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Source: Arctic, Antarctic, and Alpine Research, 43(1) : 11-21

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/1938-4246-43.1.11

Arctic, Antarctic, and Alpine Research, Vol. 43, No. 1, 2011, pp. 11–21

The "High Arctic Maritime Snow Climate" in Central Svalbard

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Abstract

In this first systematic classification of the snowpack in central Svalbard a new additional snow climate is presented. Based on field observations in the 2007–2009 period, 109 snow pits were quantitatively analyzed in terms of temperature gradients, grain shapes, grain sizes, and hardness of every snow layer. Emphasis was given to the occurrence of depth hoar, ice layers, the most observed weak layer–bed surface interfaces. These parameters in combination with meteorological observations define the "High Arctic maritime snow climate" as having a very thin and cold snowpack, a basal layer of depth hoar with winds labs and ice layers on top. The snowpack lasts for 8–10 months of the year, at higher grounds for the whole year. Snow climate classifications are an important part of improving the local avalanche characterization. This is timely, especially for the area around Svalbard's main settlement Longyearbyen, where avalanches represent a natural hazard. Also, climate models for the area predict changing meteorological conditions, especially more solid precipitation, thus a description of the snow climate as it is today is important. This "High Arctic maritime snow climate" characterization is based on the 16.8 km^2 mountainous area around Longyearbyen at 78°N, and does not fit any other High Arctic location. Svalbard has in comparison to other High Arctic locations milder climate due to an overall meteorological maritime influence.

DOI: 10.1657/1938-4246-43.1.11

Introduction

SNOW CLIMATE CLASSIFICATIONS

Over the past 50 years, numerous studies defined "snow climates" and analyzed their characteristics. The three main snow climate types are maritime, continental, and transitional (McClung and Schaerer, 2006). The analysis of a snow climate is mainly based on the combination of meteorological and snowpack factors, and builds the basis for characterizing avalanche types, frequencies, and patterns. LaChapelle (1966) was the first to describe dominant weather causing avalanches. The first quantitative analysis of snow climates was carried out by Armstrong and Armstrong (1987) in the Rocky Mountains in the western United States. Numerous other studies followed, mainly from the western United States (Fitzharris, 1987; Mock and Birkeland, 2000; Haegeli and McClung, 2003). Recently, Ikeda et al. (2009) added a new snow climate, the "rainy continental snow climate" to the common snow climate classification, and expanded the discussion to the Japanese Alps. Another snow climate classification was proposed by Sturm and Holmgren (1995). They defined each snow class in terms of snow layer sequences, grain shapes, and thickness. Sturm and Holmgren (1995) described the snow class "tundra," based on data collected in Alaska, as a thin, cold, wind-blown snow cover lasting 10 months of the year, with maximum depths of about 75 cm, consisting of a basal layer of depth hoar overlain by multiple wind slabs.

OBJECTIVES OF THE STUDY

There is no snow climate classification that provides a description of meteorological and snowpack characteristics determining avalanche activity currently operating for any Arctic area. Eckerstorfer and Christiansen (submitted) found in their study for central Svalbard that direct action avalanches are over 50% the dominant avalanche type, releasing during or immediately after snowstorms, involving only the newly fallen snow. Furthermore, extreme weather events cause extensive avalanching in the form of climax avalanches (Eckerstorfer and Christiansen, 2010), a type that results from a structural weakness in the snowpack. Thus, forecasting is, according to LaChapelle (1966), predominantly based on weather observations and the investigation of any structural weakness in the snowpack. The objective of this study is therefore to define a High Arctic snow climate and to test how it fits into traditional snow climate classifications. As climate and meteorology are well studied in central Svalbard (Hanssen-Bauer et al., 1990; Førland et al., 1997; Benestad et al., 2002), we focus in this paper on snowpack characteristics (depth, temperature, hardness, grain shapes) as well as stratigraphy of the snowpack, including detailed slab and weak layer combinations as primary indicators of avalanche formation (Schweizer et al., 2003). This study is based on field and meteorological observations in the 2007–2009 period. It represents the first systematic snowpack study from the 16.8 km^2 large mountainous area around Svalbard's main settlement Longyearbyen.

Study Area

The study area (16.8 km^2) is located around the main settlement Longyearbyen at 78°13′N (Fig. 1). Longyearbyen is situated in the center of the main island Spitsbergen (Nordenskiold-land, Inlet Fig. 1) in the Svalbard archipelago, which covers 63,000 km^2 from 74° to 81°N and 10° to 35°E. In the study area, a 70-km-long snowmobile track through 7 valleys, called the "Little Round" (Fig. 1) represents the most used winter "road." The

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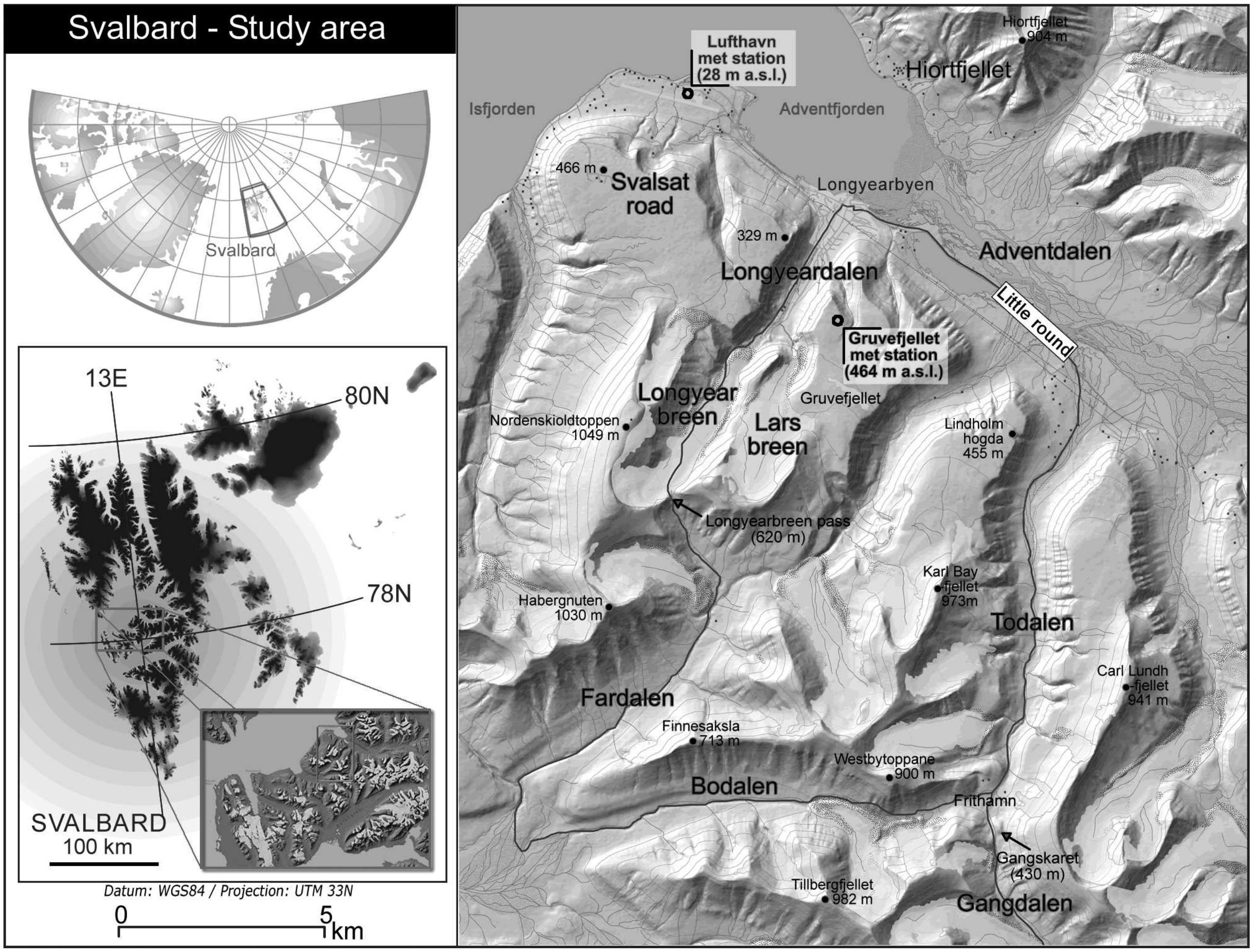

FIGURE 1. Study area in central Spitsbergen, main island of the Svalbard Archipelago. The small-scale map inlet shows Nordenskioldland where the study area is situated.

valleys display a concave curvature with the steepest parts close to the mountain crests (up to 60°). Moraines and rock glacier termini have a convex and steep curvature. At about 300–370 m a.s.l. a hard sandstone formation, in average 50–70 m in height, divides the slopes into narrow gullies on both sides of the outcrops. Continuous permafrost underlies the periglacial high-relief landscape (Humlum et al., 2003). Plateau-shaped mountain massifs dominate the landscape, with the highest peaks reaching 1000 m a.s.l.

CLIMATE AND METEOROLOGY IN CENTRAL SVALBARD

High Arctic climates are defined by French (2007) as distinct periglacial climates with extremely low winter temperatures for most of the year, and consequently the occurrence of continuous permafrost and temperatures above freezing only for 2–3 months a year. Precipitation amounts are low, winter snow cover is thin and often discontinuous because upland surfaces and exposed areas are windswept. French (2007) delimited the High Arctic climate in the northern hemisphere from the treeline or the 8–10 °C July air isotherm. The study area in central Svalbard is therefore located in the High Arctic. The climate in Svalbard is furthermore characterized as a polar tundra climate according to the Koeppen-Geiger climate classification (Kottek et al., 2006).

When comparing the mean annual air temperature (MAAT) of −3.8 °C and the mean annual precipitation of Longyearbyen (200 mm water equivalent [w.e.]) (Norwegian Meteorological Institute) in 2009 to other meteorological stations in the High Arctic between 70° and 80°N, it is obvious that Svalbard is significantly warmer (Fig. 2). The High Arctic MAATs otherwise range between −9 °C and −15 °C, and Eureka in the Canadian High Arctic is significantly cooler. Eureka is also the driest station, while Longyearbyen is close to the average. All stations except Hatonga in Siberia experience a certain maritime influence. But the significant difference with Longyearbyen is the influence of the warm Norwegian Current that flows partly along the west coast of Svalbard (Førland et al., 1997), causing mainly winter sea ice-free conditions. Likewise, Svalbard's location in the main North Atlantic cyclone track (Hanssen-Bauer et al., 1990) leads to relatively high temperatures, especially during the winter season. We therefore assume that the snowpack in other High Arctic locations show some similarities to the snowpack in our study area, with significant differences due to the warmer setting.

The study area is in the driest parts of Svalbard with an annual precipitation of 200 mm w.e. at sea level (Førland et al., 1997), but most likely with a systematic underestimation of especially the snow precipitation due to difficulties in measuring the amounts. Humlum (2002) suggested, therefore, based on modeling results, a 100% correction upwards. Large interannual variations in precipitation can be expected (Humlum, 2002). November–March may experience heavy snowfalls as well as mild spells, but snow may fall at any altitude in any month of the year and is thus the dominant type of precipitation. At sea level a snow cover exists usually from early

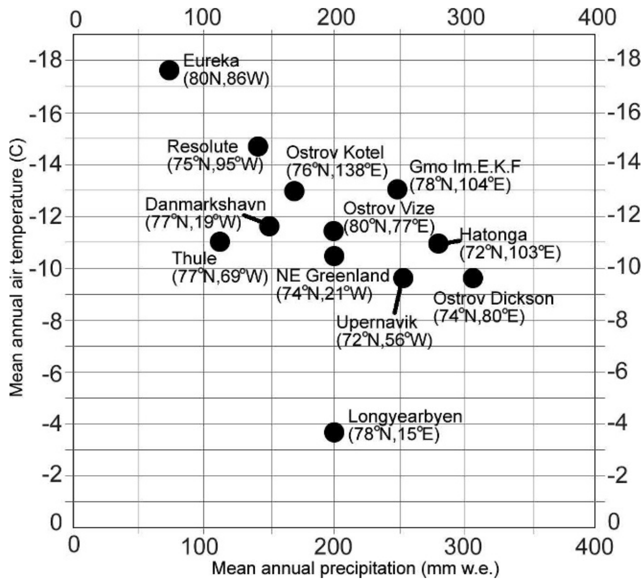

FIGURE 2. Mean annual air temperature (°C) and mean annual precipitation (mm water equivalent [w.e.]) for High Arctic meteorological stations in 2009. Data from http://www.climate-charts.com and http://www.wunderground.com. All stations are below 100 m a.s.l.

October to early June, higher altitudes tend to be covered continuously by snow. The snowpack is, however, very inhomogeneous, with snow-free areas on wind exposed slopes and mountaintops, while thick snowdrifts accumulate on lee slopes (Jaedicke and Gauer, 2005). The prevailing winter wind direction over the study area is from SE, but may locally vary due to channeling effects by topography (Humlum, 2002).

Highly fluctuating air temperatures on a daily or weekly basis are typical for Svalbard's winter weather (Humlum, 2002). A major meteorological controlling factor is the Siberian high-pressure system, a cold anticyclone that forms over eastern Siberia in winter, prevailing from late November to early March. If the Siberian High extends to the west, covering parts of Europe, but not Svalbard, it results in very cold winters in Europe (Humlum, 2002). Airflow over the Nordic seas is then strong and southerly with cyclones traveling up to Svalbard causing heavy snowfalls/rainfalls and/or snowmelt periods in mid-winter (Humlum et al., 2003). Svalbard is in general highly climatically sensitive due to its location near the confluence of ocean currents and air masses with different thermal regimes, and the rapid variations in sea-ice extent (Benestad et al., 2002).

Methods

One hundred thirty-two field trips following the "Little Round" were carried out during the two snow seasons 2007/2008 and 2008/2009 (Eckerstorfer et al., 2008). One hundred nine snow pits were dug in different valleys, aspects, and altitudes, 58 in the snow season 2007/2008 and 51 in the snow season 2008/2009. Meteorological and avalanche observations in both snow seasons were collected between mid-October and the end of May. The snow pit studies in the first observation year started not before February, thus data from autumn 2007 is missing. The timing of the field days was determined by the seasonal variation in sunlight. During the polar night, observations were difficult; therefore, the majority were carried out when light conditions allowed observations of both snow pits and avalanches (Fig. 3).

The most comprehensive snowpack study was carried out on a south-facing slope at the mountain col Gangskaret (430 m a.s.l.) (Fig. 1) where 32 pits were dug. From a climatic point of view, this location is more continental due to its inland, higher position, and it receives more snow precipitation due to orographic lifting. In general, most snow pits in both snow seasons were dug on south-facing slopes (33%). Also a NNE-facing slope on the Longyearbreen (Fig. 1) was studied more (24% of all pits) due to its easy access and representative snowpack for the area surrounding it. Both slopes are located in the 400–500 m a.s.l. elevation range, were 44% of all snow pits were dug. Favored snow pit locations were easy to access with a rather thin snowpack where higher temperature gradients in the snow enabled constructive metamorphism and thus the growth of potential weak layers. With the dominating plateau mountains reaching generally 500 m a.s.l., most snow pits were dug in the avalanche starting zone, and are therefore useful for slope stability evaluations.

Snow pits were analyzed according to the classification system of Fierz et al. (2009). All snow layers were classified quantitatively; grain shapes, grain sizes (mm), hand hardness liquid water content (by measuring snow temperature, visual observation of liquid water), thickness of each snow layer (cm), and snow temperature (every 10 cm, in °C) were recorded (Fierz et al., 2009). The weakest layers in the snowpack were identified by Compression test (Jamieson, 1999) and observed slab avalanche activity. Every snow pit was classified into one of the 10 hand hardness profiles, as presented by Schweizer and Wiesinger (2001).

The meteorological data were studied from two different meteorological stations in the study area, one located close to sea level (Lufthavn, 28 m a.s.l.), the official meteorological station of the Norwegian Meteorological Institute, and one on a mountain plateau (Gruvefjellet, 464 m a.s.l.), operated by the University Centre in Svalbard [UNIS] since 2001 (Fig. 1). The data were analyzed from 1 September until 31 May in the following year; consequently called snow seasons 2007/2008 and 2008/2009. From 1 September the snow cover usually starts to build up and begins to melt significantly by the end of May, making frequent field trips impossible.

Results

METEOROLOGY

The mean snow season air temperature (MSSAT) at sea level in 2007/20008 was −6.4 °C and in 2008/2009 −7.9 °C, both

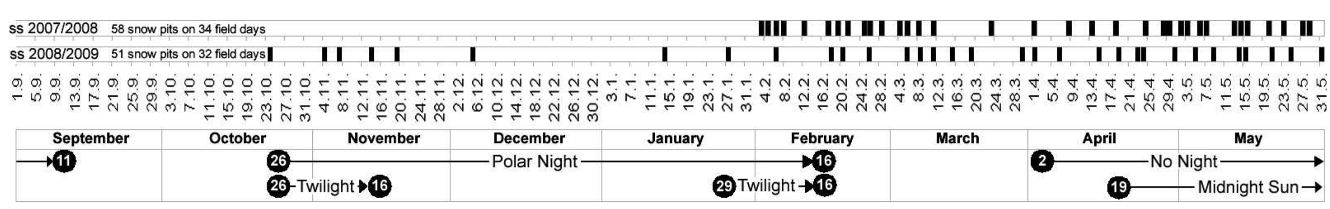

FIGURE 3. Timing of field days and snow pits dug during the two snow seasons 2007/2008 and 2008/2009. Field days are indicated as black columns with dates as vertical numbers. The polar night and the midnight sun period with their transition phases are indicated with dates.

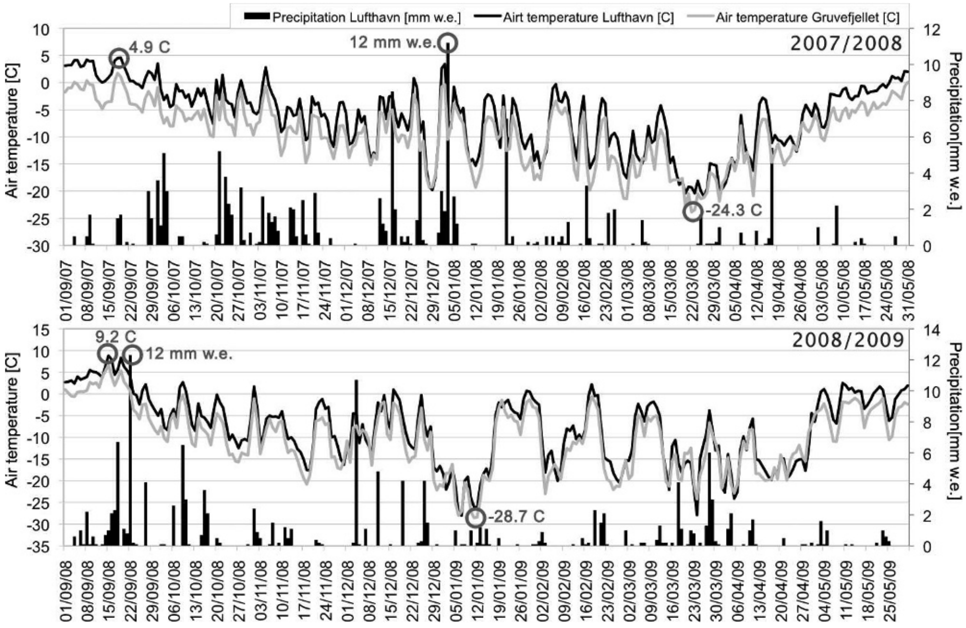

FIGURE 4. Daily average air temperatures from the two meteorological stations Gruvefjellet and Lufthavn for the snow seasons 2007/2008 and 2008/2009. Daily precipitation data is from Lufthavn in mm water equivalent (w.e.). The circles indicate the highest and lowest daily air temperatures, and highest daily precipitation rates in both snow seasons.

warmer than the 1980–2010 MSSAT average of −9.7 °C (Norwegian Meteorological Institute). The MSSAT has varied in the last 30 snow seasons between −14.1 °C in 1980/1981 and −4.7 °C in 2005/2006, with the MSSAT of the studied snow season being in the warmer quartile. Significant air temperature fluctuations on a daily and weekly base were found in both snow seasons, with very high (12.4 °C on 15 September 2008 at Lufthavn) and very low air temperatures (−32 °C on 7 January 2009 at Lufthavn) observed (Fig. 4).

Wind was almost constantly blowing over the study area (Figs. 5a, 5b). The mean wind speed during the snow seasons was 4.1 m/s in 2007/2008 and 6.6 m/s in 2008/2009 (Figs. 5a, 5b). In 2007/2008, the wind exceeded 10 m/s 22% of the time, in 2008/2009 16.5% of the time. This enabled significant snow redistribution as well as packing of the surface layers. The highest wind velocities during both snow seasons occurred in the autumn, when low pressures passed Svalbard, with a prevailing wind direction from the SE (Figs. 5a, 5b). In 2007/2008, high wind velocities were observed from the SSW, and in both snow seasons, almost no winds came from the N–E sector (Figs. 5a, 5b).

We observed snow precipitation in 81 days of both snow seasons (2007/2008 and 2008/2009). The largest amount of snowfall measured at snow stakes was 55 cm of accumulation (no water equivalent measurements carried out) in 3 days in mid-February 2008. Snow precipitation mostly came along with rising temperatures induced by passing low pressure systems. In total 144 mm w.e. (snow season 2007/2008) and 140 mm w.e. (snow season 2008/2009) were measured at sea level (Norwegian Meteorological Institute). The average snow depth of the snow pits in 2007/2008 was 143 cm, and in 2008/2009 it was 116 cm. The

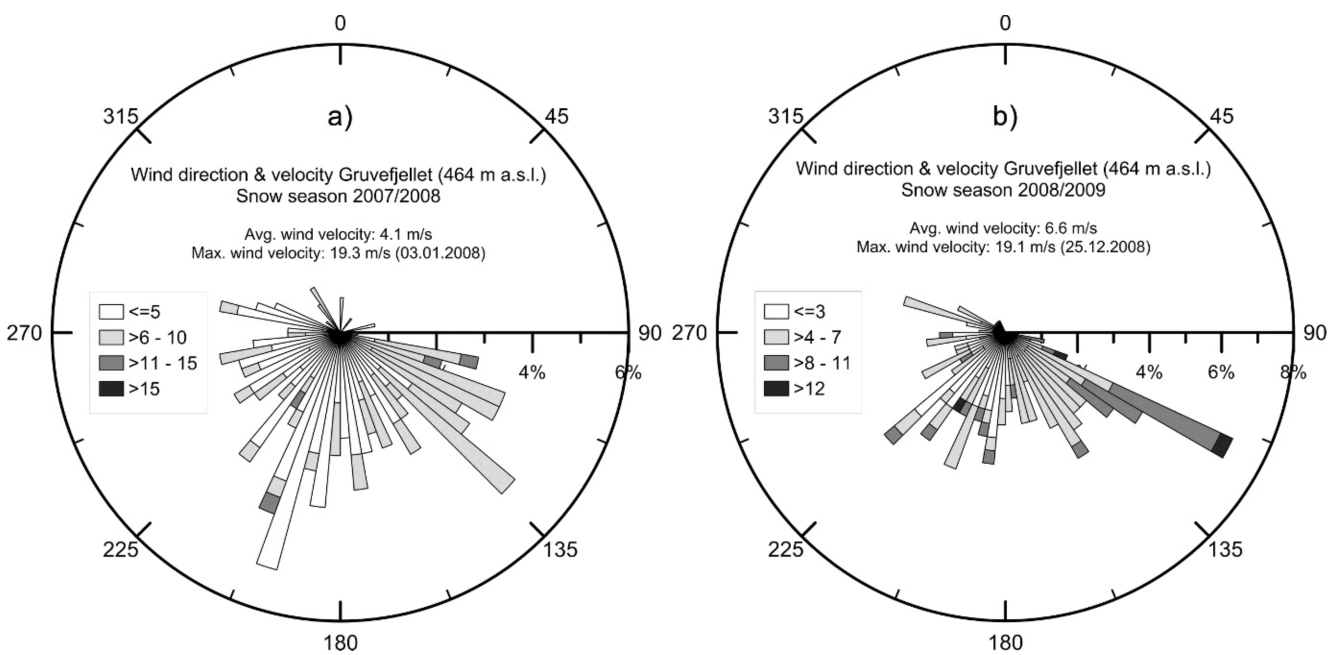

FIGURE 5. (a, b) Wind direction and velocity values from the meteorological station at Gruvefjellet for the snow seasons 2007/2008 and 2008/2009. The percentage on the *x*-axis represents the relative frequency of every wind velocity bin.

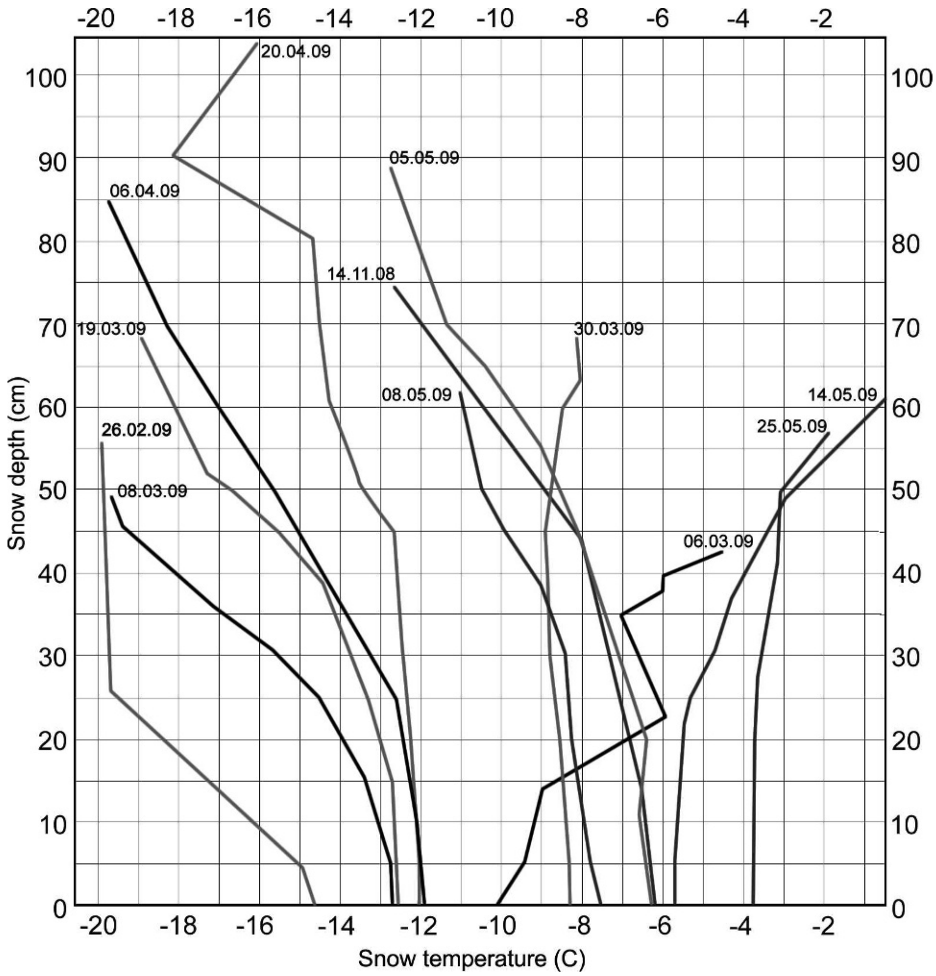

FIGURE 6. Snowpack temperature gradients (°C) at Gangskaret (464 m a.s.l.) in the snow season 2008/2009.

most shallow snowpack of 35 cm was studied at sea level, the thickest snow cover of 333 cm was investigated on a mountain col at 400 m a.s.l. The onset of the snow cover was very slow, and a more or less persistent snow cover built up by mid-October in both snow seasons. Maximum snow depths were then reached in April, and from mid-May the snow started to melt again, persisting only at higher altitudes. The extensive wind redistribution of snow causes a significant snowpack thickness variation from 0 cm on windswept landforms to a few meters of snow, mainly on glaciers and in other topographical lee positions. As a result of the SE-prevailing winter wind direction, the spatial snow distribution patterns were similar in both years.

SNOWPACK TEMPERATURES

In Figure 6 we show the typical temperature gradients of 12 snow pits dug at the south-facing slope of Gangskaret (430 m a.s.l.) (Fig. 1) in the snow season 2008/2009. Most pits were dug in March, while only 1 pit was analyzed before late December. The lowest temperatures at the surface of the snowpack were −20 °C in the coldest periods in the beginning of March 2008, and end of February until mid-March 2009 (Fig. 6). The lowest temperatures at the bottom of the snowpack reached −17 °C in a 62-cm-thick snowpack (15 January 2009). As the air temperature dropped rapidly to −28.7 °C on 12 January 2009 (Fig. 4), a fast response of the snowpack temperature down to the bottom could be observed. During this cooling process, high temperature gradients in the snowpack favored the formation of weak layers. The largest temperature gradients were observed in autumn (14 November 2008 with 7 °C/74 cm) and, for example, after significant cold spells (25 February 2009 with −23 °C air temperature resulting in a temperature gradient of 7.5 °C/48 cm) (Fig. 6). When these very cold periods persisted over longer periods, the snowpack turned isothermal, enabling only very slow snow metamorphism, and thus diminishing the probability of snow slope failures. Then, only already existing weak layers were preserved, which then failed following temperature increases, causing a decrease in the strength of the snowpack. Except for the snowpack temperature gradients from 26 February 2009 and 6 March 2009, all snow pits show a small temperature gradient in the lower 40 cm of the snowpack. The surface snow layers reached temperatures close to 0 °C by mid- to end of May, but still did not exceed −4 °C at the bottom layer due to the permafrost. The most distinctive and rapid warming events with air temperatures close to or above 0 °C, in combination with rain precipitation, created ice layers (2 January 2008 with 3 °C at sea level and 12 mm w.e. precipitation), which remained persistent over most of the snow season and built a bed surface on which avalanches released.

GRAIN TYPES

The relative number of grain types is quite similar in both snow seasons. The dominant grain type (23%) was mixed forms (rounded particles with few facets as well as faceted particles with recent rounding of facets) in both snow seasons (Fig. 7). These mixed forms were mostly found in the upper two-thirds of the snowpack. Of all grain-type layers found in the snowpack in 2007/2008 and 2008/2009, the 11–12% ice masses and the 8% mainly

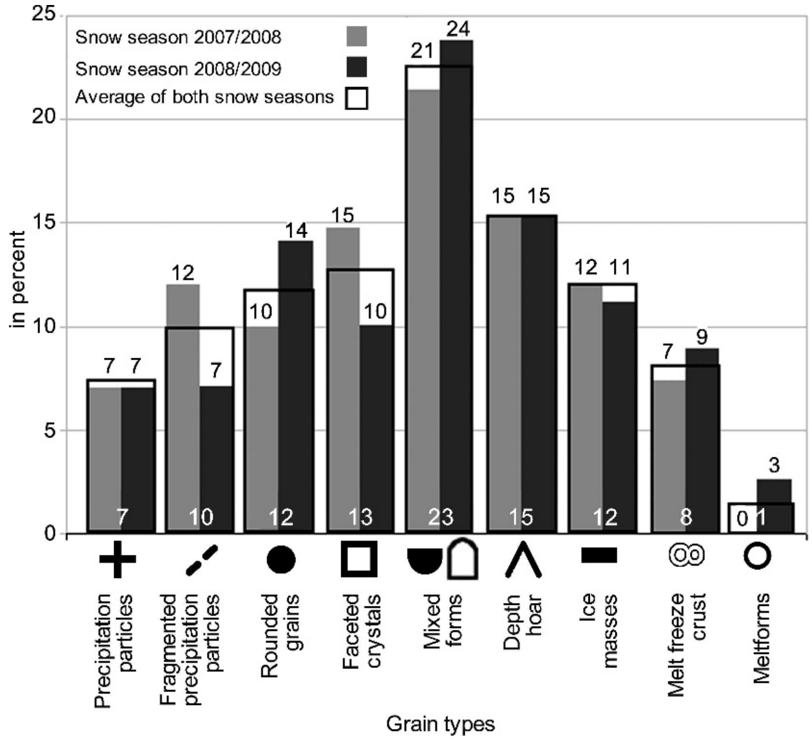

FIGURE 7. Relative amount (%) of grain types in the snowpack for the snow seasons 2007/2008 and 2008/2009 and the average of both snow seasons. Grain types are according to the classification by Fierz et al. (2009).

rain crusts are remarkable and unexpected in a cold High Arctic climate. These crusts formed after significant temperature increases during winter, when the water-saturated snow layer consequently refroze. Around these ice masses, faceted crystals were often observed due to near-crust faceting, as the ice masses are relatively impermeable to vapor transport (McClung and Schaerer, 2006). Rounded grains were mostly observed in wind slabs and less as a product of equilibrium metamorphism, which was less significant than kinetic growth. The reason for this is mainly due to fluctuating air temperature penetrating the snowpack, creating large temperature gradients. The significant effect of wind during snowfall explains also the low amount of precipitation particles found, with 7% average in both snow seasons. The small amount of wet grains is due to the limited access to the study area during the melting season. The 15% depth hoar was expected; differences in the amount of depth hoar throughout different snow pits seems to be controlled by the soil material. On coarse-grained talus slopes more depth hoar was found, most likely due to wind pumping and thus a warmer ground. Warmer ground seems to have resulted in a larger temperature gradient in the snowpack in early winter when the depth hoar developed. Still, more data needs to be collected from the early winter snowpack to verify this assumption.

HAND HARDNESS AND HAND HARDNESS PROFILES

The hand hardness (Fierz et al., 2009) of the studied pits (Fig. 8) clearly shows a dominance of hard layers. Winther et al. (2003) reported average snowpack density values of 374 kg/m^3 in Svalbard, which is comparable to our hand hardness results. The reasons are the numerous hard wind slabs in the snowpack and the low air temperatures that cool and harden the snowpack. Twenty-nine percent is referred to as "high hardness" represented by "P," 25% as "medium hardness" represented by "1F", and 21% as "very high hardness" represented by "K" for both snow seasons 2007/2008 and 2008/2009. Both snow seasons are quite uniform in terms of hand hardness of the snowpack (Fig. 8) because of the also quite uniform distribution of grain shapes (Fig. 7). Both layers with mixed forms and rounded grains were in general rather hard. Precipitation particles, fragmented precipitation particles, facets, and depth hoar were found to be usually soft (F to 4F), although facets and depth hoar could be harder as well.

Figure 9 shows that hand hardness profile type 3, with a hard middle part and softer layers at the surface, as well as on the ground, was observed the most, uniformly over both snow seasons (19%). This profile type was typically found between February and April with cold temperatures and a low temperature gradient. Usually soft precipitation snow was found on top, a hard middle part consisting of hard mixed forms and surrounding ice layers, and a weak base of depth hoar and facets. The second most observed profile type was a "staircase-like" profile (profile 4) with increasing hardness towards the ground, but a weak base occurring 16% of the time (Fig. 9). This profile type was typically found also in early spring with again cold temperatures and low temperature gradients and mixed forms building hard layers in the lower part of the snowpack, underlain by a weaker depth hoar layer. Hand hardness profile 1, with a soft snowpack throughout the entire snowpack, was observed only in 2% of all snow pits (Fig. 9). This would be a typical isotherm snowpack at 0 °C in late spring when the snow got water saturated. An extension of the fieldwork period would have resulted in an increased amount of type 1 observed. There were also significant differences in the amount of certain profiles found between the two snow seasons (Fig. 9). Twenty percent of all snow profiles in 2008/2009 could be classified as profile 2, with a reversed "staircase-like" profile, which is an early season profile. The depth hoar base formed during the slow snow onset and consequent wind slabs accumulating on top, building up profile type 2. In the snow season 2007/2008 no snow pits were dug before late December (Fig. 3), thus this discrepancy in the data can be seen. Interseasonal differences were also observed in profile 7, with two "staircase-like" parts on top of each other, found in 20% of all pits in the snow season 2008/2009, while only in 7% of all pits in 2007/2008 (Fig. 9). This profile type shows the occurrence of an ice layer sandwich with faceted

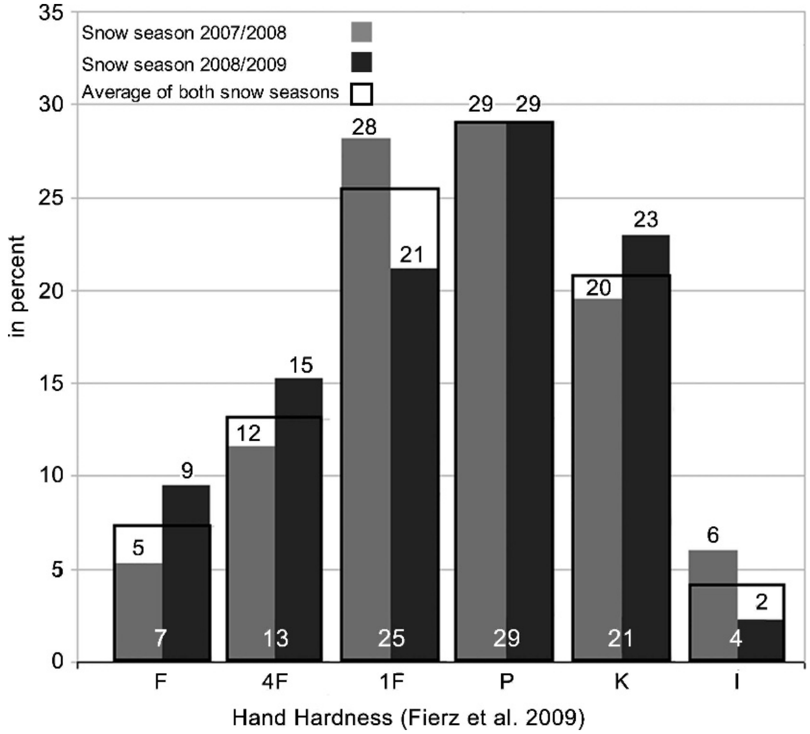

FIGURE 8. Average snow layer hand hardness of all studied snow pits. Hand hardness is used according to the classification by Fierz et al. (2009).

layers in between that formed due to the blockage of water vapor by the ice. In general large interseasonal variations in the hand hardness profiles were observed as a result of different timing of snow precipitation, rain on snow events creating ice layers, different physical properties of the snowpack in different stages of the snow season, and of course also the timing of the observations. Main characteristics of the snowpack in this High Arctic maritime setting are a persistent weakness at the bottom and an in general rather hard snowpack as a consequence of occurring ice layers and thaw/freeze cycles during the winter.

WEAK LAYER–BED SURFACE INTERFACE

Figure 10 illustrates the stratigraphy from the weakest layers to the underlying bed surface in all 109 snow pits studied. The release of a slab avalanche requires an initial failure in the weak layer induced by a triggering mechanism. This then propagates outwards to release a slab avalanche that slides down on a bed surface (Schweizer, 1999). Not all weak layer–bed surface combinations lead to avalanching. The potentially weakest combination of grain types in both seasons was depth hoar on the ground (Fig. 10) since it is the most frequently found and most persistent weak layer. Mixed forms on top of mixed forms follow this combination. Other frequent combinations were mixed forms on top of ice layers (19% in 2008/2009), and facets on top of mixed forms (18% in 2007/2008). Forty-two percent of all weakest layers in the snowpack had mixed forms, followed by facets (29%) and depth hoar (27%) (Fig. 10). Both snow seasons showed a quite similar picture with the depth hoar–ground combination dominating as well as mixed forms and facets as the dominant weak layers (Fig. 10). The kinetic growth of snow grains above ice masses is a common observed phenomena (McClung and Schaerer, 2006), and both mixed forms and facets might have comparable mechanical properties in terms of fracture initiation and propagation, with facets being more fragile. The average hand hardness of the weakest layers was "low" (= 4F [47%]), followed by "very low" (= F [32%]) and could be found in 36% in the lower third and 33% in the upper third of the snowpack (Fig. 11). Mixed forms were the most common weak layer found in the upper third of the snowpack, occurring in 22% of the analyzed profiles (Fig. 11), and facets most common in the second third of the snowpack (14%). In 37% of all analyzed snow pits, grain shapes other than depth hoar (27%), mixed forms (22%), and facets (14%) (Fig. 10) were interpreted as a weak layer. The dominance of depth hoar as a persistent weak layer is also reflected by the hand hardness profiles with a weak base in 89% of all studied pits

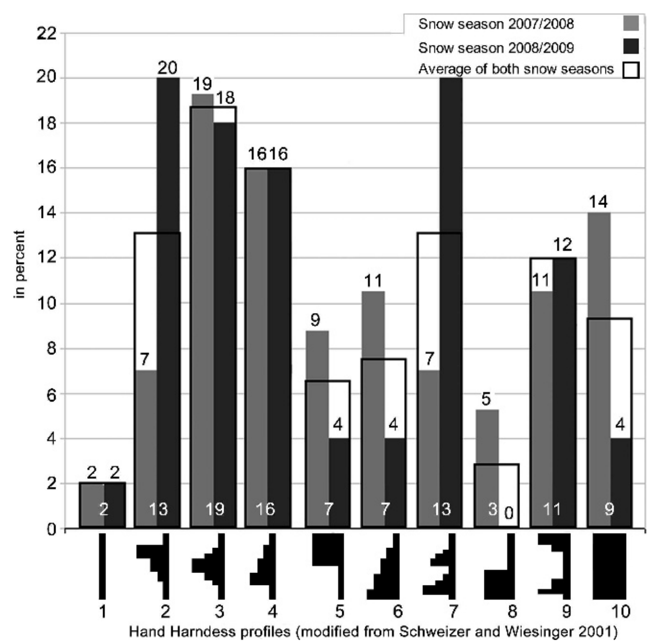

FIGURE 9. Hand hardness profiles of snow pits for the snow seasons 2007/2008 and 2008/2009 and the average of both snow seasons. The hand hardness profiles are based on the classification system by Schweizer and Wiesinger (2001). Types 7 and 9 are modified, displaying a weak base.

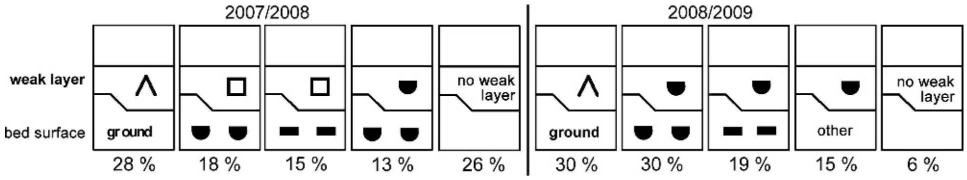

FIGURE 10. Relative amount of weak layer–bed surface combinations observed in the snowpack for the snow seasons 2007/2008 (5 snow pits on the left) and 2008/2009 (5 snow pits on the right). Grain shape symbols are explained in Figure 7.

(Fig. 9). When the weak layer was in the middle third of the snowpack, where facets were dominant (Fig. 11), hand hardness profiles 3, 7, and 9 were observed (Fig. 9). The weak mixed forms in the upper part of the snowpack were often overlain by wind slabs, building a weak old-new snow interface (Fig. 11).

Potential slab layers were in 30% of all snow pits two times and in 18% even four times harder than the weak layer on the hand hardness scale (Fierz et al., 2009), building very fragile weak layer–bed surface combinations (Fig. 12). Besides differences in grain shapes or grain sizes, hardness differences can account for weak bounding between the potential slab and the potential weak layer. Therefore, we analyzed also the hand hardness differences between potential weak layers, and the bed surfaces (Fig. 12). In 26% the potential weak layer were two steps harder on the hand hardness scale (Fierz et al., 2009) (Fig. 12). The 40% other cases take into account that the most found weak layer–bed surface interface was depth hoar on the ground (Fig. 10), thus no hand hardness difference could be taken.

DEPTH HOAR

In 2007/2008, in 81% of all snow pits, we found depth hoar with an average thickness of 10 cm. The thickest depth hoar layer was 40 cm thick on a coarse-grained talus slope. In 2008/2009, 82% of all snow pits had a depth hoar layer with an average thickness of 8 cm, reaching maximum depths of 30 cm in one pit in mid-March. The depth hoar layers did not grow significantly after late December in both snow seasons; moreover, the depth hoar got compressed by the weight of the overlying snow layers and therefore sometimes formed into columns of depth hoar, reducing the thickness of the layer. Again, also, Figure 6 shows that no significant temperature gradients were observed in the bottom part of the snowpack, partly due to the cooling influence of the permafrost. In general, thicker depth hoar layers were found on coarse-grained sediments due to enhanced conduction through blocks protruding into and through the snow and thereby acting as efficient heat bridges (Juliussen and Humlum, 2008).

Discussion

The central Spitsbergen snowpack has characteristics of an early winter snowpack (Phillips and Schweizer, 2007), with a persistent weak foundation, despite that it accumulates entirely through the winter. Depth hoar at the bottom of the snowpack persists over the entire snow season until the snowpack turns isothermal at 0 °C. The depth hoar layer accumulates during autumn and early winter due to a very slow onset of the snow cover; therefore the thin, early snow season snow cover leads to a significant temperature gradient favoring high snow crystal growth. For comparison, in the Columbia Mountains in Canada, low air temperatures and a shallow snowpack in early winter, resulting in depth hoar formation, is classified as abnormal (Haegeli and McClung, 2003). Later in the snow season as the snowpack accumulates, the minimum temperatures of the snowpack's surface layers decrease, particularly during the coldest periods of the year. Temperature gradients in the snowpack are large in the beginning of the coldest periods and then the snow turns isothermal due to the cold penetrating quickly into the relative dense and hard snowpack (Fig. 6). This hard snowpack enables efficient thermal conduction. Even when large temperature gradients exist in the snowpack, the lower 40 cm stay more or less isothermal in contrast to the upper part. Also when positive air temperatures penetrate through the snowpack in the same efficient way in spring, snow temperatures at the bottom of the snowpack respond only to a certain degree due to the influence of the cooling permafrost. This can be seen in Figure 6 when within 11 days in the beginning of March 2009, the ~50-cm-thick snowpack varied significantly in its surface temperature (15.5 °C variation) and less in its bottom temperature (4.5 °C). The air temperature influences efficiently the upper part of the snowpack and less the bottom part. And as large daily and weekly air temperature fluctuations occur very commonly in Svalbard (Fig. 4), these cycles of cold and warm air temperatures penetrating the snowpack to a certain depth happen frequently. This might explain the dominant occurrence of mixed forms and facets that were found in the upper two-thirds of the snowpack where temperature gradients were the highest (Fig. 11). The hard snowpack is a result of numerous wind slabs and ice masses.

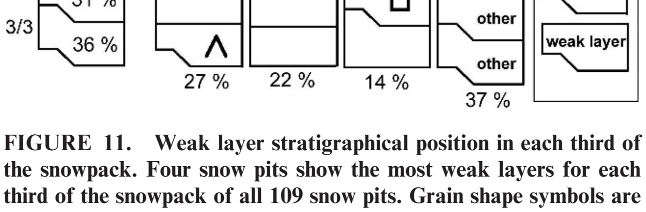

FIGURE 11. Weak layer stratigraphical position in each third of the snowpack. Four snow pits show the most weak layers for each third of the snowpack of all 109 snow pits. Grain shape symbols are explained in Figure 7.

A significant difference from the published snow class "tundra" by Sturm and Holmgren (1995), as well as already defined continental snowpacks to the Svalbard snowpack is the widespread occurrence of ice layers (Fig. 7). Warm and moist air from the south causes sudden temperature increases at any time during the winter, when low pressures reach Svalbard, leading to ice layer formation. Consequently buried ice masses favor growing of facets above and underneath, and can serve as bed surface layers, one of the prerequisites for slab avalanching. The wind slabs are a result of the significant snow redistribution over the landscape due to persistent winds with a prevailing SE wind direction for the snow season and the lack of high vegetation (Fig. 5). These observations correspond with the findings of Jaedicke and Gauer (2005), who observed higher wind speeds at mountain ridges and lower wind speeds in the valleys in Svalbard. Despite the hard and dense snowpack observed, the snow pit study shows that in 89% a substantial weakness was found somewhere in the snowpack (Fig. 11). Persistent weak layers can be found everywhere in the snowpack. The most commonly found weak

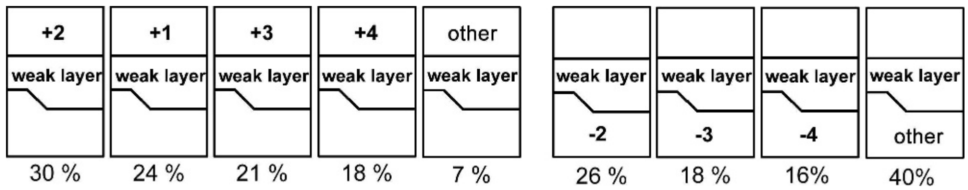

FIGURE 12. Hand hardness differences between the weak layer in the middle, the potential slab above (5 pits in the left part) and the potential bed surface beneath it (4 pits in the right part), for all 109 snow pits. Hand hardness according to Fierz et al. (2009).

layer–bed surface combination is a depth hoar layer lying on the ground (Fig. 10), where the above slab layer is two hand hardness levels harder than the weak layer (Fig. 12). This depth hoar layer undergoes no significant change during the snow season until melting starts. Nevertheless, not all weak layer–bed surface combinations lead to extensive avalanching during the snow season, since they might have been deeply buried in the snowpack and overlain by strong snow layers. On the other hand, avalanches released not only by fracture propagation in the weak layer (Schweizer et al., 2003) but also as a result of little cohesion in the new snow–old snow interface during or directly after snow loading.

Based on the presented 2-year snowpack analysis we propose to classify the central Svalbard snow climate as the "High Arctic maritime snow climate," developed as a modification of the "tundra" snow class introduced by Sturm and Holmgren (1995) (Fig. 13). While it is similar with respect to low snowpack temperatures and a generally thin snowpack, the snowpack in Svalbard has more depth hoar and significantly more ice layers than what is standard for the tundra class. Therefore, the "High Arctic maritime snow climate" has characteristics of a continental snow climate (Armstrong and Armstrong, 1987; Mock and Birkeland, 2000) with low temperatures, clear skies in winter, a small amount of snowfall, and a weak snowpack. Mock and Birkeland (2000) also stated that in a typical continental snow climate, the base of the slab involved in an avalanche is often located below the old snow–new snow interface, which we find to be true also in our study area.

Mock and Birkeland (2000) furthermore identified six snow climate variables, which classify a certain snow climate to be continental, maritime, or transitional: minimum temperature, maximum temperature, total snow depth, daily snowfall, daily snow water equivalent, and daily rainfall. Adding values to these parameters, the authors state a seasonal air temperature threshold value for determining a continental climate of −7 °C. While the average air temperature at Lufthavn was around that value during the two snow seasons, it was lower on Gruvefjellet. The Gruvefjellet meteorological station is less disturbed by sea ice variations and, due to its elevated position at 464 m a.s.l., more representative for the avalanche release zone conditions. The MSSAT at sea level ranged in the last 30 years between −14.1 °C and −4.7 °C, making it hard to clearly determine a continental climate. The maximum threshold value for snow precipitation for a continental climate, stated by Mock and Birkeland (2000), is 560 cm, which is not reached in the study area. Official snow depth measurements have a large uncertainty and vary locally, which makes it hard to compare directly with results from other continental climates, and snow water equivalent was not measured. But rainfall during the winter is more likely to occur in a maritime climate.

Koeppen (1936) in his global climate classification located Svalbard in the polar climate class. Koeppen described a polar climate with an average air temperature of the warmest month below 10 °C, and rather mild maritime-influence winters for such a high latitude. Still, by comparing meteorological data from sea level with stations located further inland, a vertical temperature and precipitation gradient exists, showing a more continental climate. LaChapelle (1966) identified in his study four different snow climates for the Rocky Mountains in the western United States. He states that the snow climates are largely determined by the overall climate of the area. The snow climate in our study area has characteristics of the "Pacific Coast" snow climate in terms of large quantities of snowfall in snowstorms as well as the frequency of mid-winter rain events that create ice layers. Both meteorological conditions lead to dominating direct-action avalanching, found also by Eckerstorfer and Christiansen (2008) for the central Svalbard study area. A large amount of depth hoar is found in the central Rocky Mountains as in our study area, as well as the accumulation of deep wind drifts within a few hours. This leads to the sliding of wind drift snow on poorly consolidated snow in the Rocky Mountains (LaChapelle, 1966), as well as in central Svalbard. This first description of the snow climate in the Rocky Mountains was confirmed by Armstrong and Armstrong (1987), who also emphasized the relation between snow structure and

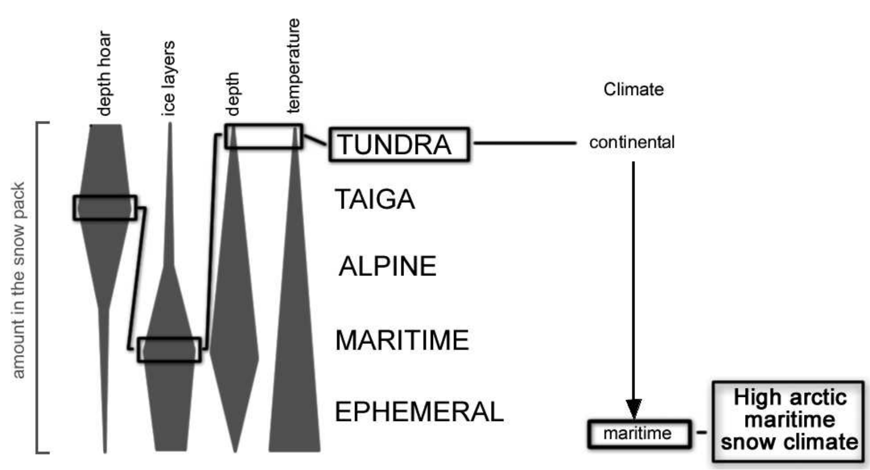

FIGURE 13. High Arctic maritime snow cover class modified after Sturm and Holmgren (1995). The black boxes indicate the amount of the certain snowpack characteristics found in the study area compared to different snow climates.

avalanche release. This was further developed by Haegeli and McClung (2003) in the Canadian Rocky Mountains, providing the term "avalanche climate" that contains also information about snowpack characteristics like weak layers. The authors found that natural avalanche activity on persistent weak layers in maritime-influenced winters was close to 0%, but up to 40% in continental winters. Still, avalanches seldom released in the Rocky Mountains on depth hoar or ice crusts. On the other hand Mock and Birkeland (2000) reported in a snow avalanche climatology study in the western United States mountain ranges that especially dangerous avalanche scenarios were caused by meager early season snowfalls and abnormally cold temperatures, favoring depth hoar growth. Also, Ikeda et al. (2009) found in a study of snow climates in the central Japanese Alps a significant amount of depth hoar, and characterized the snowpack as of the continental type with maritime influence. Our study area was maritime influenced but no natural avalanche released on depth hoar (Eckerstorfer and Christiansen, submitted). The reason for this is on one hand the domination of direct-action avalanches releasing at the new snow–old snow interface, and on the other hand the almost equal presence of weak layers in the entire snowpack. Weak layers in the upper part of the snowpack are more prone to failure, when stress on the snowpack is increased since the magnitude of this stress increase does not have to be very big. Therefore, climax avalanches more often release on facets as well as on facet-crust interfaces.

Conclusion

This study shows that the snow cover in central Spitsbergen, in a High Arctic meteorological setting with a strong maritime influence, has similarities with the snow class "tundra" proposed by Sturm and Holmgren (1995), but needs important additions and changes to fully classify it. We therefore suggest adding to the actual snow climate classification an additional snow climate: the "High Arctic maritime snow climate." This climate is characterized by a relatively thin and cold snowpack with a persistent structural weakness caused by depth hoar, as well as a significant amount of ice layering due to the overall meteorological maritime influence during the entire snow season. The snowpack lasts for 8–10 months of the year, and at higher ground parts of it for the whole year.

We propose this additional snow climate due to the fact that avalanches present a natural hazard in the mountainous area around Longyearbyen and infrastructure and because winter traffic and recreational activities are highly affected by snow avalanches. Therefore, a snow climate classification provides useful information for the establishment of modern avalanche forecasting; Haegeli and McClung (2007) emphasized the importance of snowpack observations for process-oriented avalanche forecasting. In detail, persistent weak layers especially determine the characteristics of an avalanche winter regime; Schweizer et al. (2003) showed that the primary indicator of avalanche formation is the snowpack stratigraphy. In particular, climax avalanches, a result of specific sequences of meteorological events (McClung and Schaerer, 2006) can be better predicted by including any weak layer information into the snow climate classification of an area. The three snow climates (maritime, continental, and transitional) (McClung and Schaerer, 2006) are well established and used in many studies to describe snow and avalanche characteristics on a regional scale. Despite Haegeli and McClung's (2007) warning that a snow climate classification should only be applied at full mountain range scale, we here establish a first classification of the snowpack in a smaller area, covering the full mountain landscape around Svalbard's main settlement Longyearbyen. As we have shown, even within a relatively small mountainous area, meteorological conditions and consequently snowpack characteristics—as the key factors for understanding avalanche activity patterns—can vary significantly. It therefore makes more sense to apply a snow climate classification to a smaller area.

Acknowledgments

This study was carried out as part of the CRYOSLOPE Svalbard research project (Climate change effects on High Arctic mountain slope processes and their impacts on traffic in Svalbard), funded by the Norwegian Research Councils Norklima program 2007–2009. Support for fieldwork was also received from the Svalbard Science Forum. Thanks to Ulli Neumann for brilliantly organizing and conducting the fieldwork, and to the other CRYOSLOPE Svalbard colleagues for stimulating discussions. Thanks also to editor Anne Jennings and two anonymous reviewers for very useful comments and suggestions that improved the manuscript significantly.

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MS accepted September 2010