CHARACTERISTICS OF SNOW AVALANCHE RELEASE IN FORESTS DURING A HEAVY SNOWFALL EVENT

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ABSTRACT: The heavy snowfall on February 14–15, 2014 caused many snow avalanches in the Kanto-Koshin region, Japan, where a thin snow cover exists during a normal winter season. Avalanche release (i.e., new snow avalanches) in forests was one of the important events that occurred during this heavy snowfall. To examine the characteristics of the avalanche release in forests that occurred during this heavy snowfall, the stability and the hardness of snow accumulated on slopes were estimated based on air temperature and snow depth using the viscous compression theory for snowpack. The results of the data analysis revealed that the rapid instability in short period and the reduction in the hardness of the snow that had accumulated on slopes occurred because of the high snowfall intensity (about 4 cm/h) and relatively low air temperature during the snowfall, and that these conditions induced many avalanche releases in the forests.

KEYWORDS: avalanche, forest, air temperature, snowfall intensity, hardness, stability.

1. INTRODUCTION

Heavy snowfall on February 14–15, 2014 caused many snow avalanches in the Kanto-Koshin region, Japan, where a thin snow cover exists during a normal winter season (Izumi et al., 2014). Avalanche release (i.e., new snow avalanches) in forests was one of the important events that occurred during this heavy snowfall (Akiyama et al., 2015; Nakamura et al., 2014; Izumi et al., 2014; Kamiishi et al., 2014; Abe et al., 2014; Machida et al., 2014).

In general, forests with high tree density act as an anchor for snow that accumulates on slopes, and help prevent avalanche release (Ishikawa et al., 1969; Brang et al., 2006). Avalanche release in forests has been investigated in many countries, such as Japan (Yamaguchi et al., 2004; Akiyama et al., 2012), Switzerland (Schneebeli and Meyer-Grass, 1992; Teich et al., 2012), Italy (Viglietti et al., 2010), and Canada (McClung, 2001). A statistical analysis of avalanches using meteorological data by Teich et al. (2012) indicated that avalanche release in forests tends to occur when the sum of new snow height was relatively large. However, the detailed weather and snow conditions associated with avalanche release in forests have not been thoroughly clarified.

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In this study, we examined the characteristics of avalanche release in forests during the heavy snowfall event of February 2014 in Japan using meteorological data.

2. DATA AND METHOD

2.1 *Avalanche releases in forests during the heavy snowfall of February 2014*

Figure 1 shows the locations of avalanche release in forests that occurred during this heavy snowfall (Izumi et al., 2014; Nakamura et al., 2014; Kamiishi et al., 2014; Machida et al., 2014), other avalanches that occurred during the heavy snowfall (Izumi et al., 2014), and the meteorological observatories of the Japan Meteorological Agency (JMA).

All avalanche releases in forests (○ in Fig. 1) were surface dry-snow avalanches that occurred on February 14 and 15, 2014. The elevations of the starting zones of these avalanches estimated from the terrain are between 1000 and 1100 m, with slope inclinations between 42 and 45°. However, vegetation conditions such as density and tree species are unknown.

The meteorological observatories located near the avalanche releases in forests are Kawaguchiko (KW), Minakami (MN), and Hinoemata (HN). In addition, snow accumulated on slopes slid through supporting nets and fences that are used to prevent avalanches and rockfalls (□ in Fig.1) in the neighborhoods of Chichibu (CC) and Minakami (MN) (Izumi et al., 2015; Machida et al., 2014).

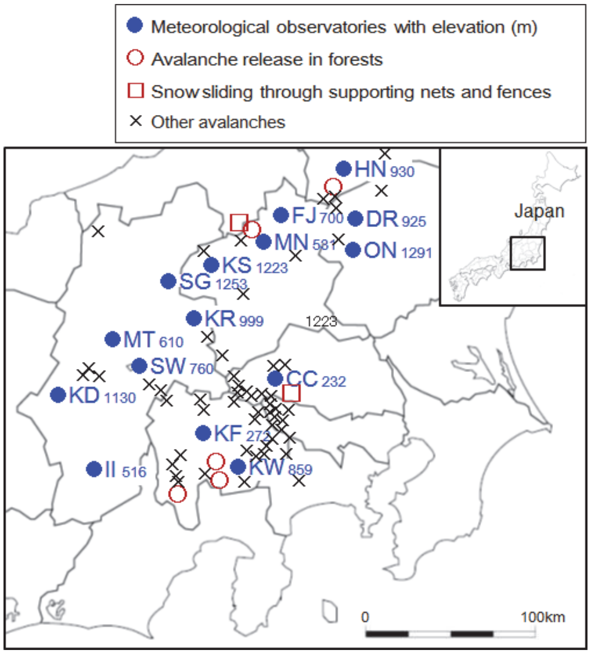

Fig. 1: Locations of avalanche release in forests (○) that occurred during this heavy snowfall (Izumi et al., 2014; Nakamura et al., 2014; Kamiishi et al., 2014; Machida et al., 2014) and locations of meteorological observatories (●). HN: Hinoemata, DR: Dorobe, ON: Okunikko, FJ: Fujiwara, MN: Minakami, KS: Kusatsu, SG: Sugadaira, KR: Karuizawa, MT: Matsumoto, SW: Suwa, KD: Kaida-kogen, II: Iida, CC: Chichibu, KF: Kofu, KW: Kawaguchiko. Locations of snow sliding through nets and fences (□) as well as other avalanches (X) (Izumi et al., 2014) that occurred during the heavy snowfall are also indicated.

Other avalanches also occurred on many slopes during the heavy snowfall (X in Fig. 1) (Izumi et al., 2014).

2.2 Meteorological data

The meteorological data used in this study were hourly snow depth and air temperature observed at the 15 observatories shown in Fig. 1.

Duration of snowfall (h) was defined as the period of increasing hourly snow depth until an interruption of increasing snow depth exceeded five hours. Depth of snowfall (cm) was calculated as the sum of differences between hourly snow depths. Snowfall intensity (cm/h) was calculated by dividing the depth of snowfall by the snowfall duration.

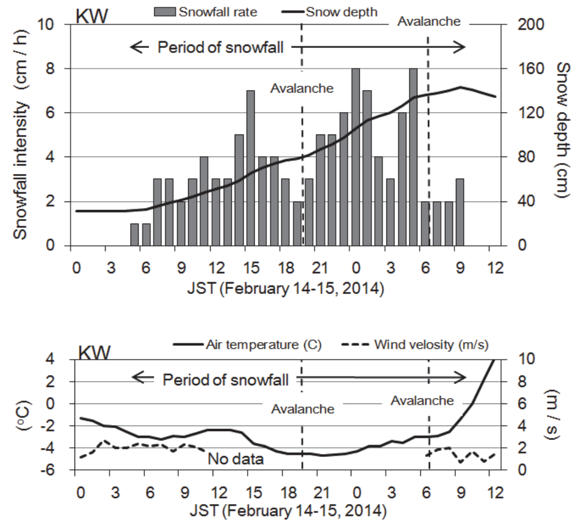

Fig. 2: Time series of hourly snow depth, snowfall intensity, air temperature and wind velocity on February 14–15 at Kawaguchiko (KW). JST stands for Japan Standard Time.

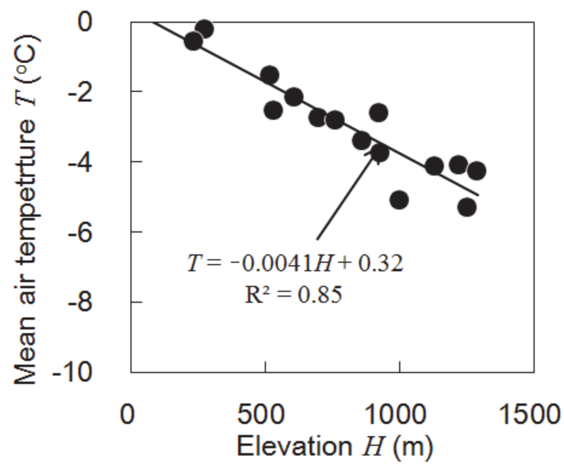

Fig. 3: Relationship between the elevation and the mean air temperature during snowfall at 15 meteorological observatories.

Figure 2 shows a sample of time series of hourly snow depth, snowfall intensity, air temperature, and wind velocity on February 14 and 15 at KW. The period of snowfall at KW began at 5 JST on February 14 and ended at 9 JST on February 15. The snowfall duration was 29 h, the depth of snowfall was 112 cm, the mean snowfall intensity during the period was 3.9 cm/h, and the mean air temperature was -3.4 °C.

However, the air temperature is dependent on the elevation of each observatory; therefore, the observed air temperature at the observatory differs from that at the starting zone of avalanche release in forests. To estimate the mean air temperature during snowfall at each observatory with respect to the elevation of the starting zone of avalanche release in forests (1100 m), we used a regression equation obtained from the relationship between elevation and mean air temperature during snowfall at 15 meteorological observatories (solid line in Fig. 3).

2.3 Method of examining the characteristics of avalanche release in forests

To examine the weather and snow conditions associated with avalanche release in forests, we considered two important factors related to an avalanche occurrence and a vulnerability of snow to avalanche release in forests.

One of the factors relating to avalanche occurrence is snow stability on a slope. We used a stability index SI that expresses the ratio of shear strength to shear stress for snowpack on a slope (Conway and Wilbour, 1999):

$$SI = \frac{\Sigma_s}{h\rho g \sin\theta \cos\theta} \quad (1)$$

where Σ_s is shear strength of a snow layer (N/m^2), h is depth of new snow above a snow layer (m), ρ is density of new snow above a snow layer (kg/m^3), g is gravitational acceleration (m/s^2), θ is slope inclination ($^\circ$), and $h\rho g \sin\theta\cos\theta$ is shear stress acting on a snow layer (N/m^2). The slope inclination θ in the example shown below is 45°. The shear strength of snow Σ_s can be estimated using Eq. (2) with respect to snow density ρ (Endo, 1993).

$$\Sigma_s = 3.10\times10^{-4}\rho_t^{\,3.08} \quad (2)$$

The snow density ρ increases with time during snow accumulation because of the densification of snowpack. Increased snow density ρ_t (kg/m^3) at time t (h) was calculated by the viscous compression theory for snowpack, shown in Eq. (3) (Endo, 1993). Increased snow density ρ_t was used to estimate the shear strength of snow Σ_s and the stability index SI:

$$\rho_t = \left\{\frac{2Ag}{C}\cdot\cos^2\theta\cdot t^2 + \rho_0^4\right\}^{1/4} \quad (3)$$

where ρ_0 is initial snow density (kg/m^3) and was given as 50 kg/m^3 in the example below, and A is snowfall intensity (kg/m^2·h). The snowfall intensity A is related to the snowfall intensity obtained from the hourly difference of observed snow depth A_{ob} (m/h), such that $A = \rho_0 A_{ob}$. C is a coefficient related to the progress of the densification of snowpack (N/(m^2·s·(kg/m^3)^4)) and can be obtained from Eq. (4), with respect to snow temperature T_s (°C) (Abe, 2001).

$$C = 0.21\exp(-0.166T_s) \quad (4)$$

For new snow, we can assume that the snow temperature T_s is equal to the air temperature during snowfall T ($T_s \approx T$).

Next, as a factor related to the vulnerability of snow to avalanche release in forests, we used snow hardness H. The snow hardness H can be estimated from Eq. (5) (Takeuchi et al., 2001) using increased snow density ρ_t due to densification.

$$H = 1.31\times10^{-5}\rho_t^4 \quad (5)$$

Based on Eqs.(1) – (5), if the slope inclination is constant (45°), the stability index SI and snow hardness H are functions that depend on snow density ρ_t, and snow density ρ_t can be calculated using the observed air temperature T and snowfall intensity A_{ob} during snowfall. A decrease in the stability index SI indicates instability of the snowpack on a slope. A reduction in snow hardness H indicates a weak structure of the snowpack and implies conditions such that avalanche release in forests is likely.

3. RESULTS

3.1 Mean conditions during the heavy snowfall

Figure 4 shows the snowfall duration, mean snowfall intensity, and total snowfall depth during the heavy snowfall at 15 meteorological observatories. The meteorological observatories located near the avalanche releases in forests are KW, MN, and HN (● in Fig. 4). The observatories at which snowfall depth exceeded 100 cm are KW, KF, HN, and KS. In particular, the mean snowfall intensities at KW and KF were greater than those noted at other observatories, and snowfall depth at KW and KF exceeded 100 cm after 30 h.

However, Figure 4 does not clearly indicate the weather conditions associated with avalanche release in forests (● in Fig. 4). This means that the avalanche release in forests does not only occur

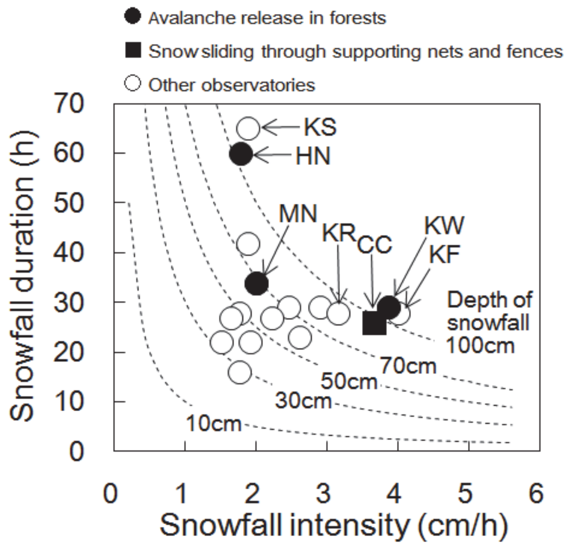

Fig. 4: Snowfall duration, mean snowfall intensity, and total snowfall depth during the heavy snowfall at 15 meteorological observatories.

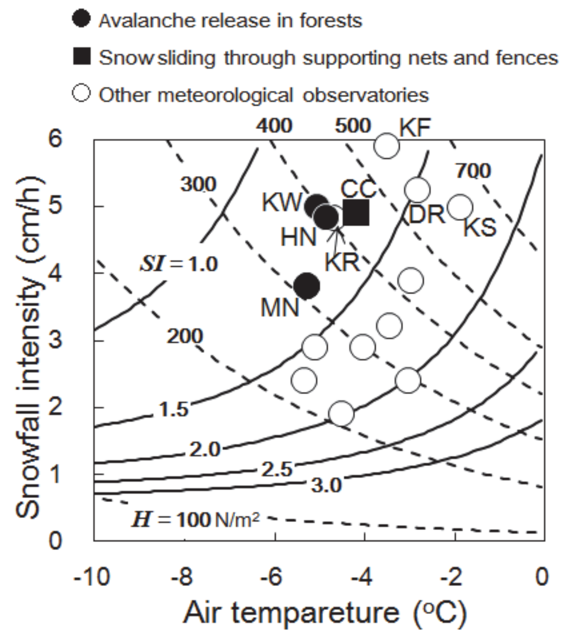

Fig. 5: Relationship between the mean snowfall intensity and the mean air temperature for the 12 h during which the mean snowfall intensity peaked at each observatory. The stability index *SI* (solid line) and the snow hardness *H* (broken line) estimated using air temperature and snowfall intensity are also shown. The mean air temperatures are the estimated values at each observatory that correspond to an elevation of 1100 m.

under conditions of high snowfall depth. In the next section, the conditions for avalanche release in forests are examined based on the stability index *SI* and the snow hardness *H* estimated using the observed air temperature and snowfall intensity.

3.2 Conditions for avalanche release in forests

Figure 5 shows the relationship between mean snowfall intensity and mean air temperature over 12 h during which the mean snowfall intensity peaked at each observatory. The mean air temperatures shown in Fig. 5 are the estimated values at each observatory that correspond to the elevation of the starting zone of avalanche release in forests (1100 m). Figure 5 also shows the stability index *SI* (solid line) and the snow hardness *H* (broken line) estimated using mean air temperature and mean snowfall intensity.

Figure 5 shows that at KW, MN, and HN, which are located near the sites of avalanche release in forests (● in Fig. 5), the mean air temperatures during heavy snowfall were below -5 °C, and the mean snowfall intensities were over 3.8 cm/h. The estimated stability index *SI* at these observatories was below 1.5, and the estimated snow hardness *H* was below 400 N/m^2. In addition, in CC where snow slid through nets designed to prevent rockfall (■ in Fig. 5), the weather and snow conditions were similar to the conditions associated with avalanche release in forests. Therefore, using the stability of snowpack on a slope and the snow hardness based on snowfall intensity and the air temperature during snowfall may indicate the conditions for avalanche release in forests. In other words, there are two characteristic of weather and snow conditions for avalanche release in forests: first, the rapid instability of snowpack on a slope due to high snowfall intensity in short period (about 12 h) and second, the reduction in hardness of snow due to low temperatures, which increases the vulnerability of snow to avalanche in forests.

In Fig. 5, the weather and snow conditions in KR are also similar to the conditions associated with avalanche release in forests. Although avalanche release in forests near KR was not reported, it is likely that it occurred.

4. CONCLUSION

In this study, the characteristics of the avalanche release in forests that occurred during the heavy snowfall event of February 2014 in Japan were examined using meteorological data. The stability and the hardness of snow accumulated on slopes were estimated based on air temperature and snowfall intensity using the viscous compression theory for snowpack.

The results shows that using the stability of snowpack on a slope and the snow hardness based on snowfall intensity and air temperature during snowfall could indicate the conditions required for avalanche release in forests. In other words, the weather and snow conditions associated with avalanche release in forests have two processes: first, the rapid instability of snowpack on slopes due to high snowfall intensity in short period and second, the reduction in hardness of snow due to low temperatures that increases the vulnerability of snow to avalanche release in forests.

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