A simple evaluation of dry-snow avalanche hazard using meteorological data

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ABSTRACT
For planning mitigative measures against snow avalanches, the size and frequency of avalanches should be evaluated in a certain region. However, avalanche hazard is not easy to evaluate directly using observed data of avalanche occurrences because long-term data on avalanches is rare. We analyzed snowfall events associated with dry-snow avalanche release conditions using meteorological data covering a few decades and evaluated the frequency of avalanches by approximation of the events to an exponential distribution.

1. INTRODUCTION

The frequency of phenomena that cause natural hazards is an important factor to consider for prevention and protection measures against the phenomena. Current methods for evaluating the frequency of avalanches are as follows: methods directly using long-term data on avalanche occurrences (e.g., Laternser and Schneebeli, 2002; Sinickas et al., 2016), methods of detecting avalanche years from damage and changes remaining in tree-rings (e.g., Decaulne et al., 2012; Corona et al., 2012), methods of estimating the potential conditions for avalanche releases using meteorological data (Jóhannesson and Jónsson, 1996), and methods using the relationship between the total amount of precipitation and the probability of avalanche occurrence (Bakkehøi, 1986). We propose to easily evaluate the frequency of avalanches using meteorological data in a region where long-term data on avalanche occurrences does not exist.

In the frequency analysis, probability distributions of extreme values, such as the annual maximum, are commonly used to ascertain the return period, but complex procedures, such as parameter setting, are necessary for fitting the data to the probability distribution. On the other hand, all values exceeding a certain threshold are sometimes used to evaluate the frequency of phenomena in peaks over threshold (POT) analysis (e.g., Blanchet et al., 2009). In addition, it has been known for a long time that the relationship between the frequency and the magnitude of natural phenomena exceeding a certain threshold could be simply approximated to exponential and/or power-law distributions (e.g., Gutenberg and Richter, 1944). The suitability of exponential and/or power-law distributions for the frequencies of rain events (e.g., Peters et al., 2010) and snow avalanches (Birkeland and Landry, 2002) also has been examined by much previous research. If the approximation could be applied to snowfall events associated with avalanche release conditions, the frequency required to plan prevention measures against avalanches could be easily evaluated using the meteorological data. We analysed the snowfall events associated with the avalanche release conditions using meteorological data covering a few decades and evaluated the frequency of the avalanches by approximation of the events to exponential distribution.

2. METHODS

2.1 Meteorological conditions associated with avalanche releases

For attempting the frequency analysis of snow avalanches using meteorological data, we focused on dry-snow avalanches during heavy snowfall. In particular, avalanche release in forests is one of the characteristic phenomena that occur during heavy snowfall. A typical heavy snowfall event that caused many avalanches occurred in the Kanto-Koshin district on February 14-15, 2014, as shown in Fig. 1a (Izumi et al., 2014). Figure 1b indicates a meteorological condition associated with dry-snow surface avalanche releases in forests as well as other avalanches that occurred during the heavy snowfall (Matsushita and Ishida, 2016). The avalanche releases in forests shown as "●" in Fig.1b occurred in conditions with relative low air temperature and large snowfall amount in a short period of 12 hours compared with other avalanches shown as "×" in Fig. 1b. In addition, conditions associated with avalanche releases in forests, including the results of examination for vegetable and terrain conditions (Matsushita et al., 2018), are summarized as follows:

(1) Snowfall amount S_{12}: During 12 hours, exceeding 45 cm on a slope with inclination of 45° or exceeding 50 cm on a slope with inclination of 30°.

(2) Air temperature T_{12}: mean value during the 12 hours is below -4 °C.

(3) Snow depth SD_{b12}: larger than 50 cm one hour before a period of 12 hours.

We focused on conditions (1)-(3) of dry-snow surface avalanche releases in forests during heavy snowfall and examined the frequency analysis of avalanches using meteorological data.

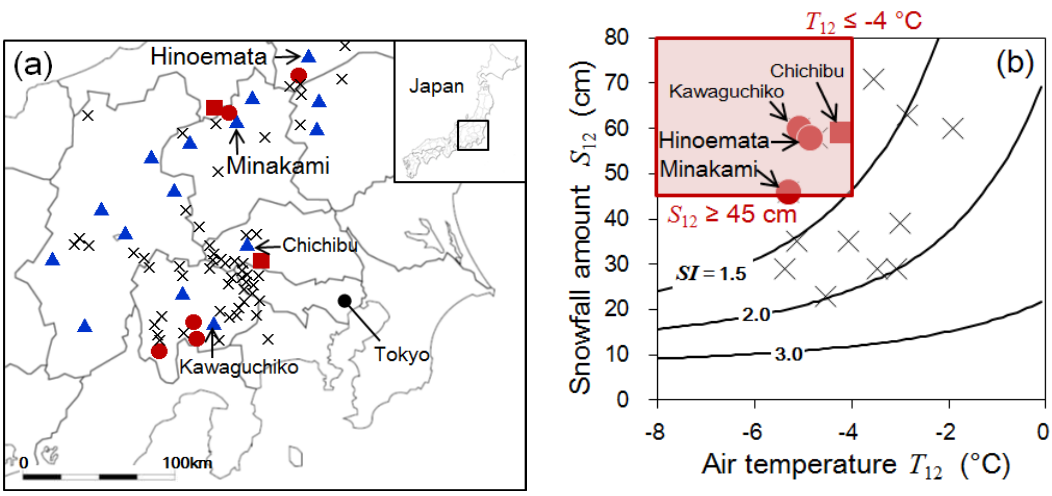

Figure 1 (a) Locations of avalanche releases in forests (●; Matsushita and Ishida, 2016) as well as other avalanches (×; Izumi et al., 2014) during extreme heavy snowfall on 14-15 February 2014. Locations of snow sliding through nets and fences for preventing falling rocks (■) and meteorological observatories of the Japan Meteorological Agency (▲) are also shown. (b) Conditions associated with avalanche releases during the heavy snowfall expressed with maximum snowfall amount S_{12} and mean air temperature T_{12} during 12 hours within snowfall period. Classical stability index SI were estimated using S_{12} and T_{12} (Matsushita and Ishida, 2016).

2.2 Selecting the snowfall events associated with avalanche release conditions

To examine the frequency of snowfall events associated with dry-snow avalanche release conditions based on the exponential approximation, we used hourly snow depth and air temperature observed at Minakami (36° 48.0' N, 138° 59.5' E, 531 m a.s.l.) and Hinoemata (37° 00.6' N, 139° 22.5' E, 973 m a.s.l.) where avalanches were released in forests during the heavy snowfall on 2014 (Fig. 1). The data were observed during the periods of 28 winters from November 1989 to April 2017 at Minakami and of 35 winters from November 1982 to April 2017 at Hinoemata by the Japan Meteorological Agency.

First of all, snowfall amount S (cm) was defined as the cumulative value of the positive difference in snow depth each hour. Each snowfall event was regarded as ending when the snowfall ceased (i.e., the hourly difference in snow depth ≤ 0 cm) for more than 5 hours. The numbers of snowfall events n with snowfall amounts S at intervals of 5 cm were counted regarding the cases of snowfall amounts S greater than 30 cm. Dividing the number of events n by the years of observation period provides the frequency of snowfall events $F(S)$ (number of events / year) with snowfall amounts S. In this paper, we used the frequency $F(S\leq)$ based on the cumulative number of snowfall events N from classes of large snowfall amounts at intervals of 5 cm. The frequency $F(S\leq)$ means the occurrence number N of snowfall events per year with snowfall amounts exceeding S cm.

Next, the maximum snowfall amount S_{12} during 12 hours within the period of each snowfall event was calculated and mean air temperature T_{12} during the 12 hours was obtained from hourly data. For evaluating the frequency of snowfall events associated with conditions of dry-snow avalanche releases in forests shown Section 2.1, the events with mean air temperature T_{12} below -4 °C and snow depth SD_{b12} over 50 cm were discriminated from the snowfall events. Frequencies $F(S_{12}\leq)$ of the discriminated events were calculated in the same manner as that of the snowfall events mentioned above. The frequency $F(S_{12}\leq)$ means the occurrence number N of snowfall events per year with snowfall amounts exceeding S_{12} cm.

3. RESULTS

3.1 Frequency of snowfall events

Figure 2 shows the numbers n and the frequencies $F(S\leq)$ of snowfall events with snowfall amounts S at intervals of 5 cm. The frequencies of snowfall events with snowfall amounts exceeding 50 cm and 100 cm are 2.96 (three times per year) and 0.25 (once per four years) at Minakami, and 4.31 (about four times per year) and 0.74 (once per 1.4 years) at Hinoemata.

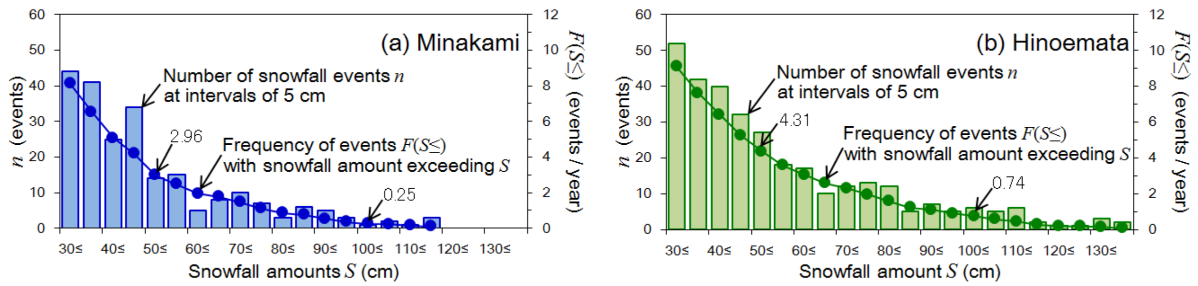

Figure 2 Numbers of snowfall events n (histograms) and frequencies of events $F(S\leq)$ with snowfall amounts exceeding S (solid lines with closed circles) at intervals of 5 cm.

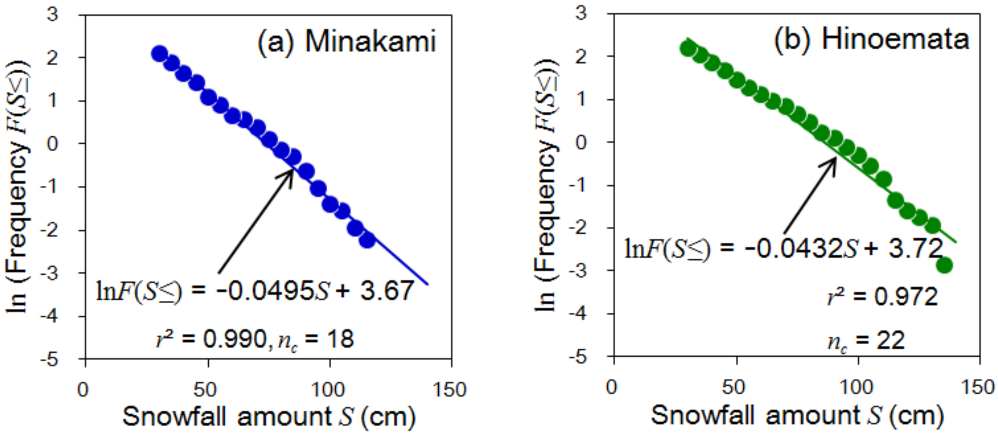

Figure 3 Snowfall amounts S versus the logarithms of frequencies $F(S\leq)$ of snowfall events. The vertical axes are expressed in natural logarithmic scale. Solid lines represent regression lines with coefficients of determination r^2 and number of classes n_c.

Figure 3 represents the relationship between the snowfall amount S and the logarithm of the frequency of snowfall events $F(S\leq)$ with snowfall amounts exceeding S at intervals of 5 cm. The vertical axis of this figure is expressed in natural logarithmic scale shown as "ln". The solid line is a regression line with coefficient of determination r^2 between the snowfall amount S and the logarithm of frequency $F(S\leq)$. The regression analysis indicates a strong linear correlation between the snowfall amount and the logarithm of frequency at a statistically significant level. The frequencies of snowfall events with snowfall amounts exceeding 50 cm and 100 cm that are estimated from the regression equations are 3.30 and 0.28 at Minakami, and 4.76 and 0.55 at Hinoemata. These estimated values agree with the observed values. Therefore, the simple regression analysis with exponential function can be used for evaluating the frequency of snowfall events with snowfall amounts exceeding a certain value.

3.2 Frequency of snowfall events associated with avalanche release conditions

The numbers of snowfall events with mean air temperature T_{12} below -4 °C and snow depth SD_{b12} over 50 cm are 56 at Minakami and 205 at Hinoemata (Fig. 4). The frequencies of

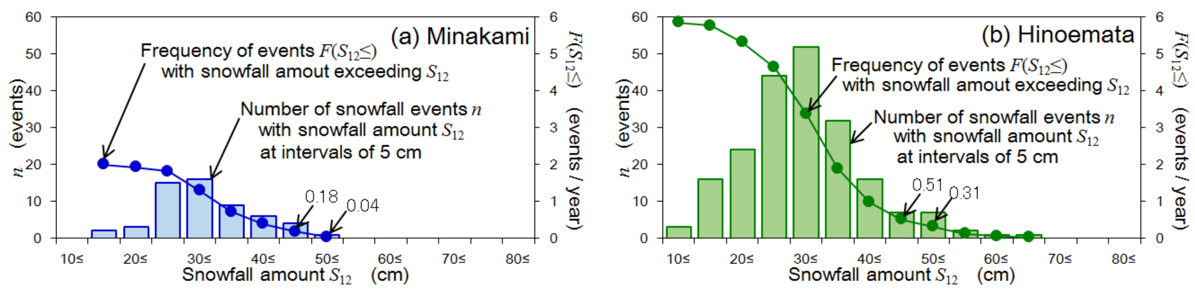

Figure 4 Numbers of events n with the maximum snowfall amount S_{12} (histograms) and frequencies of events $F(S_{12}\leq)$ (solid lines with closed circles) at intervals of 5 cm. The events were selected from the snowfall events shown in Fig. 2 as cases of mean air temperature T_{12} below -4 °C and snow depth SD_{b12} over 50 cm.

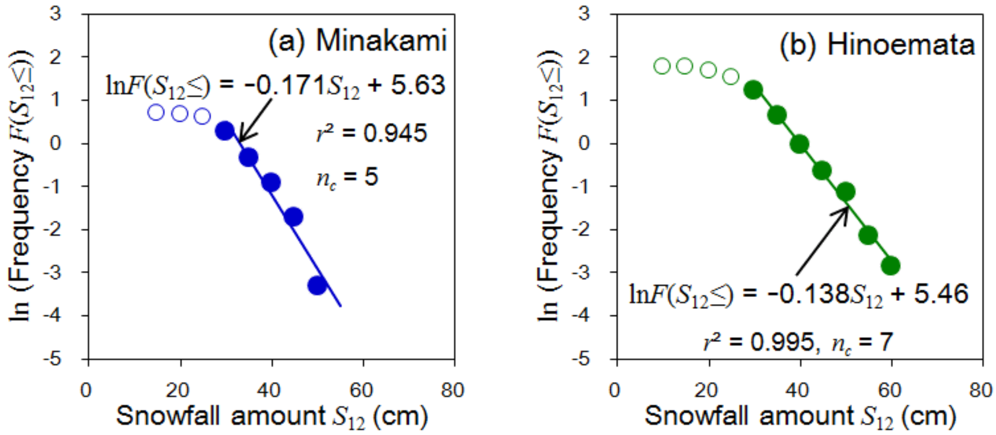

Figure 5 Relationship between the snowfall amounts S_{12} and the logarithms of frequencies $F(S_{12}\leq)$ of snowfall events shown in Fig. 4. Regression equations represented as solid lines were obtained except the events with snowfall amounts S_{12} less than 30 cm (shown as open circles). n_c is the number of classes used in regression analyses.

the snowfall events $F(S_{12}\leq)$ with snowfall amounts S_{12} exceeding 45 cm and 50 cm, which are associated with conditions of dry-snow avalanche releases in forests, are 0.18 (once per 5.5 years) and 0.04 (once per 25 years) at Minakami, and 0.51 (once per two year) and 0.31 (once per three years) at Hinoemata.

Figure 5 represents the relationship between the snowfall amount S_{12} and the logarithm of the frequency of snowfall events $F(S_{12}\leq)$ with snowfall amounts exceeding S_{12} at intervals of 5 cm. Regression lines shown in Fig. 5 were obtained, except the snowfall events with snowfall amounts S_{12} less than 30 cm shown as open circles in the figure. The frequencies of snowfall events with snowfall amounts S_{12} exceeding 45 cm and 50 cm that were estimated from the regression equations are 0.13 and 0.05 at Minakami, and 0.47 and 0.24 at Hinoemata. These estimated values agree closely with the observed values. Therefore, the simple regression analysis with exponential function can be used also for evaluating the frequency of the snowfall events associated with the conditions of dry-snow avalanche releases in forests.

4. CONCLUSIONS

We analysed the snowfall events associated with the avalanche release conditions using meteorological data covering a few decades and evaluated the frequency of the avalanches by approximation of the events to an exponential distribution. Simple regression analysis using the exponential function revealed a strong correlation between the frequency and snowfall amount (i.e., size) of snowfall events at a statistically significant level. Consequently, the exponential approximation can be used in frequency analyses for snowfall events associated with avalanche release conditions. However, avalanche release conditions using meteorological data should be defined to evaluate the frequency of the avalanches in this method.

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