NEW PERSPECTIVE ON DRIFTING SNOW SLAB AVALANCHE

Yusuke Harada[1]*, Ryuzo Wakabayashi[2] and Kengo Moriyama[3]

[1] *Civil Engineering Research Institute for Cold Region, Public Works Research Institute, Sapporo, Japan*
[2] *Alpine Research Institute of Avalanche, Hakuba, Japan*
[3] *WAKAVA Society, Hakuba, Japan*

ABSTRACT: We introduce the idea that the top of the snowpack on a slope composed of wind-broken precipitation particles by creep and saltation of blowing snow (DFbk; size vf (< 0.2 mm)) tends to promote deformation due to densification after sintering by solar radiation or warm air advection during drifting snow following a snowstorm in the mountainous area, which is the key causation of avalanche release. In addition, the risk of drifting snow slab avalanche is greater in the path of side-loading during the drifting snow since fine snow particles are well-packed due to collision and fragmentation under sub-zero temperatures.

KEYWORDS: Drifting snow, Side-loading, Slab avalanche, Densification of snowpack

1. INTRODUCTION

We introduce the idea that the top of the snowpack on a slope composed of wind-broken precipitation particles with creep and saltation of blowing snow (DFbk; size vf (< 0.2 mm): Fierz et al., 2009) tends to promote deformation due to densification after sintering by solar radiation or warm air advection during drifting snow following a snowstorm in the mountainous area, which is the key causation of avalanche release. In addition, the risk of drifting snow slab avalanche is greater in the path of side-loading during the drifting snow since fine snow particles are well-packed due to collision and fragmentation under sub-zero temperatures (Figure 1).

2. REVIEW OF THE SNOWPACK ON A SLOPE-RELATED AVALANCHE AND DRIFTING SNOW

Using aerial photographs in the Japanese snowy mountainous area (Figure 2), Wakabayashi (1976) and Nitta (1987) showed that the number of avalanches was greater on side-loading on which the wind direction was parallel to the slope more than top-loading or up-slope loading, based on avalanche tracks and snow surface patterns such as ripples. These slopes are considered to have a high frequency of fragmented snow particles moving again, overcoming multiple ridges from the side during strong winds blowing. According to Nishimura et al. (2014), who conducted field measurements of drifting snow in the French Alps using snow particle counters (hereinafter: "SPCs"), snow particle diameter distributions were generally less than 200 µm at the heights of

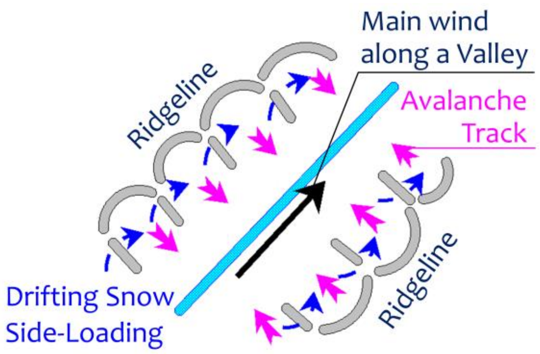

Figure 1: Pattern diagram of side-loading drifting snow (blue) and avalanche tracks (Pink) in Continuous Gullies with the main wind along a valley.

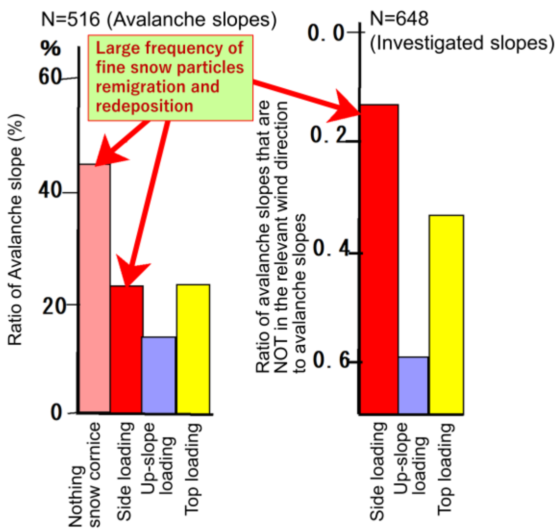

Figure 2: Relationship between Avalanches and wind directions (Based on Nitta, 1987): left, along the Hokuriku Expressway reported in 1966; right, along the Tohoku Expressway reported in 1970.

* *Corresponding author address:*
Yusuke Harada, Civil Engineering Research Institute for Cold Region, PWRI, 1-3-1-34 Hiragishi, Toyohira-ku, Sapporo, Hokkaido 062-8602;
tel: +81-11-841-1746; fax: +81-11-841-9747;
email: harada-y@ceri.go.jp

greater than 1 meter. Masuzawa et al. (2021) showed that distributions of the snow particle diameter of drifting snow were 50-200 μm regardless of the snowfall intensity, based on the field measurements of blowing snow with snowfall conducted by using SPCs on a plain field where a fetch was more than 1 km. From the above, the snow grain sizes during the drifting snow are 0.05 - 0.2 mm, corresponding to DFbk; size vf less than 0.2 mm (Fierz et al., 2009).

Wakabayashi and Marutani (1975), and Wakabayashi (1976) showed that contraction and distortion were predominant in the upper layer of the snowpack on a slope which was composed of rounded grains and decomposing and fragmented precipitation particles, based on the measurement of snow slope contraction. An example of the result is shown in Figure 3. The result shows that about one-third of the snowpack on a slope was contracting in areal extent. The slope was not in the neutral zone (neither contraction nor expansion). The upper snowpack at the top of the slope, which is conventionally considered the tensile zone, contracted not only vertically but also laterally, which caused localized areal expansion and cracking.

Harada et al. (2018) analyzed the relationship between overburden load and density, for different grain size classes of decomposing and fragmented precipitation particles from December to February near the windy ridgeline (Figure 4). Snow densities of smaller size classes vf and f were higher than those of the larger size classes m, c, and vc. In particular, this trend was greatest near the snow surface where the overburden load was low. As a result, the filling factor around the top of the snowpack is greater; and fine snow particles are well-packed due to collision and fragmentation under sub-zero temperatures. Sintering is promoted by the collision and fragmentation of fine snow particles, increasing the specific surface area due to an increase in contact points. In particular, disintegration is promoted under sintering conditions around the melting point. Therefore, snow density has increased due to densification

In general, sintering of snow particles are promoted by smaller grain size and closer to 0°C under sub-zero temperatures. In the mountainous area, the density increase by the binding and contraction of fine particles was the dominant factor of the contraction and deformation of upper snowpack layers, rather than densification by the overburden load in midwinter (Harada et al., 2018). In addition, the settlement force of snowpack was smaller at the depth from 50-70 cm to the snow surface in heavy snowfall areas, based on the observation using snow settling recorders (Nitta et al., 1991, see Figure 5). This indicates that there may also be affected by contraction and distortion with densification, in addition to low overburden load.

On side-loading slopes, the frequency of fragmentation of fine snow particles caused by creep and saltation during drifting snow is thought to be

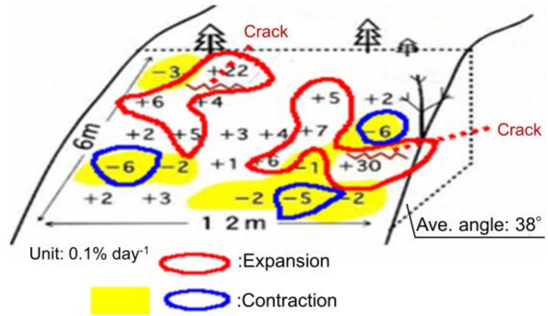

Figure 3: Distortion rate of the upper layer of the snowpack on a slope from 27th Feb. to 18th Mar. 1974 in the windy and snowy area of Hokkaido. (Based on Wakabayashi and Marutani, 1975)

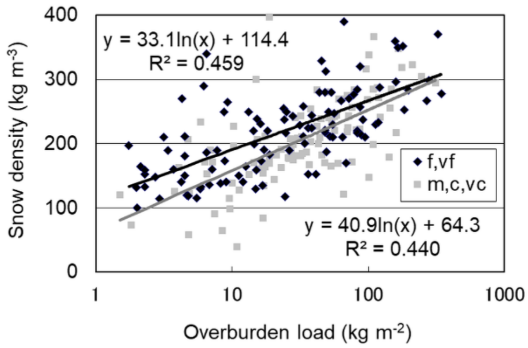

Figure 4: Grain size of decomposing and fragmented precipitation particles from December to February relationship with overburden load (Harada et al., 2018)

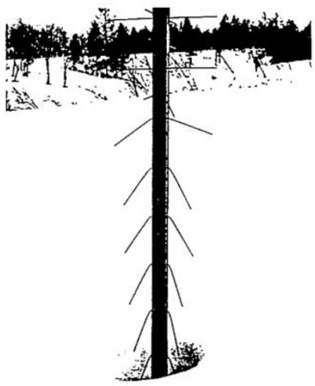

Figure 5: Snow settling recorder: 20 cm long galvanized iron wires were fixed horizontally to a 5 m tall pole at every 20 cm height increment (Nitta et al., 1991)

greater. The proportion of particles is considered to be smaller than 0.2 mm in most cases near the snow surface. Upper snowpack layers vary due to erosion and deposition caused by drifting snow. As the result, disintegration is promoted under sintering conditions around the melting point. Snow density increased due to densification. These may have been factors of formation of wind slab predominated contraction and distortion in the upper layer of the snowpack on mountainous slopes.

Even though snowstorms seem to have been subsided in the living areas, in many cases, drifting snow is continuing in the alpine areas due to strong winds. These alpine areas are where the production of fine snow particles develops efficiently because there is no supply of larger precipitation particles from the sky. It is estimated the upper layer of the snowpack on a slope is contracted and distorted to the higher position during the drifting snow. The slab cracks in areas where large snow particles cannot keep up with the contraction and distortion, for example, around tree trunks and in topographic transformation points (see Figure 3).

Natural winds are constantly fluctuating in strength, and instantaneous wind speeds (3-second average) are often about 1.5 times stronger of the 10-minute average wind speed. In case of unstable atmospheric conditions, that can be 3.0 times or more (Japan Meteorological Agency, 2017). Instantaneous wind turbulence varies depending on surrounding undulations (Council for railway high wind protection in Japan, 2006). The power spectrum of variable wind speeds in natural winds shows a period of dominance in tens of seconds (Council for railway high wind protection in Japan, 2006). The heavy snowfall on the Japan Sea side occurs when cold air from Siberia absorbs a great amount of moisture over the Japan Sea and then collides the high mountains that make up the northeast-by-southwest backbone terrain of northeastern Hokkaido and Honshu Island (Technical committee 3.2 of PIARC, 2022). These indicate that different wind speed can make different sizes of fragmented snow particles during snow storms on blowdown slopes in mountainous areas, where then the collision and fragmentation make alternative snowpack layers. When the wind speed is not greater temporarily, the surface snowpack layer may consist of decomposing and fragmented precipitation particles of DFbk and DFdc due to creep and saltation of blowing snow and snowfall. On the other hand, when the wind speed gets intense, the surface snowpack may be eroded even on the blowdown slopes. The different snow grain sizes cause differences in speed of the sintering, which creates differences in bonding strength in the alternation of snowpack layers. In addition, when the snow temperature in the upper layer of snowpack increases due to solar radiation or warm air advection during drifting snow after a snowstorm, the difference in sintering speed becomes more pronounced. As a result, one of the weak interfaces in a wind slab can become a sliding surface as the upper slab cracks down due to its contraction.

3. INFLUENCE OF DRIFTING SNOW SLAB AVALANCHE RELEASE

3.1 *In case of Artificial Trigger*

We think that the number of backcountry skiers/snowboarders increases during the drifting snow after a snowstorm in the alpine areas, and the number of slab avalanche accidents increases as a result of multiple cracks caused by the skier's/snowboarder's stimulation. In fact, avalanche accidents occasionally occur during drifting snow after a snowstorm in Japan (Figure 6).

3.2 *In case of Natural Trigger*

A loose avalanche on a blowdown gully is generally released under snowfall conditions. When the loose avalanche reaches the top of a talus slope, consequently a slab avalanche is occasionally released due to stimulation from the avalanche. In this case, we think that fine snow particles can be well-packed due to collision and fragmentation in the talus slope during blowing snow.

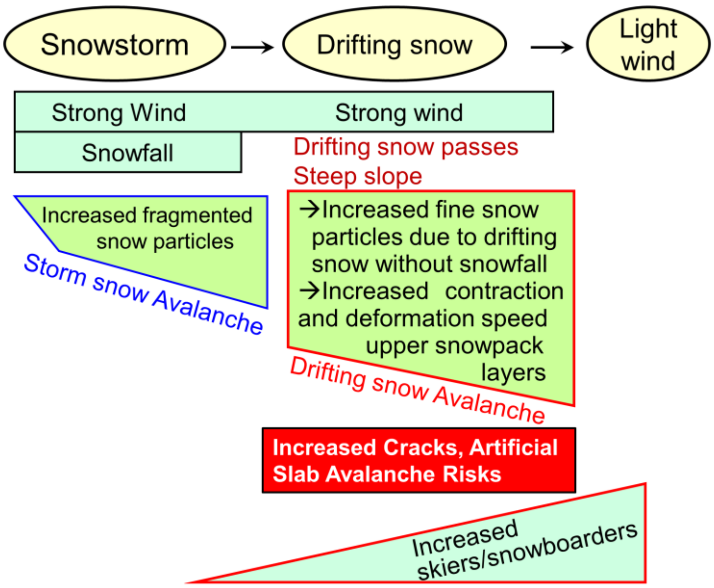

Figure 6: Transition of drifting snow slab Avalanche risk

4. CASE STUDY

In this case study, we investigated the relationship between avalanche release and drifting snow based on observations.

4.1 Methods

Study site

The study site was the mountainous area of Hakuba village from 1000 to 2900 m a.s.l., which is located on the northeast to southeast slopes of the northern Japanese Northern Alps (N36°39–46′, E137°45–50′; Figure 7). The site is one of the most famous ski/snowboard resorts and backcountry areas in Japan. The elevation of the timberline is about 2500 m a.s.l. The site has been classified as a dry snow region in midwinter (Ishizaka, 2008), and has the same characteristics as the maritime snow climate in North America (Ikeda at el., 2009). Since air temperature was not continuously measured at the study site, we extrapolated data from the Hakuba weather station (N36°41.9', E137°51.7', 703 m a.s.l.) of the Automated Meteorological Data Acquisition System (AMeDAS) by Japan Meteorological Agency, which is located approximately 4.3 km to the east of the 1400 m point (see Figure 7). Table 1 shows the average monthly temperatures at 1500, 2000, and 2500 m a.s.l. using AMeDAS data from Hakuba and a lapse rate of 6 °C km^{-1} (Ikeda at el., 2009).

Observations

On December 20, 2022, several slab avalanches of 2.5 - 3.5 size (McClung and Schaerer, 2006) were released during drifting snow after a snowstorm in the area. We corrected avalanches occurred and ski patrol information. Snow and weather observations were conducted at the 1400 m elevation point of the Hakuba Happo-One ski resort in the site (N36°41.8′, E137°48.9′, see Figure 7), following guidelines of the Canadian Avalanche Association (CAA, 2016). Vertical profiles of snowpack height, grain shape, grain size, hand hardness, and snow temperature (at 10 cm intervals) were constructed from snow-pit observations at one of the crown face (N36°41.7′, E137°47.7′, 1900 m a.s.l., see Figure 7), following the guidelines (CAA, 2016). In addition, we gained data of air temperature, wind speed and

Figure 8: The crown face near the ridgeline in the northern part of the study site on Dec. 21, 2022 (see Figure 7)

Table 1: Average monthly temperatures for the study site in the snowy season

Elevation m a.s.l.	Average monthly temperatures (°C) Dec.	Jan.	Feb.	Mar.
1500	-4.9	-7.6	-7.2	-3.6
2000	-7.9	-10.6	-10.2	-6.6
2500	-10.9	-13.6	-13.2	-9.6

Figure 7: Location of the study site: Drifting snow slab avalanches occurred on the Dec. 20th, 2022 in the study area (the information is based on the patrol overlaid the Google Earth image: red, avalanche starting points; gold, the avalanche tracks and crown faces; blue, observation points)

direction that were measured at the weather station in the resort (N36°41.9′, E137°48.3′, 1700 m a.s.l., see Figure 7).

4.2 Results

Avalanche and ski patrol information

Size 2.5 - 3.5 slab avalanches occurred in five areas of the study site above 1900 m a.s.l. One of these slope directions was northeast and the other four were southeast. Several slab avalanches of 1.0 size were released by skiers/snowboarders around the Hakuba Happo-One ski resort from 11:00 a.m. to 12:00 p.m.

Snow-ice accretion on meteorological station and lifts was comfirmed from the late evening of December the 17th to 18th by the wind of up-slope loading.

On December the 20th a.m., the Alpen Quad lift of the Hakuba Happo-One ski resort in the site was closed due to strong wind. The start time of the lift was 12:15 p.m. The wind from the west had increased since 3:00 a.m. In the early morning, drifting snow continued above the 1680 m elevation point, which is the end site of the Alpine Quad lift.

Figure 9: left, Location of the snow-pit observation site, Kuzuresawa, taken by Kimihiro Mitsuyasu; right, Crown face near the snow-pit site (see Figure 7)

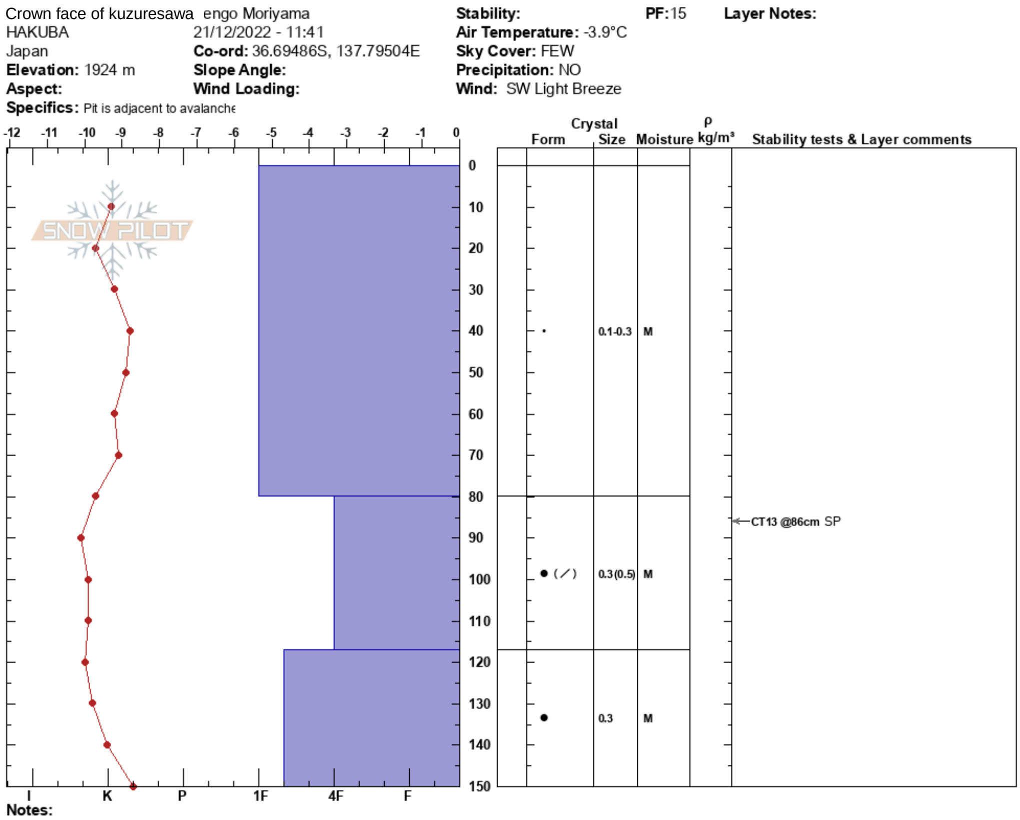

Figure 10: Snow profile at the crown face of Kuzuresawa (see Figure 9)

Snow and weather observations

The snowfall has accumulated 86 cm (HST) at the 1400 m elevation point from the date of 16th to 20th a.m. since the beginning of a storm Sky condition was partially cloudy (Scattered SCT: CAA, 2016) both 8:00 a.m. and 15:00 p.m. on the 20th based on observation at the 1400 m elevation point. In addition, there has been solar radiation confirmed between 8:00 a.m. and 15:00 p.m. from 1400 m (the ski area) to 2900 m (the main ridgeline) by qualitative visual observation.

Snow-pit observation

The images of the crown face around the snow-pit observation are shown in Figure 9. The snow profile from snow surface to 150 cm down is shown in Figure 10. Grain forms were composed of rounded grains and decomposing and fragmented particles. Grain sizes were mix of 0.1 - 0.3 mm, and 0.5 mm. Snow hardness was 1F - 4F. The result of the compression test was CTM 13 (SP) down 86cm down RG and DFdc DEC. 20th. This weak interface was larger grain sizes compared to the above and below layers.

Meteorological observations

The meteorological data of wind speed, wind direction, and air temperature for the 30-minute interval at the 1700 m point and snowfall per hour at the Hakuba AMeDAS station are shown in Figure 11. Cold air advection caused the temperatures to go down from late afternoon of the 17th, and snowfall was measured intermittently at the Hakuba AMeDAS through the 19th. Accumulated snowfall from the 16th to the 19th was 49 cm. Wind data was missing from the late evening of the 18th to the 19th at the 1700 m point.

Missing data of wind was confirmed at Hakuba AMeDAS as well. We consider that the wind sensor was stopped due to snow-ice accretion by the wind of up-slope loading. This phenomena was caused by rimed snow particles which were blown out by the wind of up-slope loading from the lower elevation, breaking the supercooling state after colliding objects at the 1700 m point, then causing rimed snow particles to freeze and stick together more easily. Based on these facts, there was not an average wind speed above 10 m s^{-1} from the 16th to the 19th. On the 20th, the average wind speed was about 10 m s^{-1} and the wind direction of was mainly west from 3 a.m. to 1 p.m. In addition, air temperature increased from -6.7 °C to -0.8 °C between 8 a.m. and noon.

4.3 Discussion

The factors about the several slab avalanches that occurred on December 20th, 2022

First, we considered meteorological conditions. As the results of 4.2, precipitation particles and decomposing and fragmented precipitation particles accumulated in the upper layer of the snowpack on a slope of about 80 cm or more in the study area from the 16th to the 19th. Drifting snow without snowfall occurred roughly from 3 a.m. to 1 p.m. on the 20th. Solar radiation and warm air advection during drifting snow continued roughly from 8 a.m. to 1 p.m. Snow redistribution during drifting snow continued due to side-loading relationship between mainly west wind and southeast slopes where avalanche was released.

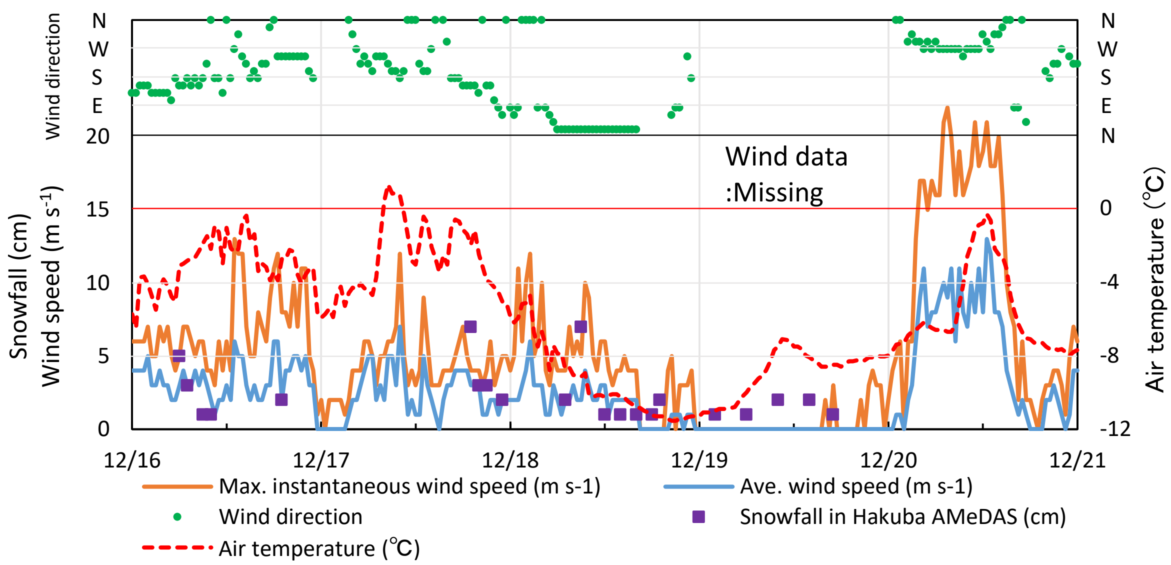

Figure 11: The meteorological data of wind speed, wind direction, and air temperature for the 30-minute interval at the 1700 m point by Logical Works Co., LTD, and snowfall per hour at the Hakuba AMeDAS station.

Next, we considered snowpack and avalanche conditions. Based on the results of snow observations, compression test, and the snow accumulation around the crown face on the next day after drifting snow, we estimate the thickness of slab avalanches to be around 80 cm in the starting zone. Based on the avalanche information of ski patrol and meteorological observations, the several slab avalanches occurred roughly from noon to 1 p.m. due to the contraction and deformation of upper snowpack layers with solar radiation and warm air advection. In addition, the patterned indented crown face (see Figure 9) seems to have different densification of the upper snowpack due to the fluctuation of wind. From the snow-pit observation, the weak interface of the sliding surface, relatively poor bond in the slab, had larger grain sizes compared to the above and below layers. In this case, grain shape and grain size of the weak interface was formed during the snowstorm with fluctuating wind speed.

Snowpack on a slope related avalanche and blowing in the mountainous area

Snow redistribution from blowing snow in the mountainous area depends on topography, elevation, slope orientation, vegetation, wind direction and speed, temperature, precipitation, fresh snow thickness, and snow surface conditions. In addition, equitemperature metamorphism of the upper snowpack on a slope depends on grain shape, grain size, and snow temperature which was affected by solar radiation and air temperature. Therefore, we consider that the drifting snow period of side-loading with solar radiation or warm air advection following a snowstorm is the key component of avalanche release. In addition, the weak interface with larger grain size compared to the above and below layers is formed when the wind speed is temporarily weak during snowstorms before drifting snow.

However, we consider that the conditions of drifting snow slab avalanches are different with terrain, meteorological and snowpack conditions. For example, when the wind speed of side-loading is intense, the surface snowpack may be eroded even on blowdown slopes. If precipitation is lower before drifting snow, the snow slab may not thicken even if the wind speed of side-loading is adequate. On the other hand, if precipitation is greater during a snowstorm, the snow slab may be thicker with several weak interfaces.

5. SUMMRY AND FUTURE WORKS

We introduce the idea that the top of the snowpack on a slope composed of wind-broken precipitation particles by creep and saltation of blowing snow (DFbk; size vf (< 0.2 mm)) tends to promote deformation due to densification after sintering by solar radiation or warm air advection during drifting snow following a snowstorm in the mountainous area which is the key component of avalanche release. In addition, the risk of drifting snow slab avalanche is greater in the path of side-loading during the drifting snow since fine snow particles are well-packed due to collision and fragmentation under sub-zero temperatures.

From now on, verification of meteorological and snow-pit data with avalanche release is necessary to reveal drifting snow slab avalanches. To grasp the condition of snow redistribution from snowstorms with snowfall and drifting snow with side-loading, solar radiation and warm air advection in each mountainous area plays an important role for understanding drifting snow slab avalanches.

In recent years, the cold snowy regions in Japan, including heavy snowfall areas of the Japan Sea side, have occasionally had severe snowstorms caused by rapidly developed low-pressure systems and convergence zone with changing weather patterns (Harada et al., 2022). Considering the above conditions, we would like to summarize several patterns of slab avalanches in Japan.

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