# SLOPE SCALE AVALANCHE FORECASTING IN THE ARCTIC (SVALBARD)

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ABSTRACT: On December 19th 2015 an avalanche struck the arctic town of Longyearbyen; 2 people were killed and 12 houses destroyed. Since this first avalanche has hit the settlement (another destructive avalanche occurred just 1 year later in February 2017) evacuations of residents in the remaining settlements are mandatory to manage avalanche hazardous conditions. To provide reliable avalanche warning and to limit the time of evacuations a correct avalanche forecast is necessary and depends strongly on the knowledge of snow cover properties in the potential avalanche prone slopes. For that reason 3 automated snow pack and weather monitoring stations were installed in the framework of the SASM (Svalbard Automated Snow Monitoring) project in the avalanche release areas that potentially endanger the town, to have knowledge about snow pack conditions especially during the dark arctic winter. These datasets represent together with meteorological measurements the first ever continuous collected data about snow depth, snow surface temperature, and snow temperatures on slopes in Svalbard. In comparison to alpine conditions this dataset allows to define typical arctic avalanche problems and typical arctic avalanche danger patterns that help to forecast avalanches in the arctic in the future. Furthermore the data was used to run the SNOWPACK model, to potentially have knowledge about the snowpack stratigraphy in those often-inaccessible slopes. Manually taken snow profiles were used to validate the model output and enabling to conclude about the model performance. Together with other observations this presentation aims to provide a detailed analysis about how to forecast avalanches under arctic conditions on the slope scale. The measurement setup will be explained; the collected data will be presented and analyzed as well as the SNOWPACK results are evaluated. We define in detail the avalanche problems the forecaster has to consider and discuss the frequency of the single avalanche trigger mechanisms.

KEYWORDS: Avalanche Forecasting, Snow Pack, Arctic, Snow Pack Properties

## 1. INTRODUCTION

Little is known about arctic snow pack conditions related to avalanche initiation in Svalbard. This is caused by limited avalanche research done in the past and a lack of continuous snow pack data to analyze. Still in 2011 Eckerstorfer and Christiansen stated "Another distinct characteristic of the avalanche climate in Longyearbyen is the increase of avalanches in the end of the snow season, with very little activity before the beginning of February and the majority of releases in April and May". In this study a strong bias is obvious due to missing avalanche observations during the arctic night (Arctic night in Longyearbyen from approximately the 14th of November until the 29th of January) underlined by the dramatic avalanche event from December 19th 2015, where an avalanche struck the arctic town of Longyearbyen; 2 people were killed and 12 houses destroyed; as well as by similar avalanche conditions just a year after on the same date and an avalanche destroying 2 houses in Longyearbyen on February 21st 2017 (Hancock et al. 2018). As manual observations in avalanche prone slopes are dangerous during darkness a need for automated snow pack observations was obvious and required by the newly initiated avalanche warning service for Svalbard after the avalanche event in December 2015 (http://www.varsom.no/en/avalanche-bulletins/).
As also evacuations of residents in the remaining settlements are mandatory, 3 automated weather and snow pack observation stations were built in avalanche prone slopes that endanger infrastructure of the town in a first step of the SASM (Svalbard Automated Snow Monitoring) project to manage avalanche hazardous conditions and to gain important data reliable for future analysis. These datasets represent together with meteorological measurements the first ever continuous collected data about snow depth, snow surface temperature, and snow temperatures on slopes in Svalbard. Data was collected since November 2017, additionally SNOWPACK modeling was performed to potentially have knowledge about the snowpack stratigraphy in those often-inaccessible slopes

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(Bartelt and Lehning 2002, Lehning et al. 2002A, and Lehning et al. 2002B)

## 2. AUTOMATED SNOW MONITORING STATIONS

Snow distribution in Svalbard is very heterogeneous. Some places are entirely snow-free on wind exposed slopes, and other places have a thick snowpack, where the wind accumulates snow on lee slopes (Jaedicke and Gauer, 2005).

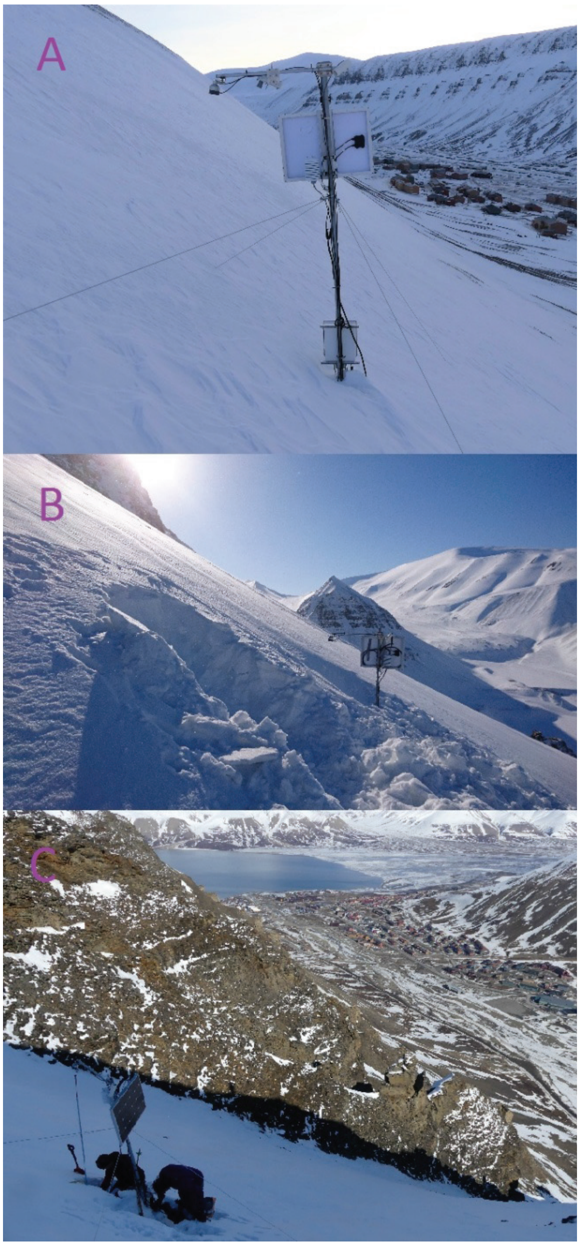


Figure 1: The 3 Automated Snow Monitoring stations: A: Lia, B: Nybyen, and C: Sverdruphamaren.

Positioning of the stations was chosen in regard of hazardous conditions for infrastructure and areas of snow accumulation. For precise positioning snow depth maps created via terrestrial laser scanning were used (Prokop, 2008, Hancock, et al. 2018). All snow monitoring stations measure air temperature and humidity, snow depth (Ultrasonic), snow surface temperature (IR), and snow temperature at the ground-snow interface (Figure 1). Data is transmitted 4 times a day and displayed online at a webpage. For avalanche forecast and the important snow drift estimations a weather station at the plateau of Gruvefjellet just above the Nybyen station is used for knowing wind speed and wind direction (Figure 2). Data from the stations described was also used to run the SNOWPACK model.

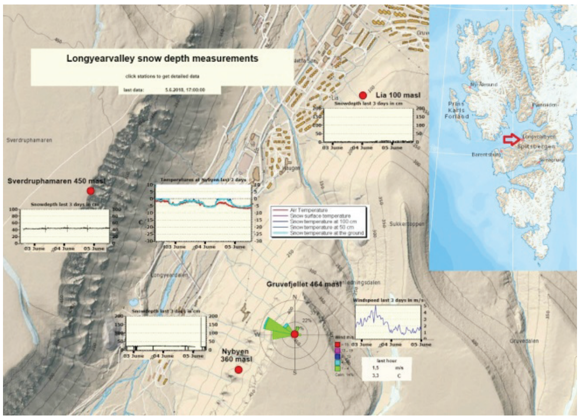


Figure 2: Location of the 3 automated snow monitoring stations in Longyearvalley (small image: location of Longyearbyen in Svalbard http://toposvalbard.npolar.no/) and web data display for avalanche forecasting including the Gruvefjellet weather station for wind analysis (http://158.39.149.181/SASM/index.html).

## 3. RESULTS

### 3.1 *Snowfall and wind*

While snowfall without wind doesn't play a role for avalanche formation – daily new snow sum measured with a precipitation gauge at Svalbard airport never exceeds 18 mm w.e. and 3 day new sum never exceeds 20 mm w.e. in the winter season 2017/18 (Figure 3) - snow drift is the main factor for avalanche formation usually with concurrent snowfall. Snow depth time lines of all stations show a gain in daily new snow depth of more than 30 cm when wind was drifting snow from the massive plateaus (massive fetch areas) into the slopes. As the stations cover 2 different expositions and measure snow drift from the 2 main wind directions (South-East by Lia and Nybyen; South-West by Sverdruphamaren) it is easy visible when snow accumulations due to snow drift happen. However, in between such snow drift events the snow depth doesn't change much. Due to the wind impact onto the snow surface the snow pack gets very hard in comparison to Alpine snow packs and does not settle significantly. Only strong winds from another direction remove snow again (Figure 3 station Sverdruphamaren).

### 3.2 Temperatures and Humidity

Looking at time series of temperature for air, snow surface, ground and humidity data other typical avalanche formation factors are visible (Figure 4). The permafrost ground usually hinders that the snow-ground interface is reaching isothermal conditions (0°C). However, during very warm weather periods and/or rain-on-snow events the snow-ground interface is reaching 0°C. As expected an elevation dependent air temperature gradient results in lower air temperatures at stations higher in altitude and less rain on snow events and isothermal snow pack conditions during winter (e.g. compare data from Lia with Nybyen station in figure 4). In the end of the winter season all stations show very rapid warming and continuous isothermal snow pack conditions, a day-night melt-freeze cycle is missing in the arctic due to all-day present sunlight from 21. April onwards. The temperature and humidity data also reveals that conditions for surface hoar formation occur several times during winter, however, strong winds usually hinder surface hoar formation or destroy existing surface hoar very fast.

### 3.3 Snow stratigraphy

To have information about snow stratigraphy we used the SNOWPACK model – the stations data act as input- and validated the results with manual taken snow pit measurements. Figure 5 shows a comparison of modeled to measured data for Lia March 28th 2018 and Sverdruphamaren May 14th 2018. As the SNOWPACK model was developed in the Swiss Alps it was expected that the model will not perform as good in the Arctic. However, the main snow stratigraphy features have been modeled with some limitations (the full analysis can be seen in Praz. 2018). No matter if modeled or measured the typical snow pack around Longyearbyen has frozen ground (except for warm weather and/or rain-on-snow events), a layer of facets and then many very shallow layers of hard snow remaining from many snow fall or snow drift events that accumulated shallow layers. Only when significant snow drift events take place, more snow is accumulated and thicker layers are formed. The snowpack is compared to alpine conditions very hard due to strong winds and low air temperatures (Figure 5).

## 4. DISCUSSION AVALANCHE PROBLEMS

The five typical avalanche problems as defined by the European Avalanche Warning Services EAWS aim to describe typical situations as they occur in avalanche terrain and to support avalanche professionals and recreationists in their evaluation of the avalanche hazard. They complement the danger level and the danger locations (slope aspect and elevation) and represent the third level in the information period (https://lawine.tirol.gv.at/data/eaws/typical_problems/EAWS_avalanche_problems_EN.pdf).
Those five “European” avalanche problems are only valid for the Alps, in e.g. Canada and the United States different avalanche problems are defined. The Norwegian avalanche service (www.varsom.no) uses the definition of the US national avalanche centre (www.avalanche.org) containing of 9 avalanche problems. If we look now at our data from the automated weather stations, the snow pit data (measured and modeled), observations from different sources of snow pack and avalanche events (http://www.regobs.no/Avalanche/SearchObservations/) as well as avalanche documentations found in literature (e.g. Hancock et al. 2018 and 2018B), it becomes obvious that none of the full definition existing is valid for the Arctic in Svalbard due to different climatic conditions. So we discuss in the following typical Arctic avalanche problems based on the European and US national avalanche centre definitions:

### 4.1 Gliding snow / Glide Avalanches

Nonexistent in the Arctic! Permafrost ground and shallow snowpack that transform fast to facets due to missing heavy snowfall events in the beginning of the season hinder glide avalanches to occur (Figure 3, 4, 5).

### 4.2 New Snow / Storm slab

Nonexistent around Longyearbyen! Due to the windy, dry, cold arctic climate, storms never deliver enough snow, that falls without or low wind-speed (Figure 3 in combination with wind data not shown).

### 4.3 Wind-drifted Snow / Wind Slab

Is the main avalanche problem in Svalbard. Only when strong winds occur with or without concurrent snow fall, enough snow is accumulated in leeward areas to form significant avalanches. All fatal avalanche accidences in Svalbard are due to this avalanche problem (Figure 3 in combination with wind data not shown; Hancock et al. 2018 and 2018B)

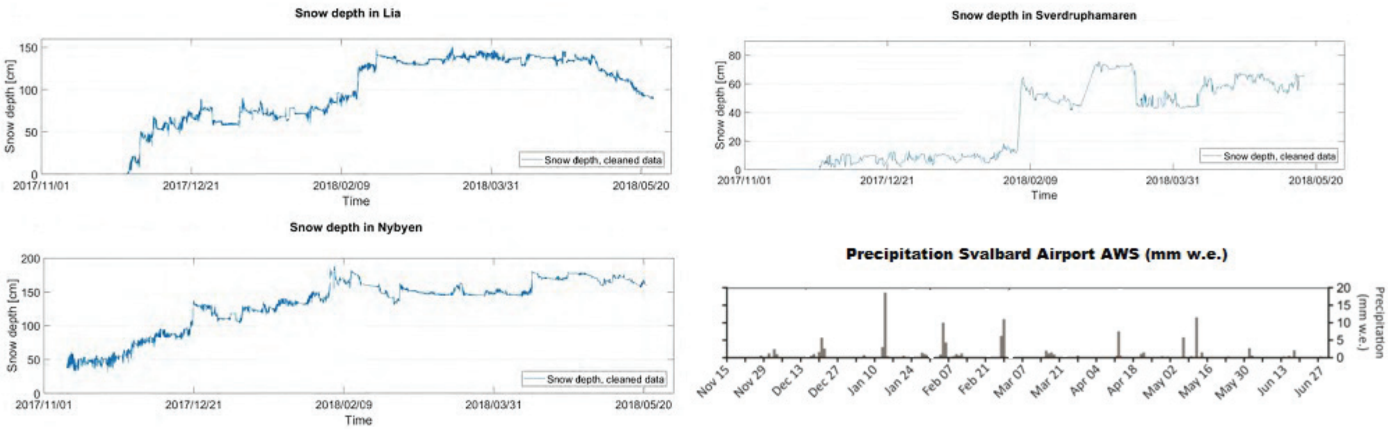


Figure 3: Measured snow depth (cm) at the 3 stations LIA, Nybyen and Sverdruphamaren and precipitation data at AWS at Svalbard airport 5.5 km northwest of the area at 28 m a.s.l. winter 2017/18.

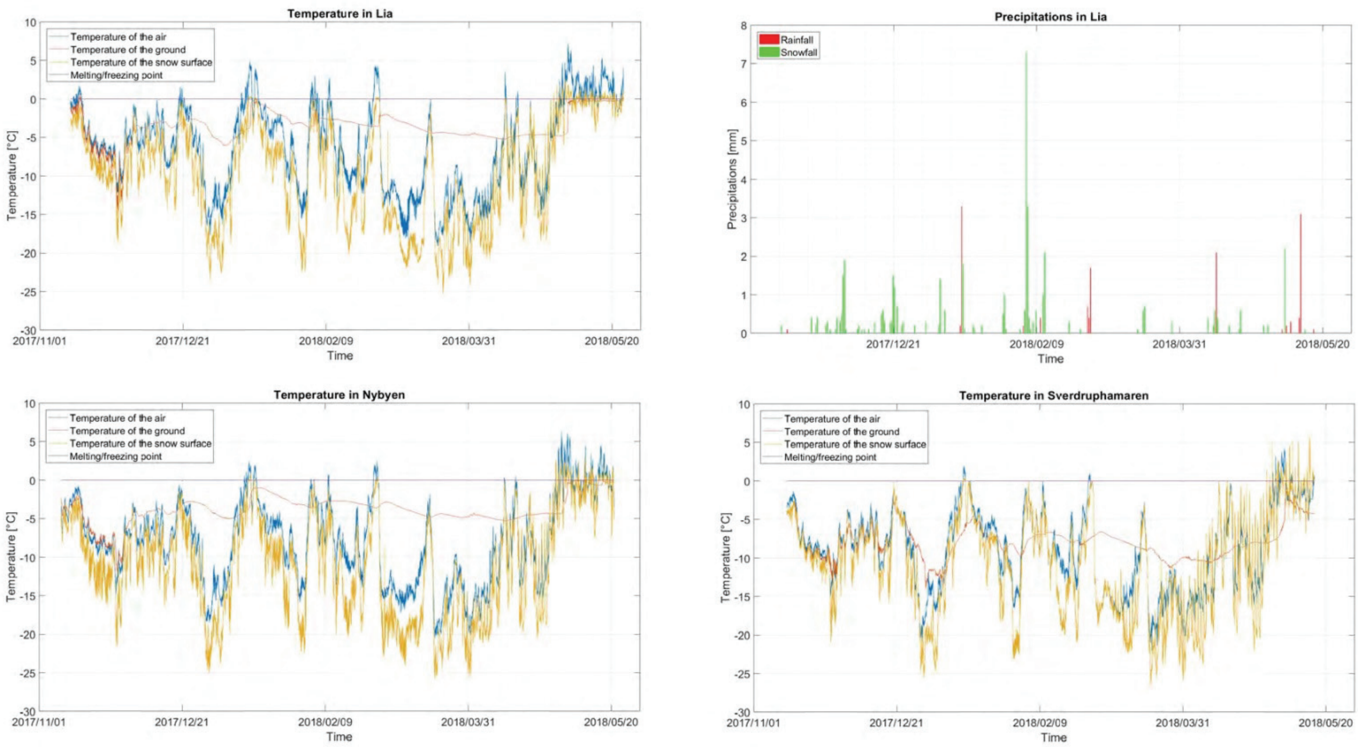


Figure 4: Temperature for air, snow surface and ground. Station elevations are: Lia: 121 m; Nybyen 352 m and Sverdruphamaren 450 m a.s.l.. Up right modeled form and amount of precipitation for Lia.

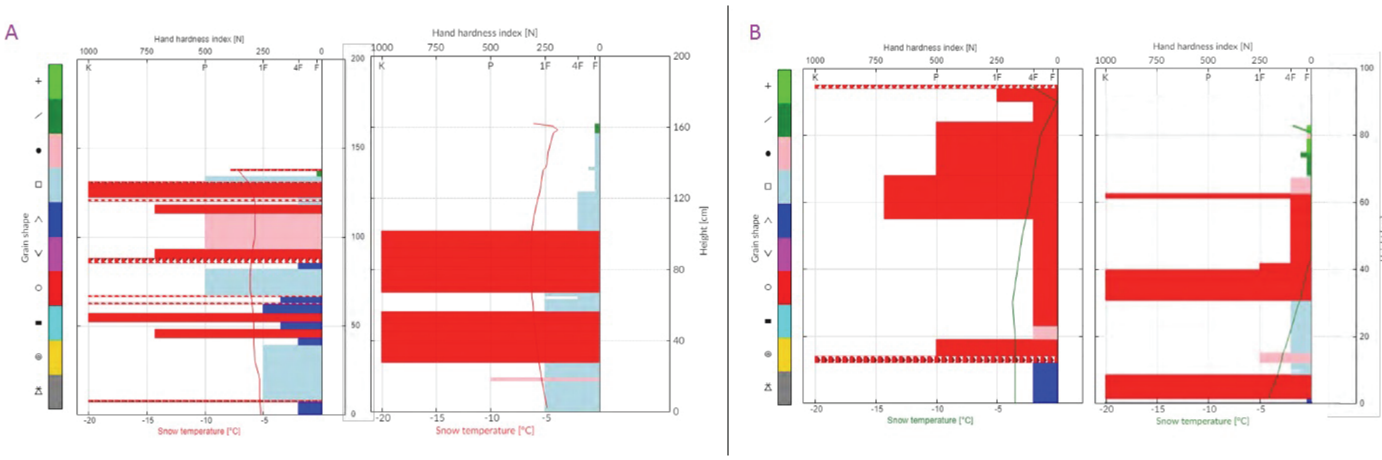


Figure 5: Examples of measured (left) and SNOWPACK modeled (right) snow stratigraphy and snow properties data. A: Lia on March 28th 2018 and B: Sverdruphamaren on May 14th 2018.

### 4.4 Cornice Fall

Related to wind cornice failures and associated cornice fall avalanches comprise nearly 50% of observed avalanche activity near Longyearbyen and endanger human life and infrastructure annually. As the very hard detached cornice blocks remained largely intact throughout the avalanching process and ran further than the main avalanche mass it is important to define cornice fall as an unique avalanche problem for Svalbard (Hancock et al. 2018B).

### 4.5 Old Snow / Persistent Slab / Deep Persistent Slab

As snow in the upper part of the snowpack transforms fast into a hard layer in Svalbard, it is often nearly impossible to trigger avalanches on old snow (facets or depth hoar). As snow packs are shallow compared to the Alps and North-America, it is not necessary to distinguish between a persistent slab or a deep persistent slab. However, as in rare occasions an old snow avalanche problem can be present, it is still a valid avalanche problem in Svalbard (Figure 5).

### 4.6 Wet Snow / Wet Slab / Wet Loose

Wet snow and related wet slabs or wet loose snow avalanches are a very important avalanche problem in Svalbard. Due to the missing day-night melt-freeze cycle in the arctic spring, wet snow conditions occur very fast. Also during winter warm weather periods and rain-on-snow events trigger wet avalanches of all forms and endanger humans, roads and infrastructure. (Figure 4)

### 4.7 Slush-Flows

We introduce here a new not yet used avalanche problem for Svalbard. Slush-flows, i.e. the rapid mass movement of water-saturated snow, is confined primarily to Arctic and high sub-Arctic regions. Slush flows are most likely to occur when appropriate water input to snowpack, suitable starting-zone conditions are available and drainage is missing due to permafrost ground (Onesti and Hestnes 1989). Dramatic slush-flow events have been damaged infrastructure in Longyearbyen and mitigation strategies have been applied. Using the automated stations data, slush flows can be easily forecasted in the future (Figure 4).

## 5. CONCLUSIONS

Establishing automated snow monitoring stations in avalanche prone slopes endangering humans and infrastructure in Longyearbyen, Svalbard provided important data for operational slope scale avalanche forecasting. Analysis of this unique continuous snow properties data combined with existing meteorological data and avalanche event documentations allowed us to define 5 typical avalanche problems for Svalbard, and exclude elsewhere existing avalanche problems that do not exist in this arctic location (Figure 6).

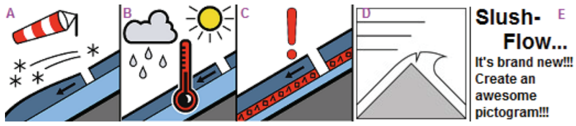


Figure 6: Svalbard’s 5 avalanche problems: A: Wind slab; B: Wet snow; C: Old snow; D: Cornice Fall and E: Slush-flow (Colored pictograms EAWS, black and white pictogram NAC)

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