Newly Identifying Active Glaciers in the Northern Japanese Alps and Their Characteristics (English Translation)

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Abstract We conducted ground penetrating radar (GPR) soundings and geodetic surveys in four perennial snow patches (PSPs) in the northern Japanese Alps (NJA) and considered the possibility that they could be active glaciers. The Kakunezato and Ikenotan PSPs had large ice bodies (>30 m thick) and flow velocities greater than 2 m/a; hence, both PSPs were admissible as active glaciers. Kuranosuke PSP also had a large ice body (25 m thick) but a flow velocity of only 3 cm/a and, therefore, the PSP was admissible as an active glacier that had been shifting to a PSP. Hama-guriyuki PSP was not admissible as a glacier because there was no evidence of a flow under current conditions. As a result of this study and the work of Fukui and Iida (2012), a total of six PSPs in the NJA were admissible as active glaciers. We also investigated the climate conditions, mass balance, and surface area changes of the active glaciers in the NJA based on in situ measurements of air temperature, snow depth, and mass balance, as well as the interpretation of aerial photographs. We found that the mountain ridges of the Tateyama Mountains were slightly higher than the climatic equilibrium line altitude (ELA). Local topographic conditions that led to huge snow accumulations by avalanches were considered likely to alter significantly the ELA of each glacier in the NJA. The Kakunezato and Ikenotan PSPs lost only 12% and 16% of their surface areas between 1955 and 2016, respectively.

Key words glacier, perennial snow patch, northern Japanese Alps, mass balance, equilibrium line altitude

Introduction

Glaciers can be regarded or defined as “a mass of snow and ice continuously moving from higher to lower ground or, if afloat, continuously spreading” (Armstrong et al. 1966; Kusunoki 1967; Ageta 2014), and are distinguished from perennial snow patches (PSPs) in the sense that they are “continuously moving”. During the last glacial period, there were several hundred glaciers in the Japanese Alps of Honshu and in the Hidaka Mountains of Hokkaido (e.g. Hashimoto and Kumano 1955; Kobayashi 1958; Iozawa 1963, 1979, 2007; Koaze et al. 1974; Ono and Hirakawa 1975; Ono 1984, 1991; Aoki and Hasegawa 2003; Iwata 2014). Japan receives some of the heaviest snowfalls in the world, and there are more than 400 PSPs in the northern Japanese Alps (NJA) (Higuchi and Iozawa 1971). Since the 1920s, PSPs with ice bodies have been found on Mts. Tsurugi, Tateyama, and Kashimayari in the NJA (Imanishi 1929, 1933, 1969; Sakita 1931; Ogasawara 1964; Higuchi et al. 1971; Iozawa 1959), Mts. Gassan and Chokai in the Tohoku region (Tsuchiya 1978), and in the Daisetsu Mountains in Hokkaido (Wakahama et al. 1968; Kawashima et al. 1993).

In Japan’s PSPs, where as much as 20 m of snow accumulates and melts in 1 year, the surface of the PSPs can decrease by as much as 10 cm/day during the ablation season (May to October) (e.g. Moribayashi and Higuchi 1980). Because it is difficult to maintain flow measurement, the movement of Japan’s PSPs with ice bodies has not been demonstrated. Thus, many Japanese glaciologists have come to believe that glaciers do not currently exist in Japan.

Hoshiai and Kobayashi (1957) estimated the present equilibrium line altitude (ELA) of the Japanese Alps to be around 4,000 m a.s.l. from the mean summer air temperature of the free atmosphere. This estimation may be inaccurate given that it was only dependent on the air temperature and did not take account of precipitation. However, this estimate has been used in many Japanese textbooks of physical geography (e.g. Yoshikawa et al. 1973; Tabuchi 1979; Kaizuka and Chinzei 1986; Sugitani et al. 1993). Thus, the assumption that glaciers could not exist because the Japanese mountains were much lower than the present ELA has become widely accepted among geographers in Japan.

Koaze and Iwata (2001) estimated the present ELA of the Japanese Alps to be 3,600 m a.s.l. by assuming that the ELA of northeast Asia decreases linearly in the north–
south direction, from 27°N in the Hengduan Mountains of China (ELA = 5,200 m a.s.l.) to 51°N at the southern tip of the Kamchatka Peninsula (ELA = 1,200 m a.s.l.). Ono et al. (2003) and Ono (2012) estimated the present ELA of the Tateyama Mountains, in the northern part of the NJA, to be about 2,970 m a.s.l. using the empirical formula of Ohmura et al. (1992), which is based on the summer air temperature and the annual precipitation. As a result, the ELA estimated by Hoshiai and Kobayashi (1957) has finally been questioned.

Fukui and Iida (2012) conducted field measurements to investigate whether the Sannomado, Komado, and Gozenzawa PSPs, located in the Tateyama Mountains were admissible as active glaciers, using ground penetrating radar (GPR) and a differential global positioning system (dGPS), which has recently been compacted and lightened to facilitate its use in the field. As a result, it was found that the Sannomado and Komado PSPs had ice bodies that were more than 30 m thick, and Gozenzawa PSP had an ice body that was 27 m thick. It was also confirmed that the flow velocity during the late ablation season (September to October), when PSPs in Japan are the thinnest, was about 30 cm/month for the Sannomado and Komado PSPs and about 5 cm/month for Gozenzawa PSP. These results indicated that these PSPs were admissible as active glaciers.

On June 30, 2012, a symposium on glaciers and PSPs in Japan was held to discuss the validity of the assertions of Fukui and Iida (2012). The symposium concluded that there was no objection to referring to the Sannomado, Komado, and Gozenzawa PSPs as glaciers (Shiraiwa et al. 2012). Thus, the existence of active glaciers in Japan has finally been recognized academically and, hereafter, we refer to these three PSPs as the Sannomado, Komado, and Gozenzawa glaciers, respectively.

In this study, the ice thickness and flow velocity of the

*Figure 1.* The study area.
a. Distribution of glaciers and PSPs around Mts. Tsurugi, Tateyama, and Kashimayari. b. The location of the NJA. The NJA consist of three mountain ranges: the Tateyama, Ushiro-Tateyama, and Yari-Hotaka.

| Name        | Toe (m a.s.l.) | Head (m a.s.l.) | Elevation range (m) | Length (m) | Width (m) | Area 2016 (m²) | Area 1955 (m²) |
|-------------|---------------|----------------|---------------------|------------|-----------|----------------|----------------|
| Kakunezato  | 1,795         | 2,160          | 365                 | 790        | 280       | 89,900         | 102,200        |
| Ikenotan    | 1,800         | 2,300          | 500                 | 950        | 110       | 58,780         | 69,900         |
| Kuranosuke  | 2,700         | 2,830          | 130                 | 350        | 120       | 25,600         | —              |
| Hamaguriyuki| 2,720         | 2,735          | 15                  | 40         | 36        | 1,280          | —              |
| Gozenzawa   | 2,500         | 2,780          | 280                 | 780        | 185       | 74,590         | —              |
Kakunezato, Ikenotan, Kuranosuke, and Hamaguriyuki PSPs (Figure 1), where the possible presence of glaciers has been advocated, were observed. In addition, the characteristics of the active glaciers in the NJA such as the characteristics of the climate, flow mechanism, mass balance, internal ice structure, and recent surface area changes were also investigated.

**Study Area**

Kakunezato PSP is located at the bottom of a glaciated valley on the northeast side of the northern peak of Mt. Kashimayari (2,842 m a.s.l.) (Figures 1, 2a). The PSP faces northeast and its surface is partly covered by debris. It has a length of 790 m, a width of 280 m, an altitude of 1,795 to 2,160 m a.s.l., and an area of 89,900 m² (Table 1). The PSP is presumed to be fed by avalanches (Iozawa 1979).

In the PSP, a large ice body was identified by Kinji Imanishi in 1930 (Imanishi 1933). From 1955 to 1958, Tomoya Iozawa found the existence of glacier-like surface morphologies, such as moulins, crevasses, and meltwater channels on the ice body (Iozawa 1959, 1979).

Ikenotan PSP is located at the bottom of a deep and narrow U-shaped valley on the western face of Mt. Tsurugi (2,999 m a.s.l.) (Figures 1, 2b). It faces northwest, with a length of 950 m, a width of 110 m, an altitude from 1,800 to 2,300 m a.s.l., and an area of 58,780 m² (Table 1). Aerial photographs taken by the United States Armed Forces on May 3, 1952 (USA-M5-3-3-155, 156), show that the entire area of the PSP is covered with thick avalanche debris and, therefore, the PSP is presumed to be fed by avalanches. A mountain rescue team found a large ice body (>30 m thick) in the PSP in the 1970s. In autumn, some crevasses, moulins, and meltwater channels appear on the surface of the PSP.

Kuranosuke PSP is located in the Kuranosuke cirque just below Mt. Fuji-no-oiritate (2,999 m a.s.l.) (Figures 1, 2c). It faces northeast, with a length of 350 m, a width of 120 m, an altitude of 2,700 to 2,830 m a.s.l., and an area of 25,600 m² (Table 1). In autumn, many moulins and meltwater channels appear on the surface of the PSP. The ice body up to 30 m thick was confirmed by impulse radar soundings (Yamamoto et al. 1986; Yamamoto and Yoshida 1987).

Kuranosuke PSP is presumed to be fed by avalanches and snowdrifts (Yoshida et al. 1983). The snow depth reaches over 16 m during the maximum snow season (March to April) (Watanabe 1986; Yoshida et al. 1990). A protalus rampart has formed in the center of the PSP (Sekine 1973; Ono and Watanabe 1986; Fukui 2002).

A research group of Toyama University and Hokkaido University found an ice body in Kuranosuke PSP in early October 1963 (Ogasawara 1964). Yoshida et al. (1990) determined that the age of the ice body was 1,000 to 1,700 years BP by 14C dating of plant remnants in the ice collected from the bottom of the moulins.
Hamaguriyuki PSP is located in the lee (north-eastern) slope of the Bessan-nokkoshi saddle (2,755 m.a.s.l.) (Figures 1, 2d), and is fed by snowdrifts (Hiyama and Iida 2007). The PSP faces northeast, with a length of about 40 m, a width of about 36 m, an area of 1,280 m², and an altitude of 2,720 to 2,735 m a.s.l. (Table 1).

A research group of Toyama University and Hokkaido University found an ice body in Hamaguriyuki PSP in early October 1962 (Ogasawara 1964; Yoshida 1964). Since 1967, a research group from Nagoya University has been continuously conducting a geodetic survey of the volume of the PSP. The annual ablation depth was significantly correlated with the initial depth (at the beginning of the ablation season), whereas a less significant correlation was found with a temperature index that is generally believed to correlate well with ablation (Fujita et al. 2010).

At the end of the ablation season in 1998, the PSP completely disappeared and then regenerated in the following year (Hiyama and Iida 2007).

The Gozenzawa glacier is located in the Gozenzawa cirque on the east-facing slope of Mt. Oyama (3,003 m a.s.l.) (Figures 1, 2e). The glacier faces northeast, with a length of 780 m, a width of 185 m, a thickness of 27 m, an altitude of 2,500 to 2,780 m a.s.l., and an area of 74,590 m² (Table 1). The glacier has a partly debris-covered area in its center (Figure 2e). From summer to autumn, many moulins and meltwater channels appear on the surface of the glacier (Tsujimura 1913; Sakita 1931). The surface flow velocity of the glacier in the autumns of 2010 and 2011 was about 5 cm/month (Fukui and Iida 2012).

Figure 3. Ice body extent of the PSPs and the Gozenzawa glacier.

a: Kakunezato PSP; b: Ikenotan PSP; c: Kuranosuke PSP; d: Hamaguriyuki PSP; e: Gozenzawa glacier.
Methods

Identifying new active glaciers

Ground penetrating radar soundings Most glaciers experience distinct creep at a depth of about 30 m (e.g., Iwata 2011). Ground penetrating radar (SIR3000 system, GSSI Corp., Nashua, NH, USA) soundings were conducted to clarify whether the Kakunezato, Ikenotan, Kuranosuke, and Hamaguriyuki PSPs had ice bodies of over 30 m thickness, which could flow as glaciers. The central frequencies of the GPR antennas used were 100 MHz on the Kuranosuke and Hamaguriyuki PSPs and 270 MHz on the Kakunezato and Ikenotan PSPs.

We measured longitudinal GPR profiles that extended along the central flowline of Kakunezato PSP on June 19, 2011 (maximum sounding depth = 45 m and length = 938 m), Ikenotan PSP on September 25, 2012 (maximum sounding depth = 60 m and length = 854 m), Kuranosuke PSP on October 4, 2016 (maximum sounding depth = 46 m and length = 112 m), and Hamaguriyuki PSP on August 24, 2013 (maximum sounding depth = 29 m and length = 173 m) (Figure 3).

The GPR profiles were processed using the Radan 7 software (GSSI Corp.). The dielectric constant used in the depth analysis was 3.2, which is the mean value of the dielectric constant of firn in Murododaira (Izumi et al. 2009) and temperate glacier ice. The locations of the GPR profiles and topographical data for each PSP were obtained from a kinematic dGPS (GEM-1, Enabler Ltd., Tokyo, JAPAN) survey. The errors of the kinematic dGPS surveys were about 10 cm in the horizontal direction and about 20 cm in the vertical direction.

Geodetic survey Geodetic surveys of each PSP were conducted to measure the surface flow velocity of the ice bodies. In September, aluminum stakes (length, 4.6 m) were inserted vertically in the ice bodies of each PSP (Figure 3), and the positions of the stakes were surveyed using the dGPS (GEM-1). After a certain period, the positions of the stakes were surveyed again, and the surface flow velocities of the ice bodies were obtained from the distances that the stakes had moved.

The duration of the dGPS surveys was: 24 days (five stakes) from September 24, 2015, to October 18, 2015, for Kakunezato PSP; 31 days (the lower two stakes) from September 26, 2012, to October 27, 2012; 42 days (the upper two stakes) from September 10, 2013, to October 22, 2013, for Ikenotan PSP; 1,844 days (two stakes) from September 7, 2011, to September 24, 2016, for Kuranosuke PSP; and 29 days (two stakes) from September 10, 2015, to October 9, 2015, for Hamaguriyuki PSP.

The dGPS survey data were post-processed using the Justin ver. 2.122 software (JAVAD Corp., San Jose, CA, USA). The benchmarks were installed on stable rocks near each PSP (Figure 3). In Kuranosuke PSP a benchmark near Gozenzawa glacier was used (Figure 3e). We performed repeated dGPS surveys on the benchmarks to assess the dGPS survey uncertainties. The error of the geodetic surveys was assumed to be 1–2 cm (Kakunezato, Ikenotan, and Hamaguriyuki PSPs) and about 4 cm (Kuranosuke PSP).

Investigations of the characteristics of Japanese glaciers

Characteristics of the climate Glaciers are maintained by a mass balance composed of accumulation, mainly by snowfall and avalanches, and ablation, mainly by melting snow and ice. Ohmura et al. (1992) found that the mean summer (June, July, and August) air temperature of the free atmosphere represents ablation, and annual precipitation (snow depth + summer precipitation) represents accumulation.

Mean summer air temperatures were calculated from air temperature observed at the Kuranosuke Hut (2,780 m a.s.l.) from 1998 to 2009 (Fukui 2010) and at the Onanji Hut (3,000 m a.s.l.) from 2011 to 2014 (Fukui and Iida 2015). Both mountain huts were located in the vicinity of the peaks of the Tateyama Mountains (Figure 1). Annual precipitation was calculated from maximum snow depth at Murododaira (2,450 m a.s.l.) from 1996 to 2016 (Iida et al. 2016) and summer precipitation at Tateyama (AMeDAS Tateyama) (2,291 m a.s.l.) acquired from the Automated Meteorological Data Acquisition System of Japan Meteorological Agency from 1979 to 2008.

Flow mechanism Glacier flow is caused by three flow components: (1) plastic deformation of ice, (2) sliding of ice over its bed, and (3) deformation of the bed itself (Paterson 1994). The surface flow of the glacier is the sum of these three flow components.

Based on observations inside moulins in Kuranosuke PSP in 2016, we confirmed that there was a wide range of cavities between the ice body and the bed, which is composed of clast-supported angular rock debris. The flow by plastic deformation was indicated from a C-axis orientation distribution, and the anisotropy of the bubble shapes within the ice sampled from the lower part of the ice body (Kiyota et al. 1990). The results indicated that the flow component by basal sliding and deformation of the
bed could be neglected in Kuranosuke PSP. To examine whether the flow of ice bodies could be estimated only by plastic deformation, the flow velocities by plastic deformation for the Kuranosuke and Kakunezato PSPs were calculated by a numerical model assuming the flow components by basal sliding and bed deformation were zero. The results were compared with the measured surface flow velocity obtained from the dGPS surveys.

**Mass balance** Mass balance observations were made at the Gozenzawa glacier using the stake method. The height of four stakes on the glacier (Figure 3e) was measured on October 27 and 28, 2011, and the height of the stakes was measured again on October 12, 2012, to obtain the difference in height of the ice surface. The annual mass balance was calculated by multiplying the difference by the average density of the firn (695 kg/m³) in the ice core of the glacier on October 4, 2013. We also measured the heights of two stakes on the glacier on September 9, 2016, and October 3, 2016 (Figure 3e), and obtained the difference in the height of the ice surface between 2012 and 2016. The annual mass balance was calculated by multiplying the difference by the average density of the firn (695 kg/m³).

**Internal ice structure** We drilled an ice core on the Gozenzawa glacier on October 4, 2013, at 2,550 m a.s.l. (Figure 3e). The diameter and length of the ice core were 7.2 cm and about 7 m, respectively. The stratigraphy and density of the ice core were measured in the low-temperature room of the Tateyama Caldera Sabo Museum. On October 19, 2015, we entered a crevasse that appeared in the upper part of Kakunezato PSP (Figure 3a) and measured the stratigraphy and density from the surface to a depth of 6 m.

**Changes in the ice extent over 61 years** The surfaces of the PSPs in the NJA are often covered with snow, even at the end of the ablation season. It is therefore difficult to determine changes in the surface area of their ice body. However, once every 10 to 20 years, extreme snowmelt occurs, and their ice body may be exposed on the PSP surface. A comparison of the area of the PSPs in years when their ice body was widely exposed enabled us to determine changes in the surface area of their ice body.

In 2016 a considerable snowmelt occurred in the NJA (Iida et al. 2016), and the ice bodies were widely exposed on the surfaces of most PSPs in the late autumn. On September 27, 2016, and October 7, 2016, about 50 aerial photographs of each PSP were taken using a helicopter upstream an unmanned aerial vehicle (UAV) (Phantom 4, DJI Corp., Shenzhen, China). The aerial photographs were orthorectified using the structure from motion (SfM) software (PhotoScan 1.3, Agisoft Corp., St. Petersburg, Russia). We plotted the ice body extent of the Kakunezato, Ikenotan, Kuranosuke, and Hamaguriyuki PSPs, and the Gozenzawa glacier on the orthorectified images using geographical information system (GIS) software (ArcGIS 10.3, ESRI Corp., Redlands, CA, USA).

There was also considerable snowmelt in the NJA in 1955 (Higuchi 1968). Iozawa (1979) confirmed that the ice body on the surface of Kakunezato PSP was widely

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**Figure 4. Longitudinal GPR profiles of the PSPs.**

- a: Kakunezato PSP (June 19, 2011); b: Ikenotan PSP (September 25, 2012); c: Kuranosuke PSP (October 4, 2016); d: Hamaguriyuki PSP (August 24, 2013).
exposed in September 1955. In aerial photographs taken by the U.S. Armed Forces on September 25, 1955 (USA-M 1147-N-12, 13), the exposed ice bodies of the Kakunezato and Ikenotan PSPs were visible. We plotted the ice body extent of the Kakunezato and Ikenotan PSPs in 1955 on the orthorectified in 2016, based on our interpretation of the aerial photographs. By comparing the ice body extent of both PSPs in 1955 and 2016, the changes in the ice body areas of both PSPs over 61 years were determined.

Identification of new active glaciers

Figure 4 shows the longitudinal GPR profiles of each PSP and its interpretation. In the GPR profile of Kakunezato PSP on June 19, 2011, there was an internal structure interpreted as snow cover of 13–18 m thickness and an ice body of over 30 m thickness (Figure 4a). The length of the ice body was about 800 m. Two reflection planes from the ice body bottom dipped in an up-glacier direction at a distance from 300 to 550 m (Figure 4a). Because these two reflection planes ran toward the debris-covered area (Figure 3a) on the ice body surface, they could be a debris-rich layer that was thrust up with the flow of the ice body (e.g. Fukui et al. 2008).

As a result of the geodetic survey for 24 days in autumn, 2015, it was confirmed that Kakunezato PSP had flowed 12–17 cm (Figure 5a). The flow direction was northeast and almost coincided with the maximum tilt direction of the PSP. Fujii and Takenaka (1990) reported that the snow load on the ice bodies of the PSPs in the NJA reached a minimum during the late ablation season; therefore, the flow velocity of the ice bodies was slowest during this season. Kakunezato PSP could flow constantly throughout the year because an ice body flow was observed during the late ablation season and, therefore, the PSP was admissible as an active glacier.

Assuming that the flow velocity is constant throughout the year, the annual flow velocity of Kakunezato PSP was 1.8–2.6 m/a. This flow velocity was comparable to that of the Lewis glacier on Mt. Kenya, Kenya (0.6–2.5 m/a) (Hasterath 1992) and the No. 31 glacier in the Suntal Hyata Mountains, Russia (1.57 m/a) (Shirakawa et al. 2008).
In the GPR profile of Ikenotan PSP on September 25, 2012, there was an internal structure that was interpreted as snow cover of 2–4 m thickness and an ice body of 39 m thickness (Figure 4b). The length of the ice body was 850 m, and it was determined that the ice body was thickest in the downstream part of the PSP.

It was confirmed that the downstream part of the ice body of Ikenotan PSP had flowed 11–12 cm during the 31 days in autumn 2012 and 22–23 cm during the 42 days in autumn 2013 (Figure 5b). The flow directions were to north-northwest in both 2012 and 2013, which coincided with the maximum tilt direction of the PSP. Because an ice body flow was observed during the late ablation season, it was considered possible that the Ikenotan PSP had flowed constantly throughout the year. Thus, the PSP was admissible as an active glacier.

In the GPR profile of Kuranosuke PSP obtained on October 4, 2016, there was an internal structure interpreted as an ice body, with a thickness of 25 m and a length of 112 m (Figure 4c). The thickness of the ice body was similar to the depth of the moulin (about 24 m) near the middle of the GPR profile. There was a strong reflection plane that was parallel to the surface at a depth of 5–6 m, and there were multiple reflection planes dipping up-glacier in the lower layer from the strong reflection plane (Figure 4c). Iida et al. (1990) confirmed by observations inside the moulin that there was an unconformity plane consisting of a debris-rich layer almost parallel to the surface at a depth of 2–9 m and debris-rich layers dipping up-glacier in the ice body below the unconformity plane. Therefore, the reflection plane of 5–6 m depth was assumed to be the unconformity plane, and the reflection dipping up-glacier was assumed to constitute the debris-rich layers.

The GPR profile on October 4, 2016, almost followed the impulse radar profile (Line No. 3) on September 14, 1983 (Yamamoto et al. 1986). The maximum thickness of the ice body in 1983 and 2016 were 28 and 25 m, respectively (Figure 4c). Thus, the ice body of Kuranosuke PSP was estimated to have thinned by about 3 m between 1983 and 2016.

In Kuranosuke PSP, during the 1,844 days from September 7, 2011, to September 24, 2016, flows of 11–14 cm were observed (Figure 5c). The flow direction almost coincided with the maximum tilt direction of the ice surface from northeast to east-northeast. Although the annual flow velocity was only 2–3 cm, Kuranosuke PSP was admissible as an active glacier that was shifting to a PSP.

In the GPR profile of Hamaguriyuki PSP on August 17, 2013, there was an internal structure interpreted as snow cover of 3–9 m thickness and an ice body of 7 m thickness (Figure 4d). The length of the ice body was 77 m. The ice body of Hamaguriyuki PSP temporarily disappeared in 1998. Therefore, the present ice body is considered to have grown over the subsequent 15 years. The growth rate of the ice body was estimated to be about 47 cm/a.

We conducted geodetic surveys of Hamaguriyuki PSP in the autumn of 2015, but no stake movement beyond the error value was observed (Figure 5d). Therefore, Hamaguriyuki PSP was not admissible as an active glacier.

As a result of this study and Fukui and Iida (2012), six PSPs in the NJA were admissible as active glaciers (Table 2). All of them had ice thicknesses of more than 25 m. Only a few PSPs in the NJA, such as Karamatsu, Kaerazu, and Shakushi PSPs in the Ushiro-Tateyama Mountains, had the potential to acquire an ice thickness of more than 25 m.

| Name          | Observation period | Days | Flow (cm) | Surface velocity (cm/a) | Ice thickness (m) | Surface slope (°) |
|---------------|-------------------|------|-----------|-------------------------|-----------------|------------------|
| Komado        | 18 SEP–19 OCT 2011| 31   | 32        | 377                     | >30             | 19               |
| Sannomado     | 17 SEP–18 OCT 2011| 31   | 31        | 365                     | 48              | 27               |
| Kakunezato    | 24 SEP–18 OCT 2015| 24   | 17        | 259                     | >30             | 25               |
| Ikenotan      | 26 SEP–27 OCT 2012| 31   | 12        | 141                     | 39              | 24               |
| Ikenotan      | 10 SEP–22 OCT 2013| 42   | 23        | 200                     | 39              | 24               |
| Gozenzawa     | 6 SEP–28 OCT 2011 | 52   | 9         | 63                      | 27              | 14               |
| Kuranosuke    | 7 SEP 2011–24 SEP 2016 | 1,844 | 14    | 3                       | 25              | 8                |
| Hamaguriyuki  | 10 SEP–9 OCT 2015 | 29   | 1 n     | —                       | 7               | 32               |

1) Lower 2 stakes, 2) Upper 2 stakes, n) This vale is a margin of error.
(Data of the Komado, Sannomado, and Gozenzawa glaciers are from Fukui and Iida (2012)).
The characteristics of the glaciers in the NJA

Characteristic of the climate

The mean summer temperatures between 1998 and 2009 for the Kuranosuke Hut and between 2011 and 2014 for the Onanji Hut were 9.2°C and 8.0°C, respectively (Fukui 2010; Fukui and Iida 2015). The snow water equivalent (w.e.) of the maximum snow depth in Murododaira was 2,979 mm on average from 1996 to 2016 (Iida et al. 2016), and the summer precipitation (late June to early October) from AMeDAS Tateyama was 1,872 mm on average from 1979 to 2008. Annual precipitation in the Tateyama Mountains is estimated to be at least 4,851 mm based on the sum of the maximum snow depth (w.e.) and the summer precipitation.

The distribution of the ELAs of 70 glaciers worldwide is presented in Figure 6 in a precipitation–temperature (P–T) diagram (Ohmura et al. 1992). If the P–T condition falls above the cluster of data points (Figure 6), the site is likely to be in an accumulation area. Likewise, if the P–T condition falls below the cluster of data points, the site is either in an ablation area or unglaciated (Ohmura et al. 1992).

The P–T conditions at the elevation of mountain ridges of the Tateyama Mountains fall slightly above the cluster of data points (Figure 6). Although the mountain ridges of the Tateyama Mountains are located in an area with relatively high summer temperatures, compared to the world’s current glaciated area, the mountain ridges of the Tateyama Mountains could be slightly higher than the climatic ELA. This suggests that accumulation due to the extremely heavy snowfall in this area may exceed the large ablation during summer. There are some glaciers in the world where the P–T conditions around the ELA are relatively close to that of Mt. Tateyama, such as the Nisqually glacier in the USA, Høgtuvbreen in Norway, and the Sentinel glacier in Canada (Ohmura et al. 1992).

Verification of flow velocity due to plastic deformation by the ice-flow model calculation

The flow velocity of Kakunezato PSP was verified by a simple numerical ice-flow model based on Glen’s law (Glen 1952), which is the general law of glacier flow by plastic deformation. It is assumed that a glacier is a rectangular object lying on a bed of slope β without basal sliding, as shown in Figure 7, with z in an upward direction perpendicular to the bed, and the thickness of the glacier is h. The flow direction of the glacier is x. The length and width of the glacier are assumed to be sufficiently long compared to h.

Assuming that the ice is incompressible, there is two-dimensional laminar flow (Figure 7), and the ice temperature is 0°C, the following relationships between the strain rate (\(\dot{\varepsilon}_{zx}\)) and shear stress (\(\tau_{zx}\)) are obtained (Paterson 1994).

\[
\dot{\varepsilon}_{zx} = A \tau_{zx}^{n} \quad (1)
\]
\[
\dot{\varepsilon}_{zx} = \frac{1}{2} \frac{du}{dz} \quad (2)
\]
\[
\tau_{zx} = \rho g (h-z) \sin \alpha \quad (3)
\]

Here, A is a variable that depends on ice temperature, crystal orientation, and impurity content; \(\rho\) is the density of ice (900 kg/m³); g is the gravitational acceleration....
(9.8 m/s²); \(u\) is the flow velocity in the \(x\) direction; and \(n\) is a constant that often takes the value of 3 in many actual experiments and field experiments on glaciers (Cuffey and Paterson 2010). By substituting equations (2) and (3) into equation (1), and integrating from the glacier bottom \((z=0)\) to the glacier surface \((z=h)\), the flow velocity \(U\) can be obtained as follows:

\[
U_s-U_b = \frac{2A}{n+1}(\rho g \sin \alpha)^n h^{n+1}
\]

(4)

Assuming that the velocity at the bottom is \(U_b=0\) and \(n=3\), the surface velocity \(U_s\) is given by:

\[
U_s = \frac{A}{2}(\rho g \sin \alpha)^3 h^4
\]

(5)

The shape factor \(F\) (Paterson 1994) is introduced into equation (5) to account for friction from the side walls of the valley:

\[
U_s = \frac{A}{2}(F\rho g \sin \alpha)^3 h^4
\]

(6)

Here, \(A\) is \(6.8 \times 10^{-15}/s\) (Paterson 1994) at an ice temperature of \(0^\circ\)C. The shape factor \(F\) was about 0.8 for Kakunezato PSP, according to Paterson (1994: 269–270). Figure 8a shows the relationship between flow velocity and ice thickness, with the surface slope \(\alpha\) as a parameter.

The flow during the late ablation season in the middle of Kakunezato PSP was evaluated. Assuming that the surface slope was \(25^\circ\) (Table 2) and the ice thickness was 30 m (Figure 4a), the flow velocity was calculated to be about 2.4 m/a (Figure 8a). The flow velocity during the late ablation season obtained from the geodetic surveys was 2.3–2.6 m/a (Figure 5a, Table 2), which was similar to the flow velocity calculated by the model. Therefore, it was proven that the flow velocity of Kakunezato PSP could be maintained at a reasonable quantity due to plastic deformation by the ice-flow model calculation.

Because the snow depth of Kakunezato PSP on June 19, 2011, was 18 m (Figure 4a), the maximum snow depth was estimated to exceed 18 m. When the snow density was half that of ice, the ice equivalent thickness of Kakunezato PSP during the maximum snow season was estimated to be more than 39 m. The flow velocity at this time is calculated much larger than 6.9 m/year (Figure 8a).

The flow velocity of Kuranosuke PSP was obtained using equation (6). The shape factor \(F\) was about 0.6 according to Paterson (1994: 269–270). Figure 8b shows the relationship between the flow velocity and ice thickness, with surface slope \(\alpha\) as a parameter.

The flow velocity in the central part of Kuranosuke PSP was calculated. Assuming a surface slope of \(8^\circ\) (Table 2), an ice thickness of 25 m (Figure 4c) during the late ablation season, and an ice equivalent thickness of 33 m (snow depth was 16 m) during the maximum snow season, the flow velocity was calculated to be 2–5 cm/a (Figure 8b). The annual average value of the flow velocity was 3.5 cm/a, which was close to the measured value of 2–3 cm/a (Table 2) from the geodetic surveys. Therefore, the flow velocity of Kuranosuke PSP could also be maintained at a reasonable quantity due to plastic deformation by the ice-flow model calculation.

The GPR sounding results indicated that the ice body of Kuranosuke PSP thinned by about 3 m over the 33-years from 1983 to 2016. According to the ice-flow model, if the ice body in the central part of Kuranosuke PSP (surface slope \(8^\circ\)) thinned to 22 m, the flow velocity was estimated to be 1 cm/a (Figure 8b) and, therefore, the ice body was almost stagnant. If the volume of ice body continued to shrink, Kuranosuke PSP was expected...
to stop flowing and transition to a PSP.

**Mass balance**

The annual mass balance of the Gozenzawa glacier in 2011/2012 was almost zero at 2,539 m a.s.l. near the glacier toe (Figure 9). Negative values of $-1,328$ and $-573$ mm w.e. were obtained at 2,545 and 2,565 m a.s.l., respectively, and a positive value of 347 mm w.e. was obtained at 2,711 m a.s.l. (Figure 9). In the Gozenzawa glacier, the annual mass balance was almost zero near the glacier toe. Typically, the mass balance would be negative in this region of a glacier, which suggests that snow supply by avalanches was a major contributor to the accumulation of the Gozenzawa glacier.

The average annual mass balance of the Gozenzawa glacier during the four years of 2012 to 2016 was $-229$ mm w.e. at 2,565 m a.s.l. and $-329$ mm w.e. at 2,711 m a.s.l. (Figure 9). During 2013–2015, all of the stakes were buried in snow and could not be observed on the surface of the glacier. It is likely that the entire area of the Gozenzawa glacier was an accumulation area from 2012 to 2015 and was an ablation area from 2015 to 2016.

Arai (1975) advocated the idea that the locations of the PSP toes, where the sum of accumulation by snowfall, avalanches, and snowdrifts is equal to ablation, are the ELA of the glaciers in the Japanese mountains. Based on this premise, the ELA was 2,500 m a.s.l. for the Gozenzawa glacier, 2,700 m a.s.l. for Kuranosuke PSP, 1,795 m a.s.l. for Kakunezato PSP, and 1,800 m a.s.l. for Ikenotan PSP (Table 1). Despite their close horizontal distance (only 13.5 km apart), the ELAs of Kuranosuke and Kakunezato PSPs differed by more than 900 m. Therefore, this region can be characterized by significantly variable ELA depend on the individual glacier. Local topographic conditions that lead to huge amounts of snow accumulation by avalanches are likely to lead to the variable ELA of each glacier in the NJA.

**Internal ice structure**

Figure 10a shows the stratification and density profile of the ice core taken from the Gozenzawa glacier on October 4, 2013. The surface to a depth of 0.7 m was firn (remnant snow from the previous winter), while the 0.7–7 m depth layer was glacial ice. Dirty layers were found at depths of 0.6, 1.7, and 4.4 m. The density of the firn was 570–740 kg/m³ (average 695 kg/m³) and that of the glacier ice was 824–907 kg/m³ (average 860 kg/m³).

Figure 10b shows the stratification and density profile of the crevasse in Kakunezato PSP observed on October 19, 2015. The surface to a depth of 0.9 m was firn, and the depth of 0.9 m to 6 m was a glacial ice layer. Dirty layers were found at depths of 0.7–0.9, 1.5–1.6, and 2.5 m. The density of the firn was 710–780 kg/m³ and that of the glacier ice was 820–880 kg/m³.
Changes in the ice extent over 61 years

The ice bodies of Kakunezato PSP on September 25, 1955, and September 27, 2016, were 102,200 and 89,900 m², respectively (Table 1, Figure 3a). The surface area of the ice body of the PSP declined by 12% from 1955 to 2016. The ice bodies of Ikenotan PSP on September 25, 1955, and October 7, 2016, were 69,900 and 58,780 m², respectively (Table 1, Figure 3b). The surface area of the ice body of the PSP declined by 16% from 1955 to 2016. The ice bodies of both PSPs partly disappeared near their upper or lower edges, while the main parts of the ice bodies were almost unchanged (Figure 3a, b).

Due to global atmospheric warming, glaciers around the world have experienced considerable area and mass losses in recent decades (e.g., Zemp et al. 2015). For example, Lewis Glacier on Mt. Kenya lost 74% of its surface area in the 63 years from 1947 to 2010 (Prinz et al. 2011). The Martial glaciers in Argentina lost 65% of their surface area over the 59 years between 1943 and 2002 (Strelin and Iturraspe 2007). Because the decline in surface area of Kakunezato and Ikenotan PSPs seems to be very slow in comparison with these glaciers, it is possible that both are less sensitive to climate change and/or the NJA has experienced negligible regional climate warming in recent decades (Suzuki and Sasaki 2019).

Conclusion

In this study, we conducted GPR soundings and geodetic surveys in four PSPs in the NJA and considered the possibility that they could be active glaciers. The Kakunezato and Ikenotan PSPs had large ice bodies (>30 m thick) and flow velocities greater than 2 m/a; hence, both PSPs were admissible as active glaciers. Kuranosuke PSP also had a large ice body (25 m thick) but a flow velocity of only 3 cm/a and, therefore, the PSP was admissible as an active glacier that had been shifting to be a PSP. Hamaguriyuki PSP was not admissible as a glacier because there was no evidence of a flow under current conditions. As a result of this study and the work of Fukui and Iida (2012), a total of six PSPs in the NJA were admissible as active glaciers.

We also examined climate conditions, mass balance, and changes in the surface area of the active glaciers in the NJA based on in situ measurements of air temperature, snow depth, and mass balance, as well as interpretation of aerial photographs. The mean summer temperatures from 1998 to 2009 at the Kuranosuke Hut, and from 2011 to 2014 at the Onanji Hut, were 9.2°C and 8.0°C, respectively. The annual total precipitation in the Tateyama Mountains was estimated to be 4,851 mm. According to the P–T conditions (Ohmura et al. 1992), the mountain ridges of the Tateyama Mountains may be slightly higher than the climatic ELA. Although the Kuranosuke and Kakunezato PSPs are only 13.5 km apart, their ELAs vary in the range of 900 m. Therefore, the NJA may be characterized by significant variation in ELA among glaciers. Local topographic conditions can lead to massive snow accumulation due to avalanches and are therefore likely to significantly alter the ELAs of glaciers in the NJA. The Kakunezato and Ikenotan PSPs lost only 12% and 16% of their surface area between 1955 and 2016, respectively. Since the changes in the area of these PSPs appear to be very small in comparison with those of glaciers worldwide, the Kakunezato and Ikenotan PSPs may be less sensitive to climate change and/or the NJA has experienced negligible regional climate warming in recent decades.

Based on these findings, we classified the six active glaciers of the NJA according to glacier inventory guidelines established by the United Nations Educational, Scientific and Cultural Organization (UNESCO)/International Association of Scientific Hydrology (IASH) in 1970, as part of the International Commission on Snow and Ice, to inventory glaciers worldwide during the International Hydrological Decade (IHD) in 1965–1974 (UNESCO/IASH 1970). The Sannomado and Komado glaciers and Ikenotan and Kakunezato PSPs were classified as “650223” because they are fed by avalanches and flow through valleys, and their termini are nearly stagnant. The Gozenzawa glacier and the Kuranosuke PSP were classified as “640203” because they are fed by both snowdrifts and avalanches and flow through cirques, and their termini are almost stagnant.

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