	-1.79	-2.04±0.70

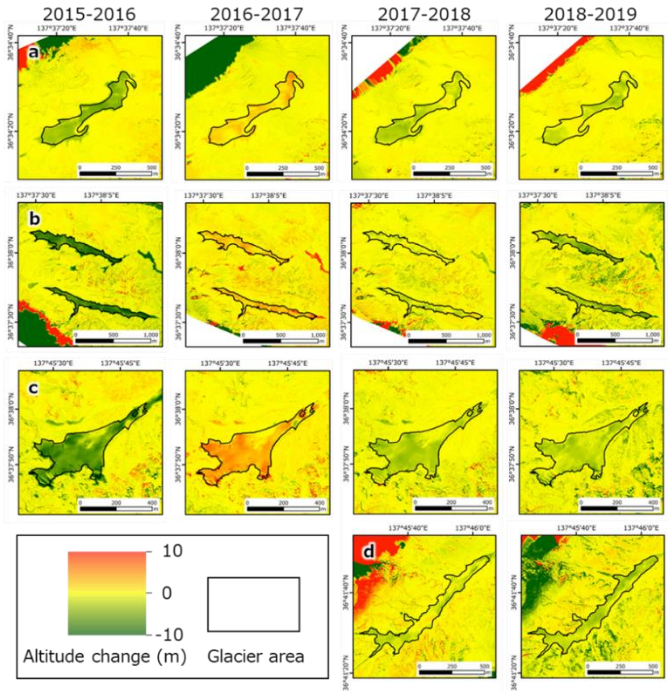
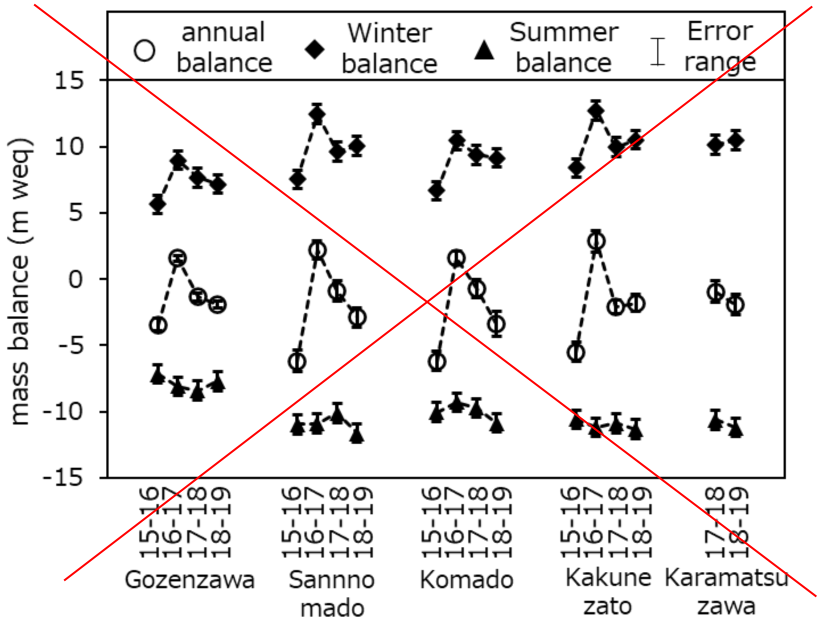


Figure 8 Annual altitude changes of each glacier and year. a) Gozenzawa. b) Sannomado (lower), Komado (upper). c) Kakunezato. d) Karamatsuzawa.

Table 4 Accumulation and ablation depth ~~Winter and summer balances~~ (m-~~weq~~).

Year	Gozenzawa		Sannomado		Komado		Kakunezato		Karamatsuzawa	
	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
2015-2016	5.63	7.16	7.52	10.97	6.65	10.04	8.38	10.59		
2016-2017	8.96	8.09	12.43	10.90	10.44	9.29	12.72	11.19		
2017-2018	7.64	8.42	9.62	10.10	9.37	9.72	9.95	10.89	10.15	10.63
2018-2019	7.16	7.72	10.03	11.64	9.14	10.87	10.51	11.34	10.45	11.21
Average	7.35	7.85	9.90	10.90	8.90	9.98	10.39	11.00	10.30	10.92
SD	1.19	0.47	1.74	0.54	1.39	0.58	1.55	0.29	0.15	0.29

Year	Gozenzawa		Sannomado		Komado		Kakunezato		Karamatsuzawa	
	Accumulation	Ablation	Accumulation	Ablation	Accumulation	Ablation	Accumulation	Ablation	Accumulation	Ablation
2015-2016	13.16	-16.61	17.49	-25.46	15.53	-23.35	19.45	-25.16		
2016-2017	20.80	-18.92	28.90	-25.32	24.28	-21.57	29.51	-25.97		
2017-2018	17.73	-19.53	22.35	-23.44	21.80	-22.60	23.08	-25.27	22.70	-23.97
2018-2019	16.61	-17.91	23.44	-27.11	20.84	-24.81	24.39	-26.31	23.99	-26.07
Average	17.08	-18.24	23.05	-25.33	20.61	-23.08	24.11	-25.68	23.35	-25.02
SD	2.73	1.11	4.06	1.30	3.19	1.18	3.61	0.48	0.65	1.05



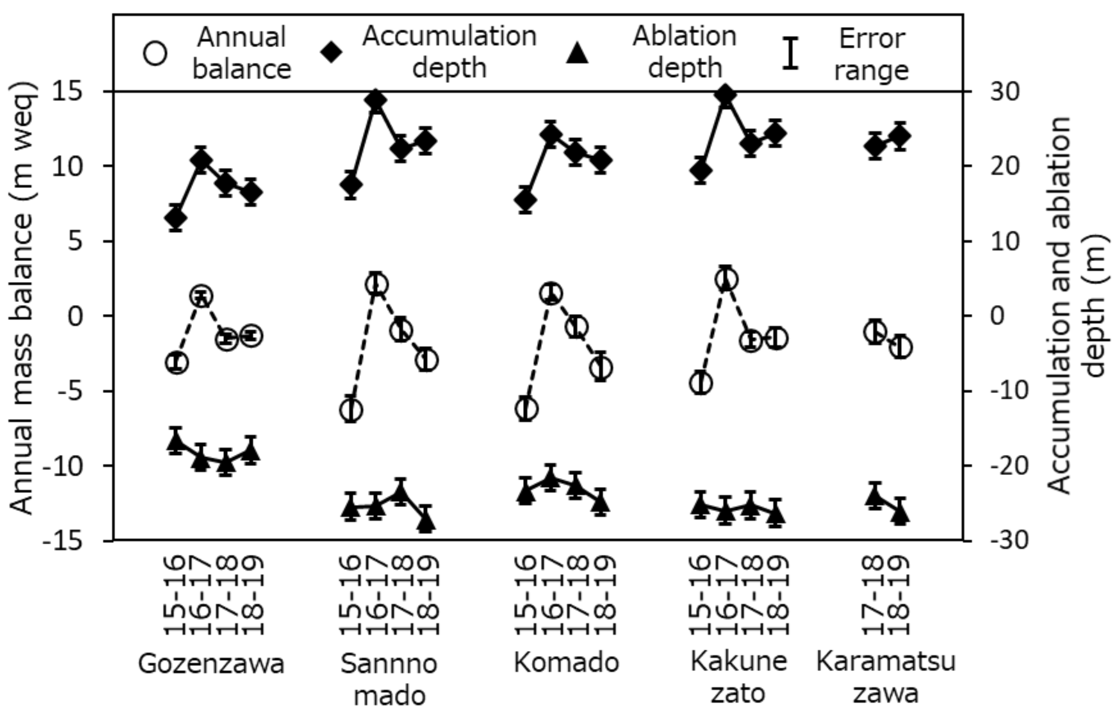
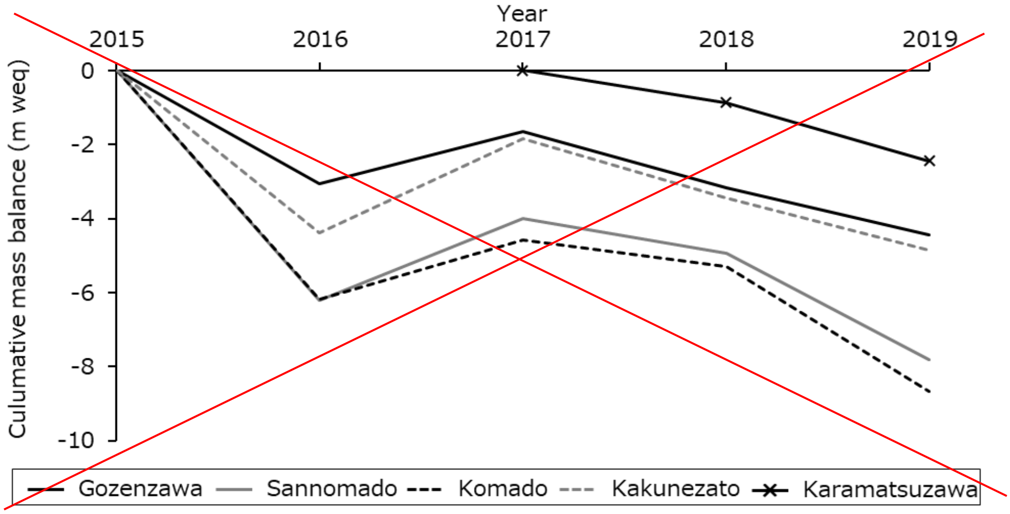


Figure 9 Annual mass balance, accumulation depth, and ablation depth ~~winter balance, and summer balance~~ of each glacier in 2015-2019.



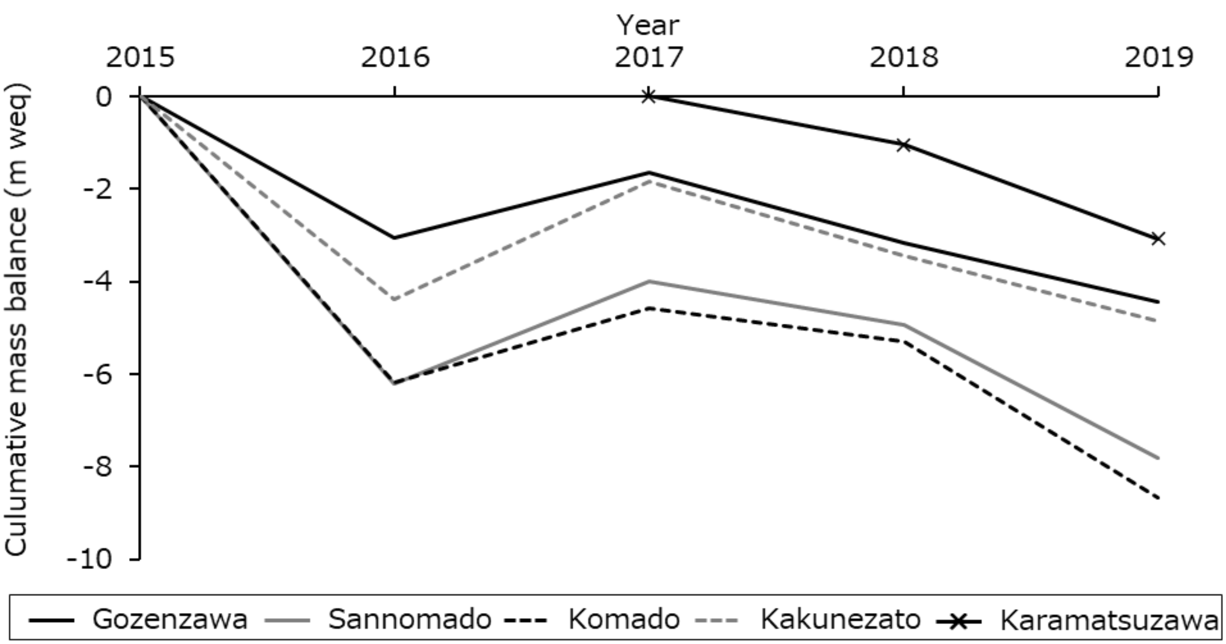


Figure 10 Cumulative mass balance of each glacier with baseline on 2015 data (2017 for Karamatsuzawa).

4.3 Mass balance amplitude

The mass balance amplitudes of these four glaciers, are much higher than glaciers studied elsewhere, even in the case of the snow density at Tateyama Murododaira is 431 kg/m³. We plot the comparison in Fig. 11. In general, the mass balance amplitudes of glaciers in polar regions and HMA (high mountain Asia) are low, and those for glaciers in maritime climates such as New Zealand and Kamchatka are higher (Cogley et al., 2011). One exception to this trend is the relatively high value for glaciers in the Urals, despite their dry, cold climate. The SD of the annual mass balance increases linearly with ~~These~~ the mass balance amplitudes ~~increase nearly linearly with the SD of the annual balance~~ as shown in Fig. 12.

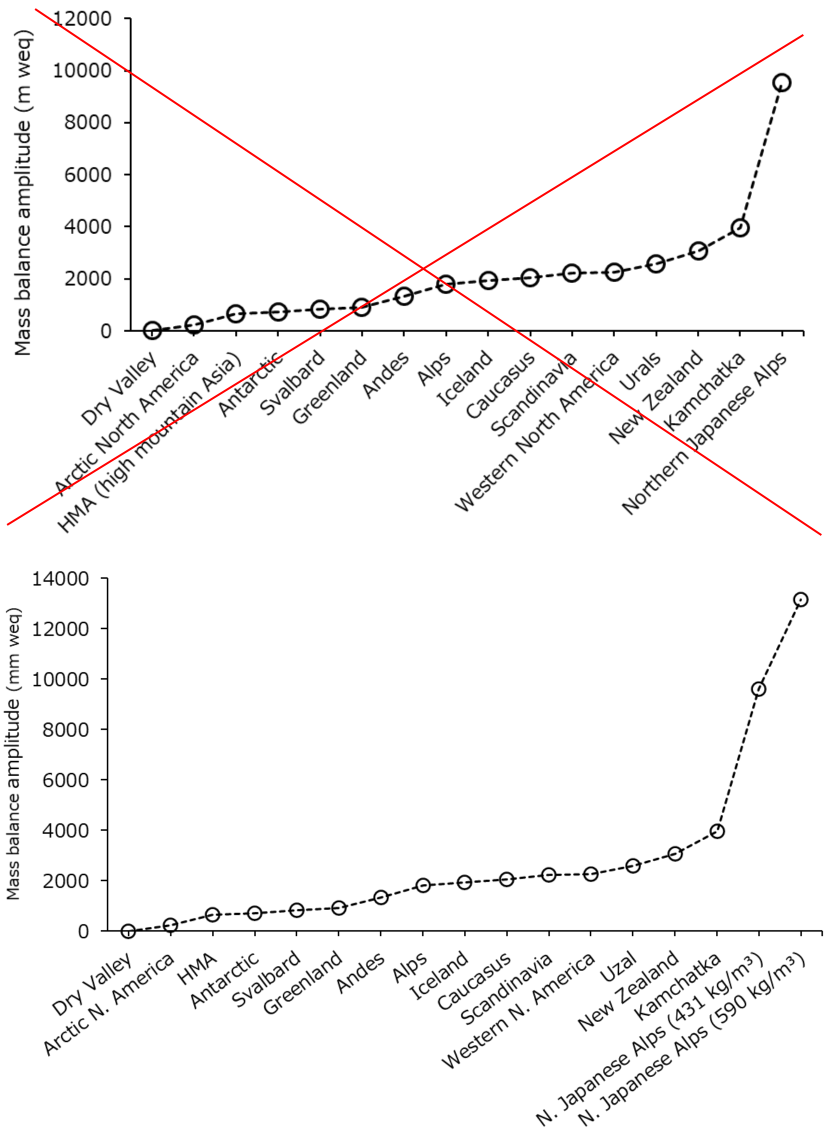


Figure 11 Mass balance amplitudes of glaciers.

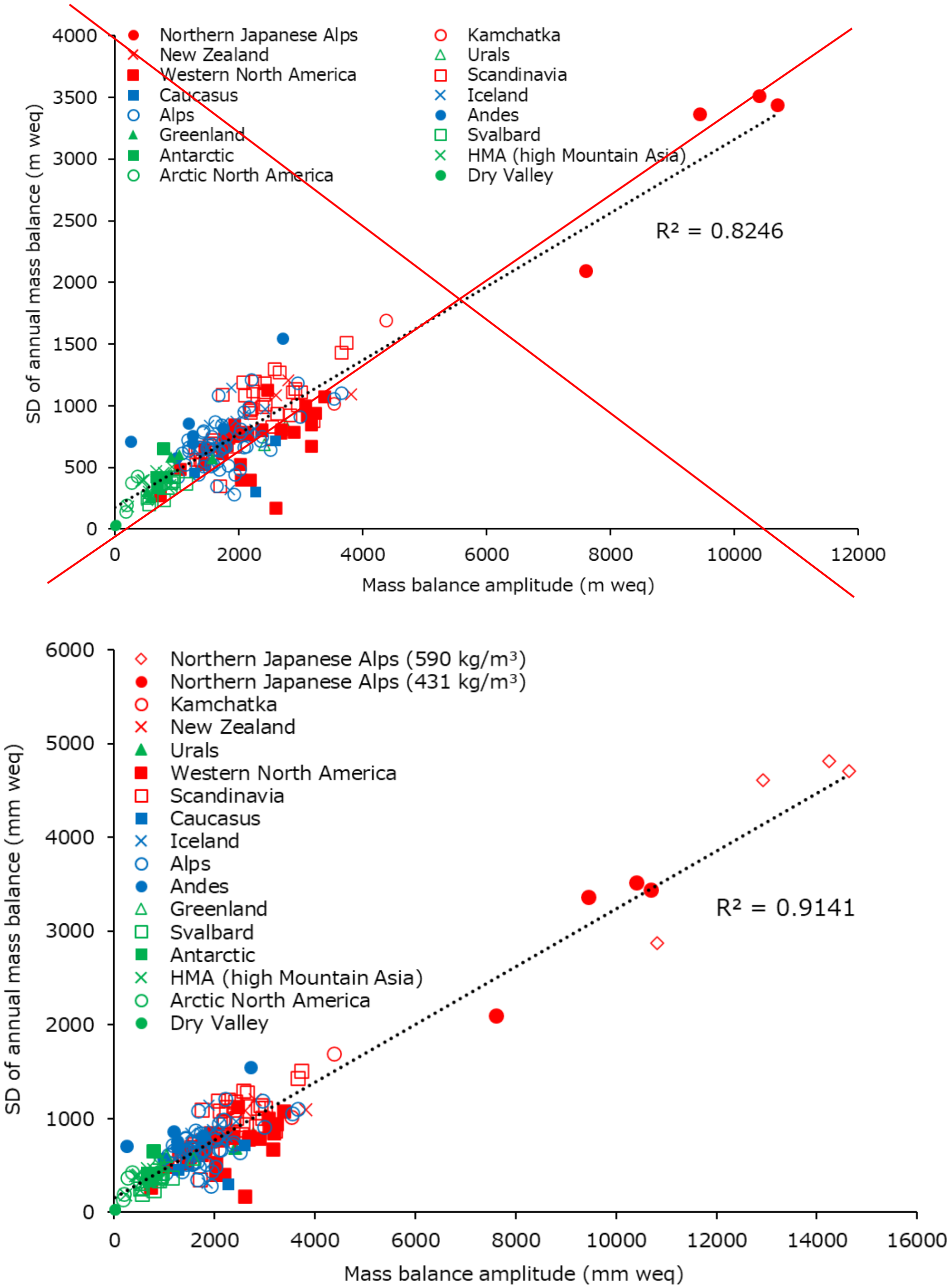


Figure 12 Standard deviation of annual mass balance versus mass balance amplitude.

305

4.4 Emergence velocity of VSGs in the northern Japanese Alps ~~Karamatsuzawa Glacier~~

The measurement error of the GNSS survey was set at 0.07 m, according to annual migration relative to a base point near the glacier terminal. The annual flow of Karamatsuzawa Glacier is shown in Table 5; all measurements exceeded the error level of 0.07, indicating significant flow. Using the measured results for the Karamatsuzawa Glacier (Table 5), we find the emergence velocity in the different target areas to range from –0.04 to 0.16 m/a.

In the Changri Nup glacier in Nepal, the emergence velocity of the glacier terminus is about 0.37 m a-1 against an average horizontal velocity of 9.7 m a-1 (Vincent et al., 2016). In the Argentière Glacier in the French Alps, the emergence velocity of the glacier terminus is 3-6 m a-1 against a horizontal velocity of 35-60 m a-1 (Vincent et al., 2021). As shown in these references, the emergence velocity is less than a tenth of the horizontal velocity on the glacier surface. In the case of VSGs in the northern Japanese Alps, the horizontal velocity is less than 4 m a-1, and the emergence velocity is estimated to be extremely small. Therefore, the profile of altitude change shows the characteristics of a mass balance profile (next chapter 4.5).

Table 5 Analyses results of the Karamatsusawa Glacier. Regions refer to Fig. 6.

	P1	P2	P3	P4	P5	a	b	c	d
Flow Velocity (m a-1)	1.90	2.32	2.03	2.14	2.20				
Ice thickness (m)	28	35	28	27	28				
Width (m)	106	72	92	90	86				
longitudinal length of target area (m)						60	47	40	40
Mean width of target area (m)						89	82	91	88

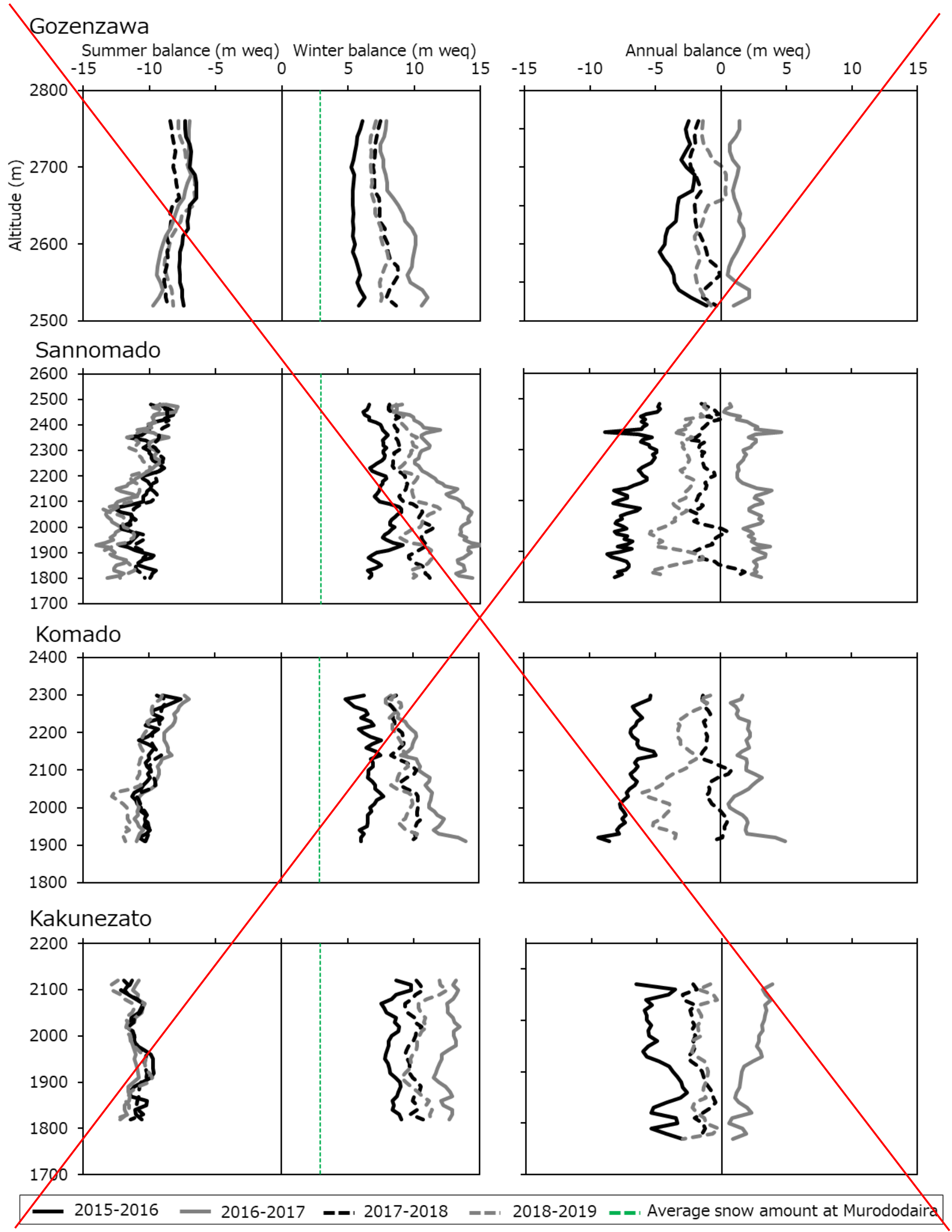
	P1	P2	P3	P4	P5	a	b	c	d
Flow Velocity (m a-1)	1.90	2.32	2.03	2.14	2.20				
Ice thickness (m)	28	35	28	27	28				
Width (m)	106	72	92	90	86				
longitudinal length of target area (m)						60	47	40	40
Mean width of target area (m)						89	82	91	88

4.5 Mass balance profile ~~gradient~~

We now examine the ~~mass-balance~~ profiles of altitude changes of the four VSGs studied during 2015–2019. Consider the gradient trends of these profiles of altitude changes in summer, as shown at left in Fig. 13. The gradients of altitude changes in summer~~r-summer balance~~ for Sannomado and Komado Glaciers are positive, consistent with those of a typical glacier. On the other hand, the profiles of the Gozenzawa and Kakunezato Glaciers are nearly flat, particularly in 2015-2016, where it is negative for the Kakunezato Glacier. These glaciers differ from the other two by having a debris-covered area in their downstream parts in ablation years, such as the light snow year of 2015-2016. In general, most glaciers have a positive gradient in both summer and winter, the balance increasing with altitude due to the decrease in temperature. Thus, this trend is consistent with the VSGs here for cases with little-to-no debris cover, but not for cases having a debris-covered area downstream in ablation years.

Now consider the gradient trends of these profiles of altitude changes in winter ~~winter balance~~. In contrast to the usual trend for a larger glacier, the ~~winter balance~~ profiles of altitude changes in winter of these four VSGs are roughly zero or negative. In the light snow year of 2015-2016, the gradient trends of the four glaciers are nearly zero. Even in the heavy snow year of 2016-2017, the gradient of winter balance of the Kakunezato Glacier is nearly zero. Differing even more from mountain ~~typical~~ glaciers in the world, the gradients of altitude changes in winter ~~winter balance~~ of Gozenzawa, Sannomado, and Komado Glaciers are negative in the heavy snow year. Another common feature of the altitude changes in winter ~~winter balance~~ of these VSG is that their altitude changes in winter ~~balances~~ are always significantly larger than the average snow depth of the Murododaira (2.93 m weq: Iida et al., 2018). ~~The large contribution to the total balance comes from avalanches and snowdrift and thus probably likely is the cause of the near-zero and negative profiles.~~ Moreover, compared to the ~~summer balance~~ profiles of altitude changes in summer, those in winter have much greater year-to-year variation.

On the right side of Fig. 13, we show profiles of annual altitude changes ~~the annual balance~~. ~~The annual mass balance is positive for these VSGs only in the heavy snow year. However, t~~The gradients vary significantly by year and by glacier. For the Sannomado and Komado Glaciers, the gradients are positive in the light snow year of 2015-2016 and negative in the heavy snow year of 2016-2017. For the Gozenzawa Glacier, the gradient is slightly negative in all years, whereas the gradient for the Kakunezato Glacier is negative in the light snow year and positive in the heavy snow year. Thus, the gradients of the annual altitude changes ~~the annual balance~~ of the four VSGs differ from the positive trend for typical glaciers and show significant variation between themselves.


Gozenzawa
Summer balance (m weq)
Winter balance (m weq)
Annual balance (m weq)
Altitude (m)
Sannomado
Komado
Kakunezato
2015-2016
2016-2017
2017-2018
2018-2019
Average snow amount at Murododaira

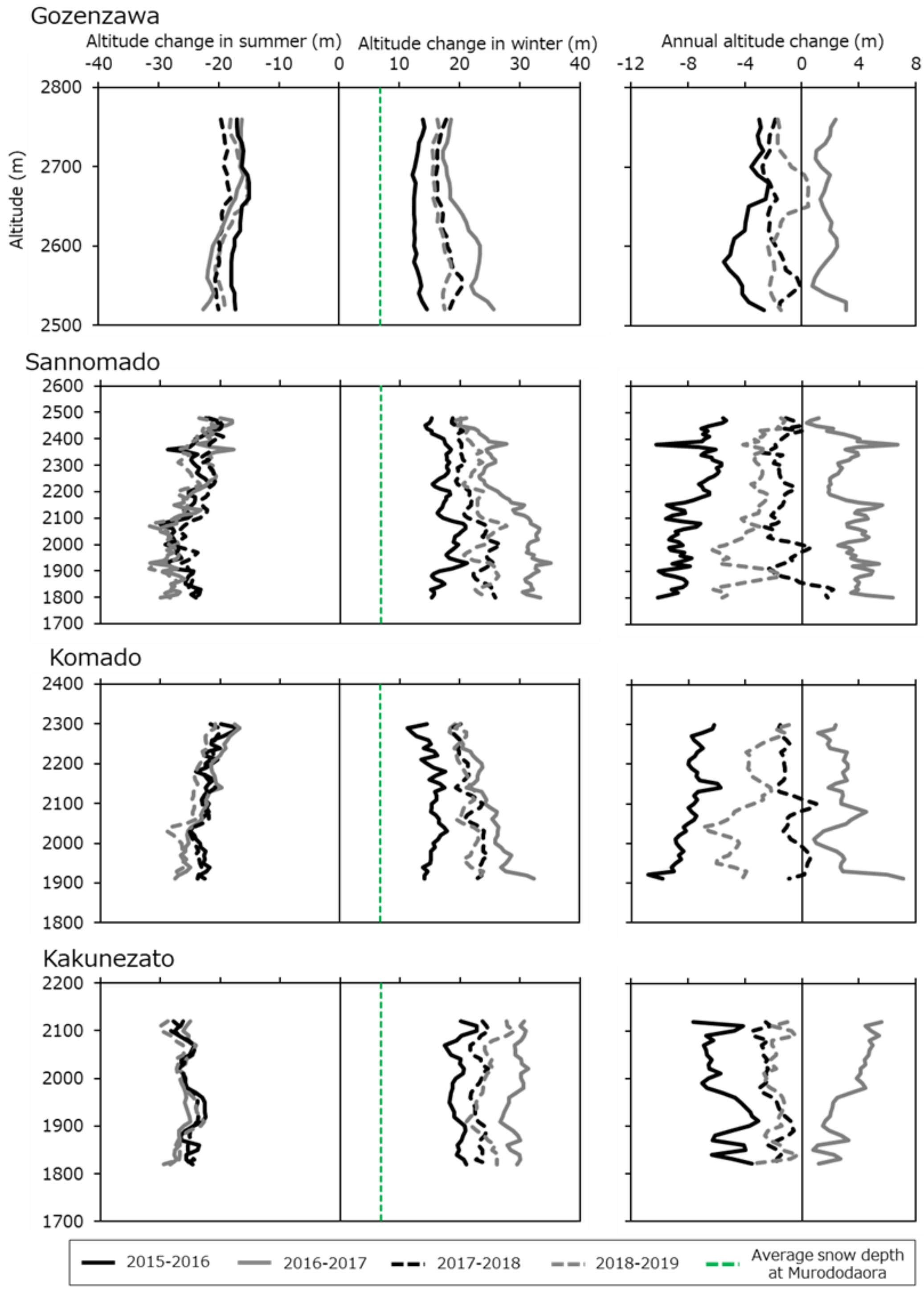


Figure 13 Profiles of the altitude changes ~~the mass balances~~ of Gozenzawa, Sannomado, Komado, Kakunezato Glaciers. The green line is the average snow depth ~~amount~~ of the Murododaira (6.8 ~~2.93~~ m ~~weq~~: Iida et al.,

5 Discussion

5.1 Mass balance characteristics of VSGs in Japan: comparison to other glaciers

We reported on our measurements of the accumulation depth, ablation depth, ~~winter and summer balances~~ and continuous annual mass balances of the recently classified VSGs in Japan. To help understand their behaviour, we compared them with previously reported measurements of other glaciers worldwide. In general, the glacier mass balance amplitude increased from polar, to continental, and then to maritime climates. An exception to this trend was the Ural glaciers, which appeared to have anomalously high amplitude for their dry, cold climate. The Urals have small glaciers that inhabit valley bottoms, where the large effects of ~~climate and~~ topography (avalanche and snowdrift) are localized (Dolgushin, 1961), leading to higher mass balance amplitudes (Dyurgerov and Meier, 1999). Like the VSGs studied here, the glaciers in the Urals are located at high latitude, and lie in narrow cirques ~~valley~~, gaining much of their mass through avalanches or snowdrifts. However, while the Urals are located at a colder environment and dry, the northern Japanese Alps has some of the heaviest snowfall in the world. Steep bedrocks surrounding VSGs cause avalanches and the avalanches supply to much snow at the trough bottom. In addition, strong northwesterly winds through winter supply to much snow in the east part of the mountain ridge due to snowdrift. This combination of heavy snowfall, strong northwesterly winds (snowdrift), and narrow valleys (avalanche) may explain why the mass balance amplitude of VSGs in Japan was found to be higher than the other glaciers worldwide (Fig. 11). ~~In addition,~~ Braithwaite and Hughes (2020) showed that the mass balance amplitude correlated with summer temperature, which is also relatively high in the northern Japanese Alps. In addition, we found the standard deviation of the annual mass balance to be nearly proportional to the mass balance amplitude (Fig. 11), with the result that VSGs in Japan have a variation in annual mass balance higher than the other glaciers worldwide.

Why do the glaciers exist here? The high accumulation depth ~~winter balance~~ is probably ~~likely~~ a major factor. We found the winter balance of VSGs in Japan to be the highest of all investigated glaciers worldwide to date, being more than double those of the Kamchatka glaciers, the second highest. However, despite the very heavy snowfall here, the winter snowfall cannot keep pace with the rapid snowmelt in summer, and hence the perennial snow patches form only where avalanches and snowdrifts deposit significant snow (Higuchi, 1968). Here, the VSGs receive more than double the snowfall depth ~~amounts~~ due to recharge from avalanches and snowdrifts. This source of snow is thus the reason five VSGs located in the altitude range of 1750–2770 m can exist in such a warm climate in mid-latitude.

Concerning the yearly fluctuations in mass balance, the ablation depth ~~summer balances~~ of the VSGs here are relatively constant, whereas the accumulation depth ~~winter~~ and annual mass balances fluctuate significantly from year to year (Fig. 9). This result indicates that the variable accumulation depth ~~winter balance~~ dominates the behaviour of the annual mass balance of VSGs in Japan ~~these mountains~~. Higher mass balance amplitudes result in the annual mass balance having lower sensitivity to the summer balance and higher sensitivity to the winter balance (Dyurgerov and Meier, 1999).

The profiles of these altitude changes ~~mass balances~~ were found to differ from those typical of glaciers elsewhere. A typical glacier consists of an upstream accumulation area and a downstream ablation area, separated by an equilibrium line altitude (ELA), a structure that produces a positive gradient in the annual mass balance. Even if the glacier can become an ablation area throughout ~~annual balance can become an ablation-area throughout~~ due to recent climate change effects (e.g., the Ålfotbreen Glacier (Bjarne Kjøllmoen (Ed.) et al., 2019)), the glacier's gradient can remain positive (Oerlemans and Hoogendoorn, 1989). In these cases, the ELA can be defined above the glacier altitude range. In contrast, we found that the gradients of altitude changes in the summer ~~mass balance~~ of VSGs in Japan vary greatly in light or heavy snow years, often being near zero or negative. Although the Sannomado and Komado Glaciers had positive summer gradients, the Gozenzawa and Kakunezato Glaciers, where debris-covered areas appear in the downstream parts of the glacier in light snow years, did not. Suppression of melting in the downstream parts in these cases is probably ~~likely~~ due to their debris cover (e.g., Nicholson and Benn, 2006). In addition, the gradients of altitude changes in winter ~~winter balance~~ of VSGs in Japan did not have a positive gradient. We argued that this property of the VSGs is probably ~~likely~~ due to the significant effect of avalanches and snowdrift, which can be greater downstream. As a result, the gradient of the annual altitude changes ~~mass balance~~ of VSGs in Japan can be negative. Furthermore, the annual mass balances were negative (ablation-area throughout) most years, being positive (accumulation-area throughout) for all VSGs only in the heavy snow year. Taken together, these results suggest that VSGs in Japan are not divided by a distinct glacier ELA into an upstream accumulation zone and a downstream ablation zone.

5.2 Climate sensitivity of VSGs in Japan

The VSGs in Japan persist where the accumulation depth ~~winter balance~~ is more than double the snowfall depth ~~amount~~ due to avalanche and snowdrift deposit ~~accumulation~~. Thus, of the two types of VSGs (Kuhn 1995), the VSGs in Japan can be classified as topographically controlled VSGs.

Generally, VSGs are more sensitive and react faster to climatic change than larger glaciers (Hoelzle et al., 2003; Hoffman et al., 2007; Jóhannesson et al., 1989). However, the responses of individual VSGs to changes in climatic forcing depend on the site, being influenced by topographic factors, feedbacks, and non-linearities (e.g., Carturan et al., 2013; Kuhn, 1995; López-Moreno et al., 2006). Like the VSGs here, other topographically controlled VSGs tend to have annual mass balances ~~be~~ strongly correlated with the winter balance and weakly correlated with the summer balance (De Marco et al., 2020; Hughes, 2009; Huss and Fischer, 2016; Pecci et al., 2008). Huss and Fischer (2016), modeling the climate sensitivity of 1,133 VSGs in the Swiss Alps, argued that most ~~about 80% of the~~ VSGs in the Swiss Alps would disappear by 2060 ~~2030~~. However, they reported that the topographically controlled VSGs are less sensitive to temperature fluctuations and thus some may survive future warming. The lower sensitivity of topographically controlled VSGs to temperature rise has also been reported in the Eastern Alps (Carrivick et al., 2015) and Canadian Rockies (DeBeer and Sharp, 2009).

To help understand how these topographically controlled VSGs in Japan may respond to climate, we consider their high sensitivity to the accumulation depth ~~winter balance~~. Their dependence on accumulation depth ~~winter balance~~ suggests a dependence on snowfall depth variation. How has snowfall depth changed over recent years? Yamaguchi et al. (2011) made meteorological observations in the alpine zone of central Japan, finding no decreasing trend in snow depth in the alpine zone for 1990–2010, yet large yearly fluctuations. Suzuki and Sasaki (2019) found similar results for 2002–2017. Regional climate projections using a high-resolution non-hydrostatic regional climate model (NHRCM) with 5-km resolution and 1 km grid spacing concluded that the amount of snow in the northern Japanese Alps will decrease if the temperature rises by 2 °K (Kawase et al., 2020).

If the non-decreasing trend in snow depth continues, VSGs in Japan should persist like other topographically controlled VSGs worldwide. On the other hand, a temperature rise and snow-depth decrease would deplete these VSGs, which are already less than 50 m thick. If glacier shrinkage continues at the same rate as that in 2015–2019, the VSGs will probably ~~likely~~ transform into perennial snow patches and then vanish.

Understanding ~~the~~ variation in the annual mass balance of a glacier requires measurements of the seasonal balance for at least 30 years (Ohmura, 2010). As this study covered only four-years, further mass balance observations of the VSGs in Japan are needed.

6 Conclusion

In this study, we calculated the annual mass balances, accumulation depth and ablation depth ~~seasonal mass balances~~ of VSGs in the northern Japanese Alps using a geodetic method based on SfM–MVS technology and aerial images. Their ablation depth ~~summer balances~~ showed very small ~~almost no~~ yearly fluctuations, whereas they had large yearly fluctuations in the accumulation depth ~~winter balance~~ and annual mass balance. Therefore, their annual mass balance was dominated by their accumulation depth ~~winter balance~~. The annual mass balance of the entire area represented an accumulation area during a heavy snow year and an ablation area during a lighter snow year. These characteristics differ from those of a ~~the~~ typical glacier, which instead have both an upstream accumulation area and a downstream ablation area, separated by a glacier ELA. Moreover, VSGs in Japan had a lack of positive annual mass balance gradient ~~negative annual balance gradients~~, which suggests that they are not divided by a distinct glacier ELA into an upstream accumulation area and a downstream ablation area ~~negative annual balance gradients, which suggests that these VSGs did not have an equilibrium line~~ during the observation period. A comparison of the mass balance amplitudes of VSGs in Japan with those of other glaciers worldwide showed that mass balance amplitude increased from polar to continental to maritime climates. The VSGs studied here had the highest mass balance amplitudes, probably due to the warm climate at mid-latitude with very heavy snowfall and recharged avalanche and snowdrift deposits. ~~We argued that their continued existence probably likely depends on their acquiring most of their ice from avalanches.~~ For this reason, we classified them as topographically controlled VSGs.

Like other topographically controlled VSGs worldwide, the VSGs in Japan showed relatively low sensitivity to summer balance fluctuation. However, if the amount of snow in Japan were to decrease due to climate change, these VSGs would probably ~~likely~~ respond within 10–20 years by significantly shrinking, transforming into perennial snow patches, and then vanishing. Before they experience such climate changes, they should be continually observed for at least 30 years to better predict their future development.

~~Appendices~~

~~Appendices A Area, average winter (ABw) and summer (ABs) mass balance amplitudes (Aα), standard deviations of annual mass balance (sBn), and observation periods of VSGs and Hamaguri-yuki perennial snow patch in the northern Japanese Alps and glaciers around the world.~~

NO.	Name	Region	Lat (°)	Log (°)	Area (km²)	Abw (m weq)	ABs (m weq)	Aα (m weq)	SBn (m weq)	observation periods (Year)
1	KAKUNEZATO	Northern Japanese Alps	36.63	137.76	0.08	10390.33	-10696.34	10696.34	3438.07	2015-2019(4years)
2	SANNOMADO	Northern Japanese Alps	36.63	137.64	0.10	9898.99	-10904.30	10401.65	3514.50	2015-2019(4years)
3	KOMADO	Northern Japanese Alps	36.63	137.63	0.11	8900.15	-9979.81	9439.98	3364.74	2015-2019(4years)
4	GOZENZAWA	Northern Japanese Alps	36.57	137.62	0.03	7348.55	-7847.43	7905.34	2098.18	2015-2019(4years)
5	KORYTO	Kamchatka	54.83	161.80	7.54	4430.00	-4320.80	4375.40	1696.12	1982-2000(5years)
6	IVORY	New Zealand	-43.13	170.93	0.80	2630.00	-5013.33	3821.67	1092.86	1970-1975(6years)
7	HANSEBREEN	Scandinavia	61.75	5.68	2.75	3426.28	-4034.72	3730.50	1511.49	1986-2017(32years)
8	LUPO	Alps	46.08	9.99	0.20	3354.11	-3948.44	3651.28	1108.90	2010-2018(9years)
9	AALFOTBREEN	Scandinavia	61.75	5.65	3.98	3606.65	-3692.61	3649.63	1436.59	1963-2017(54years)
10	OSSOUE	Alps	42.77	-0.14	No record	2798.13	-4281.88	3540.00	1056.16	2002-2017(16years)
11	KOZELSKIY	Kamchatka	53.23	158.82	1.80	3451.96	-3608.26	3530.11	1017.90	1973-1997(23years)
12	NOISY CREEK	Western north America	48.67	-121.53	0.46	3130.87	-3652.67	3391.77	1071.96	1993-2016(15years)
13	NORTH KLAWATTI	Western north America	48.57	-121.09	1.48	2904.87	-3570.47	3237.67	937.77	1993-2016(16years)
14	HOEGTUVBREEN	Scandinavia	66.45	13.64	2.56	3210.00	-3206.14	3208.07	877.41	1971-1977(7years)
15	SPERRY	Western north America	48.63	-113.75	0.78	2958.46	-3405.38	3181.92	844.93	2005-2017(13years)
16	NISQUALLY	Western north America	46.82	-121.74	6.67	2796.00	-3551.00	3173.50	670.11	2006-2015(10years)
17	SENTINEL	Western north America	49.89	-122.98	1.74	3180.52	-3042.39	3111.46	922.16	1966-1989(23years)
18	SOUTH CASCADE	Western north America	48.35	-121.06	1.90	2790.23	-3380.04	3085.13	999.97	1959-2017(57years)
19	SVELGJABREEN	Scandinavia	59.95	6.28	22.34	3060.73	-2942.82	3001.77	1114.09	2007-2017(11years)
20	SURETTA MERID.	Alps	46.51	9.36	0.13	2358.43	-3614.14	2986.29	909.68	2010-2018(7years)
21	CALDERONE	Alps	42.47	13.57	0.03	2903.75	-2999.50	2951.63	1187.81	2006-2017(10years)
22	ENGABREEN	Scandinavia	66.65	13.85	36.25	3044.50	-2848.00	2946.25	1007.17	1970-2017(48years)
23	BLOMSTOELSKARDSBREEN	Scandinavia	59.95	6.33	22.54	3171.09	-2657.64	2914.36	1141.75	2007-2017(11years)
24	SANDALEE	Western north America	48.41	-120.79	0.18	2877.46	-2917.38	2897.42	786.63	1995-2016(13years)
25	SVARTISHEIBREEN	Scandinavia	66.55	13.76	5.53	3053.29	-2687.71	2870.50	1114.62	1988-1994(7years)
26	JOSTEFONN	Scandinavia	61.42	6.55	3.88	2749.60	-2913.40	2831.50	924.08	1996-2000(5years)
27	ROLLESTON	New Zealand	-42.89	171.53	0.11	2538.63	-3075.63	2807.13	1203.26	2011-2018(8years)
28	OBRUCHEV	Urals	67.64	65.78	0.30	2666.82	-2864.55	2765.68	838.37	1958-1979(23years)
29	ECHAURREN NORTE	Andes	-33.58	-70.13	0.40	2473.31	-2948.48	2710.89	1548.04	1976-2017(42years)
30	EMMONS	Western north America	46.85	-121.72	11.27	2366.36	-3029.09	2697.73	803.34	2006-2016(11years)
31	WOOLSEY	Western north America	51.11	-118.06	3.92	2588.00	-2772.22	2680.11	779.98	1966-1975(10years)
32	BREIDABLIKKBREA	Scandinavia	60.07	6.37	3.21	2298.75	-3004.38	2651.56	1274.18	1963-2012(16years)
33	BONDHUSBREA	Scandinavia	60.03	6.33	10.67	2556.00	-2682.60	2619.30	937.54	1977-1981(5years)
34	BREWSTER	New Zealand	-44.07	169.43	2.03	2466.79	-2749.50	2608.14	1086.89	2005-2018(14years)
35	TIEDEMANN	Western north America	51.33	-125.05	62.69	1926.67	-3275.00	2600.83	168.93	1981-1990(6years)
36	DJANKUAT	Caucasus	43.19	42.76	2.69	2470.63	-2719.38	2595.00	715.47	1968-2018(48years)
37	GRAAFJELLSBREA	Scandinavia	60.08	6.40	8.05	2356.65	-2792.41	2574.53	1302.32	1964-2012(17years)
38	LANGFJORDJOEKELEN	Scandinavia	70.13	21.74	3.22	2060.85	-3009.85	2535.35	734.32	1989-2017(27years)
39	TROLLBERGDALSBREEN	Scandinavia	66.72	14.44	1.80	2308.60	-2750.50	2529.55	831.46	1970-1994(10years)
40	HALLSTAETTER G.	Alps	47.48	13.62	2.83	1975.33	-3034.58	2504.96	644.54	2001-2017(12years)
41	WOLVERINE	Western north America	60.42	-148.90	No record	2297.48	-2638.00	2467.74	1126.28	1966-2017(50years)
42	STORGLOMBREEN	Scandinavia	66.67	14.00	61.12	2153.80	-2707.80	2430.80	1010.57	1985-2005(10years)
43	LANGJOKULL ICE CAP	Iceland	64.67	-20.10	871.00	1774.79	-3078.86	2426.82	971.37	2001-2017(14years)
44	IGAN	Urals	67.58	66.00	0.81	2319.55	-2519.64	2419.59	685.54	1958-1979(22years)
45	BLAABREEN	Scandinavia	60.09	6.44	2.31	2025.33	-2811.67	2418.50	1186.35	1963-1968(6years)
46	AUSTDALSBREEN	Scandinavia	61.82	7.35	10.63	2176.37	-2616.63	2396.50	1094.00	1988-2017(30years)
47	RUKLEBREEN	Scandinavia	60.07	6.43	1.85	2485.00	-2274.00	2379.50	993.33	1964-1968(5years)
48	SILVER	Western north America	48.98	-121.24	0.40	2318.07	-2435.87	2376.97	796.60	1993-2016(15years)
49	MALADETA	Alps	42.65	0.64	0.23	2051.04	-2700.70	2375.87	751.72	1992-2016(23years)
50	HELM	Western north America	49.96	-122.99	1.41	1893.33	-2853.73	2373.53	807.67	1976-2017(15years)

NO.	Name	Region	Lat (°)	Log (°)	Area (km^2)	Abw (m weq)	ABs (m weq)	Aα (m weq)	SBn (m weq)	observation periods (Year)
51	SCHWARZBACH	Alps	46.60	8.61	0.04	1936.80	-2769.00	2352.90	720.78	2013-2017(5years)
52	BUBA	Caucasus	42.75	43.74	3.75	2154.92	-2379.23	2267.08	306.48	1968-1980(13years)
53	TUNSBERGDALSBREEN	Scandinavia	61.60	7.05	52.21	2218.43	-2302.57	2260.50	1197.82	1966-1972(7years)
54	EYJABAKKAJOKULL	Iceland	64.65	-15.58	112.00	1988.40	-2514.90	2251.65	809.54	1991-2017(20years)
55	VESLEDALSBREEN	Scandinavia	61.85	7.26	4.10	2040.17	-2429.17	2234.67	1120.75	1967-1972(6years)
56	SARENNES	Alps	45.12	6.13	0.10	1637.47	-2772.57	2205.02	1214.02	1949-2018(70years)
57	OKSTINDBREEN	Scandinavia	66.02	14.29	14.01	2294.45	-2111.30	2202.88	980.06	1987-1997(11years)
58	BENCH	Western north America	51.43	-124.92	10.35	1863.75	-2523.75	2193.75	400.50	1981-1990(8years)
59	RUNDVASSBREEN	Scandinavia	67.30	16.06	10.85	1846.90	-2533.50	2190.20	947.48	2002-2017(10years)
60	THRANDARJOKULL	Iceland	64.70	-14.88	19.40	2086.67	-2268.33	2177.50	787.75	1991-1996(6years)
61	NIGARDSBREEN	Scandinavia	61.72	7.13	46.61	2227.86	-2113.48	2170.67	965.51	1962-2017(56years)
62	TSANFLEURON	Alps	46.32	7.23	2.47	1467.38	-2869.13	2168.25	991.74	2010-2017(8years)
63	PLACE	Western north America	50.43	-122.60	3.45	1710.44	-2597.68	2154.06	762.04	1965-2017(25years)
64	GOLDBERG K.	Alps	47.04	12.97	1.03	1687.19	-2558.50	2122.84	669.49	2001-2017(16years)
65	BRIDGE	Western north America	50.82	-123.57	88.10	1864.00	-2334.00	2099.00	787.93	1981-1985(5years)
66	REMBESDALSKAAKA	Scandinavia	60.54	7.37	17.26	2056.25	-2136.36	2096.31	1088.30	1963-2017(55years)
67	SEX ROUGE	Alps	46.33	7.22	0.26	1455.33	-2705.67	2080.50	950.81	2012-2017(6years)
68	TUNGNAARJOKULL	Iceland	64.32	-18.07	345.00	1569.72	-2587.78	2078.75	927.48	1986-2017(18years)
69	PENDENTE (VEDR.) / HANGENDERF.	Alps	46.97	11.22	0.85	1463.86	-2692.71	2078.29	666.57	1999-2017(14years)
70	OMNSBREEN	Scandinavia	60.63	7.48	1.50	1612.00	-2536.00	2074.00	1190.31	1966-1970(5years)
71	ANDREI	Western north America	56.93	-130.97	91.89	1810.00	-2263.33	2036.67	396.67	1978-1990(9years)
72	ALEXANDER	Western north America	57.10	-130.82	5.74	1676.25	-2391.25	2033.75	522.52	1978-1990(8years)
73	PLAINE MORTE	Alps	46.38	7.49	7.41	1325.63	-2721.63	2023.63	813.03	2010-2017(8years)
74	PIZOL	Alps	46.96	9.39	0.06	1401.00	-2639.00	2020.00	482.25	2007-2017(11years)
75	BASODINO	Alps	46.42	8.48	1.76	1704.44	-2331.28	2017.86	776.10	1993-2017(25years)
76	HOFSJOKULL E	Iceland	64.80	-18.58	213.10	1651.38	-2254.83	1953.10	880.68	1989-2017(29years)
77	HARBARDSBREEN	Scandinavia	61.70	7.68	13.17	1780.40	-2099.00	1939.70	673.83	1997-2001(5years)
78	SANKT ANNA	Alps	46.60	8.60	0.18	1525.00	-2349.33	1937.17	442.34	2012-2017(6years)
79	EKLUTNA EAST BRANCH	Western north America	61.23	-148.97	No record	1637.50	-2225.00	1931.25	843.86	2008-2015(8years)
80	FORNO	Alps	46.30	9.70	8.95	1609.00	-2247.17	1928.08	283.29	1955-1960(6years)
81	SYKORA	Western north America	50.87	-123.58	25.35	1858.00	-1998.00	1928.00	752.85	1976-1985(10years)
82	HOFSJOKULL SW	Iceland	64.72	-19.05	48.80	1631.67	-2142.50	1887.08	1145.15	2006-2017(12years)
83	BREIDAMJOKULL E. B.	Iceland	64.22	-16.33	995.00	1295.20	-2414.80	1855.00	315.31	2001-2005(5years)
84	BLOMSTERSKARDSBREEN	Scandinavia	68.34	17.85	2.18	1772.67	-1922.33	1847.50	772.04	2007-2017(11years)
85	EKLUTNA	Western north America	61.25	-148.99	31.60	1622.27	-2058.64	1840.45	738.67	1986-2015(11years)
86	WURTEN K.	Alps	47.03	13.00	0.34	1403.21	-2258.72	1830.97	520.48	1983-2011(29years)
87	ZAVISHA	Western north America	50.79	-123.41	6.49	1750.00	-1888.00	1819.00	680.83	1976-1985(15years)
88	HINTEREIS F.	Alps	46.80	10.77	6.39	1186.33	-2413.67	1800.00	754.18	2013-2018(6years)
89	CARESER ORIENTALE	Alps	46.45	10.70	1.43	881.33	-2689.67	1785.50	673.33	2006-2011(6years)
90	EKLUTNA WEST BRANCH	Western north America	61.23	-149.01	No record	1475.00	-2063.75	1769.38	763.31	2008-2015(8years)
91	SATUJOKULL	Iceland	64.92	-18.83	90.60	1623.00	-1905.00	1764.00	864.37	1988-1997(10years)
92	CARESER OCCIDENTALE	Alps	46.45	10.69	0.19	998.50	-2526.83	1762.67	669.56	2006-2011(6years)
93	DE LOS TRES	Andes	-49.33	-73.00	0.81	1575.29	-1931.29	1753.29	816.35	1996-2018(7years)
94	BRUARJOKULL	Iceland	64.67	-16.17	1525.00	1652.60	-1849.60	1751.10	781.48	1993-2017(15years)
95	YURI	Western north America	56.98	-130.68	3.58	1435.00	-2047.78	1741.39	610.58	1978-1990(10years)
96	TARFALAGLACIAEREN	Scandinavia	67.93	18.64	1.01	1647.70	-1834.55	1741.13	1090.38	1986-2015(20years)
97	HOFSJOKULL N	Iceland	64.95	-18.92	73.70	1456.67	-2015.33	1736.00	674.11	1988-2017(15years)
98	KLEINFLEISS K.	Alps	47.05	12.95	0.79	1420.06	-2051.63	1735.84	658.00	2001-2017(16years)
99	KOLDUKVISLARJ.	Iceland	64.58	-17.83	300.00	1482.00	-1988.82	1735.41	848.55	1992-2017(17years)
100	GRIES	Alps	46.44	8.34	4.35	1322.98	-2121.77	1722.38	846.70	1962-2018(57years)

NO.	Name	Region	Lat (°)	Log (°)	Area (km²)	Abw (m weq)	ABs (m weq)	Aα (m weq)	SBn (m weq)	observation periods (Year)
101	KARSOJIETNA	Scandinavia	68.36	18.32	1.23	1887.50	-1513.33	1700.42	351.82	1982-1993(8years)
102	MALAVALLE (VEDR. DI) / UEBELTALF.	Alps	46.95	11.19	6.03	1243.23	-2118.54	1680.88	485.17	2005-2017(13years)
103	JAMTAL F.	Alps	46.86	10.16	2.79	1188.04	-2171.54	1679.79	640.00	1989-2018(26years)
104	CARESER	Alps	46.45	10.71	0.96	991.94	-2350.28	1671.11	1084.43	1976-2018(18years)
105	ZETTALUNITZ/MULLWITZ K.	Alps	47.08	12.38	2.78	1221.42	-2101.75	1661.58	548.26	2007-2018(12years)
106	ALBIGNA	Alps	46.30	9.64	5.68	1385.00	-1906.83	1645.92	350.12	1955-1960(6years)
107	CIARDONEY	Alps	45.52	7.39	0.57	1166.35	-2067.50	1616.92	871.78	1992-2017(26years)
108	STORBREEN	Scandinavia	61.57	8.13	5.14	1416.35	-1770.28	1593.31	723.70	1949-2017(75years)
109	PLATTALVA	Alps	46.83	8.99	0.80	1530.08	-1643.55	1586.82	644.02	1948-1985(38years)
110	RHONE	Alps	46.62	8.40	15.52	1358.69	-1810.80	1584.74	525.81	1885-2017(35years)
111	MITTIVAKKAT	Greenland	65.70	-37.80	15.94	1203.08	-1950.00	1576.54	569.76	1996-2015(13years)
112	KESSJEN	Alps	46.07	7.93	0.45	1447.45	-1682.83	1565.14	692.44	1956-1995(40years)
113	FONTANA BIANCA / WEISSBRUNNF.	Alps	46.48	10.77	0.40	1116.13	-2006.23	1561.18	753.13	1984-2017(31years)
114	OCHSENTALER G.	Alps	46.85	10.10	2.59	1311.71	-1795.43	1553.57	511.23	1992-1998(7years)
115	STORGLACIAEREN	Scandinavia	67.90	18.57	2.90	1418.90	-1677.89	1548.40	701.05	1946-2018(73years)
116	VERMUNT G.	Alps	46.85	10.13	2.16	1052.25	-2035.25	1543.75	527.75	1991-1998(8years)
117	DYNGJUJOKULL	Iceland	64.67	-17.00	1060.00	1615.57	-1440.86	1528.21	848.10	1992-2017(14years)
118	RIUKOJIETNA	Scandinavia	68.08	18.05	2.65	1255.12	-1798.50	1526.81	674.81	1986-2017(23years)
119	RIES OCC. (VEDR. DI) / RIESERF. WESTL.	Alps	46.90	12.10	1.70	1122.89	-1898.44	1510.67	684.87	2009-2017(9years)
120	LUNGA (VEDRETTA) / LANGENF.	Alps	46.47	10.62	1.60	970.46	-2047.46	1508.96	657.47	2004-2017(13years)
121	STORSTEINSFJELLBREEN	Scandinavia	68.22	17.92	5.91	1604.70	-1379.60	1492.15	598.45	1964-1995(10years)
122	LIMMERN	Alps	46.81	8.98	2.41	1385.08	-1574.63	1479.86	657.78	1948-1985(38years)
123	GULKANA	Western north America	63.28	-145.43	31.30	1163.22	-1758.20	1460.71	643.80	1966-2017(50years)
124	VENEDIGER K.	Alps	47.13	12.34	1.99	1141.00	-1779.20	1460.10	548.09	2013-2017(5years)
125	PEYTO	Western north America	51.66	-116.56	11.74	1129.32	-1784.29	1456.80	525.70	1966-2017(28years)
126	CORBASSIERE	Alps	45.98	7.29	15.08	1034.63	-1826.68	1430.66	514.11	1997-2017(19years)
127	SCHWARZBERG	Alps	46.02	7.93	5.10	1293.25	-1556.90	1425.08	797.20	1956-2017(60years)
128	SILVRETTA	Alps	46.85	10.08	2.62	1236.57	-1604.22	1420.40	783.83	1919-2018(100years)
129	AUSTRE MEMURUBREEN	Scandinavia	61.55	8.50	8.75	1064.40	-1746.80	1405.60	547.99	1968-1972(5years)
130	GIETRO	Alps	46.00	7.38	5.27	1193.71	-1595.78	1394.74	664.13	1967-2017(49years)
131	VESTRE MEMURUBREEN	Scandinavia	61.53	8.45	9.17	1156.80	-1597.60	1377.20	565.46	1968-1972(5years)
132	RABOTS GLACIAER	Scandinavia	67.91	18.50	3.13	1162.09	-1591.34	1376.72	632.12	1982-2017(32years)
133	LA MARE (VEDRETTA DE)	Alps	46.43	10.63	1.99	982.71	-1745.43	1364.07	654.26	2004-2017(14years)
134	FINDELEN	Alps	46.00	7.87	12.89	1083.40	-1601.60	1342.50	443.09	2005-2017(10years)
135	GRAASUBREEN	Scandinavia	61.66	8.60	2.12	1136.83	-1540.65	1338.74	622.41	1962-2017(56years)
136	MARMAGLACIAEREN	Scandinavia	68.08	18.68	3.31	1082.59	-1528.89	1305.74	562.78	1990-2017(27years)
137	HELLSTUGUBREEN	Scandinavia	61.56	8.44	2.90	1095.84	-1492.84	1294.34	664.96	1962-2017(56years)
138	GARABASHI	Caucasus	43.30	42.47	4.00	1106.18	-1457.12	1281.65	459.58	1984-2018(62years)
139	CONCONTA NORTE	Andes	-29.98	-69.65	0.10	534.83	-1978.83	1256.83	756.15	2008-2015(6years)
140	BROWN SUPERIOR	Andes	-29.98	-69.64	0.18	547.83	-1960.17	1254.00	700.13	2008-2015(7years)
141	GRAND ETRET	Alps	45.48	7.22	0.53	955.73	-1429.73	1192.73	635.90	2000-2015(11years)
142	PILOTO ESTE	Andes	-32.59	-70.14	No record	957.50	-1419.58	1188.54	860.47	1980-2003(24years)
143	ALLALIN	Alps	46.05	7.93	9.65	1094.57	-1275.15	1184.86	663.39	1956-2017(60years)
144	MURTEL VADRET DAL	Alps	46.41	9.82	0.30	935.40	-1404.80	1170.10	722.71	2013-2017(5years)
145	HANSBREEN	Svalbard	77.08	15.63	56.74	960.23	-1324.46	1142.35	371.34	1989-2017(26years)
146	VERNAGT F.	Alps	46.88	10.82	7.08	906.84	-1356.35	1131.60	522.87	1966-2017(51years)
147	GROSSER ALETSCH	Alps	46.50	8.03	83.02	848.27	-1310.47	1079.37	615.05	1940-1999(60years)
148	RAM RIVER	Western north America	51.85	-116.48	1.80	891.11	-1211.11	1051.11	482.55	1966-1975(9years)
149	QAPIARFIUP SER.	Greenland	65.58	-52.21	20.85	1120.00	-962.00	1041.00	602.58	1981-1985(5years)
150	ADLER	Alps	46.01	7.87	1.98	823.44	-1210.67	1017.06	423.53	2009-2017(12years)

NO	Name	Region	Lat (°)	Log (°)	Area (km²)	Abw (m weq)	ABs (m weq)	Aα (m weq)	SBn (m weq)	observation periods (Year)
151	MARTIAL ESTE	Andes	-54.78	-68.40	0.09	934.75	-1041.00	987.88	576.28	2001--2017(16years)
152	AUSTRE LOVENBREEN	Svalbard	78.87	12.15	No record	688.64	-1196.55	942.59	420.88	2008-2018(11years)
153	VOERINGBREEN	Svalbard	78.04	13.95	No record	604.33	-1258.67	931.50	392.78	1974-1988(15years)
154	TS.TUYUKSUYSKIY	HMA (high mountain Asia)	43.05	77.08	2.26	696.87	-1147.27	922.07	505.29	1965-2017(52years)
155	AUSTRE BROEGGERBREEN	Svalbard	78.89	11.83	6.12	641.13	-1168.15	904.64	374.26	1967-2017(40years)
156	FREYA	Greenland	74.38	-20.82	5.30	748.29	-1059.86	904.07	581.18	2008-2017(7years)
157	MIDTRE LOVENBREEN	Svalbard	78.88	12.05	5.45	697.63	-1105.90	901.76	338.53	1976-2017(40years)
158	LEVIY AKTRU	HMA (high mountain Asia)	50.08	87.69	5.95	835.22	-954.35	894.78	355.01	1977-200(23years)
159	KARA-BATKAK	HMA (high mountain Asia)	42.14	78.27	2.47	504.70	-1244.91	874.80	336.24	1976-2018(23years)
160	MALIY AKTRU	HMA (high mountain Asia)	50.05	87.75	2.73	789.95	-874.20	832.08	435.53	1962-2009(44years)
161	BELLINGSHAUSEN	Antarctic	-62.17	-58.89	11.02	750.60	-900.20	825.40	422.21	2008-2012(5years)
162	SHUMSKIY	HMA (high mountain Asia)	45.08	80.23	2.81	442.12	-1129.33	785.73	456.05	1967-1991(26years)
163	WALDEMARBREEN	Svalbard	78.68	12.07	2.50	496.93	-1069.07	783.00	239.37	1996-2009(14years)
164	KONGSVEGEN	Svalbard	78.80	12.98	101.90	691.97	-777.53	734.75	368.91	1987-2017(30years)
165	GOLUBIN	HMA (high mountain Asia)	42.46	74.50	5.45	719.85	-720.91	720.38	339.97	1969-2018(34years)
166	JOHNSONS	Antarctic	-62.67	-60.35	5.36	785.00	-591.25	688.13	339.09	2002-2017(16years)
167	HURD	Antarctic	-62.69	-60.40	4.03	642.50	-685.63	664.06	423.02	2002-2017(16years)
168	SARY TOR (NO.356)	HMA (high mountain Asia)	41.83	78.17	2.64	424.78	-903.33	664.06	470.94	1985-2018(9years)
169	VALHALTINDE	Greenland	61.44	-45.32	1.90	496.00	-662.00	579.00	256.18	1979-1983(5years)
170	BATYSH SOOK/SYEK ZAPADNIY	HMA (high mountain Asia)	41.79	77.75	1.01	242.73	-863.82	553.27	300.64	1971-2018(11years)
171	KRONEBREEN	Svalbard	78.97	13.18	No record	500.00	-606.00	553.00	201.54	2013-2017(5years)
172	AMITSULOQ ICE CAP	Greenland	66.14	-50.32	198.00	494.33	-562.22	528.28	305.06	1982-1990(9years)
173	NORDENSKIOELDBREEN	Svalbard	78.70	17.18	No record	486.77	-552.31	519.54	256.52	2006-2018(13years)
174	GLACIER NO. 354 (AKSHIYRAK)	HMA (high mountain Asia)	41.80	78.15	6.38	251.38	-780.13	515.75	238.26	2011--2018(8years)
175	URUMQI GLACIER NO. 1 E-BRANCH	HMA (high mountain Asia)	43.11	86.81	1.02	124.19	-822.94	473.56	395.16	1996-2017(16years)
176	URUMQI GLACIER NO. 1 W-BRANCH	HMA (high mountain Asia)	43.12	86.80	0.57	138.70	-772.10	455.40	394.51	1996-2017(20years)
177	URUMQI GLACIER NO. 1	HMA (high mountain Asia)	43.12	86.81	1.59	172.79	-672.25	422.52	393.55	1989-2017(24years)
178	MELVILLE SOUTH ICE CAP	Arctic north America	75.40	-115.00	51.00	185.63	-540.58	363.10	433.28	1963-2017(43years)
179	MEIGHEN ICE CAP	Arctic north America	79.95	-99.13	58.00	171.92	-370.14	271.03	375.52	1960-2017(51years)
180	CHACALTAYA	Andes	-16.35	-68.13	0.03	17.60	-484.00	250.80	709.83	2000-2004(5years)
181	QIYI	HMA (high mountain Asia)	39.24	97.76	2.98	316.80	-124.80	220.80	185.52	1975-1985(5years)
182	DEVON ICE CAP NW	Arctic north America	75.42	-83.25	1688.00	115.43	-264.52	189.97	195.27	1961-2017(56years)
183	COMMONWEALTH	Dry Valley	-77.55	163.08	52.20	9.47	-19.26	14.37	36.75	1994-2012(23years)
184	HOWARD	Dry Valley	-77.76	163.51	8.30	-2.13	-8.39	5.26	32.25	1994-2012(19years)

Code and data availability

The full sample of glaciological observations for individual glaciers is publicly available from the WGMS (doi:10.5904/WGMS-FOG-2020-08, 2020; WGMS, 2020).

Author contributions

Authors K.A., C.N. and R.Y. conducted the field survey and performed an analysis of field data. K.A. wrote the paper. ~~C.N. and~~ C.N., K.F. and H.I. checked and improved the manuscript and suggested some discussion points. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

We would like to express thanks to the captain of Cessna aircraft: T. Kinoshita (New Central Airservice Co.), K. Tomooka (IBEX Aviation Co.), and H. Miyata (Tokyo Koku Co.), Mountain Guides: Y. Matsuzawa, M. Matsumoto, Y. Furuhata, S. Arakawa, S. Matsumoto, S. Hisada, S. Matsubara, T. Nishida, H. Izumi, S. Hirata, and Y. Ito, Research Center for Mountain Environment, Shinshu University: K. Suzuki, A. Sasaki, M. Nishimura, National Research Institute for Earth Science and Disaster Resilience: S. Yamaguchi, S. Sunako, ~~S. Arakawa, S. Matsumoto, and Y. Ito,~~ Niigata University: H. Hata, Y. Mori, H, Takadama, N. Sakurai, H. Sugiyama, K. Matsumoto, R. Yoshimura. ~~, A. Ayano, and N. Yamada,.~~ This study was supported by Toyama Prefecture Energetic Snow Country Creation Project in 2015 and 2016, Research commissioned expense ~~fee~~ from Hakuba village, Nagano prefecture in 2018, and Research Grant from the Japan landslide society in 2019. We appreciate the Matsumoto Sabo office, Tateyama mountain area Sabo office, and Kurobe river office of the Ministry of Land, Infrastructure, Transport and Tourism Hokuriku Regional Development Bureau for providing high-resolution aerial laser data.

References

Abe, O., Nakamura, K., Sato, K. and Kenji, K.: Observation of Frequent Avalanches in Sekiyama Pass along Route 48 and Assessment of Snowpack Stability on the Valley Slopes, Natural Disaster Research Report, (49), 39–46 [online] Available from: https://dil-opac.bosai.go.jp/publication/nied_natural_disaster/pdf/49/49-06.pdf, 2016.

Arie, K., Narama, C., Fukui, K., Iida, H. and Takahashi, K.: Ice thickness and flow of the Karamatsuzawa perennial snow patch in the northern Japanese Alps, Journal of the Japanese Society of Snow and Ice, 81(6), 283–295, https://doi.org/10.5331/seppyo.81.6_283, 2019.

Asahi, K.: Snow patch distribution and variations last until autumn in Central Japan by means of aerial photographs interpretation, in Academic Research Grant Reports, vol. 2, edited by Public Service, Geographical Society of Japan, 239pp, Public Service, Geographical Society of Japan, Tokyo., https://www.kokudo.or.jp/grant/pdf/h25/asahi.pdf, 2016.

Benn, D. and Evans, D. J. A.: Glaciers and Glaciation, 2nd edition, Routledge. [online] Available from: https://play.google.com/store/books/details?id=dkjKAgAAQBAJ, 2014.

Bjarne Kjøllmoen (Ed.), Liss M. Andreassen, Hallgeir Elvehøy and Miriam Jackson: Glaciological investigations in Norway 2018, NVE Rapport, 46, 84 [online] Available from: http://publikasjoner.nve.no/rapport/2019/rapport2019_46.pdf, 2019.

Braithwaite, R. J. and Hughes, P. D.: Regional Geography of Glacier Mass Balance Variability Over Seven Decades 1946–2015, Front Earth Sci. Chin., 8, 302, doi:10.3389/feart.2020.00302, 2020.

Brun, F., Buri, P., Miles, E. S., Wagnon, P., Steiner, J., Berthier, E., Ragettli, S., Kraaijenbrink, P., Immerzeel, W. W. and Pellicciotti, F.: Quantifying volume loss from ice cliffs on debris-covered glaciers using high-resolution terrestrial and aerial photogrammetry, J. Glaciol., 62(234), 684–695, doi:10.1017/jog.2016.54, 2016.

Carrivick, J. L., Berry, K., Geilhausen, M., James, W. H. m., Williams, C., Brown, L. E., Rippin, D. M. and Carver, S. J.: Decadal-scale changes of the ödenwinkelkees, central Austria, suggest increasing control of topography and evolution towards steady state, Geogr. Ann. Ser. A. Phys. Geogr., 97(3), 543–562, doi:10.1111/geoa.12100, 2015.

Carturan, L., Baldassi, G. A., Bondesan, A., Calligaro, S., Carton, A., Cazorzi, F., Dalla fontana, G., Francese, R., Guarnieri, A., Milan, N., Moro, D. and Tarolli, P.: Current behaviour and dynamics of the lowermost italian glacier (montasio occidentale, julian alps), Geogr. Ann. Ser. A. Phys. Geogr., 95(1), 79–96, doi:10.1111/geoa.12002, 2013.

Cogley, J. G., Hock, R., Rasmussen, L. A., Arendt, A. A., Bauder, A., Braithwaite, R. J., Jansson, P., Kaser, G., Möller, M., Nicholson, L. and Zemp, M.: Glossary of glacier mass balance and related terms, IHP-VII Technical Documents in Hydrology, 86, 114, doi:10.5167/uzh-53475, 2011.

Colucci, R. R., Žebre, M., Torma, C. Z., Glasser, N. F., Maset, E., Del Gobbo, C. and Pillon, S.: Recent Increases in Winter Snowfall Provide Resilience to Very Small Glaciers in the Julian Alps, Europe, Atmosphere , 12(2), 263, doi:10.3390/atmos12020263, 2021.

Dai, F., Feng, Y. and Hough, R.: Photogrammetric error sources and impacts on modeling and surveying in construction engineering applications, Visualization in Engineering, 2(1), 2, doi:10.1186/2213-7459-2-2, 2014.

De Marco, J., Carturan, L., Piermattei, L., Cucchiaro, S., Moro, D., Dalla Fontana, G. and Cazorzi, F.: Minor Imbalance of the Lowermost Italian Glacier from 2006 to 2019, Water, 12(9), 2503, doi:10.3390/w12092503, 2020.

DeBeer, C. M. and Sharp, M. J.: Topographic influences on recent changes of very small glaciers in the Monashee Mountains, British Columbia, Canada, J. Glaciol., 55(192), 691–700, doi:10.3189/002214309789470851, 2009.

Dolgushin, L. D.: Main features of the modern glaciation of the Urals, IASH Publ, 54, 335–347, 1961.

Dussaillant, I., Berthier, E., Brun, F., Masiokas, M., Hugonnet, R., Favier, V., Rabatel, A., Pitte, P. and Ruiz, L.: Two decades of glacier mass loss along the Andes, Nat. Geosci., 12(10), 802–808, doi:10.1038/s41561-019-0432-5, 2019.

Dyurgerov, M. B. and Meier, M. F.: Analysis of winter and summer glacier mass balances, Geogr. Ann. Ser. A. Phys. Geogr., 81(4), 541–554, doi:10.1111/1468-0459.00082, 1999.

Fukui, K. and Iida, H.: Identifying active glaciers in Mt. Tateyama and Mt. Tsurugi in the northern Japanese Alps, central Japan, Journal of the Japanese Society of Snow and Ice, 74, 213–222, 2012.

Fukui, K., Iida, H. and Kosaka, T.: Newly Identifying Active Glaciers in the Northern Japanese Alps and Their Characteristics, Geographical Review of Japan Series A., 91(1), 43–61 [online] Available from: https://ci.nii.ac.jp/naid/40021445177/ (Accessed 22 March 2021), 2018.

Higuchi, K.: A Review of the Glaciological Studies on Perennial Ice and Snow Masses in Japan, Journal of the Japanese Society of Snow and Ice, 30(6), 195–207, doi:10.5331/seppyo.30.195, 1968.

Higuchi, K., Iozawa, T.: Atlas of perennial snow patches in Central Japan. Water Res. Lab., Faculty of Science, Nagoya U., 81 pp., 1971.

~~Higuchi, K., Iozawa, T., Fujii, Y. and Kodama, H.: Inventory of perennial snow patches in Central Japan, GeoJournal, 4(4), doi:10.1007/bf00219577, 1980.~~

Hoelzle, M., Haeberli, W., Dischl, M. and Peschke, W.: Secular glacier mass balances derived from cumulative glacier length changes, Glob. Planet. Change, 36(4), 295–306, doi:10.1016/S0921-8181(02)00223-0, 2003.

Hoffman, M. J., Fountain, A. G. and Achuff, J. M.: 20th-century variations in area of cirque glaciers and glacierets, Rocky Mountain National Park, Rocky Mountains, Colorado, USA, Ann. Glaciol., 46, 349–354, doi:10.3189/172756407782871233, 2007.

Hughes, P. D.: Twenty-first Century Glaciers and Climate in the Prokletije Mountains, Albania, Arct. Antarct. Alp. Res., 41(4), 455–459, doi:10.1657/1938-4246-41.4.455, 2009.

Huss, M.: Mass balance of Pizolgletscher, Geogr. Helv., 65(2), 80–91, doi:10.5194/gh-65-80-2010, 2010.

Huss, M.: Density assumptions for converting geodetic glacier volume change to mass change, The Ceryosphere, 7(3), 877–887, doi:10.5194/tc-7-877-2013, 2013.

Huss, M. and Fischer, M.: Sensitivity of Very Small Glaciers in the Swiss Alps to Future Climate Change, Frontiers in Earth Science, 4, doi:10.3389/feart.2016.00034, 2016.

Huss, M., Farinotti, D., Bauder, A. and Funk, M.: Modelling runoff from highly glacierized alpine drainage basins in a changing climate, Hydrol. Process., 22(19), 3888–3902, doi:10.1002/hyp.7055, 2008.

Iida, H., Fukui, K. and Osada, K.: Long-term Snow pit survey in Murodo-Daira, the Tateyama Mountains (II), JSSI & JSSE Joint Conference – 2018 in Sapporo, Hokkaido, Japan, 9-12 September 2018, 2018, 253, doi:10.14851/jcsir.2018.0_253, 2018.

Immerzeel, W. W., Kraaijenbrink, P. D. A., Shea, J. M., Shrestha, A. B., Pellicciotti, F., Bierkens, M. F. P. and de Jong, S. M.: High-resolution monitoring of Himalayan glacier dynamics using unmanned aerial vehicles, Remote Sens. Environ., 150, 93–103, doi:10.1016/j.rse.2014.04.025, 2014.

Jóhannesson, T., Raymond, C. and Waddington, E.: Time–Scale for Adjustment of Glaciers to Changes in Mass Balance, J. Glaciol., 35(121), 355–369, doi:10.3189/S002214300000928X, 1989.

Kawase, H., Yamazaki, T., Sugimoto, S., Sasai, T., Ito, R., Hamada, T., Kuribayashi, M., Fujita, M., Murata, A., Nosaka, M. and Sasaki, H.: Changes in extremely heavy and light snow-cover winters due to global warming over high mountainous areas in central Japan, Prog. Earth Planet. Sci., 7(1), 1–17, doi:10.1186/s40645-020-0322-x, 2020.

Kawashima, K.: Formation processes of ice body revealed by the internal structure of perennial snow patches in Japan, Bull. Glac. Res., (15), 1–10 [online] Available from: https://pascal-francis.inist.fr/vibad/index.php?action=getRecordDetail&idt=2764924 (Accessed 23 March 2021), 1997.

Kawashima, K., Yamada, T. and Wakahama, G.: Investigations of internal structure and transformational processes from firn to ice in a perennial snow patch, Annals of Glaciology, 18, 117–122, doi:10.3189/s0260305500011368, 1993.

Kuhn, M.: The mass balance of very small glaciers, Z. Gletscherkd. Glazialgeol., 31(1), 171–179, 1995.

López-Moreno, J. I., Nogués-Bravo, D., Chueca-Cía, J. and Julián-Andrés, A.: Glacier development and topographic context, Earth Surf. Processes Landforms, 31(12), 1585–1594, doi:10.1002/esp.1356, 2006.

Meier, M. F.: Contribution of small glaciers to global sea level, Science, 226(4681), 1418–1421, doi:10.1126/science.226.4681.1418, 1984.

Meier, M. F.: Ice, Climate, and Sea Level; Do We Know What is Happening?, in Ice in the Climate System, pp. 141–160, Springer Berlin Heidelberg., 1993.

Nicholson, L. and Benn, D. I.: Calculating ice melt beneath a debris layer using meteorological data, J. Glaciol., 52(178), 463–470, doi:10.3189/172756506781828584, 2006.

Nosaka, M., Kawase, H., Sasaki, H. and Murata, A.: Influence of the Temporal Resolution of Sea Surface Temperature on Winter Precipitation over the Coastal Area of the Sea of Japan, SOLAIAT, 15, 107–112, doi:10.2151/sola.2019-020, 2019.

Nuimura, T., Fujita, K., Fukui, K., Asahi, K., Aryal, R. and Ageta, Y.: Temporal Changes in Elevation of the Debris-Covered Ablation Area of Khumbu Glacier in the Nepal Himalaya since 1978, Arct. Antarct. Alp. Res., 43(2), 246–255, doi:10.1657/1938-4246-43.2.246, 2011.

Oerlemans, J. and Hoogendoorn, N. C.: Mass-Balance Gradients and Climatic Change, J. Glaciol., 35(121), 399–405, doi:10.3189/S0022143000009333, 1989.

Ogasahara, K.: Characteristics of the glaciers in the Japanese Alps at the time of the glacial age, The Nature of the Northern Japan Alps, Toyama University, 5–34, 1964.

Ohmura, A.: Mass balance of glaciers and ice sheets during the observational period and climate change, J. Geog., 119(3), 466–481, doi:10.5026/jgeography.119.466, 2010.

Ohmura, A.: Observed Mass Balance of Mountain Glaciers and Greenland Ice Sheet in the 20th Century and the Present Trends, Surv. Geophys., 32(4), 537–554, doi:10.1007/s10712-011-9124-4, 2011.

Pecci, M., D’Agata, C. and Smiraglia, C.: Ghiacciaio del Calderone (Apennines, Italy): the mass balance of a shrinking Mediterranean glacier, Geografia Fisica e Dinamica Quaternaria, 31(1), 55–62 [online] Available from: http://www.glaciologia.it/wp-content/uploads/FullText/full_text_31_1/07_Pecci_55_62.pdf, 2008.

Pelto, B. M., Menounos, B. and Marshall, S. J.: Multi-year evaluation of airborne geodetic surveys to estimate seasonal mass balance, Columbia and Rocky Mountains, Canada, cryosph. discuss., 1–30, doi:10.5194/tc-2019-30, 2019.

Piermattei, L., Carturan, L. and Guarnieri, A.: Use of terrestrial photogrammetry based on structure-from-motion for mass balance estimation of a small glacier in the Italian alps: SfM-MVS APPROACH FOR GLACIER MASS BALANCE ESTIMATION, Earth Surf. Processes Landforms, 40(13), 1791–1802, doi:10.1002/esp.3756, 2015.

Piermattei, L., Carturan, L., de Blasi, F., Tarolli, P., Dalla Fontana, G., Vettore, A. and Pfeifer, N.: Suitability of ground-based SfM–MVS for monitoring glacial and periglacial processes, Earth Surf. Dyn., 4(2), 425–443, doi:10.5194/esurf-4-425-2016, 2016.

Sakita, R.: Ice Block at a Valley Head in Mt Tateyama, Geogr. Rev. Jpn., 7(9), 734–747 [online] Available from: https://www.jstage.jst.go.jp/article/grj1925/7/9/7_9_734/_article/-char/ja/, 1931.

Sato, H. P., Sekiguchi, T., Orimo, K. and Nakajima, T.: Accuracy validation of airborne laser scanning DTM using the ground control points, J. Jpn. soc. photogramm. remote sens., 43(4), 13–21, doi:10.4287/jsprs.43.4_13, 2004.

Suzuki, K. and Sasaki, A.: Meteorological observations in the Japanese Alps region, Journal of Geography (Chigaku Zasshi), 128(9), 19, 2019.

Shimizu, H., Fujioka, T., Nakagawa, M., Kamada, K., Akimiya, E. and Narita, H.: Study of High-Speed Avalanche in Kurobe Canyon III, Low temperature science. Series A, Physical sciences, 32, 113–127 [online] Available from: https://eprints.lib.hokudai.ac.jp/dspace/bitstream/2115/18251/1/32_p113-127.pdf, 1974.

Tsuchiya, I.: The Glacio-Climatological Study on the Kai-gata Glacieret, Mt. Chokai (2) Instrumental Surveys of Shape and Size and Movement Measurements, Journal of the Japanese Society of Snow and Ice, 40(1), 1–9 [online] Available from: https://www.jstage.jst.go.jp/article/seppyo1941/40/1/40_1_1/_article/-char/ja/, 1978.

~~Unesco/IASH.: Combined Heat, Ice and Water Balances at Selected Glacier Basins: A Guide for Compilation and Assemblage of Data for Glacier Mass Balance Measurements : a Contribution to the International Hydrological Decade. [online] Available from: https://books.google.com/books/about/Combined_Heat_Ice_and_Water_Balances_at.html?hl=&id=dndSxgEACAAJ, 1970.~~

Vincent, C., Wagnon, P., Shea, J. M., Immerzeel, W. W., Kraaijenbrink, P., Shrestha, D., Soruco, A., Arnaud, Y., Brun, F., Berthier, E. and Others: Reduced melt on debris-covered glaciers: investigations from Changri Nup Glacier, Nepal, The Cryosphere, 10(4), 1845–1858 [online] Available from: https://tc.copernicus.org/preprints/tc-2016-75/, 2016.

Vincent, C., Cusicanqui, D., Jourdain, B., Laarman, O., Six, D., Gilbert, A., Walpersdorf, A., Rabatel, A., Piard, L., Gimbert, F. and Others: Geodetic point surface mass balances: a new approach to determine point surface mass balances on glaciers from remote sensing measurements, The Cryosphere, 15(3), 1259–1276 [online] Available from: https://tc.copernicus.org/preprints/tc-2020-239/, 2021.

World Glacier Monitoring Service (WGMS): Fluctuations of Glaciers Database, , doi:10.5904/WGMS-FOG-2020-08, 2020.

Yamaguchi, S., Abe, O., Nakai, S. and Sato, A.: Recent fluctuations of meteorological and snow conditions in Japanese mountains, Ann. Glaciol., 52(58), 209–215, doi:10.3189/172756411797252266, 2011.