STRONG WIND, SOFT SLAB – POSSIBLE EXPLANATIONS

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ABSTRACT: Snowfall, strong winds up to 80 km/h, and super powder skiing conditions the next day – a situation which was reported multiple times during the winter season 2023/24 in the province of Salzburg, Austria. Looking at the wind-speeds alone we would have expected hard wind-slabs at the top of the snowpack, possibly increased slab-avalanche activity, and bad skiing. However, conditions in the field showed clear wind effect on the snow surface, but there was little avalanche activity and the slab was soft. Past research validates our observations and states that maximum wind gusts and average unobstructed wind speeds do not necessarily correlate with slab hardness, but near surface wind speed does. These findings point towards the importance of terrain and its influence on wind speeds at the snow surface level. There is, however, still a lack of research in determining factors influencing slab hardness. We therefore took a closer look at the situations of high wind speeds and soft slabs of last winter, comparing snowpack properties and meteorological data. Studying literature of previous research on this subject, we found three possible explanations or at least contributing factors for the combination "strong wind, soft slab": Firstly, we saw large stellar sizes of up to five millimeters during the snowfall events producing relatively soft slabs despite strong winds. In comparison to smaller fresh snow crystals, the large stellar crystals remain relatively large even after mechanical breakage through transport. Secondly, high wind speeds (especially gusty wind) might lead to more suspensions and less saltation, which leads to less deposition at the snow surface as compared to lower wind speeds. Thirdly, the observed situations all occurred during relatively cold phases. As past research states, other contributing factors to hard wind slabs are temperature and to some extent humidity. The higher the temperature, the higher the sintering process leading to a harder slab. The lower the humidity, the higher the sublimation rate and therefore a less dense slab. Next winter we plan to study the occurrence of wind slabs more closely, making use of our large observer network in the mountain region of Salzburg, Austria.

KEYWORDS: wind slab, slab hardness, wind slab properties, wind speed.

1. INTRODUCTION

The winter season of 2023/24 in the province of Salzburg, Austria was marked by frequent heavy snowfall and wind speeds reaching up to 80 km/h, surprisingly creating excellent powder skiing conditions (Fig. 1). Scientists and practitioners have long recognized the significance of wind-transported snow in an avalanche risk assessment. In Austria, avalanche forecasters reported wind slabs as the dominant avalanche problem on more than 50% of the days in some regions during the 2023/24 winter season. Given its critical role in avalanche forecasting, extensive research (Atwater, 1954; Mellor, 1965; Perla, 2011; Seligman, 1936) has been dedicated to understanding the formation of wind slabs as well as forecasting wind slab instabilities. However, the anticipated slab hardness during periods of wind slab instabilities remains challenging in avalanche forecasting.

Figure 1: Wind transport with soft slab formation in the mountains of Salzburg (© Daniel Harreither).

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Generally, high wind speeds are thought to lead to the formation of hard wind slabs, elevated avalanche danger, and poor skiing conditions (Fierz et. al., 2009; Martinelli, 1971). Contrary to expectations, however, field observations during winter 2023/34 in Salzburg, Austria recorded only sporadic avalanche activity and the presence of soft slabs even after strong winds recorded by automated weather stations in the area. Previous research has highlighted that hard slabs, although more challenging to trigger, have a greater propensity for propagation and can therefore result in larger avalanches compared to soft slabs (van Herwijnen and Jamieson, 2007; McClung and Schweizer, 2006). Avalanche warning services incorporate factors such as the likelihood of triggering and the expected size of a potential avalanche into their daily bulletins to communicate avalanche risk. Therefore, being able to forecast the slab hardness during wind slab instabilities using available forecasting tools plays and important role in avalanche forecasting. Furthermore, anticipating slab hardness is also crucial to slope-specific avalanche control work aimed at protecting infrastructure by artificially releasing avalanches with explosives. Firstly, the slab hardness influences the required impact to initiate a fracture in the weak layer and secondly it again allows a better estimation of avalanche size. Our study aims at researching available literature as well as examining cases from the 2023/24 winter season in Salzburg, Austria.

2. METHODS

For most avalanche warning services, automated weather station data as well as field measurements and observations are the most valuable sources to estimate the slab hardness of wind transported snow. Various modelling solutions have been developed (e.g. Doorschot et al., 2001) to quantify snow transport but to the authors knowledge there are no models providing an output with information on wind-slab properties.

For this study, we used data from the automated weather stations in the province of Salzburg, mostly maintained by the avalanche warning service. For the avalanche problem wind-slab, the assessment as well as the interpretation of the parameters wind speed and direction, snow temperature, air temperature, as well as humidity are used in order to estimate slab hardness. Wind speed and direction measurements are however challenging in mountainous areas. Measuring results are often obstructed due to the topography or infrastructure in proximity of the measurement location (e.g. Gultepe, 2015). Other challenges are the power supply and accessibility as well as external factors such as icing conditions for some measuring methods. Therefore, background information on the measuring location is a prerequisite for interpreting the results. To cancel out site specific obstruction of the measurements, this study refers to the station "Hoher Sonnblick" where unobstructed wind speeds are measured and devices are permanently monitored by meteorologists and technicians.

In addition to data provided by automated weather stations, we use field measurements or observations from nine observations sites that provide daily observations and field measurements recorded by trained observers in a structured procedure. The observation data is recorded at 8 am every morning and includes penetration depth (PS (cm)), the height of new snow (HN (cm)) and the wind speed during the morning (St1) and in the afternoon/evening (St2) of the previous day and during the night before the observation (St3). In addition, the surface roughness (Sf), character of the snow surface (SS), the snow temperature (Ts (°C)) and weather on the previous day (W) are recorded. Wind speeds are characterized in Table 1, the snow surface is characterized in Table 2, surface roughness in Table 3, and weather from the previous day in Table 4.

Table 1: Categorization of windspeeds

St	*Windspeed*	*Km/h*
2 & 3	Light wind	6-19
4	Moderate wind	20-28
5	Moderately strong wind	29-38
6	Strong wind	39-49
7	Very strong wind	50-61
8	Stormy wind	62-74

Table 2: Categorization of snow surface characters

SS	*Snow surface character*
9	Unconsolidated, loose, fresh, dry
6	Consolidated, breakable wind crust or slab

Table 3: Categorization of surface roughness

Sf	*Surface roughness*
1	Planar
3	Wavy, furrowed

Table 4: Categorization of weather on the previous day

W	*Weather on the previous day*
1	Mix of sun and clouds
3	Wind transport without precipitation
8	Snowfall with wind transport

Figure 2: Standardized measurements of the penetration depth are done by dropping a penetrometer into the snow when the tip touches the surface.

The penetration depth is measured daily with a standardized iron penetrometer which is 1 m long and dropped into the snow when the tip touching the snow surface (Fig. 2). Observed wind speeds are determined using descriptions of different categories (Table 5).

Table 5: Descriptions of winds speeds used by observers.

St	*description*
2 & 3	Wind noticeable on skin; flags in continuous movement; comparable to the draft when riding a bike at medium speed;
4	Dust and pieces of paper are caught in the wind
5	Wind is perceived as unpleasant; larger flags are straightened
6	Wind is audible in the vicinity of telegraph wires and buildings
7	Medium sized trees are moving; walking against the wind is strenuous
8	Big trees are in movement; walking against the wind is difficult; small branches are breaking;

3. RESULTS

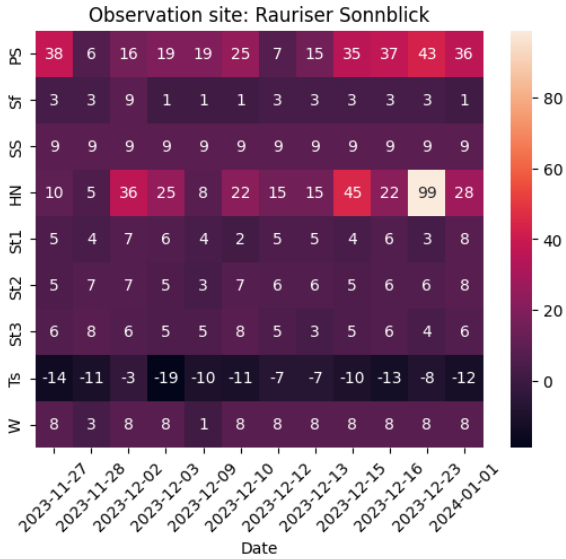

Figure 3: Heat map with a selection of days in the 2023/24 winter season at the observation station at Hoher Sonnblick.

To examine cases during which strong winds created soft slabs we created heat maps with data from our observation stations across the province of Salzburg. The heat map of the data from the station Hoher Sonnblick is shown in Figure 3.

As the data in Figure 3 shows, several days were recorded during which wind speeds were St 5 or more and the penetration depth was more than 20 cm. On December 26 wind speeds reached St 6 during the morning hours and 10 cm of fresh snow were recorded. Observers stated that new snow crystals consisted of large stellars measuring 3-5 mm in diameter. The weather was described as snow with wind transport, the snow surface was characterized as unconsolidated, loose and dry and the roughness of the snow surface was described as wavy or furrowed. During the time of the observation on November 27 the penetration depth was 38 cm. A snow profile performed in close proximity to the observation site shows that the top 17 cm of the snowpack consisted of a soft slab (Figure 5). Automated weather station data recorded at the observation site shows, that the unobstructed wind speed reached 50 km/h with gusts up to 100 km/h on November 26. Air temperatures at 3106 masl was between -15 and -20 °C for the observation period (Figure 4).

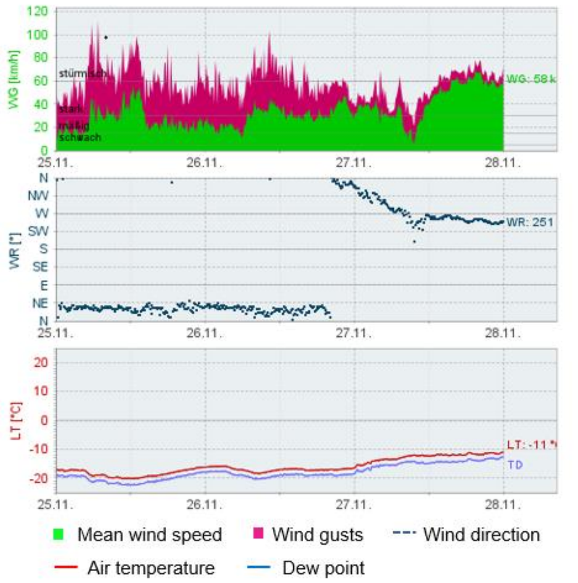

Figure 4: Automated weather station data recorded in close proximity to the observation station with unobstructed wind speed measurement.

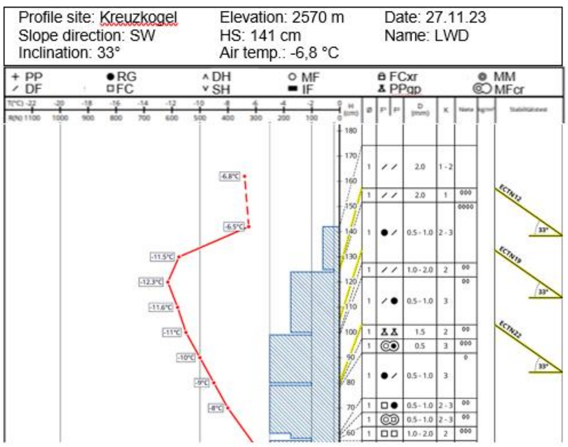

Figure 5: A snowprofile performed on the 9th of December in the proximity of the observation station by local observers shows that the top 13 cm consist of a soft slab. (PP-percipitation particles, DF- Decomposed fragments, RG- rounded grains, FC- facets, DH- depth hoar, SH- surface hoar, MF- melt forms, IF- ice formations, FCxr- rounded factes, PPgp- graupel, MM- machine made snow, MFcr- melt-freeze crust).

4. DISCUSSION

Our results show that strong winds, especially strong gusts, can nevertheless lead to the formation of soft slabs.

4.1 *Meteorological factors*

Our findings are in accordance with the recent study of de Leeuw et al. (2023), who found that unobstructed wind speed, maximum gust, and the duration of wind transport could not be associated with wind slab hardness. The study states that average wind speeds at 0.5 m and 1.5 m above the snow surface were significantly higher when hard wind slabs formed. De Leeuw et al. (2023) also found that temperatures correlate with the formation of hard wind slabs while the situations with an increase in temperature during wind transport showed the most significant correlation. No correlation between wind slab hardness and humidity was found. However, the previous study by Seligman (1936) claims that the hardening of the slab during wind-packing is due to an increased vapor flux which is caused by humidity in the air and through sublimation of snow during transport.

De Leeuw et al. (2023) also examine the changes in wind slab hardness over time. This is due to two main factors: bonding and stiffening. Bonding formation or slab settlement begins as soon as the wind-transported snow settles on the ground and this process happens more rapidly in high temperatures. On the contrary stiffening becomes the dominating effect leading to an increase in hardness at low temperatures (Li and Pomeroy, 1997; McClung and Schweizer, 1999). The results of our study refer to the day after wind transport took place.

4.2 *Snow characteristics*

In early research (e.g. Kotlyakov and Avsyuk, 1966) has found that mechanical fragmentation during wind transport plays and important role in slab hardening. Mechanical fragmentation describes the process of snow crystals breaking down into smaller fragments through sublimation and when rebounding on snow surface and one another during transport (Comola et al., 2017). When deposited these fragmented crystals often form a harder layer of snow because smaller crystals are packed more densely than larger crystals and secondly because the fragmented particles have more contact points amongst each other, which enhances the sintering, process. Precipitation particles are relatively large and diverse in shape depending largely on the temperature and humidity during the snowfall event (Nakaya, 1954). Due to the vast shapes and sizes of snow crystals a universal fragmentation theory cannot be developed according to past research (Comola et al., 2017). Research by Huang et al., (2011) however finds that snow particles of varying shapes, such as spherical, ellipsoidal, star-shaped, hexagonal prisms, and cylinders, have significantly different impacts on snow transport rates and particle endurance. Notably, spherical, ellipsoidal, and cylindrical particles demonstrate much higher transport rates and endurance than star and hexagonal particles. These differences are primarily due to variations in wind-induced drag forces and potential energy at different heights. Even though these findings are crucial to better understand wind transport of snow and the importance of taking grain shapes into account, the study does not further examine the impact the differences in grain shapes have on slab hardness.

5. CONCLUSION AND OUTLOOK

Our study shows that better understanding factors influencing slab hardness is of great importance. Valuable research on meteorological factor influencing wind slab hardness is available and could be confirmed by the findings in our study. The challenges connected to measuring wind speeds close to the snow surface however, leave practitioners with a great deal of uncertainty when interpreting data from automated weather stations. This highlights the importance of manual field measurements and observations to reduce uncertainty. Further research is needed to comprehend the dependency of crystal shape and sizes on the hardness of the slab after wind transport.

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