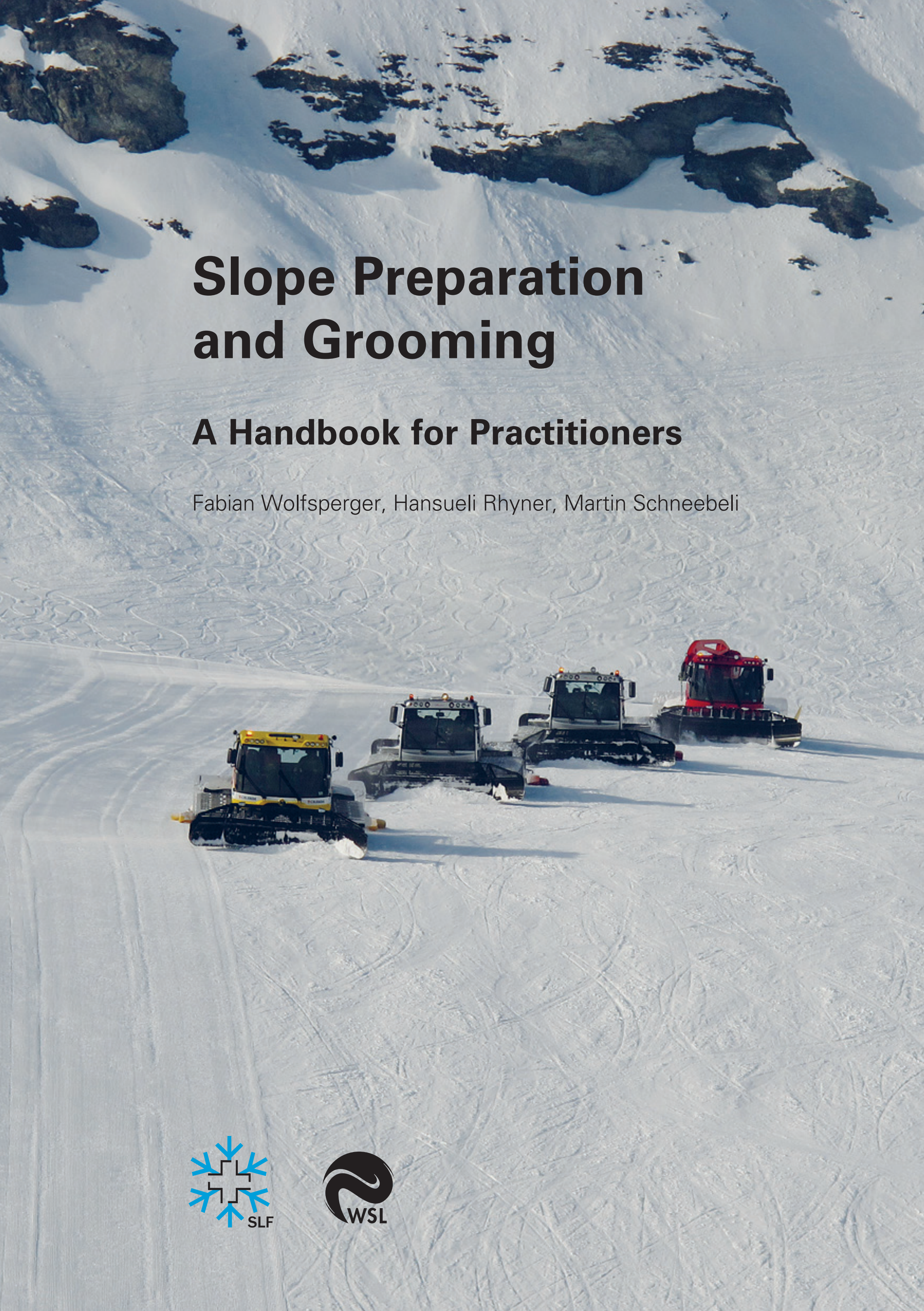

Slope Preparation and Grooming

A Handbook for Practitioners

Fabian Wolfsperger, Hansueli Rhyner, Martin Schneebeli

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Foreword

Snow sports remain very popular. As well as classic skiing on slopes in traditional winter sports destinations like the Alps, new and often fun alternatives are now available in snow parks. Meanwhile, populous countries in Asia are discovering the potential of skiing as a recreational sport. All these developments are imposing increasingly stringent requirements on snow preparation. At the same time, climate change is presenting additional challenges for managers of slopes and cross-country ski trails.

This new edition of Slope Preparation and Grooming: A Handbook for Practitioners takes account of the rapid developments in snow sports from both a scientific and practical point of view. The book starts with an in-depth summary of the relevant scientific principles, written in readily understandable language so that readers can learn all about the processes taking place in snow. Subsequent more detailed chapters and sections deal with specific topics, including snowmaking, snow farming, measurement technology, and climate change. The book not only provides information for professionals in slope preparation and snow and ski management to consult, but is also a straightforward and highly readable guide for interested non-specialists that can be used for training and teaching purposes.

The text, drawn up in close collaboration between scientists and practitioners, was designed to be of practical use. At the same time, it is meant to help reconcile ecological standards and economic constraints. The efficient use of energy and other resources is crucial in a world where resources are limited and waste is no longer acceptable. Dealing efficiently with snow as a resource is not just economically beneficial for ski resorts: it can also help to make snow sports safer and can play a vital role in protecting the environment.

So I would like to offer profuse thanks to all the authors and other, unnamed contributors who selflessly allowed their material, know-how, and experience to be used for this book. Many employees at the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), and in particular at the WSL Institute for Snow and Avalanche Research (SLF), and numerous snow sports enthusiasts in Switzerland and abroad deserve credit for this updated edition of the handbook. Applying the latest scientific findings in this handbook for practitioners is a prime example of the work done by SLF Davos.

Michael Lehning
Former Head of the Snow and Permafrost
Research Unit

Contents

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Special thanks are also due to Mathieu Fauve, whose original 2002 book served as the basis for this second edition.

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Introduction

The book Preparation and Maintenance of Pistes was first published in 2002. Shortly afterwards, it was translated into various languages, and since then has been used in many institutions and associations worldwide as a textbook and basic training manual on slope preparation and grooming.

Our prime reason for completely reworking the first edition was the rapid practical progress made for example in snowmaking, the construction of increasingly diverse snow parks, or the use of satellite snow-depth measurements during slope preparation. In addition, more and more research in recent years has been devoted to topics relevant to skiing facilities. Examples include the physics of snow farming, the preparation of race tracks, and the issue of water loss in snowmaking.

Last, but not least, increasingly strict quality requirements and the expanding range of snow sports on offer have created a need for sound, up-to-date sources of information, particularly since climatic conditions are becoming increasingly unfavorable for snow sports and making snow an increasingly expensive resource in ski resorts. This is making it more and more important to handle snow the right way as a building material. The book focuses on the sustainable management of snow as a resource while presenting international state-of-the-art knowledge on the subject.

This new edition contains a completely new introductory chapter on snow as a material, making snow's physical processes and resulting properties understandable even to non-specialist readers. For the first time, current snowmaking technologies are contrasted and new knowledge with practical applications is summarized in a readily comprehensible way. The core chapter Ski Slope Preparation and Grooming has been restructured to make it clearer, and some interesting data have been added. During the 2017 Alpine World Ski Championships, race track preparation as a whole and the watering of ski slopes in particular were analyzed. The results are described in the chapter Race Track Preparation and Grooming. The chapter Snow Park Construction, Maintenance, and Management has been updated with help from experts with practical experience. A new chapter, Snow Management, covers methods of managing snow, research results on future snow reliability in the Alps, and practical information on conducting snow farming projects. The book then ends with the chapter Measurement Methods and Tools, which describes both established and new tools for practitioners who work with snow every day.

We hope readers enjoy the book and wish them every success in their daily work with the captivating medium that snow is.

The team of authors

1 Snow as a Material

Snow comes in many different forms. The biggest differences in the properties of snow become apparent to anyone working with it. For example, fresh new snow is best removed using a blower, whereas a chainsaw is required to clear snow from a take-off on a ski racing track. These material properties vary tremendously due to the snow's **wide-ranging porosity,** its **proximity to the melting point**, and markedly different degrees of sintering, as explained below.

1.1 Basic Structural Characteristics

1.1.1 Snow Density

At temperatures below 0°C, snow consists of an **ice framework** with air-filled pores. When snow starts melting at 0°C, **liquid water** is also present. The weight of snow is determined solely by the mass of ice and liquid water. The mass of the air in pores can be ignored. But pores do have a decisive impact on the density, i.e. the mass per unit volume of snow.

$$density = \frac{mass\ [kg]}{volume\ [m^3]}$$

The bigger the pore space, the lower the snow's solid mass content and therefore the lower the snow density. **Porosity** is the measure of snow's pore content. Since pores in dry snow are only filled with air, porosity is also called **air content**. The snow's remaining volume consists of its ice structure, or ice content. So the density of dry snow depends directly on its porosity and **ice content**. If snow is wet, that **water content** increases its density (see Section 1.1.3).

In practice, density is important because it significantly impacts many other physical properties of snow, such as thermal conductivity (see Section 1.2.2) and hardness (see Section 1.4).

Snow is a **porous material made of ice**, but because its porosity varies considerably, snow is classed as a material in its own right. In materials

$$porosity = \frac{pore\ volume\ [m^3]}{total\ volume\ [m^3]}$$

$$ice\ content = \frac{ice\ volume\ [m^3]}{total\ volume\ \ [m^3]}\ 1 - porosity$$

science, snow with a density of up to approximately 250 kg/m^3 would be referred to as foam; anything with a higher density would be classified as porous material. In snow and avalanche science, the term snow only applies to densities up to 550 kg/m^3. For densities between 550 and 830 kg/m^3, the material is described as firn, and above 830 kg/m^3 as ice (Fig. 1.2).

The mechanical processing and compression of snow severs the connections in its ice framework, making it briefly behave like a granular material whose grains are pressed tightly together. This reduces the pore space, and the ice content reaches a maximum of 60% (550 kg/m^3) (Schleef 2014). This density is reached on a heavily compacted regular ski run. Higher snow densities only result from exposure to very high pressure (far higher than that applied by snowcats) or the addition of water, which is an easier, more efficient compaction method. This reduces pore spaces and enlarges the bonds between grains (see Section 1.3.2).

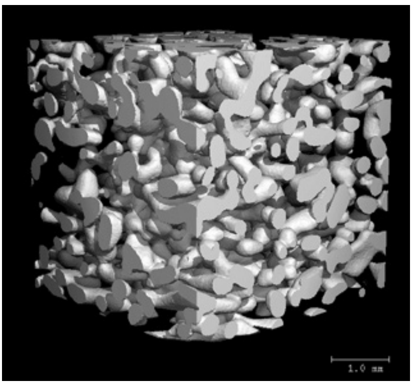


Fig. 1.1: Three-dimensional (3D) image of typical round-grained snow with a density of 248 kg/m^3 and a porosity of 0.73, equivalent to a 73% air content. So one cubic meter of this snow consists of 0.73 m^3 of air and 0.27 m^3 of ice, weighing 248 kg. The gray 3D structures represent the ice framework, consisting of coalesced (sintered) monocrystalline ice interspersed with air-filled pores. The ice framework and pores are both contiguous.

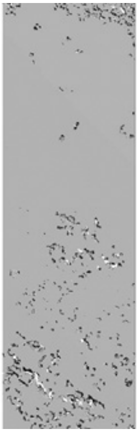
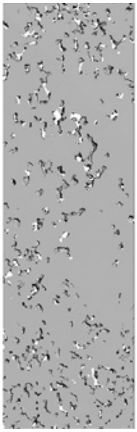
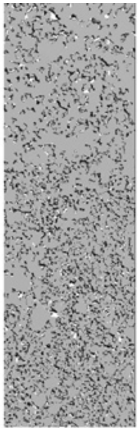
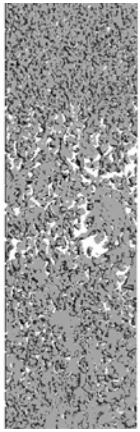
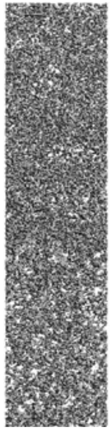
Porous ice[1] 915-830 kg/m^3	**Firn** 830-550 kg/m^3		**Old snow** 550-250 kg/m^3	**New snow** 250-50 kg/m^3
805 kg/m^3	784 kg/m^3	577 kg/m^3	424 kg/m^3	104 kg/m^3
				
Downhill run, Lake Louise, CAN 2010/2011	Downhill run, Beaver Creek, USA, 2010/2011	Downhill run, Are, SWE 2010/2011	Downhill run, Lake Louise, CAN 2011/2012	Natural snow, Weissfluhjoch, CHE, 2016

Fig. 1.2: Density-based classification of snow, firn, and ice, with examples of on-piste and natural snow. The mean densities of snow samples were determined using computed tomography (with an image field measuring 26.4 mm x 8.2 mm, or 6.4 mm for natural snow). The density of the snow samples from Lake Louise varies significantly across their height range (912-672 kg/m^3 and 294-517 kg/m^3).

1.1.2 Snow Structure

The conventional method for examining the structure of snow, using a magnifying glass, breaks up the sintered snow structure to assess and describe the **size and shape of its grains**[2]. This simple description usually says little about the physical properties of the snow. Measuring the **specific surface area**[3] (SSA) yields a better description. The SSA expresses

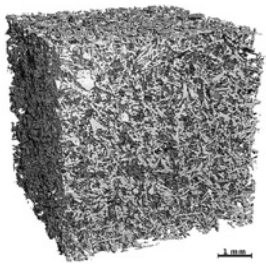
1 Pore-free ice has a density of 917 kg/m^3 at 0°C. At lower temperatures this density increases slightly.

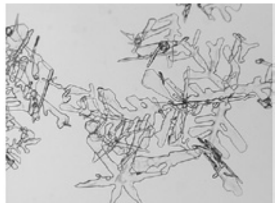
2 Since the ice framework is broken up in the course of conventional examination, the cohesion of the snow crystals or strength of the bonds between grains can no longer be ascertained.

3 The size of a material's surface area is very important because physical processes such as heat transfer directly depend on it (see Section 1.3).

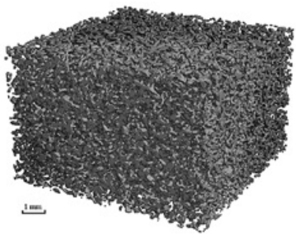
the ratio of a body's surface area to its volume and is affected by both the size and shape of the grain. Thus, a sphere has a smaller SSA than a cuboid (of the same volume) and a small sphere has a larger SSA than a large sphere.

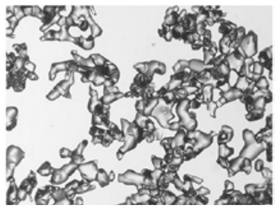
New snow/Decomposing and fragmented precipitation particles
0.2-5 mm
69 mm^{-1}
90 kg/m^3
⁄ **(DF)**



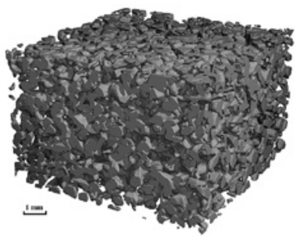


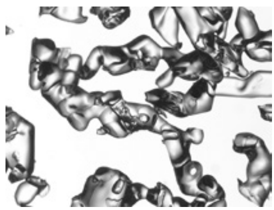
Old snow, small, rounded grains
<0.25 mm
25.5 mm^{-1}
184 kg/m^3
• **(RGsr)**



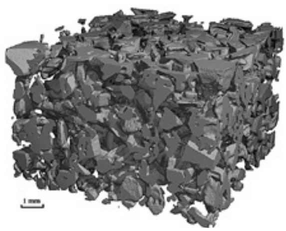


Old snow, large, rounded grains
> 0.25 mm
11.9 mm^{-1}
265 kg/m^3
• **(RGlr)**





Old snow, faceted crystals
1-3 mm
9.4 mm^{-1}
278 kg/m^3
□ **(FC)**



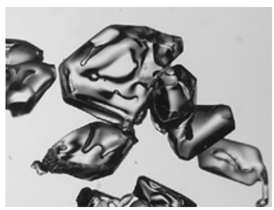
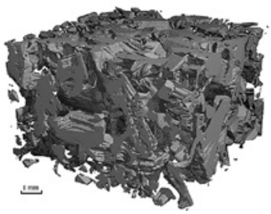
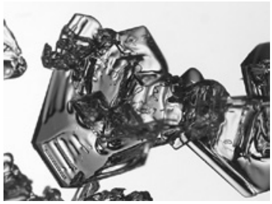


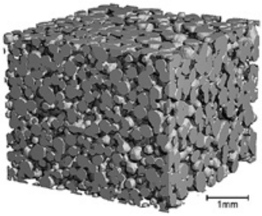
Fig. 1.3: Continues on page 17.

Old snow, depth hoar
1–5 mm
11.3 mm^{-1}
234 kg/m^3
∧ **(DH)**





Machine-made snow
0.1-1 mm
15.0 mm^{-1}
394 kg/m^3
⊙ **(MM)**



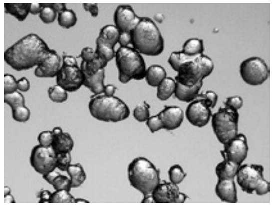


Fig. 1.3: Examples of the microstructure of various snow types based on microscopic images (image field 4.3 x 3.2 mm) and computed tomograms, indicating the typical grain size range for the snow type, the SSA and density measured, and the symbol and abbreviation according to the International Classification for Seasonal Snow on the Ground (FIERZ 2009). In reality, the boundaries between snow types are fluid.

$$SSA = \frac{surface\ area\ [m^2]}{volume\ [m^3]}$$

This means that, when describing snow structure, even highly complex shapes, such as those occurring in new snow and depth hoar, can be precisely measured and thus also distinguished. Figure 1.3 clearly shows that although a precipitation particle may be roughly the same size as a depth-hoar crystal, the former's dendritic shape gives it a much larger specific surface area.

The geometry of the snow crystals interlinked in the ice framework is called the **snow microstructure** and is closely linked to the SSA: the coarser the structures of the ice framework, the smaller the SSA.

It is important to emphasize the considerable influence of the microstructure on the physical properties of snow and the processes taking place inside it. For example, bonds between grains in snow with a large SSA, i. e. small rounded grains, grow much faster than large grained snow with sharing the same density (see Section 1.3.2).

Tab. 1.1: The nine main grain shapes.

Name	Abbreviation	Symbol
precipitation particles	PP	+
decomposing and fragmented particles	DF	/
rounded grains	RG	•
faceted crystals	FC	□
depth hoar	DH	ʌ
surface hoar	SH	v
melt forms	MF	O
ice formations	IF	■
machine-made snow	MM	⊙

1.1.3 Snow Wetness

Snow wetness describes the **liquid water content** (LWC) in a specific volume of snow. Liquid water can only be present when the snow reaches its melting point temperature, i.e. 0 °C. So whenever the snow's temperature is below 0 °C, its wetness will be 0 %.

$$LWC\,[\%] = \frac{water\ volume\ [m^3]}{total\ volume\ [m^3]}\ x\ 100$$

When snow melts, the small grains dissolve first, but the water is retained, capillary forces binding it to curvatures in the ice framework. If the liquid water content exceeds 3–6 % of the total snow volume, the water starts flowing through the snowpack. Exactly when this starts to happen very much depends on the snow's structural characteristics (density, SSA). The denser and smaller the structures of the ice framework, the more water can be retained. If water flows away, it forms drainage channels which concentrate and accelerate the run-off, resulting in an uneven distribution of water in the snowpack.

The volumetric liquid water content of snow rarely exceeds 15%. Snow containing a higher proportion of liquid water has already turned into slush. Measuring the dielectric constant[4] of snow (DENOTH 1989) is one way of determining snow wetness. The more ice and water in the snow, the higher its dielectric constant. If the snow's ice content[5] is known, its liquid water content can be calculated from the measured dielectric constant. An easier method for estimating the liquid water content in snow is the **snowball test** (Tab. 1.2).

Tab. 1.2: Snowball test to estimate snow wetness according to FIERZ (2009). Snow's wetness is indirectly derived from its temperature, the cohesion between the snow crystals when compressed, and the visibility of the water in the snow.

Snow Wetness		**Snowball test**	**LWC [%]**
dry	1	T_{Snow} <= 0°C Snowball hard to form, disintegrates when lightly pressed together	0%
moist	2	T_{Snow} = 0°C Snowball sticks together when lightly compressed	0-3%
wet	3	T_{Snow} = 0°C Snowball turns grayish when subjected to firm (fingertip) pressure owing to water accumulation, but the water cannot be pressed out	3-8%
very wet	4	T_{Snow} = 0°C Water can be pressed out of the snowball	8-15%
soaked	5	T_{Snow} = 0°C The snow is saturated with water; slush	>15%

[4] The dielectric constant (or electric permittivity), a frequency-dependent material property that indicates the transmittance of a material as a function of electric fields, should not be confused with electrical conductivity.

[5] The ice content of dry snow can be determined by taking a simple density measurement. Measuring the density of wet snow helps to estimate its ice content with a view to calculating its liquid water content.

1.2 Thermal Properties

1.2.1 Snow Temperature

Snow and ice only exist on the ground in the high-temperature range. A high-temperature material is one in which the current temperature is above 60 % of its melting point. On the Kelvin absolute temperature scale, the melting temperature of ice is 273.15 K (0 °C). For any substance, the ratio of its current temperature to its melting point indicates **how “hot” the material is**. This is referred to as its **homologous temperature**.

$$\textit{homologous temperature} = \frac{\textit{actual temperature}\ [K]}{\textit{melting temperature}\ [K]}$$

The homologous temperature reveals that snow is still very “hot”, even at a temperature of –20 °C (253.15 K), comparable to aluminum at around 600 °C ($T_{homologous}$ = 0.93). **Snow's state in the high-temperature range** determines many of its typical characteristics. For example, it means that relatively small differences in snow temperature significantly change the material's behavior (Fig. 1.4).

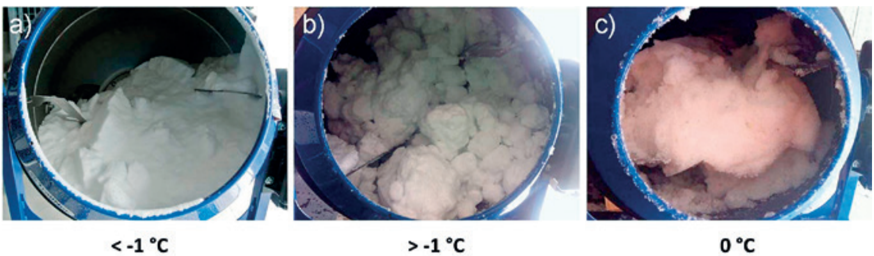


Fig. 1.4: Temperature-dependent material behavior of snow. In a concrete tumbler experiment, STEINKOGLER (2015) showed that minor temperature differences are decisive for determining whether snow remains powdery, forms clumps, or becomes a viscous mass. In experiment b), the snow was already moist by the end of the experiment.

1.2.2 Thermal Conductivity

To equalize any temperature differences in a material, a heat transfer will take place, always conducting heat from its warmer to its cooler area. The quantity of heat "flowing" through the material over a certain time period depends on two factors:

- **thermal conductivity** is a material property that indicates how much heat passes through 1 m of material at a temperature difference of 1 °C. It depends on the composition and state of the material (temperature, state of aggregation). Solids and liquids have significantly higher thermal conductivity than gases.
- the **temperature gradient (∇T)** is the relationship between a temperature difference and the distance away from the locations where the temperature difference occurs, e.g. different heights in a snowpack (Fig. 1.5).

The higher the temperature gradient and thermal conductivity, the higher the **heat flow in the material**. The thermal conductivity of snow crucially depends on the size of the ice, air, and liquid water content. Since ice conducts heat a hundred times better than air, loose new snow's high air content gives it very low thermal conductivity. This makes it a good thermal insulator that protects soil and vegetation from frost by preventing geothermal heat from being transmitted to the snow surface and released into the atmosphere. The higher the **snow's density**, and therefore its ice content, the higher its thermal conductivity (Fig. 1.6).

$$\nabla T = \frac{\textit{temperature difference}\,[^\circ C]}{\textit{height difference}\,[m]}$$

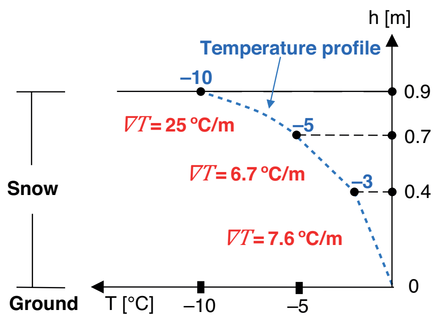


Fig. 1.5: Temperature gradient in the snowpack.

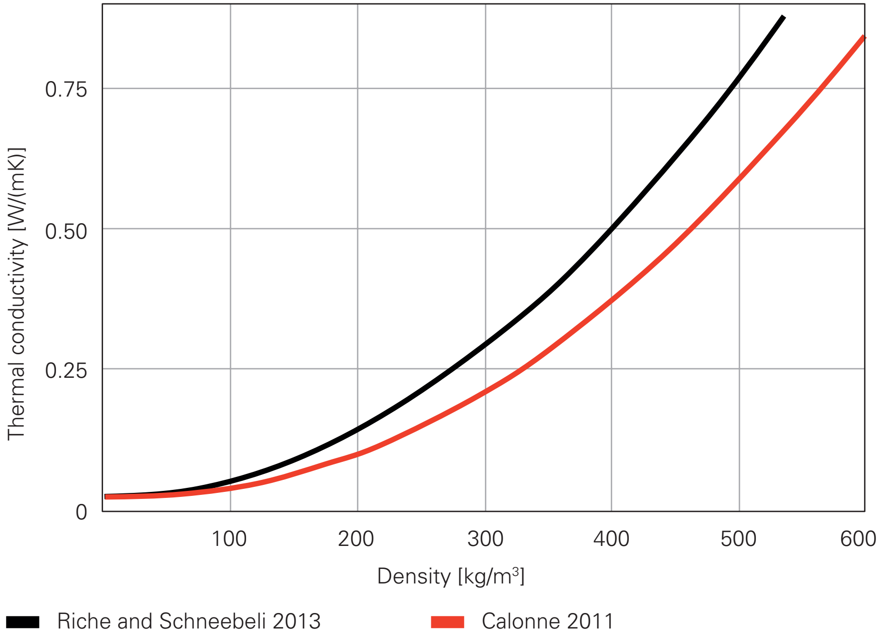


Fig. 1.6: Impact of snow density on thermal conductivity according to Riche and Schneebeli (2013) and Calonne (2011). As well as density, other properties (e.g. temperature, microstructure) affect snow's thermal conductivity, which explains the different curves in the figure.

Tab. 1.3: Thermal conductivity of various materials according to Sturm (1997), among others.

Material	**Thermal conductivity [W/(mK)]**
Air (at 0°C)	0.02
New snow (100 kg/m³)	ca 0.05
Piste snow (500 kg/m³)	ca 0.6
Ice (at 0°C)	2.21
Water (at 0°C)	0.56
Concrete	ca 0.8–2.1
Steel	ca 15–58

Most of the heat transferred in snow passes through its ice framework. Around 50 % of the heat in new snow is conducted through its ice framework. In piste snow this figure is higher than 90 %. The rest is conducted through pore air. In new snow, heat transfer via water vapor transport only plays a role at high temperature gradients. Heat transfers between the ambient air and the snow surface are described in Chapter 2.

Temperature gradients not only boost heat conduction, but also result in different concentrations of water vapor in the snowpack, thus also triggering further processes in the snow (see Section 1.3).

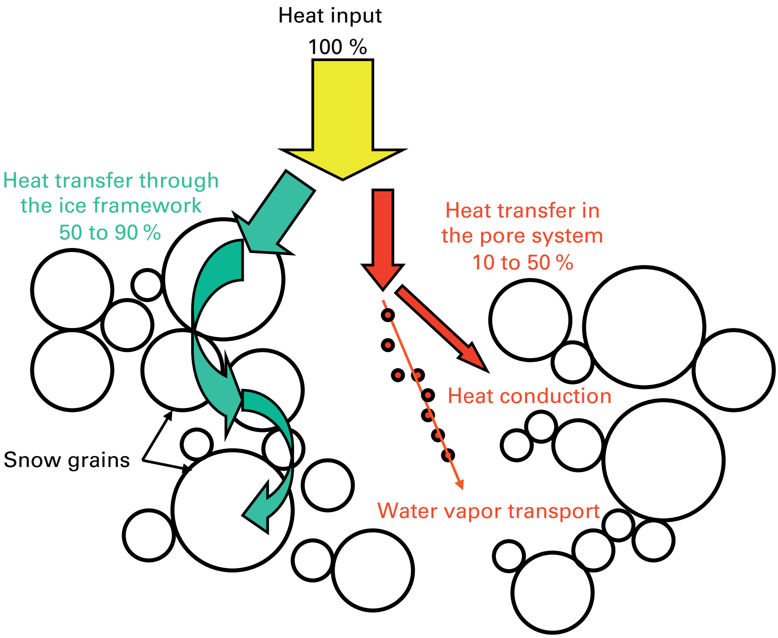


Fig. 1.7: Mechanism for heat conduction in the snowpack.

1.3 Processes in Snow

1.3.1 Phase Transitions

A **change in a material's state of aggregation**[6] is called a phase transition or phase transformation. The transitions between water, ice, and water vapor, and the various properties of these three material states are of decisive importance to the processes taking place in snow.

At each phase transition, the material absorbs or releases energy in the form of heat. This energy is called **latent heat** and is expressed per kilogram of transformed material (Fig. 1.8). Heat that changes the temperature of a material rather than causing a phase transformation is referred to as **specific heat**[7]. Very high quantities of energy are absorbed or released during phase transitions. For example, freezing 1 kg of water takes the same quantity of energy as required to cool 1 kg of ice from 0 °C to –160 °C.

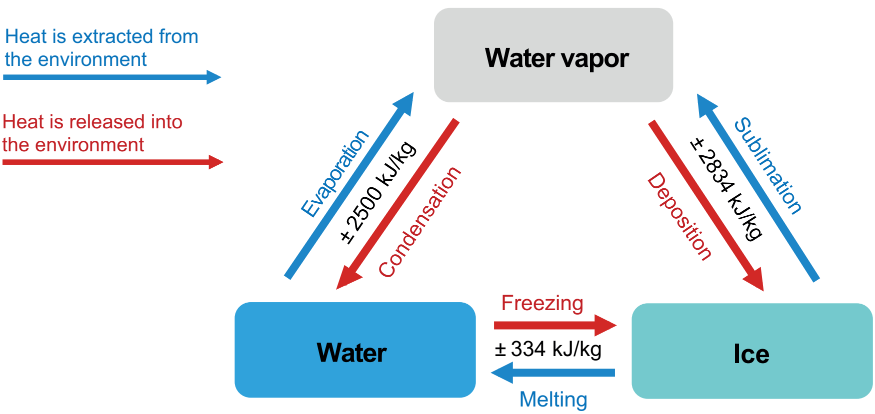


Fig. 1.8: States of aggregation of water and the energy required for or released during the phase transition.

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6 There are three states of aggregation: solid, liquid, and gas.

7 The heat required to raise the temperature of 1 kg of material by 1°C. For ice, this is 2.1 kJ/(kg K) at 0°C; for water, it is 4.18 kJ/(kg K). This property is also referred to as specific heat capacity.

A balance is always sought between the individual phases. When water and air are in a closed container, the water evaporates until the air is saturated, meaning it cannot absorb any more water molecules. This is called **saturation vapor pressure** and primarily depends on the air's temperature, but also on its pressure. Directly above the surface of water there is constant saturation vapor pressure (E_w). The same happens when ice and air are kept enclosed in a container at a constant temperature. Water molecules sublime from the ice into the air until it is saturated.

Because the bonds between ice molecules are stronger than those between water molecules, there is always a lower vapor pressure (E_i) over ice than over water. This means that $E_w > E_i$, particularly when the temperature is below 0 °C, so **water vapor migrates continuously** in a mixture of water, ice, and air (Fig. 1.9 b). Vapor pressure depends on both the state of aggregation and temperature (Fig. 1.9 d) and the geometric shape of the ice crystals:

- on **convex surfaces** (curved outwardly), the bonds between molecules are weaker than in flat surfaces
- on **concave surfaces** (curved inwardly) molecules are bonded more strongly to the crystal lattice than in a flat surface

As a result, vapor pressure is higher over convex surfaces than flat surfaces and higher over flat surfaces than concave surfaces (Fig. 1.9 a). Since small particles have a higher curvature, vapor pressure increases as their size decreases (Fig. 1.9 c). Likewise, large particles have a lower vapor pressure. Therefore, processes in snow that depend on water vapor transport become less effective as the specific surface area (SSA) decreases (i.e. grain size increases)[8].

Consequently, **differences in saturation vapor pressure** are always the driving forces of mass transport in snow, leading to local differences in the concentration of water vapor in pore air. This phenomenon, referred to as the **vapor pressure gradient**, causes water vapor in the snow to migrate from areas with a higher concentration to areas with a lower

8 For this reason, coarse-grained spring snow is often rightly described as "dead" in colloquial speech. Hardly any mass transport takes place in this type of snow, and this also prevents sintering and consolidation (see Sections 1.3.2 and 1.4).

concentration. As a result, water vapor sublimates on one surface and is deposited on another. The greater the vapor pressure gradient, the more intensive the process.

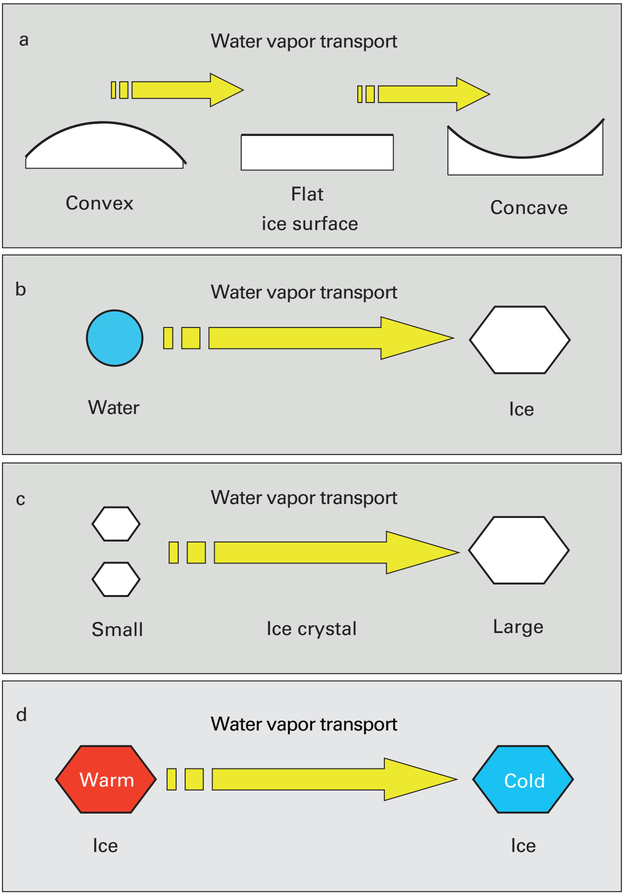

Fig. 1.9: The four rules of water vapor transport in snow. a) From left to right: the drop in water vapor pressure depending on the curvature of the surface. b) Water vapor transport from water to ice. c) Water vapor transport from small to large ice crystals. d) Water vapor transport from warm to cold ice crystals.

1.3.2 Sintering

If we saw out and carefully lift up a block of snow, it immediately becomes clear that snow is not a granular material made up of individual grains. Unlike in a material like sand, in snow bonds quickly develop between individual crystals. This **coalescence of individual grains** to form a porous material is called sintering. If the block of snow is dropped, some of the bonds between the crystal grains are broken, causing the snow to briefly behave like a granular material again. It has been shown that bonds in snow form within milliseconds. This is important for the mechanical behavior of very rounded grains in particular (SZABO 2007).

There are **two types of sintering**: liquid sintering when the snow contains water, and dry sintering when it consists of just ice and water vapor, with no liquid water present.

1.3.2.1 Dry Sintering

At temperatures below 0 °C, sintering occurs through the transport of water vapor. Differences in vapor pressure resulting from different-sized snow structures or temperature gradients cause water molecules to sublime from the ice framework and deposit elsewhere. Sintering through vapor transport gives rise to **more substantial bonding** and **coarser structures** (grains and pores) but does not compact the snow. Bonds between grains grow very quickly at first, but ever more slowly as time passes.

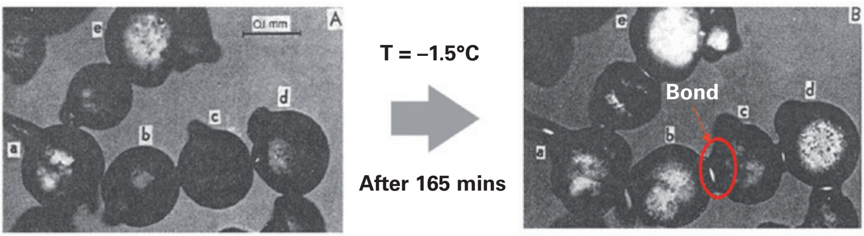

Fig. 1.10: Formation and expansion of bonds between ice crystals during the sintering process (after KUROIWA 1975).

Unlike the technical sintering of plastics or metals, the sintering of snow takes place on the surface without any increase in pressure or temperature. This is a direct consequence of snow's high homologous temperature (close to its melting point) and of water's high vapor pressure. However, **environmental conditions** and the **state** of the snow greatly affect the sintering process:

- the greater the diversity in particle size, i.e. the broader the **distribution of grain sizes**, the better snow sinters, as smaller particles can embed themselves between larger ones. This creates more contact points that can coalesce.
- **smaller grains** dissolve more quickly. Their mass serves to form bonds elsewhere. So the coarser the snow structure, i.e. the smaller the SSA, the slower the sintering process. As small particles dissolve, grain size distribution gradually diminishes.
- the greater the **vapor pressure gradient** in the snow, the quicker the sintering process. If there is no temperature gradient in the snowpack, vapor pressure differences are caused by different-sized snow structures (grains) and are therefore relatively small.
- the **colder the snow**, the less vapor sublimates from the ice framework into the pore air. Less mass is then transported, slowing the sintering process.
- significantly more mass is transported when there is a **temperature gradient** in the snowpack (Fig. 1.11 b). The sintering process is accelerated and strong bonds develop much faster, provided that the snow has a **high density**, as is the case on piste. However, high temperature gradients can make the structure of low-density snow considerably coarser and weaker.

Van Herwijnen's model (2013) provides rough indications of when piste snow has reached sufficient strength[9] through sintering after preparation. Unfortunately, there are hardly any data from field measurements to verify (Fig. 1.12) and improve the model.

[9] The strength of a material is how much force it can absorb before it breaks (see Section 1.4).

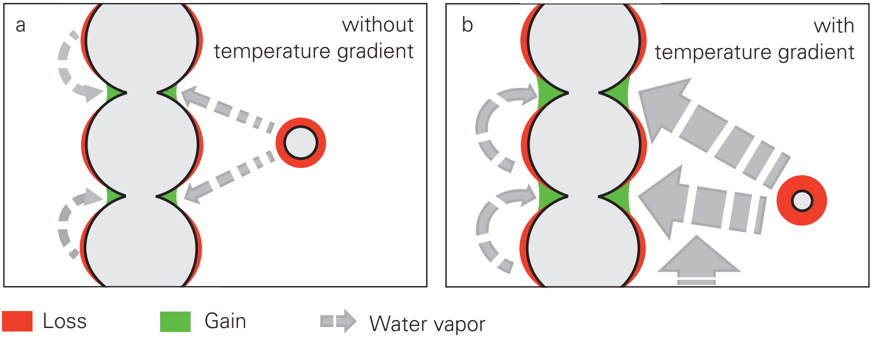

Fig. 1.11: a) Redistribution of ice during dry sintering. When there is no temperature gradient, mainly ice from small grains is transported to the bonds. b) When there is a temperature gradient, considerably more ice is redistributed per time unit, making the bonds grow much more quickly.

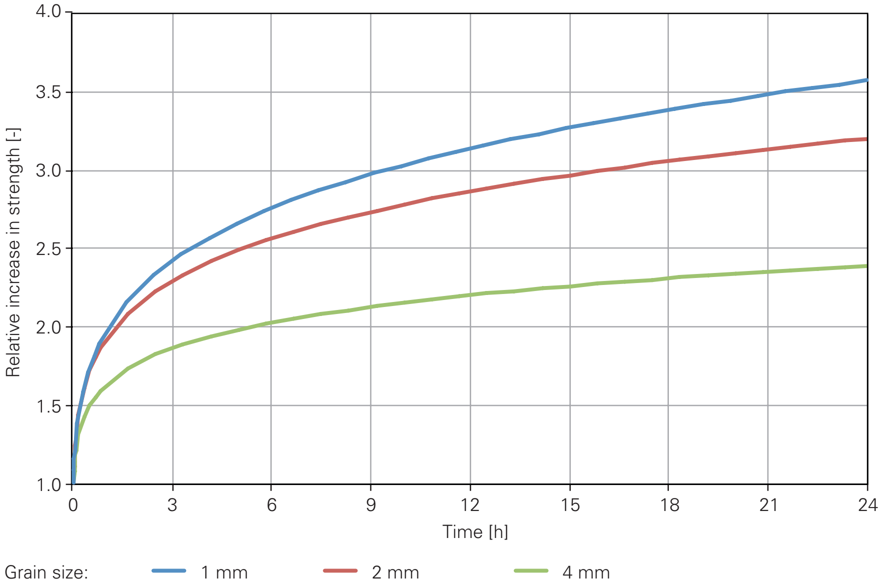

Fig. 1.12: Impact of time and grain size on dry sintering and the resulting increase in snow strength (after VAN HERWIJNEN 2013).

1.3.2.2 Liquid Sintering

Snow starts to melt when its temperature reaches 0°C. But if **it contains water** and there are differently sized snow structures, this causes minor local disparities in the ice framework's melting temperature[10], similar to the vapor pressure differences associated with dry sintering. Parts of the ice framework with higher melting temperatures increasingly start melting, while in parts with lower melting temperatures additional water freezes. Under certain circumstances, this can cause the **bonds between grains to grow** and become stronger. This is referred to as liquid-phase sintering. Like sintering in the vapor phase, this also invariably makes **snow structures coarser**. Small structures dissolve at the expense of

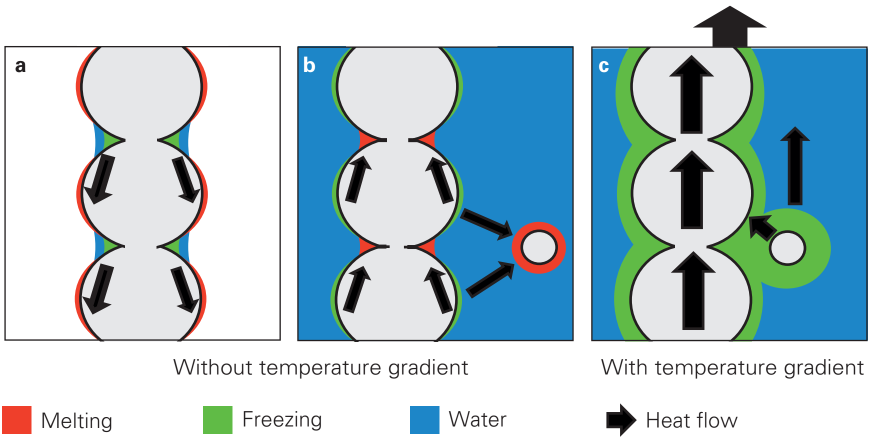

Fig. 1.13: Liquid sintering when the liquid water content is a) low and b) high, and when c) energy released on the snow surface results in freezing. When the liquid water content is low, water freezes at grain boundaries, strengthening the bonds. But when it is high, the bonds between grains melt. If heat can be released into the environment, all the water in the snow freezes, giving rise to very strong bonds between the grains.

[10] Differences in melting temperature are caused by the high capillary pressure when the liquid water content is low and by the different curvatures of grain surfaces and bonds.

larger ones. For liquid sintering, however, **no mass has to be transported**. Since heat is conducted in snow, the heat released when freezing occurs causes the ice framework to melt elsewhere, prompting a swift redistribution of the ice (ARMSTRONG 2008).

The bonds between grains are only strengthened if the snow's liquid water content is not too high. The water retained by capillary forces freezes at the grain boundaries, at the expense of ice structures not coming into contact with water (Fig. 1.13 a). But if the snow is saturated with water, the opposite happens: the **bonds between grains weaken** so ice melts there, and water only freezes on the surfaces of coarser structures (Fig. 1.13 b).

Weather conditions determine whether snow melts and how much water it contains (see Chapter 2). Consequently, liquid sintering on ski slopes primarily depends on **melting and subsequent freezing** due to fluctuations in temperature and radiation throughout the day. The large temperature gradient resulting from the cooling of the snowpack overnight has a greater impact than small temperature differences in the ice framework. As a result, smaller structures no longer melt. Instead, water begins to freeze throughout the pore space (Fig. 1.13 c). This increases snow density and gives rise to very strong bonds between the crystals.

1.3.3 Settlement

Snow compacts and becomes deformed under its **own weight**. This process is called settlement. Settlement leads to the **natural consolidation** of snow layers through both **compaction** and improved sintering conditions.

The colder and denser snow is, the less quickly it settles. Settlement is generally a very **slow process** in which the ice framework becomes plastically deformed without the bonds breaking (see Section 1.4). The process is therefore largely irrelevant in slope preparation. Snow can only be compacted quickly by breaking the ice framework and compressing the snow. Only the subsequent sintering process gives the snow the required strength.

1.3.4 Snow Metamorphism

As mentioned in previous sections (see Tab. 1.1), and as readers surely know from personal experience, snow grains come in different shapes. The section on sintering described how points of contact between ice crystals grow into bonds, whereby material is redistributed in the snow's ice framework. This not only changes the bonds between ice crystals: the entire **geometry of the ice framework is transformed.**

The term snow metamorphism is used to describe changes in the size and shape of snow structures. A distinction is drawn between **three types of snow metamorphism**, depending on whether the focus is on the result, conditions, or causes:

– dry metamorphism:
  - isothermal or destructive metamorphism
  - temperature-gradient or constructive metamorphism
– wet metamorphism
  - wet-snow or melt-freeze metamorphism

1.3.4.1 Dry Metamorphism

Like dry sintering, dry metamorphism occurs when snow contains no liquid water. The processes that occur are the same as those that take place during sintering. Differences in vapor pressure cause the continuous redistribution of mass throughout the snow through sublimation and deposition. At the same time, the snow also settles, and the compaction and displacement of snow crystals in turn affect redistribution processes in the ice framework. This prompts **interactions** between the **sintering and settlement** processes.

Numerous laboratory experiments that studied **isothermal[11] metamorphism**, also known as equilibrium metamorphism, have shown that in the absence of a temperature gradient precipitation particles decompose from a dendritic shape to a **coarser, rounder shape** (BADER 1939). If there is no

[11] An isothermal snowpack has no temperature differences, i.e. no temperature gradient. In nature, this usually only occurs when snow melts, i.e. when the snowpack has a temperature of 0°C.

temperature gradient, the vapor pressure difference between convex and concave surfaces, the driving force behind snow metamorphism, very quickly diminishes. Isothermal metamorphism is always a slow process. At low temperatures in particular, no change is visible in the snow's structure even after several days (Fig. 1.14).

Isothermal metamorphism plays a negligible role in natural snow, as dry, isothermal snowpacks hardly ever occur. In actual fact, there are always small temperature gradients, which are enough to trigger considerable water vapor transport. These small temperature disparities are now considered to also be the main drivers of equilibrium metamorphism[12]. This was demonstrated in experiments with temperature gradients of only 5 K/m, which proved sufficient to completely recrystallize snow within

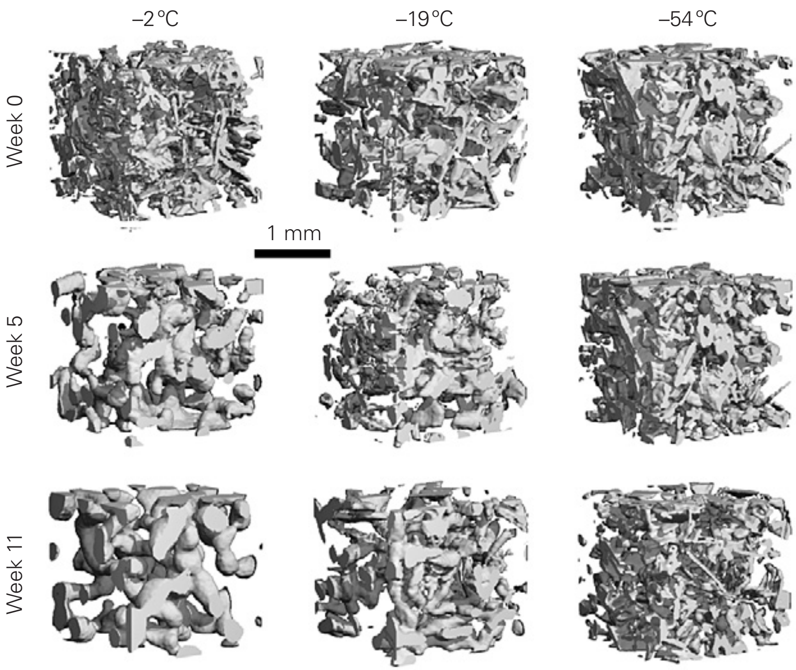

Fig. 1.14: Isothermal snow metamorphism at different temperatures.
The depicted cubes have an edge length of 2 mm (after KAEMPFER 2007).

[12] As a result, the term isothermal metamorphism no longer really applies.

20 days (Kaempfer 2007). Equilibrium metamorphism was even observed in experiments with large temperature gradients (90 K/m) that changed direction depending on diurnal variations (Schneebeli 2015).

It used to be assumed that **kinetic metamorphism** occurred at temperature gradients of more than 10 K/m. This process turns small, rounded grains into large, faceted crystals and, in extreme cases, **depth hoar** (Fig. 1.15). This **weakens the snow** as there are fewer bonds per unit volume (see Section 1.4).

It is now known that the cup-shaped crystals characteristic of depth hoar only form when water vapor has the clearest possible path through the snow's pores and therefore flows evenly towards the deposition location over a lengthy period (Pinzer 2012). The larger the snow's air pores, the clearer the phenomenon, which also explains the formation of large, faceted ice crystals on the walls of freezers. The large space (compared to the air in snow pores) enables the water vapor to move around completely freely and always deposit at the same place. The higher the snow density, the smaller the pores. Kinetic metamorphism therefore hardly ever takes place on well-compacted ski slopes.

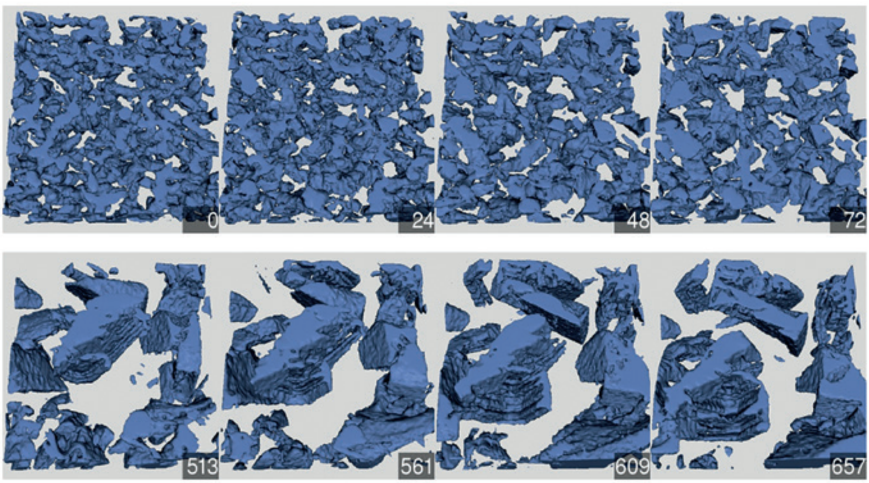

Fig. 1.15: Snow metamorphism with a temperature gradient of 50 K/m during the first 72 hours (top) and the last 6 days of a 27-day experiment, using computed tomography (after Pinzer 2012).

1.3.4.2 Wet Metamorphism

The processes involved in wet metamorphism are **liquid sintering** and successive **melting and freezing** due to weather conditions (see Section 1.3.2). If the snow contains liquid water, small structures (grains) melt. The latent heat needed for melting to occur is extracted from the environment, causing the deposition of a thin layer of ice on larger grains, making them even coarser.

Wet snow metamorphism never produces faceted structures. Instead, **rounded structures** usually develop and often bond to form **clusters** (Fig. 1.16). This is driven by both liquid sintering and freezing that occurs overnight or in cooler weather conditions. Snow farming (see Section 7.4) is a good example of wet snow metamorphism that takes place without melt-freeze cycles, but nevertheless makes snow structures coarser and causes cluster formation.

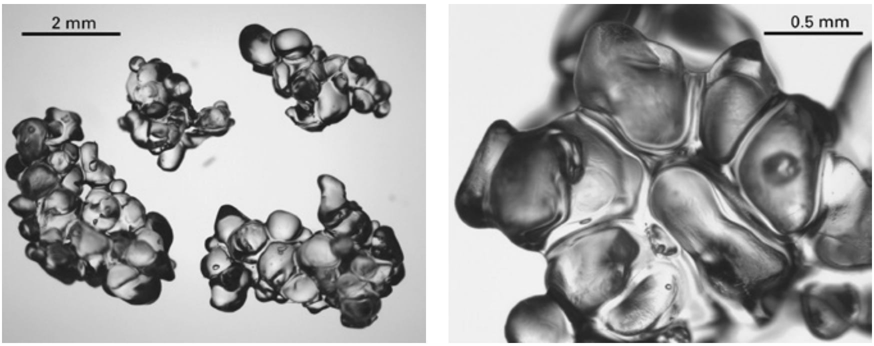

Fig. 1.16: Typical clusters of rounded snow structures resulting from wet snow metamorphism – images: Charles Fierz.

1.4 Mechanical Properties

The mechanical properties of a material describe how it behaves when subjected to a force. A material's **rigidity** indicates how much it deforms under stress. Its **strength** is measured by determining how much force it can absorb before it breaks[13].

How snow behaves under stress primarily depends on the **structural properties** described above and on its **temperature**. For example, differences in density explain why new fallen snow is far less pressure-resistant than groomed snow. But even if two race tracks have snow of the same density, its resistance can differ if there are any major disparities in temperature or microstructure. Anyone seeking to gain a deeper understanding of snow's interactions with machines, sports equipment, or people needs to have a firm grasp of the material's mechanical properties.

Snow reacts differently depending on how quickly it is deformed. If the **process is slow**, snow is plastically deformed and behaves similarly to a viscous fluid (Fig. 1.18 a). Glacier flow and snow settlement both result from such deformations, whereby bonds in the ice framework remain intact and compaction results in the formation of additional bonds. The

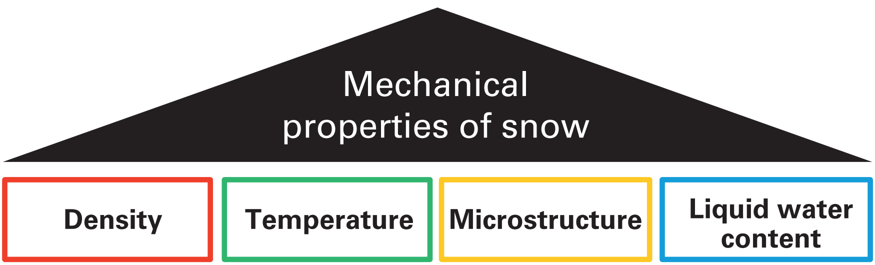

Fig. 1.17: The most important factors influencing the mechanical properties of snow.

[13] Whether a material breaks without significant deformation, like glass (brittle), or gradually by means of severe plastic deformation, like a chocolate bar, depends on its fracture toughness.

colder the snow, the more viscous it is and the more slowly it deforms. This slow process of viscous snow deformation has little relevance for slope preparation.

When snow is **quickly deformed**[14], by a skier for example, it becomes elastically brittle, deforming when subjected to stress, but quickly returning to its original state once that stress has been removed. But if the stress intensifies, bonds in the ice framework abruptly start breaking (brittle behavior), and this deformation remains permanent (Theile 2009).

Snow, particularly loose, new fallen snow, can also be **compressed**. Its strength can be measured in terms of pressure, tension, and shear. Its penetration resistance, or hardness, is heavily dependent on the four strength components (Fig. 1.17). Even if snow is stressed in a specific direction, the bonds in the heavily dendritic ice framework are nonetheless exposed to forces pulling in very different directions. Even when simply under the burden of the ice framework's own weight, individual bonds are subject to both pressure and tensile stress (Fig. 1.19 b). Ice is far less resilient to tensile stress than to pressure. Consequently, elements under tensile stress can break relatively quickly, causing snow failure.

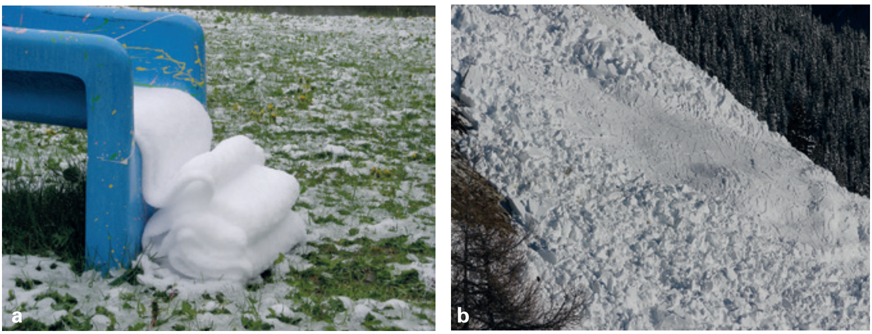

Fig. 1.18: a) Slow (viscous-plastic) deformation of snow slipping down a slide – photo: Jürg Schweizer. b) Snow breaking due to elastic-brittle deformation at the start of an avalanche – photo: Tom Feistel.

[14] Elastic-brittle behavior predominates at deformation speeds in excess of roughly 1 mm/s (Fukue 1979).

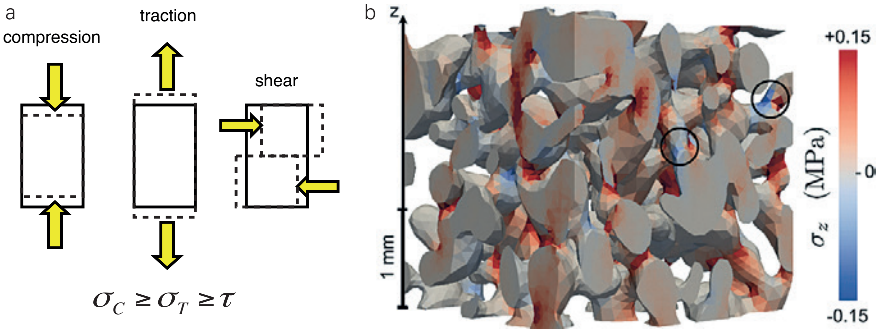

Fig. 1.19: a) Types of stress exerted on snow. Snow can absorb extremely large forces under pressure. It breaks most easily when subjected to shear forces. b) Numerical simulation of the pressure (red) and tensile stress (blue) of a snow sample under tensile load. The ice framework can break easily in areas where tensile stress is concentrated (circled) (after HAGENMULLER 2013).

1.4.1 Factors Influencing Mechanical Properties

1.4.1.1 Snow Temperature

The colder the snow, the harder it is (Fig. 1.20). So snow at low temperatures is difficult to prepare because it is hard and not easily deformed. The closer it is to its melting point, the more readily it deforms. Temperature is a very important factor for determining compressive strength, which doubles between –1°C and –20°C. Consequently, the mechanical energy required to work the snowpack can rise sharply at low temperatures.

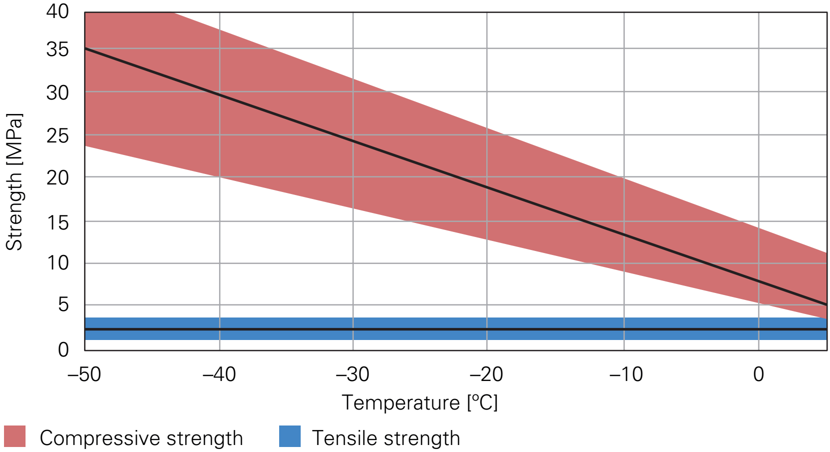

Fig. 1.20: Impact of temperature on ice strength (after PETROVIC 2003).

1.4.1.2 Structural Properties (Density, Microstructure, and Snow Wetness)

In most cases, **the denser the snow, the stronger it is** (Fig. 1.21). However, density values need to be treated with caution. For example, depth hoar comprising faceted crystals can reach a density of around 300 kg/m^3 but be of very low strength.

Snow with fine, rounded grains is generally harder than snow with large, stellar, or faceted grains. To attain maximum hardness, snow must have a **wide range of grain sizes** and those grains need to be as rounded as possible. This gives the snow smaller and fewer pores, and means it contains less air, increasing its density and facilitating bond formation.

Bonds are the key parameter for determining snow hardness. The more bonds there are per volume of snow, and the greater their diameter, the harder the snow will be (Fig. 1.23). Small, rounded structures have far more bonds per unit volume than large, faceted structures like depth hoar (Fig. 1.22). Bonds in depth hoar are usually larger than those between small, rounded structures, but there are far fewer of them. Furthermore, the distance between individual elements is much greater, so there is a far bigger "lever effect" per bond (PROKSCH 2016).

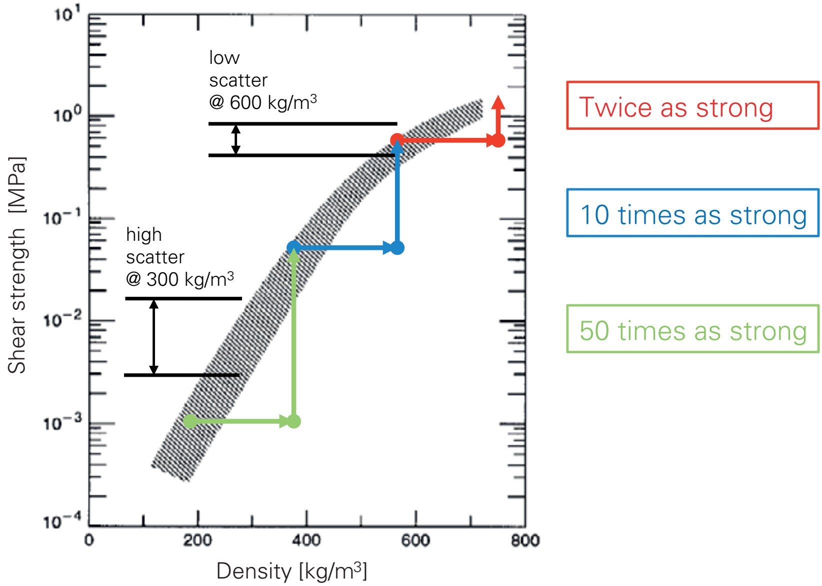

Fig. 1.21: Impact of density on snow's shear strength (after SHAPIRO 1997). Increasing snow's density from 200 to 400 kg/m³ makes it 50 times as strong, whereas an increase from 600 to 800 kg/m³ merely doubles its strength.

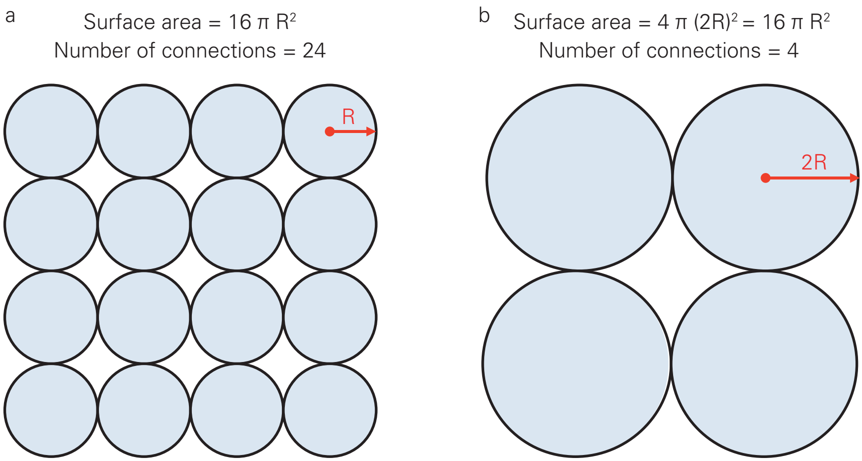

Fig. 1.22: Representation of how the number of bonds per cross-sectional area significantly decreases if the snow structure is coarser (b).

If **snow wetness** is less than 5 %, capillary forces and the formation of new bonds boost cohesion, particularly in snow with rounded grains (see Section 1.3.2). When snow's liquid water content is higher, the bonds between its grains gradually begin to melt, quickly and significantly reducing its strength. Above a liquid water content of roughly 15 %, snow loses all its cohesion and strength, turning into corn snow or slush. If weather conditions cause the water in the snow to refreeze, its strength increases sharply. On the one hand, the water mainly freezes at the bonds between grains, making them stronger than before the snow melted. But on the other hand, the melt-freeze cycle also compacts the snow, through settlement and the filling of pore spaces.

Since wet snow always has a temperature of 0 °C, it is never as strong as comparable, equally dense, dry snow, whose temperature is always below 0 °C (Fig. 1.20).

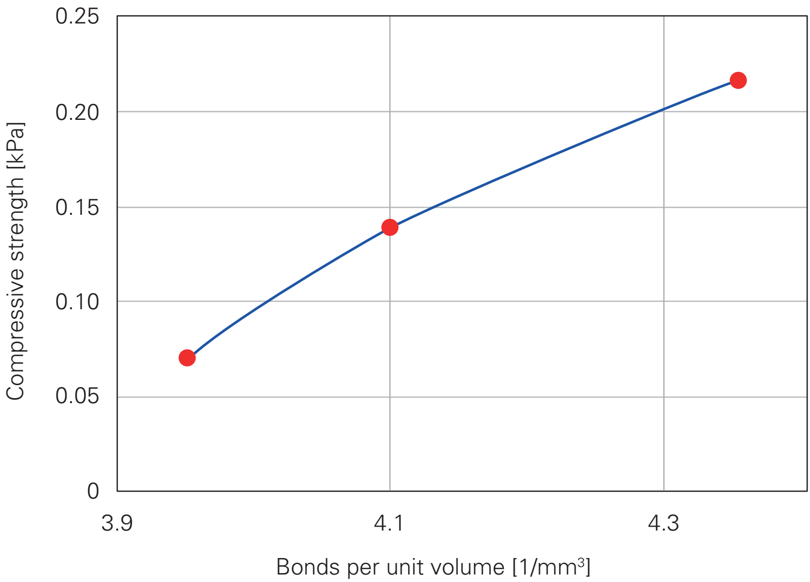

Fig. 1.23: Impact of the number of bonds per unit volume on snow's pressure resistance (Fauve 1997).

Tab. 1.4: Impact of the snow's properties on its deformability and strength. Strength is inversely proportional to deformability: if deformability is high, strength is low, and vice versa.

Parameter	**Snow's deformability is...**		
	low	**variable**	**high**
Density	high	medium	low
Grain shape	rounded	rounded and faceted	new snow faceted and hollow
Grain size	small	medium	large
Bonds	many	some	few
Temperature	cold	rising or falling	warm
Snow Wetness	dry	wet	soaked

1.5 Formation of Natural Snow

1.5.1 Atmospheric Conditions Required for the Formation of Snow

There are three basic requirements for the formation of snow:
- sufficient air humidity
- air temperature below 0 °C
- freezing nuclei, which trigger ice crystal formation

Air always contains some water vapor, referred to as **air humidity**. The amount of humidity is temperature-dependent. The warmer the air, the more water vapor it can absorb (see Chap. 2, Tab. 2.1). Clouds start to form when a mass of air is saturated with water vapor (= 100 % relative humidity).

The excess water vapor forms minute water droplets on **condensation nuclei**[15]. These water droplets are first supercooled, without freezing. Ice crystals only form in clouds at temperatures of less than –12 °C. Below –35°C, ice crystals predominate. But ice crystal formation depends on the number and type of freezing nuclei, as well as on temperature. If there are no **freezing nuclei**, pure water only freezes at around –40 °C. The nucleation temperature of the freezing nuclei most commonly occurring in clouds is around –12 °C.

1.5.2 Precipitation Particles

Snow crystal formation in the atmosphere begins in clouds containing supercooled water droplets, water vapor, and minute ice crystals. There are two types of snow crystal formation:

[15] Condensation nuclei may be particles of any chemical composition that are small and light enough to float in the air (e.g. particles from combustion processes, like soot). Not all particles qualify as freezing nuclei (usually silicates, e.g. desert dust). Whereas all freezing nuclei can also act as condensation nuclei, the reverse does not apply (Pruppacher 2010).

- **crystal growth through deposition**: supercooled water droplets and small, warmer ice crystals that release water vapor molecules, being subjected to higher vapor pressure. These molecules are deposited on a larger, colder ice crystal (Fig. 1.24 a).
- **crystal growth through the freezing of water droplets**: when supercooled water droplets freeze upon coming into contact with an ice crystal. This creates heavily rimed snow crystals and irregularly shaped graupel (Fig. 1.24 b).

Individual snow crystals usually start out as hexagonal shapes, though their subsequent form depends on the air's temperature and water vapor supersaturation[16] (Fig. 1.25). Column-shaped crystals usually form at air temperatures between –4 °C and –10 °C, plates and dendrites between –10 °C and -22 °C as well as close to 0 °C. Below –22 °C plates and column form depending on the supersaturation.

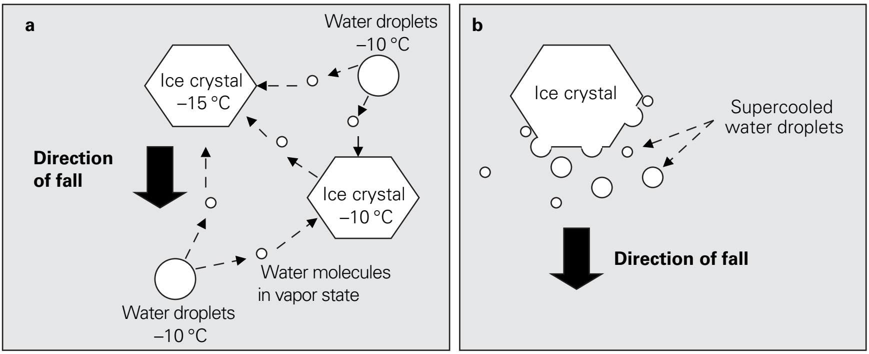

Fig. 1.24: Crystal growth. a) through deposition. b) through the freezing of water droplets.

[16] Supersaturation is said to occur when the air contains more water vapor than in a saturated equilibrium state. Under normal conditions, excess vapor condenses on condensation nuclei and forms water droplets to establish an equilibrium. Supersaturation occurs when there are too few condensation nuclei.

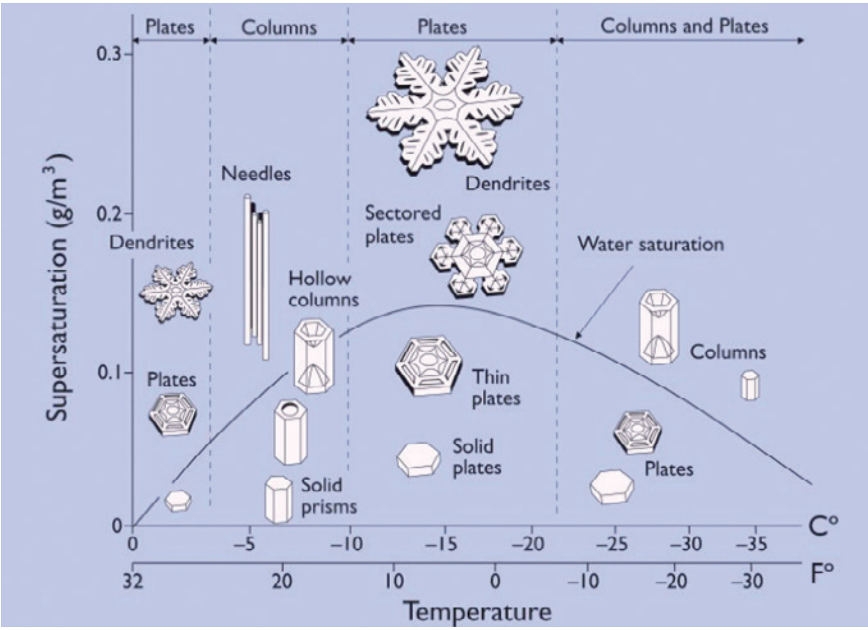

Fig. 1.25: Formation of different snow crystals depending on air temperature and supersaturation – adapted from Libbrecht (2005) and Furukawa (1997). A detailed description of the various shapes that solid precipitation takes can be found in the International Classification for Seasonal Snow on the Ground (Fierz 2009).

1.5.3 Deposition of New Fallen Snow

When snow falls, some crystals bind together to form **snowflakes** before being deposited on the ground. Because it takes time for enough heat to transfer from the air to the snowflakes to melt them, snow can pass through layers of air above 0 °C without melting completely[17]. As a result, on average the snowfall level (snowline) is 200 to 400 m below the zero-degree line. Below the **snowline**, precipitation contains more than 50 % liquid water in the form of rain.

[17] There can be a number of reasons for this (Hächler 2002).

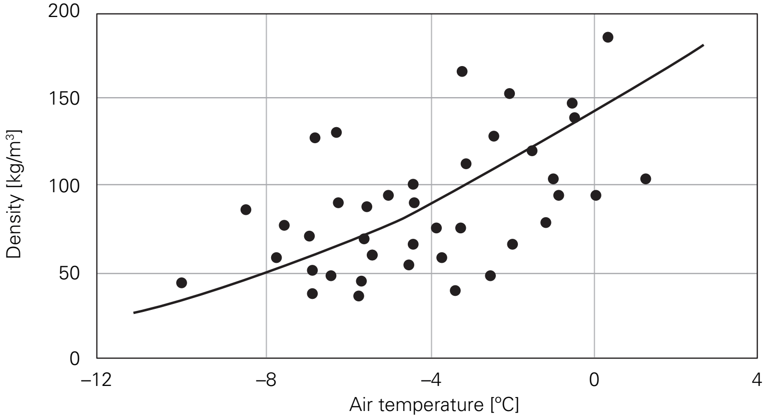

Fig. 1.26: Impact of air temperature on the density of new fallen snow (after POMEROY 1995).

When snow crystals collide or hit the ground, their tips break off. So the **mechanical metamorphism** of snow already begins in the air. As snow falls, wind intensifies this process.

The **density of new fallen snow** is heavily dependent on air temperature. The warmer the air, the denser the snow deposited on the ground will be (Fig. 1.26).

1.5.4 Man-Made Nature-Identical Snow

Snow crystal formation in clouds can be recreated in a **cold chamber** using straightforward apparatus (Fig. 1.27). The Japanese scientist H. Nakamura was the first to describe this simple working principle in 1978: cold air is blown over a water basin, saturating it with water vapor, and then transferred to a colder chamber. As the saturated air cools, it becomes supersaturated, forcing the air to release moisture. The excess moisture is deposited as a solid on stretched nylon wires. In other words, ice crystals form directly from the water's vapor phase, which very closely approximates the **natural snow crystal formation** in clouds.

As snow crystals move freely in clouds, they usually form symmetrical hexagonal shapes. If, as with the SLF SnowMaker, static **nylon wires are**

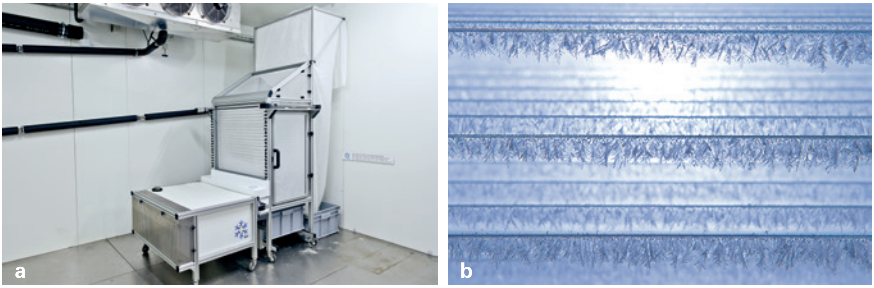

Fig. 1.27: a) SLF SnowMaker with b) snow crystals deposited on nylon wires – photos: Mallaun Photography.

used as the freezing nuclei to grow snow crystals, the resulting structures usually grow downward, tending to form individual crystal branches. Nevertheless, the physical properties of such man-made nature-identical snow are very similar to those of natural snow. Moreover, by adjusting the air's supersaturation level and temperature, **various crystal types** can be grown, similar to those shown in Fig. 1.25 (Schleef 2014).

Nature-identical snow is mainly produced for research purposes. Despite low productivity and the low density of the resulting material, further devices designed to make snow for use on slopes are currently under development (Breiling 2016; Enzenhofer 2016).

1.6 Machine-Made Snow[18]

As climate change progresses, snow reliability in the Alps (see Section 7.6) will continue to deteriorate (Abegg 2013). If enough water is available, intensive use of modern snowmaking equipment will enable many ski resorts to maintain sufficient levels of snow during the second half of the 21st century. Technical snowmaking will thus become even more important in the years to come. The main **goals of technical snowmaking** are:

– guaranteeing skiing throughout the winter season, with the focus on **ensuring that the season starts on time** and securing business over the important Christmas period.
– making sure that **slopes are open for all activities**, including downhill skiing, connecting routes, snow parks, and other snow attractions and events (e.g. igloos, toboggan runs, World Cup cross-country skiing).
– **eliminating danger zones** (e.g. replenishing snow where slopes are crossed by streams, covering over stones or patches of grass, etc.).

1.6.1 Properties of Snowmakers (Snow Guns)

The goal of snowmaking is to turn as much water as possible into good snow while consuming the least quantity of energy. Production must remain possible even in critical ambient conditions in the marginal temperature range[19]. Consequently, the most important properties to bear in mind when comparing snowmakers are their productivity, energy efficiency, and the quality of the snow they produce.

[18] The term machine-made snow is preferred to the colloquial term artificial snow, because snowmaking generally uses no artificial additives.

[19] When making snow, the term marginal temperature range refers to wet-bulb temperatures (see below) of between –2 °C and –4 °C. Snowmaking can just begin at these temperatures.

1.6.1.1 Snow Quality[20]

In practice, snow quality is a common parameter used when setting automatic snow guns, corresponding in this context to snow wetness (LWC). If low snow quality is selected, more water is sprayed at a given wet-bulb temperature (WBT)[21], producing wetter snow. Free water that fills pore spaces and is subsequently frozen leads to the formation of more ice and larger grains. This makes it more difficult to create a homogeneous, grippy regular ski run. If there is only a small quantity of free water, which accumulates at the grain boundaries, there is less ice formation and grain growth, so snow quality remains acceptable. Water present only inside frozen ice balls does not lower snow quality. Therefore, high-quality machine-made snow requires the **lowest possible liquid water content (LWC)**, and **small, rounded shapes** to accelerate the sintering process and thereby quickly increase snow strength.

1.6.1.2 Productivity

The productivity of a snow gun indicates the volume of snow produced per machine hour, depending on the water input. The snow-water ratio (SWR) shows the relationship between productivity and water flow[22].

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20 As with wetness, snow quality is graded along a five-point scale ranging from very good (LWC = 0), to good (<3%), acceptable (3–8%), low (8–15%), and insufficient (>15%). Quality can be assessed using the snowball test (see Section 1.1.3). Unfortunately, most manufacturers provide no information on how they determine their snow quality scales and the underlying snow wetness.

21 The air's WBT indicates the lowest temperature a falling water droplet can reach. Snow can only be made using nozzle technology if droplets can quickly cool to around –1°C. If the relative humidity is 100%, the WBT is the same as the air temperature. At lower air humidity, the WBT is lower than the air temperature (see Table 1.31). Lower air pressure reduces the WBT at low air humidity (10%) to around 1°C.

22 This is also referred to as the snow-water factor.

$$productivity = \frac{volume\ of\ snow - loss\ [m^3]}{time\ [h]}$$

The **SWR** specifies how much snow can be produced from the quantity of water used. It depends on the following factors:

- **environmental conditions and water temperature:** in the marginal temperature range and at high water temperatures, the water flow, and thus productivity, needs to be significantly reduced, and even then, not all water droplets will freeze completely. Wet snow accumulates more densely on the ground. So the same water flow will produce less, but heavier, snow and lower the snow-water ratio. Moreover, ambient conditions also affect water loss.
- **snowmaker properties:** within the marginal temperature range, the snow-water ratio thus depends on how well the snow gun uses the existing cold to turn as much of the sprayed water into ice as possible. The factors that determine this are the type of water nozzle and air jet used, their configuration, and the snow gun's automatic control settings. At very low temperatures, depending on the machine used, the maximum flow rate will limit the output, producing dry snow while the snow-water ratio remains relatively constant.
- **losses:** in a snowmaking context, mass loss is the term used when snow is not deposited at the desired location, i.e. on the slope (Fig. 1.28). Various factors can cause this to happen:
  - *wind losses:* above all, small droplets or small, frozen ice beads are blown away from the target area
  - *evaporation and sublimation:* when cooling and freezing as they fall, water droplets and ice beads lose some of their mass. Small droplets incur higher losses because they are in the air for longer and have a larger specific surface area. Lower relative humidity and higher ambient temperatures also cause more such losses.
  - *drainage:* drops that are not frozen when they hit the ground, seep into it or drain away. If there is already snow on the ground, its bottom layer will be compacted while its volume remains the same. If snow compaction is not the aim, this is practically synonymous with mass loss.

The latest studies indicate major differences in losses. Field studies conducted on snow lances at the WSL Institute for Snow and Avalanche Research (SLF) revealed losses of between 12 and 38 %. A further study by the University of Grenoble Alpes showed **losses of between 10 and 50 %** (Spandre 2017). Losses have a major impact on productivity and the snow-water ratio, and should therefore always be taken into account when planning how much snow to produce.

Figure 1.29 illustrates how the snow-water ratio depends on losses and snow density. Low snow-water ratios typically occur within the marginal temperature range, when only wet, very dense snow can be produced. In practice, a snow-water ratio[23] higher than 2.2 m^3 of snow per cubic meter of water never occurs. For this would require optimal conditions in which losses remained low (<10 %) and dry snow with a density of less than 400 kg/m^3 could be produced.

[23] The highest snow-water ratios can only be reached at a far lower snow density, e.g. as with nature-identical man-made snow. However, this type of snow still has to be heavily compacted, like new fallen snow. The quantity of snow effectively available for slope preparation is thus much lower than the produced volume of snow would suggest.

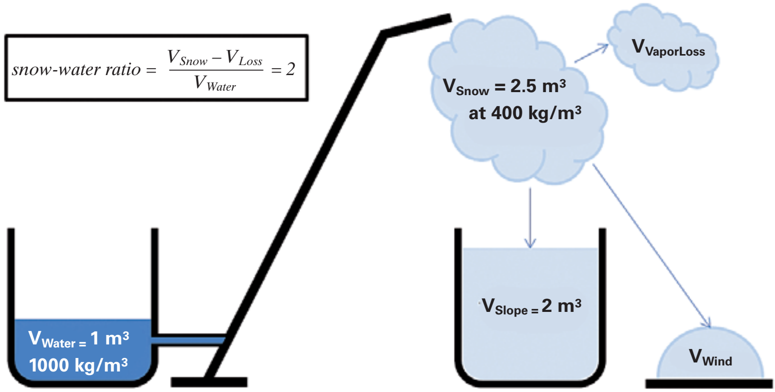

Fig. 1.28: Illustration of how loss and snow density affect the snow-water ratio. In theory, 1 m³ of water and a density of 400 kg/m³ produces 2.5 m³ of snow. But in reality there are always some losses. If the loss is 20%, 2 m³ of snow remains. The snow-water ratio is 2 in this case.

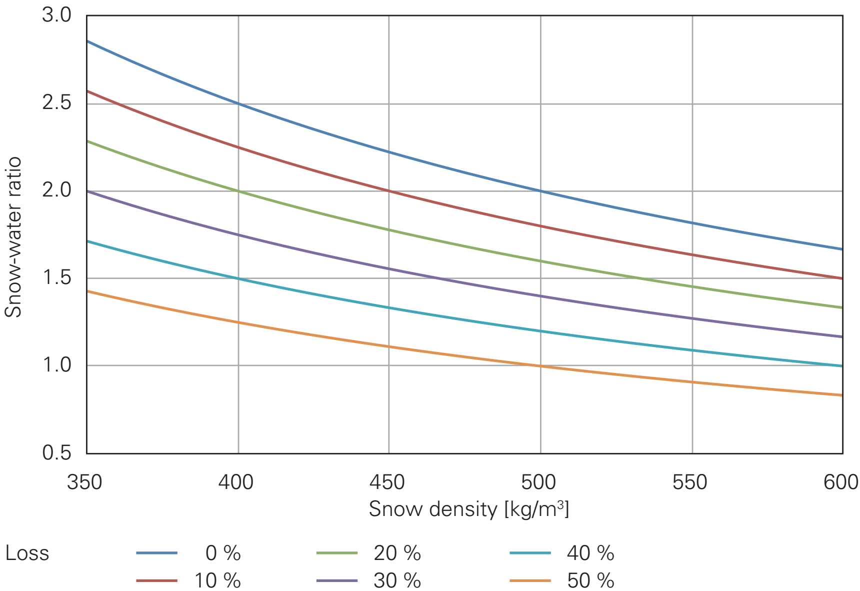

Fig. 1.29: Impact on the snow-water ratio of losses during snowmaking and of the density of the machine-made snow.

1.6.1.3 Energy Efficiency

The energy efficiency of a snow gun indicates how much energy needs to be used to produce a certain quantity of snow and is defined in this book as the **energy-to-snow ratio** (ESR)[24].

Power consumption and productivity determine a snow gun's energy efficiency. Especially in the marginal temperature range, when productivity is low and power consumption is high, and for propeller-driven snow guns in particular, it takes a lot of energy to produce just a small quantity of snow (Fig. 1.30).

Field studies and surveys in Sweden indicated an average energy efficiency[25] of 4.3 kWh/m³, with **the extreme values lying between 0.6 and 14 kWh/m³** (ROGSTAM and DAHLBERG 2011). In the marginal temperature range, the energy efficiency of non-weather-dependent snowmakers is even markedly worse than that of fan guns and snow lances using nozzle technology (Tab. 1.5).

$$\textit{energy-snow ratio} = \frac{\textit{power}\ [kW]}{\textit{productivity}\ [m^3/h]} = \frac{\textit{energy}\ [kWh]}{\text{volume of snow} - \text{loss}\ [m^3]}$$

24 The energy terms depending on the snowmaker (propeller engine, compressor to provide pressurized air, heating to prevent icing up) are also taken into account, as is the energy required to create water pressure of 50 bar (efficiency level of 0.6), corresponding to a pumping height of 500 m. The energy required to cool the water is not taken into account.

25 Excludes consideration of pump capacity and water cooling.

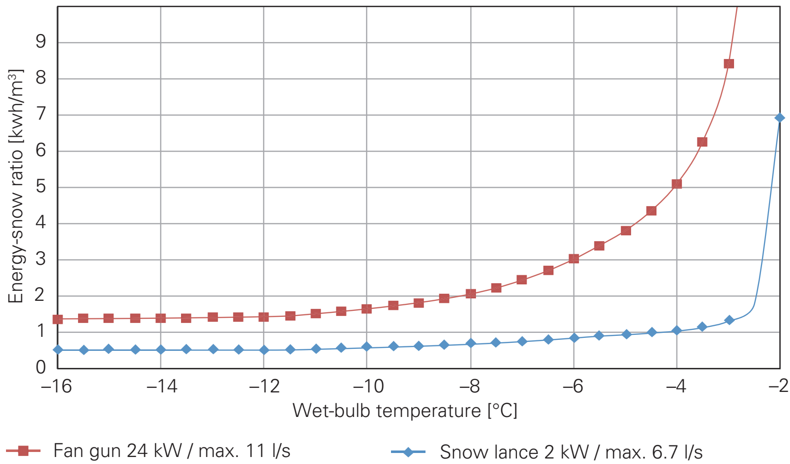

Fig. 1.30: The energy-snow ratio of two snowmakers with high-flow-rate nozzle technology: the DemacLenko Titan 2.0 fan gun and the Bächler SnoTek snow lance. As temperatures fall, the flow rate increases and the snow produced becomes drier, lowering the ESR. The calculation assumes a 15% loss and a limited flow rate in the marginal temperature range, so that snow wetness does not exceed 15%.

Air temperature [°C]	Relative humidity									
	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
5°C	-2.3	-1.5	-0.6	0.3	1.1	1.9	2.7	3.5	4.3	5.0
4°C	-3.0	-2.1	-1.3	-0.5	0.3	1.0	1.8	2.6	3.3	4.0
3°C	-3.6	-2.8	-2.1	-1.3	-0.6	0.2	0.9	1.6	2.3	3.0
2°C	-4.3	-3.5	-2.8	-2.1	-1.4	-0.7	0.0	0.7	1.4	2.0
1°C	-5.0	-4.3	-3.6	-2.9	-2.2	-1.5	-0.9	-0.3	0.4	1.0
0°C	-5.6	-5.0	-4.3	-3.7	-3.0	-2.4	-1.8	-1.2	-0.6	0.0
-1°C	-6.3	-5.7	-5.1	-4.5	-3.9	-3.3	-2.7	-2.1	-1.6	-1.0
-2°C	-7.0	-6.4	-5.8	-5.3	-4.7	-4.2	-3.6	-3.1	-2.5	-2.0
-3°C	-7.7	-7.2	-6.6	-6.1	-5.6	-5.0	-4.5	-4.0	-3.5	-3.0
-4°C	-8.4	-7.9	-7.4	-6.9	-6.4	-5.9	-5.4	-4.9	-4.5	-4.0
-5°C	-9.2	-8.7	-8.2	-7.7	-7.3	-6.8	-6.3	-5.9	-5.4	-5.0
-6°C	-9.9	-9.5	-9.0	-8.6	-8.1	-7.7	-7.3	-6.8	-6.4	-6.0
-7°C	-10.7	-10.2	-9.8	-9.4	-9.0	-8.6	-8.2	-7.8	-7.4	-7.0
-8°C	-11.4	-11.0	-10.6	-10.2	-9.9	-9.5	-9.1	-8.7	-8.4	-8.0
-9°C	-12.2	-11.8	-11.5	-11.1	-10.7	-10.4	-10.0	-9.7	-9.3	-9.0
-10°C	-13.0	-12.6	-12.3	-12.0	-11.6	-11.3	-11.0	-10.6	-10.3	-10.0

Slush can be produced

A small quantity of wet snow can be produced

Dry snow and larger quantities of wet snow can be produced

Large quantities of dry snow can be produced

Fig. 1.31: Wet-bulb temperature at an ambient pressure of 0.9 bar (LIMACHER-LEHNER 2009).

1.6.2 Snowmaking Technologies

All snowmaking technologies are designed to turn a certain quantity of **water into ice** and disperse it in typical snow grain sizes. When a certain quantity of water is frozen, the same quantity of energy is released in the form of heat, regardless of the technology used.
The various snowmaking technologies differ in terms of the technical solutions they use to lower the water temperature to freezing point, initiate crystallization, and dissipate the released heat. In addition, artificially produced ice particles differ in their size and shape, which determine how well they bond (sintering) to form a porous ice framework (= snow). A distinction can be drawn between **three basic principles** in snowmaking:
- **Nozzle technology:** heat is released directly into the ambient air (weather-dependent)
- **Cooling technology:** heat is released into the refrigeration circuit of a cooling system (not weather-dependent)
- **Cryogenics:** heat is released directly into a specified refrigerant (non-weather-dependent)

When using **nozzle technology**, a large part of the required energy can be gained from the **ambient air**. However, electricity is also required to power

Fig. 1.32: NESSy snow lance, Bächler Top Track AG (Switzerland) – Davos (Switzerland).

Fig. 1.33: T40 fan gun, TechnoAlpin (Italy) – Davos (Switzerland).

Tab. 1.5: Comparison of the properties of various snowmakers.

Technology (version) (refrigerant)	**Manufacturer type**	**Productivity**[26]	**Snow quality**	**Energy efficiency ESR** (incl. pumping capacity)
Snow lance with nozzle technology; WBT = –3 to –16 °C	Bächler SnoTek	3.6 to 51 m^3/h 550–400 kg/m^3	low– very good	1.3 to 0.5 kWh/m^3
Fan gun with nozzle technology; WBT = –3 to –16 °C	DemacLenko Titan 2.0	3.6 to 89 m^3/h 550–400 kg/m^3	low– very good	8.4 to 1.4 kWh/m^3
Refrigeration (ammonia)	TechnoAlpin[27] SF220	9.2 m^3/h at 450 kg/m^3	low	25 kWh/m^3 (36 kWh/m^3)
Refrigeration (ammonia)	SnowGen[28]	8.3 m^3/h	low	31 kWh/m^3 (40 kWh/m^3)
Refrigeration (water)	IDM[28] VIM 100GO	35.8 m^3/h at 650 kg/m^3	low	30 kWh/m^3 (40 kWh/m^3)

the water and compressed air supply (pumps, compressors), any water cooling systems[28], and heating to prevent any build-up of ice[29]. Since freezing expends the most energy, non-weather-dependent snow guns consume far more energy (between 3 and 60 times as much) than those using conventional nozzle technology (Vagler 2016).

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26 The upper limit is based on the manufacturer's specifications minus an assumed snow loss of 15% (using nozzle technology). The lower limit is based on field measurements taken at the SLF (Bächler, NESSy).

27 With the specified power input, productivity, and snow density, only around 65% of the water mass in the snow can be turned into ice. Therefore, in addition to the manufacturer's specifications, another ESR value is provided in parentheses, these calculations being based on the assumption that at least 85% of the propelled water mass freezes (0.85 * productivity * density * 334 kJkg). This would result in 15% snow wetness.

28 The energy required depends on the water flow through the cooling tower and is relatively low, around 0.1 kWh/m^3 of snow, because the water is cooled by the ambient air (www.technoalpin.com/files/2013_cooltech_de_it_fr_en.pdf).

29 The NESSy ZeroE snow lance constitutes an exception, since it only consumes electricity to pump its water supply.

1.6.2.1 Weather-Dependent Snowmaking (Nozzle Technology)[30]

Fan guns and **snow lances** are the most common snowmakers. The energy-to-snow ratio of fan guns is some 3 to 11 times higher than that of snow lances, because both the fans and air compressors of the former consume power. That said, the droplets they produce are dispersed over a wider area in the air, enabling them to freeze better. Accordingly, in perfect ambient conditions, higher flow rates can be achieved, enabling more snow to be produced. The largest fan guns are claimed to be capable of producing up to 100 m^3 of snow per hour. Recently, snow lances with very high flow rates have also been launched on the market with a productivity of up to 60 m^3/h. Snow lances are also cheaper to buy, not as noisy, and usually require less maintenance. As they are taller, however, and the resulting snow cloud moves more slowly, not being propeller driven, they are more susceptible to wind. Snowmaking based on nozzle technology can be broken down into the following **steps**: atomization, ice nucleation, seeding, cooling and solidification of the water droplets in the air, and solidification and sintering on the ground (Fig. 1.34). Each of these steps is essential for successful snowmaking.

Atomization: an array of water nozzles atomizes water under pressure (around 12–60 bar), forming small droplets with a diameter of between 0.1 and 1 mm. The purpose of atomization is to give the water a large surface area, as this increases energy and mass exchanges with the ambient air and enables more water to freeze per unit of time. Having a small diameter creates a large surface area (see Section 1.1.2), though such atomization also consumes more energy. Poor atomization, creating many large droplets, reduces snow quality because the droplets fall to the ground more quickly and fail to freeze completely, even when it is very cold. How effectively a nozzle atomizes water is determined by the **distribution of droplet sizes** in the spray. Optimal droplet size distribution depends on the ambient conditions where the snowmaker is deployed. In cold, wind-exposed locations, somewhat larger droplets reduce wind and sublimation losses. But at

[30] A distinction used to be made between high-pressure and low-pressure nozzle technology (fan guns as opposed to snow lances). Yet since both systems now use water pressure and compressed air, this categorization no longer makes sense.

warm, wind-protected locations, smaller droplets improve snow quality and productivity in the marginal temperature range. So **optimal droplet size** always entails a compromise between snow loss and snow quality. According to calculations[31], the optimal droplet diameter is around 0.2 mm for the marginal temperature range (where the wet-bulb temperature equals roughly –2 °C) and 0.5 mm for wet-bulb temperatures of around –10 °C.

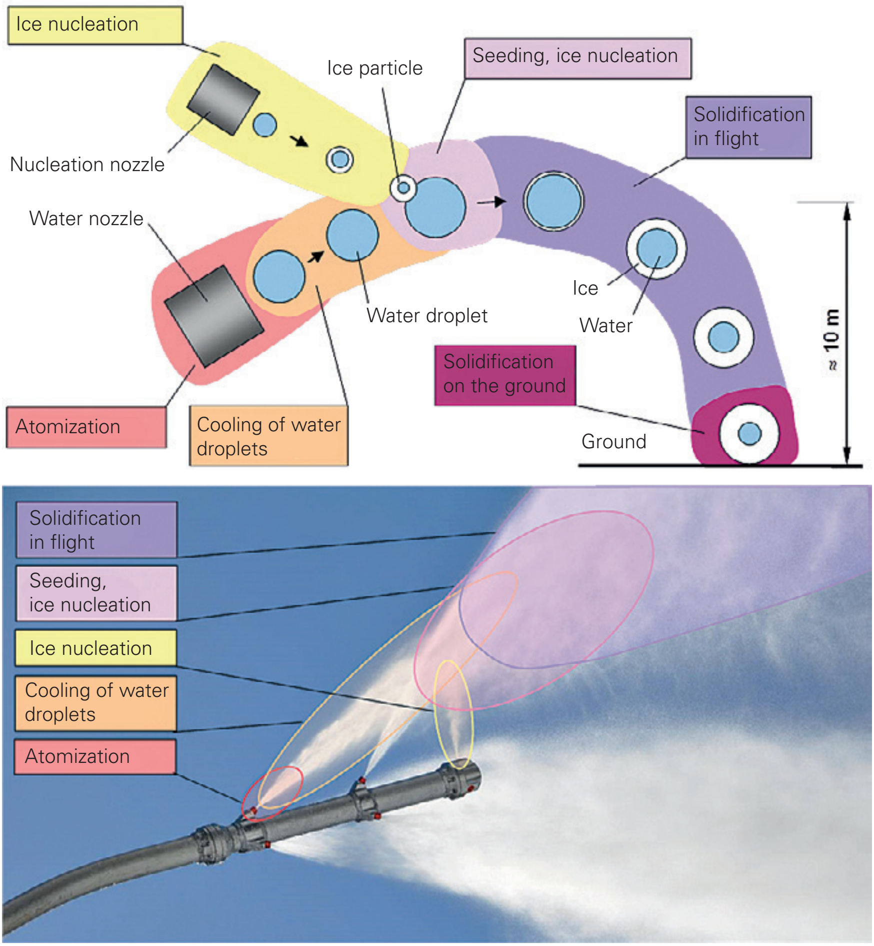


Fig. 1.34: The various stages of the snowmaking process using nozzle technology (LIMACHER-LEHNER 2009).

Higher relative velocities between droplets and the ambient air, and a lower concentration of droplets in a **large snow cloud** also improve the energy transfer from the droplets to the air and therefore a snowmaker's productivity. Higher water pressure, entailing higher discharge velocities, and good nozzle distribution are needed to create larger snow clouds.

Cooling of water droplets: as soon as the main water spray exits the nozzles, it starts to cool. Droplets are cooled when heat dissipates into the ambient air through evaporation and convection[32]. As a result, that ambient air is heated and saturated with liquid, and the droplets lose part of their mass. Cooling is limited by the wet-bulb temperature and occurs very rapidly. If the **wet-bulb temperature** exceeds the nucleation temperature, snow cannot be made. It takes a droplet no more than a second to cool from 8 °C to around –6 °C[33].

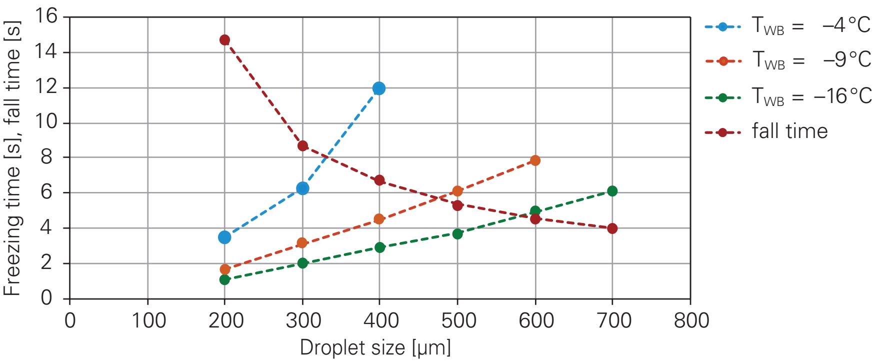


Fig. 1.35: A comparison of fall times and freezing times depending on droplet size and wet-bulb temperature. If the freezing time is longer than the fall time, the droplets will not be fully frozen by the time they reach the ground, making the resulting snow fairly wet.

33 $v_{Droplet}$ = 0.1 m/s; $D_{Droplet}$ = 0.2 mm; T_{Air} = –5°C; relative humidity = 70%

31 When the fall height is 10 m. The calculations were based on a single-droplet model (Limacher-Lehner 2009).

32 Convective or turbulent heat transfers occur in flowing liquids or gases, with the respective substance's extensive motion playing a decisive role. By contrast, in non-flowing substances heat can only be transferred via minute molecular movements (see Section 1.2.2, Heat Conduction).

Water can only freeze if it contains nucleation active particles (Fig. 1.36). If these nuclei come into contact with water molecules in the liquid, they catalyze their movement and thereby increase the likelihood of a few molecules arranging themselves in the necessary crystal structure, initiating crystallization. The temperature at which water finally begins to freeze is called the **nucleation temperature**, and it strongly depends on the type and quantity of foreign substances in the water, which catalyze the crystallization process. Experience shows that the nucleation temperature in stream water is between –9 and –4 °C. Commercial freezing nuclei like Snomax[34] that are injected into the water used for snowmaking raise the nucleation temperature (–3.5 to –3 °C). Ice itself has a particularly high nucleation temperature (ca –0.5 °C). Consequently, minute ice particles are used as freezing nuclei in nozzle technology. Whether a water droplet has been sufficiently cooled when it comes into contact with a freezing nucleus depends on the wet-bulb temperature of the air and other factors, particularly the water temperature.

Ice nucleation and inoculation (seeding): in addition to water nozzles, there are so-called nucleator nozzles, which mix compressed air[35] with small quantities of water and atomize it. Small ice particles (measuring around 0.1–50 μm) forming in and around the nozzle outlet are sprayed as ice mist[36]. The ice particles in the compressed air act as **freezing nuclei**: when they collide with water droplets in the spray, they initiate the freezing process, provided that the water droplets have already cooled down to the nucleation temperature. If the droplets are still too warm, the ice particles

34 Snomax® is made from the protein of dead bacteria *(Pseudomonas syringae)* and is used to improve the productivity, quality, and efficiency of snowmaking. The Swiss Federal Office for the Environment (FOEN) has classified it as harmless. However, some countries have prohibited its use. The nucleation temperatures cited here are those listed by the manufacturer.

35 In the past, the use of air jets alone proved relatively unsuccessful at intensifying the cooling of droplets expelled from the nozzle by expanding compressed air (the Joule-Thomson effect).

36 Acceleration in the nucleation nozzle results in a marked decrease in pressure and a sharp drop in temperature. This causes minute ice particles and water droplets to form and entrained water droplets to cool significantly and partially freeze. The use of pressure-compensating nozzles upon expulsion, and collisions between pre-formed ice particles or foreign nucleation particles and supercooled water droplets also foster ice nucleation.

loose all their effect, as they begin to melt again. Successful seeding at a high nucleation temperature causes the droplets to start crystallizing early. This gives them more time to freeze as they fall, resulting in drier snow.

Solidification in the air: once a droplet has undergone nucleation, it can begin solidifying (freezing). Droplets' solidification is analogous to cooling. However, alongside a heat transfer through convection, it is sublimation rather than evaporation that plays a role (Fig. 1.8). Unlike with cooling, during the phase transformation the droplets' temperature remains at 0 °C. The inward growing ice layer steadily thickens, forming an insulating layer, which increasingly slows down the solidification process. Droplets need a certain **fall time** to freeze completely, depending on their size and on ambient conditions. If this time is too short, snow cannot be made because it would be too wet. Atomization at the end of a snow lance takes place at a height of around 10 m (Fig. 1.32). Fan guns have a built-in fan, which causes droplets to travel 20 to 45 m before landing on the slope and thus increases their fall time. Fan gun towers (Fig. 1.33) extend the **freezing time** by combining drop height and throw distance.

Solidification and sintering on the ground: small fully and partly frozen ice beads are deposited on the ground. They begin to sinter at their contact points, forming a porous ice matrix similar to settled old snow with small and rounded grains. Free water from broken, partially frozen ice beads or still completely unfrozen liquid water droplets penetrates the pore space, increasing the snow's density. If enough heat and mass is transferred from the snow surface to the ambient air, the water in the deposited snow can still freeze during the snowmaking process. This is facilitated by low temperatures, and low air humidity, as well as wind, and a large, variable deposition area (e.g. using continuously swiveling snow guns). Otherwise, new falling snow will cover the existing snow surface too quickly.

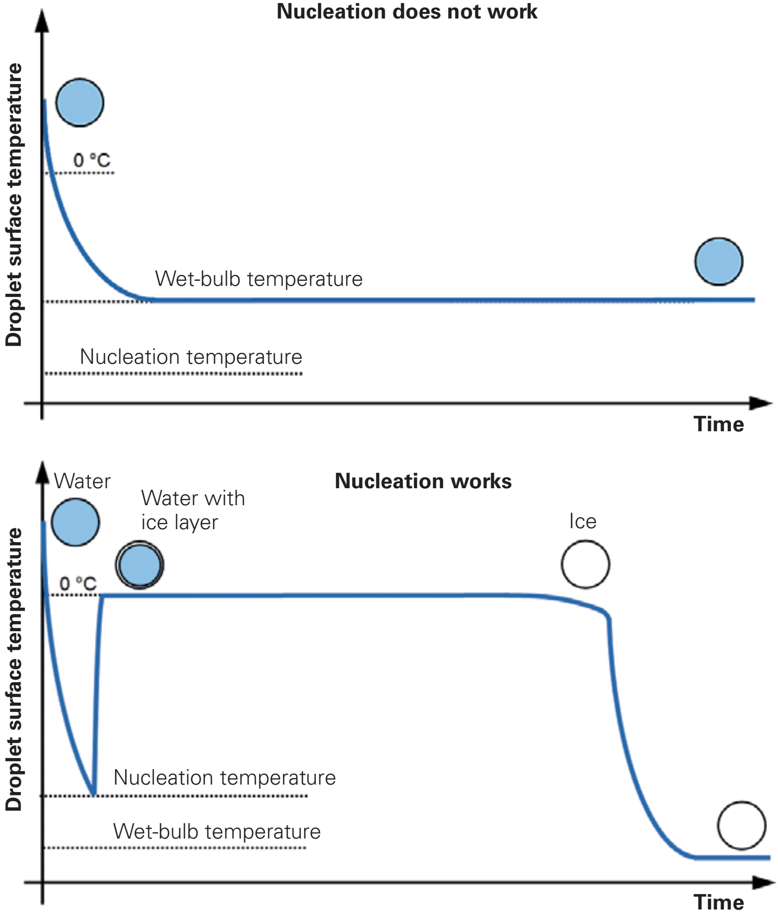


Fig. 1.36: How a droplet's temperature changes during snowmaking with and without nucleation. Nucleation only works when droplets cool down sufficiently. As soon as freezing begins, the temperature leaps to 0 °C, as latent heat is released into the environment (Limacher-Lehner 2009).

1.6.2.2 Non-Weather-Dependent Snowmaking

Various **refrigeration processes** are used and sometimes combined for non-weather-dependent snowmaking. So it is virtually impossible to clearly distinguish separate processes. Three basic processes are described below:

Refrigeration – flake ice machine: water is poured onto a cooled surface and freezes into compact ice. The surface can be cooled through direct contact or via a separate coolant circuit. The ice is then completely or partially separated from the surface and, if necessary, mechanically crushed to create the desired grain size. Using water or heat to free the ice adds water to the ice granules. A flake ice machine therefore initially produces wet or dry ice granules that only transform into coarse-grained snow (similar to spring snow) through sintering during storage (Fig. 1.37). Compared to the ice beads made by nozzle technology, ice granules are much coarser, resulting in poorer sintering and low snow strength.

Refrigeration – vacuum ice machine: water is atomized in a vacuum (at a pressure of roughly 6.1 mbar). Under such low pressure, a large proportion of the water evaporates, removing heat from it, while another part freezes as a result. The vacuum thus helps to ensure that the water drop-

Fig. 1.37: Freshly produced ice granules from the TechnoAlpin SF220 (left) and the transformed coarse grained snow after a few days (right) (from Vagler 2016).

lets can release enough heat to freeze. The heat to be dissipated during freezing remains unchanged, however, at 334 kJ per kilogram of water, even in the vacuum (Fig. 1.8). Small ice particles are then filtered out of the **ice-water mixture** and discharged as wet ice granules. To maintain the vacuum, water vapor is continuously discharged, repressurized, and condensed back into a liquid. Any heat generated during condensation must be dissipated via a cooling circuit. The basic principle of transporting heat energy by means of evaporation and condensation is widespread and is used in most freezers (compression refrigeration machine).

Cryogenics – cryogenic cannon: a cryogenic liquid (e.g. liquid carbon dioxide or nitrogen) is brought into **direct contact** with a water spray. The **vaporizing refrigerant**, which is very cold and subjected to ambient pressure, significantly cools the water spray and absorbs the heat generated when the droplets freeze. This technique results in the refrigerant evaporating into the environment and being lost, which makes it very costly. So nowadays it is only used rarely, where only very little snow is needed. Buying snow, e.g. for use in an indoor ski center, even if it has to be shipped in from far away, is still cheaper than producing it using a cryogenic system[37].

Snowmaking using nozzle technology in indoor ski centers: when making snow in an indoor ski center, there is only a limited volume of air to absorb the heat and water vapor when freezing water droplets. Consequently, high-quality snow can only be made if productivity is very low (around 1.25 m^3/h; 0.15 l/s per snow gun; CLULOW 2006). The energy required to transform atomized water into machine-made snow is supplied by the **ski center's air-conditioning system**. In the above example, this consumes twice as much energy as the facility's normal operation (CLULOW 2006). Yet, since there is no wind and no evaporation loss, very small droplets can be produced, which facilitates freezing and improves the quality of the snow.

[37] Example: Neuss indoor ski center (Germany): 1 m^3 of snow, including shipping and transport, costs between €100 and €350. By contrast, nitrogen costing more than €500/m^3 is required for cryogenic snowmaking.

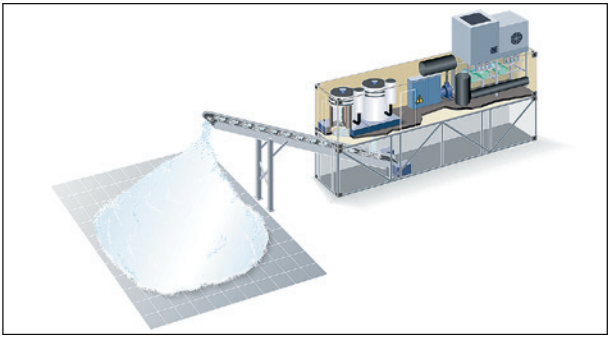


Fig. 1.38: TechnoAlpin SF220 (www.technoalpin.com).

Fig. 1.39: IDE Vacuum Ice Maker (VIM) 100 All Weather Snowmaker (www.ide-tech.com).

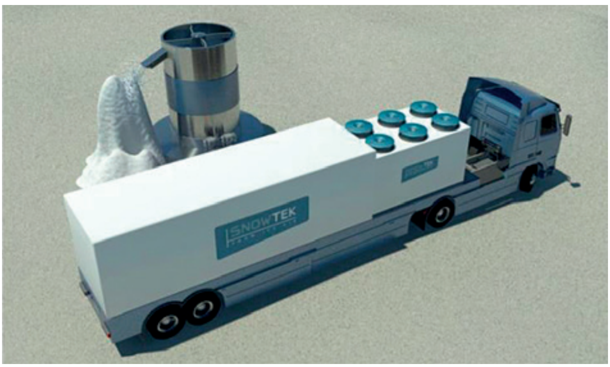


Fig. 1.40: SnowTek, SnowGen, (from Vagler 2016) (www.allweathersnowmake.com).

1.6.3 Properties of Machine-Made Snow

Because machine-made and natural snow are formed in very different ways, their properties usually differ greatly. Natural snow is formed of filigree, dendritic, hexagonal structures. Machine-made snow consists of water droplets that freeze relatively quickly from the outside in to form **ice beads**.

Machine-made snow only changes slowly once it has been produced (grain growth), whereas natural snow undergoes very major changes. Due to snow metamorphism (see Section 1.3.4), mechanical crushing, compaction during slope preparation, natural compaction through settlement (see Section 1.3.3), and snowmelt, dendritic precipitation particles are transformed into small, rounded shapes similar to those found in machine-made snow (SPANDRE 2017). Consequently, the differences between machine-made and natural snow are very large at first, but decrease significantly over time (Fig. 1.41).

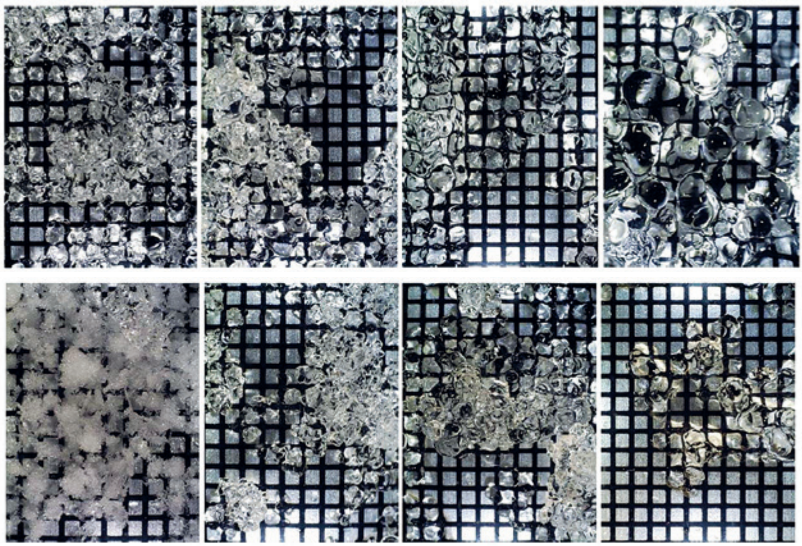


Fig. 1.41: Changes in grain size and shape in machine-made snow (top) and natural snow (bottom) between February and May 2014 (MEIER 2012).

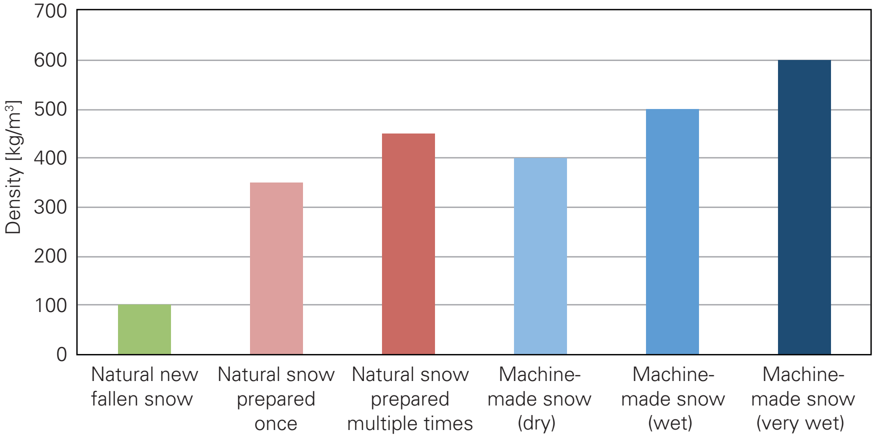


Fig. 1.42: Comparison of the average snow densities of natural snow, prepared natural snow, and machine-made snow.

By the end of the season, there are few differences between the properties of slopes covered entirely in natural snow or in machine-made snow. That said, there is a far greater covering on slopes covered in machine-made snow, as becomes clear in the late stages of ablation.

1.6.3.1 Snow Density

The density of natural new fallen snow usually lies between 50 and 250 kg/m^3, averaging at around 100 kg/m^3. Machine-made snow has a density of between 350 and 550 kg/m^3. If the snow produced is very wet or soaked, its density can even exceed 600 kg/m^3. Dry machine-made snow has a density of around 400 kg/m^3. Snow of this density meets the requirements of a ski slope in two ways, being dense enough to withstand use, while retaining sufficient volume to cover as much of the slope surface as possible. Accordingly, machine-made snow does not need to be further compressed during slope preparation (see Chapter 3). Freshly prepared natural snow has a density of 350 kg/m^3, which is even lower than that of unprepared machine-made snow (see Chapter 3).

1.6.3.2 Grain Size and Shape, and Specific Surface Area

Machine-made snow consists of small spherical grains (0.1 to 1 mm in diameter), on which bulges are often visible as a result of the freezing process (Fierz 2009). A pile of man-made snow will contain **various grain sizes**, depending on the distribution of droplet sizes during atomization. Relative to their mass, small droplets have **greater air drag** and therefore fall more slowly. Being airborne for longer, the wind carries them further, depositing them farther away from the snow gun. Larger droplets are transported a shorter distance (Fig. 1.44). Faceted fragments and clusters are an indication of wet machine-made snow that only froze when on the ground (Fig. 1.43).

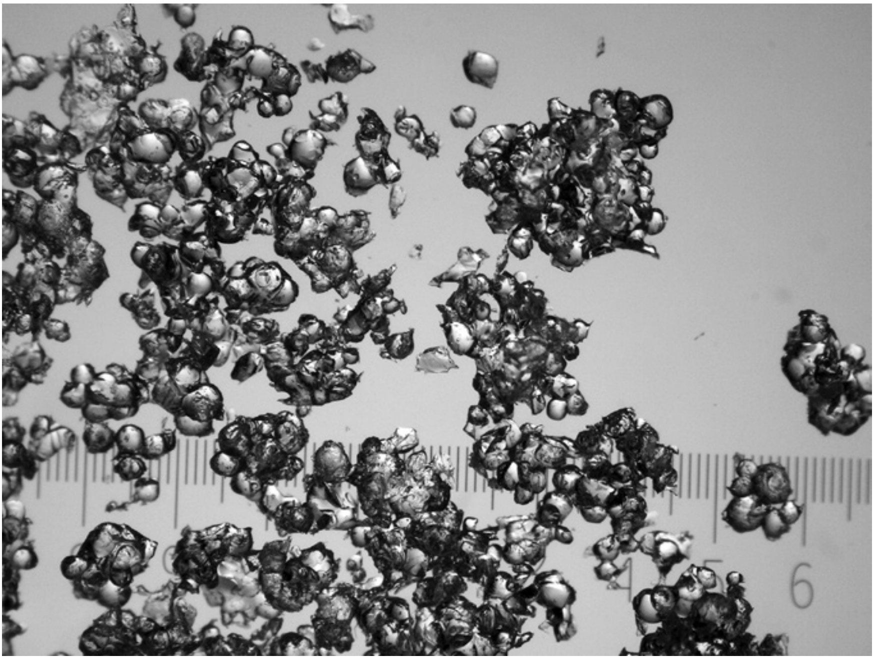
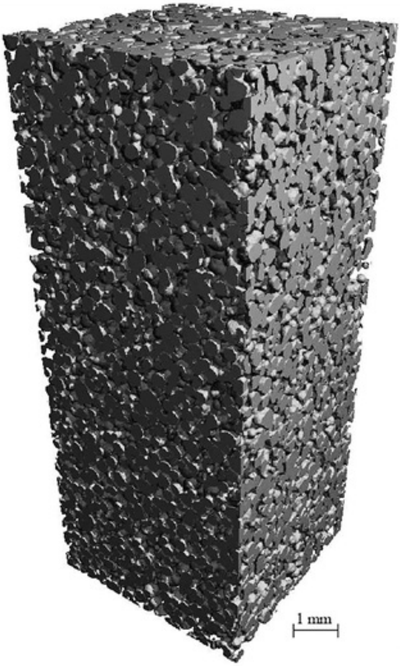
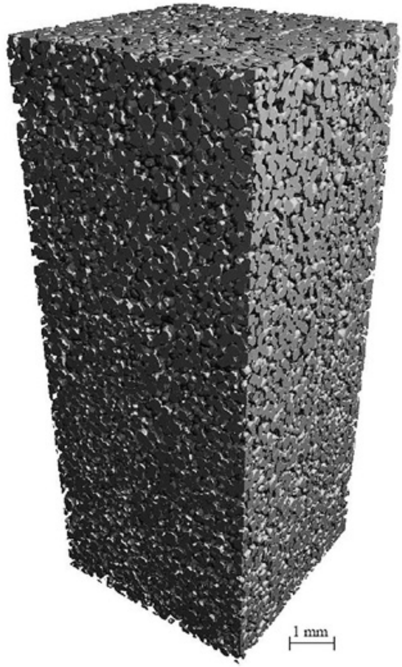


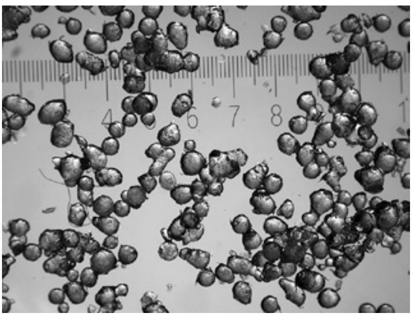
Fig. 1.43: Wet machine-made snow (LWC = 4.8%) with large clusters, frozen free water, and faceted fragments.





Sample taken 10 m away from the lance
Snow depth at sample location: 41 cm
ρ = 408 kg/m^3; SSA = 15.7 mm^{-1}
LWC = 0.2%; T_{Snow} = 0°C;
Grain size ca 0.3-0.7 mm

Sample taken 19 m away from the lance
Snow depth at sample location: 14 cm
ρ = 398 kg/m^3; SSA = 21.8 mm^{-1}
LWC = 0%, T_{Snow} = −8°C
Grain size ca 0.2-0.4 mm



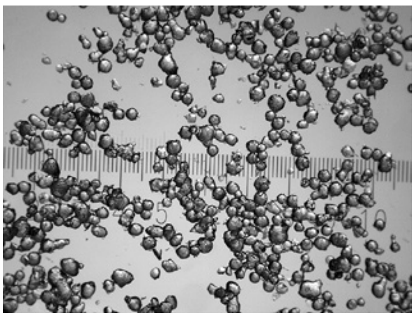


Fig. 1.44: Machine-made snow produced by a TechnoAlpin V3ee snow lance (flow = 1.1 l/s; T_{WB} = −6.5°C; T_{Water} = 1.2°C; v_{Wind} = 0.81 m/s). The snow quality is classified as good to very good. There are clear differences between the diameters of ice balls deposited close to (left) and far away from (right) the lance.

1.6.3.3 Snow Wetness

Freshly produced snow very often still contains **liquid water**, both inside its ice beads and between its grains, the latter being due to broken ice balls and droplets that never froze at all. The liquid water content of machine-made snow depends on the snow gun settings, meteorological conditions, and water temperature (see Section 1.6.1). Wetter snow also has a **higher density**[38]. This density is generally higher near the snow gun, where larger ice balls land before being fully frozen, and where the most snow is deposited, since it does not freeze as well there as elsewhere.

If machine-made snow has a wetness exceeding 5 %, there is a risk that the slope surface will become very icy as compression by a snowcat forces water towards the surface. Moreover, additional water is released if grains of machine-made snow break up during the preparation process, before

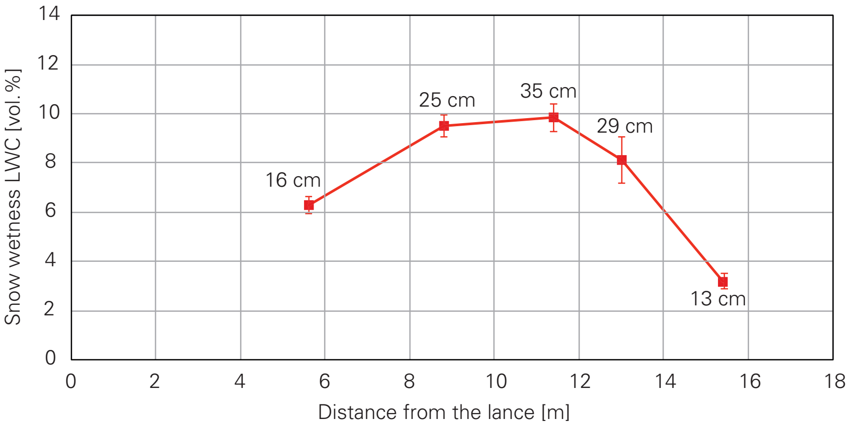


Fig. 1.45: Distribution of wetness in the deposition area of a snow pile immediately after production. The lowest wetness level was measured 15 m away from the snow gun. At approximately the same depth but just 5 m away, the snow is far wetter.

[38] Yet the reverse does not apply: highly dense machine-made snow will not necessarily be wet, because the liquid water it contained may have frozen since the snow was produced. In this case, high density indicates that the snow was wet when produced.

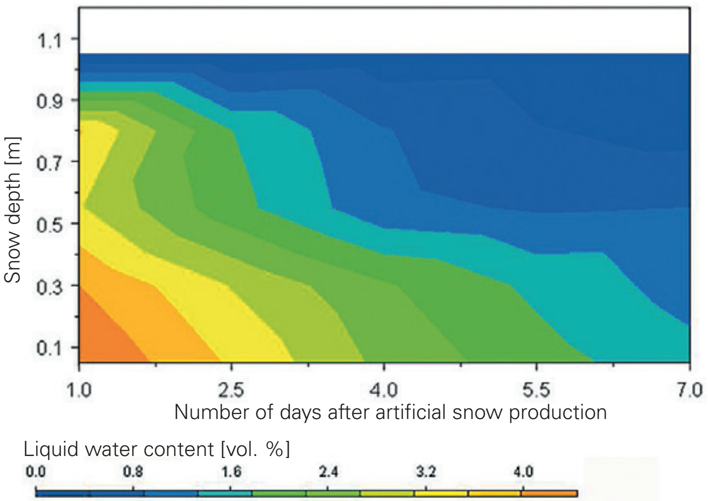


Fig. 1.46: Decreasing wetness of a snow pile during storage ($T_{Air\text{-}Storage}$ = –6.6°C). Snow is produced at a rate of 150 l/min at T_{WB} = –9.7°C, T_{Water} = –4.4°C, v_{Wind} = 0.9 m/s.

they are fully frozen. For this reason, wetness should be reduced to under 2 % before machine-made snow is spread and processed. This can take between a few hours and several days, depending on meteorological conditions, the quantity of new snow, and its initial wetness. If large heaps of wet snow (>1.5 m high) are produced, liquid water will remain in the snowpack for weeks (Fig. 1.46). When the temperature of this man-made snow, including deep down, is also less than 0 °C, the water will be fully frozen. So a simple temperature measurement can help to determine whether snow is ready to be prepared.

1.6.3.4 Snow Temperature

The temperature of machine-made snow depends on its wetness. If it contains liquid water, its temperature will be 0°C. If the water freezes on the ground, a crust will form on the snow pile, whose temperature will drop below 0 °C. Snow that is dry when it is made will already be several degrees below 0 °C by the time it hits the ground.

1.6.3.5 Mechanical Properties

If spherical grains of machine-made snow are deposited next to each other during the production process, the pore spaces between them will be small, there will be numerous contact points between the spheres, and their temperature will be close to 0 °C, which will **accelerate sintering** (see Section 1.3.2). As a result, machine-made snow is **very strong**. If wet or very wet snow is produced, it will only become strong when fully frozen. But that strength will be even greater, due to its higher density. Due to the uniform structure of man-made snow, its mechanical properties are also less variable than those of natural snow. This changes over time, however, as the structure of machine-made snow transforms into a coarser material, becoming less homogeneous[39] concerning its microstructure in the same way as its mechanical properties (Fig. 1.47).

The high resistance of machine-made snow, and **the low effort associated with its preparation** generally make it highly suitable for use on slopes. Nonetheless, differing requirements of respective slopes or snowpark obstacles should be taken into account when making snow. For example, wet machine-made snow is ideal for race tracks or as a foundation for a slope, whereas dry, somewhat softer machine-made snow is better for cross-country ski trails or the surfaces of regular ski runs.

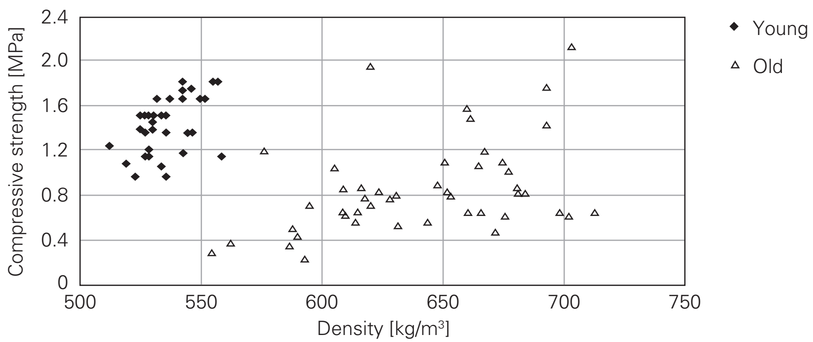


Fig. 1.47: Compressive strength of machine-made snow depending on its density and age (from LINTZEN 2014).

[39] Uniform mechanical properties improve energy transfers during ski-snow interaction. However, weak points in the snow break, reducing the traction between skis and snow.

2 Meteorological Influences on Snow

Energy transfers between the **snowpack and the atmosphere** are mainly triggered by meteorological phenomena. Energy transfers on the surface of the snow change its properties, especially its temperature, and thereby its **workability**.

2.1 The Atmosphere

The Earth's atmosphere is a **layer of gases enveloping the planet's surface** (Fig. 2.1). Among other things, the state of the atmosphere determines how much solar energy reaches the Earth's surface and how much of that energy is released back into space.

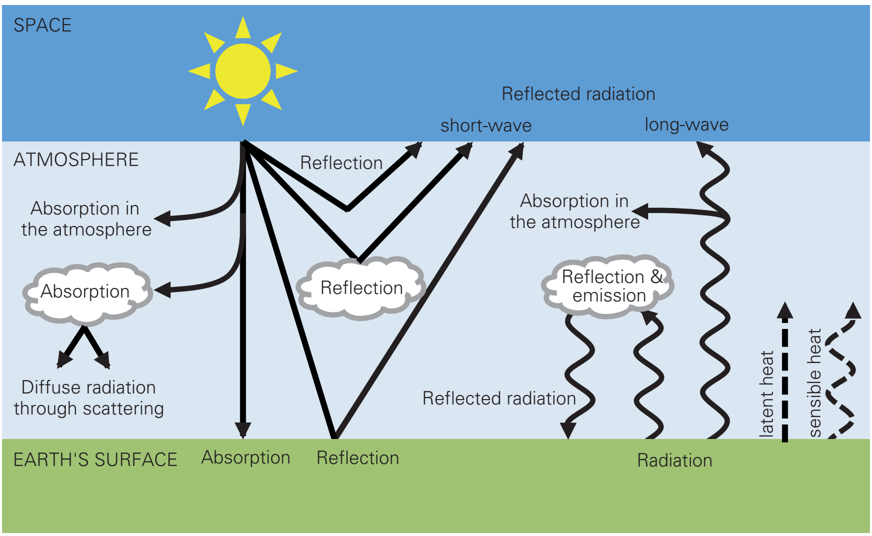


Fig. 2.1: The Earth's energy balance.

2.1.1 Air and Humidity

The composition of the air and the Earth's albedo (reflectivity) (see Section 2.1.2), determine how much energy reaches the planet's surface. Air consists of:

- ca 21 % oxygen
- ca 78 % nitrogen
- ca 1 % other gases
- water vapor, with a highly variable concentration (0–4 %)

Water vapor is released into the air through evaporation and by sublimation from surface water, snow, and ice (see Section 1.3.1). It consists of individual water molecules (not water droplets) and takes the form of an invisible gas in the air. Humidity is the air's water vapor content. **The higher the temperature, the more water vapor the air can absorb.** The maximum volume of water vapor a cubic meter of air can contain is called the saturation amount (Tab. 2.1).

Tab. 2.1: Temperature-dependent air saturation in grams of water vapor per kilogram of dry air. 1 kg of air has a volume of 773 l at 0°C and an air pressure of 1,013 hPa.

Air temperature [°C]	–20	–10	0	10	20
Water vapor [g/kg air]	0.8	1.8	3.8	7.8	15

2.1.2 Radiation

Every material, including air and snow, can either:

- **absorb**
- **reflect**
- **transmit** or
- **emit** electromagnetic radiation (e.g. visible light, thermal radiation, microwaves).

How strongly a material reflects, absorbs, or transmits radiation depends primarily on the characteristics of its surface. The wavelength of incident radiation is also decisive. For example, new fallen snow reflects up to 95 %

of **solar radiation**, whereas coarse-grained old snow only reflects up to 70 %. However, snow almost completely absorbs longwave **thermal radiation**.

The wavelengths of electromagnetic radiation range from millionths of a micrometer of gamma radiation to kilometers-long radio waves. Only **shortwave radiation** (0.28–3.5 µm; solar radiation) hitting the Earth's surface, and **longwave radiation** (3.5–100 µm; thermal radiation[1]) emitted by clouds, trees, the ground, and buildings affect the snowpack. There are two types of shortwave radiation: direct and diffuse[2]. Diffuse radiation occurs when sunlight hits particles in the atmosphere (e.g. water vapor or droplets in clouds or fog) and is reflected, or scattered, in all spatial directions.

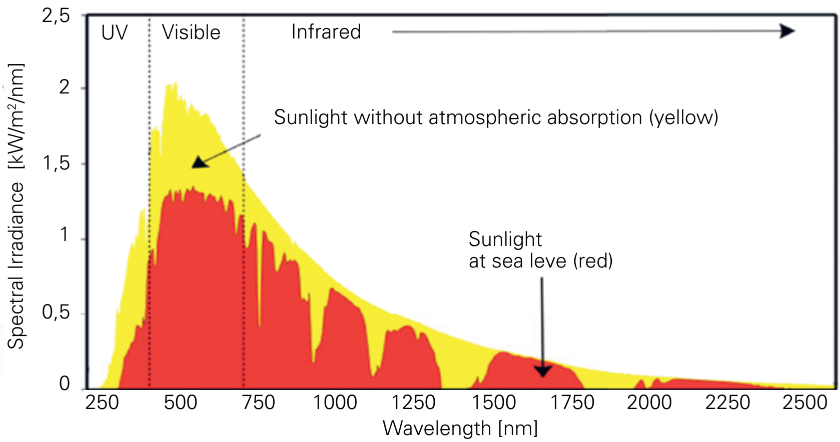


Fig. 2.2: Shortwave solar radiation spectrum. The maximum intensity is at a wavelength of 0.5 µm, which human eyes perceive as the color green. Furthermore, 42 % of radiation energy lies within the visible spectrum of 0.36 to 0.76 µm, 7 % lies within the ultraviolet spectrum (0.2–0.36 µm), and 49 % lies within the infrared spectrum (0.76–2.4 µm) (after Rhode 2007).

[1] The wavelength range of thermal radiation emitted by a body depends on its temperature. The hotter the body, the shorter the wavelength. At 300 K (27 °C), that wavelength will lie between roughly 2.5 and 200 µm. Since the surface of the sun has a temperature of around 6,000 K, solar radiation has a very short wavelength. Longwave radiation is also known as terrestrial radiation, i.e. emitted by the Earth.

[2] The sum of both direct and diffuse radiation is called global radiation.

Every body continuously emits longwave radiation. The strength of this **radiation** depends on both the temperature and characteristics of the surface. The better a body emits heat as longwave radiation[3], the more effectively it will absorb incident longwave radiation.

In a **cloudless sky**, longwave radiation escapes the Earth's surface into space. However, if it is overcast, the clouds absorb longwave radiation and reflect a considerable proportion of it back toward the Earth's surface. This is why the Earth's surface is only substantially cooled on clear nights.

2.1.3 Temperature and Heat

Temperature describes a substance's thermal state. Matter at different temperatures exchanges energy in the form of heat in various ways, namely through:

- **heat conduction:** e.g. rain drops on the snow surface
- **convective heat transfers:** e.g. wind blowing over the snow surface
- **heat transfers through radiation:** e.g. solar radiation

As with heat conduction (see Sections 1.2.2 and 1.6.2.1), **convective heat transfers** also depend largely on the temperature difference between the various media, e.g. between the wind and the snow surface. The bigger that **temperature difference**, the more sensible heat[4] is transferred per time unit. Unlike heat conduction in a solid, air can move about freely during convective heat transfers, thereby supplying or dissipating significantly more heat to and from the snow surface. Accordingly, the higher the **wind speed**, the more heat is transferred.

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3 Emissivity is a measure of how well a body radiates heat. The emissivity of new fallen snow is 99% and that of forest areas 90% (Zmarsly 2007).

4 A distinction is made between sensible heat, which changes the temperature during a transfer, and latent heat, which can be absorbed or emitted as energy during a phase change (see Section 1.3.1). Latent heat transfers on the snow surface depend on air humidity as well as on wind and temperature.

When **heat is transferred by radiation**, interactions in the material convert radiation energy into thermal energy. How much thermal energy is transferred to the snow in this process will depend on the wavelength and on the properties of the snow, as well as on the radiation's angle of incidence (see Section 2.2.2).

In practice, the key variables are the temperatures of the **air**, **snow**, and **ground**. The height or depth at which all three variables are measured is decisive. Air temperature is commonly measured at heights of 2, 5 and 10 m.

2.2 Thermal Balance of the Snow Surface

The **snow surface** is directly exposed to the elements. Its properties, particularly its temperature, can therefore change significantly over a short time. Exchanges of energy and mass between the surface and deeper layers are crucial for the **processes in snow**, e.g. metamorphism (see Section 1.3).

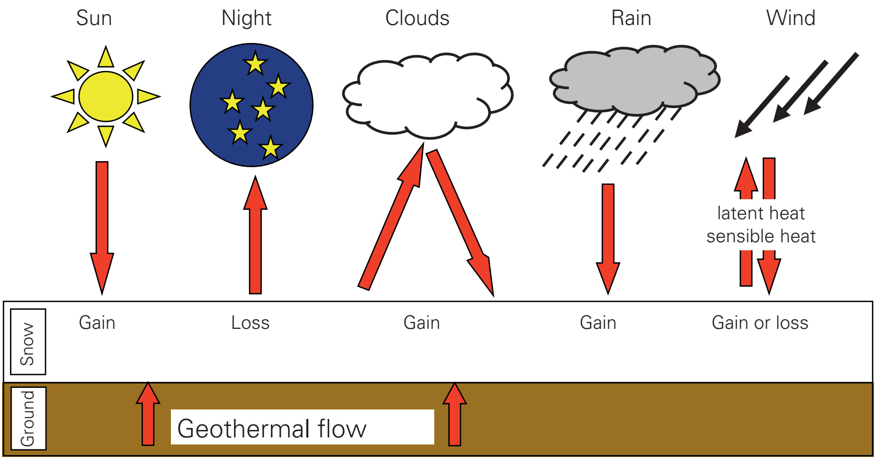

Fig. 2.3: Energy gains and losses on the snow surface.

The **snow surface exchanges heat with the atmosphere**. The thermal balance of the snow surface is the difference between gained and lost thermal energy (Fig. 2.3). If the balance is positive, the snow absorbs more heat than it emits into the atmosphere, so its surface heats up. If the balance is negative, the surface cools down. The following **meteorological factors** determine the thermal balance on the snow surface:

- **ambient air** (temperature, humidity, and wind)
- **radiation** (short and longwave)
- **precipitation** (rain and snow)

Heat transfer is affected by the snow's properties as well as by meteorological factors. Weather changes the snow surface, which in turn determines the impact exerted by meteorological factors on the snowpack. For this reason, energy exchanges between the snowpack and atmosphere are regarded as interactions.

2.2.1 The Impact of Ambient Air

Wind speed[5] is crucial to heat exchanges between the air and snowpack. The higher the wind speed, the more heat is transferred:

- **strong wind:** the snow temperature aligns with the air temperature. A significant quantity of heat is transferred to the air. Other meteorological factors have far less impact.
- **no wind:** the air temperature (close to the ground[6]) slowly aligns with the temperature of the snow. Little heat is exchanged with the air, leaving radiation and precipitation as the major factors influencing the snowpack.

[5] The unevenness of the snow surface (roughness) also promotes heat transfers with the air.

[6] Air is said to be stably layered when the warm layers lie above the cold layers that have sunk to the ground (particularly in areas sheltered from wind, such as valley floors and clearings, for example). This means that the air temperature 5–10 m above the snow surface can be considerably higher than that of the snow and the air close to the ground (2 m). In the free atmosphere (around 300 m above the Earth's surface), air temperature does not depend on radiation, so it is the same during the day and night.

Alongside wind speed, **air temperature** is the other major factor affecting heat transfers on the snow surface. The greater the temperature difference between the air and the snow surface, the faster the change in the snow's temperature. Since the highest temperature snow can reach is 0 °C, air temperatures above that always result in energy being transferred to its surface.

Air humidity also plays a role in such heat exchanges. The drier the air, the more ice sublimates or the more water evaporates from the snow surface into the air, causing the surface to cool. Therefore, low air humidity helps the snow surface to freeze, whereas high humidity can induce a build-up of ice (hoarfrost) or water (dew) on the surface, which then warms up. That said, humidity **influences snow less** than is generally believed[7]. It mainly affects the snowpack indirectly, through its significant impact on radiation.

2.2.2 The Impact of Radiation

The **difference** between **absorbed** and **emitted** radiation determines whether snow releases heat into the atmosphere or absorbs it. The difference between short and longwave incoming and outgoing radiation is called **net radiation**.

The intensity of **shortwave radiation** and the properties of the snow surface determine how much solar energy is absorbed. Because snow **strongly reflects** shortwave radiation, often it has less of an impact than assumed.

By contrast, snow almost **completely absorbs longwave radiation**, which therefore often has a greater effect on the snowpack than shortwave solar radiation[8]. The **cloudier it gets**, the higher longwave radiation becomes.

7 In particular, air humidity (= the air's water vapor content) does not directly affect snow wetness (= snow's liquid water content).

8 One reason why the impact of longwave radiation is underestimated is because unlike solar radiation it is imperceptible. In addition, longwave radiation exerts an impact both day and night.

In **strong winds**, the snow temperature is mainly affected by heat exchanges with the air. Thus, a warm wind (foehn) can heat and melt snow despite nighttime radiation losses.

2.2.2.1 Shortwave Radiation

The impact of shortwave solar radiation on the snowpack depends on the following factors:

- **the season and geographical location[9]:** the highest levels of solar radiation occur in the summer and the lowest in the winter (Tab. 2.2). In the northern hemisphere they are also higher in the south than in the north, due to the **sun's angle of incidence** to the Earth, which is shallower in the winter and in the north. When the angle of incidence is shallow, radiation spreads over a larger surface, substantially lowering the radiation energy per unit of area. Furthermore, when the angle of incidence is shallow, slightly more radiation is absorbed from the atmosphere (Fig. 2.4).

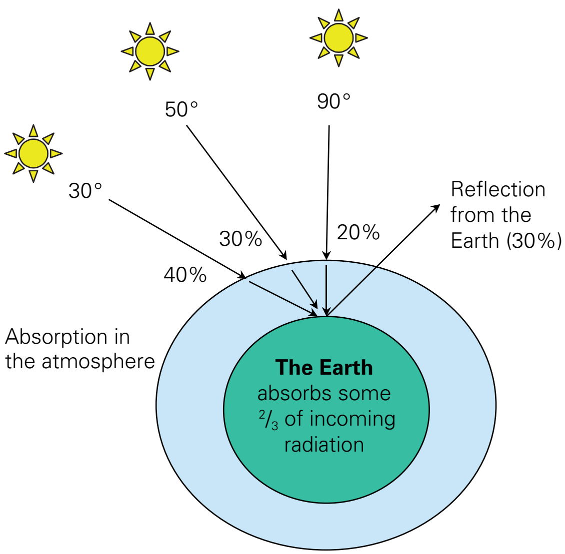

Fig. 2.4: Solar radiation on the Earth. When the sun shines down from directly overhead, around 80 % of that energy reaches the Earth's surface. This figure drops to just 60 % when the angle of incidence is 30 ° (which is average for sunshine falling on a flat area in winter).

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9 The intensity of UV radiation also increases with altitude by 8–10 % per 1,000 m (Vanicek 2000).

- **the time of day, slope gradient, and exposure** determine the angle of incidence to the snow surface. In December, a south-facing slope with a gradient of 30° is exposed to almost two-and-a-half times as much radiation as a horizontal surface (Fig. 2.5).
- **cloud cover:** even when the sky is overcast, some shortwave solar radiation reaches the Earth's surface. When that happens, fog or thin cloud scatters the radiation, decreasing the incident energy by up to 35 %. However, diffuse radiation affects all exposed slopes.

Tab. 2.2: Average power per square meter of incident and reflected shortwave radiation, and the associated albedo values (Dec. 2015–Apr. 2017; Weissfluhjoch, Davos, Switzerland).

Month	**Dec.**	**Jan.**	**Feb.**	**Mar.**	**Apr.**
Incoming radiation [W/m²]	67	76	119	193	248
Reflected radiation [W/m²]	55	64	100	158	194
Average albedo [%]	81	84	84	82	78
Minimum albedo (during the day) [%]	72	78	76	71	68

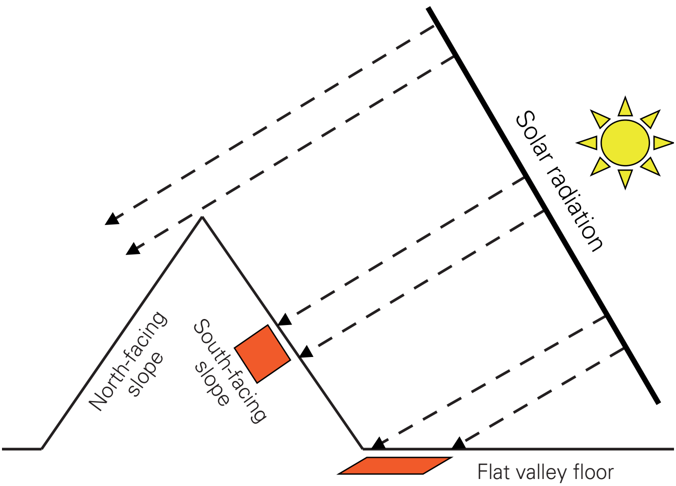


Fig. 2.5: Solar radiation depending on slope gradient and exposure.

Tab. 2.3: Albedo values of various types of snow and other surfaces (Armstrong 2008; Zmarsly 2007; Conway 1996, SLF 2017).

Type of snow	**Albedo [%]**
New fallen snow (dry)	80–95
Machine-made snow (dry)	72–78
Old snow	70–80
Wet snow	50–70
Dirty snow	18–41
Water (vertical radiation)	5–10
Arable land, meadows, forests	5–20
Concrete	14–22

– **properties of snow:** the larger the specific surface area (SSA; see Section 1.1.2), the more shortwave radiation will be reflected by the surface snow. New fallen snow reflects up to 95 % (and thus absorbs just 5 %) of this radiation[10]. The ratio of reflected to incident shortwave radiation is known as albedo. Albedo also depends on the snow's impurities and liquid water content (see Tab. 2.3), and it decreases steadily. The coarser, dirtier, or wetter the snow, the more radiation is absorbed and converted into heat.

2.2.2.2 Longwave Radiation and Net Radiation

Cloudiness determines how much energy the snowpack absorbs from longwave radiation[11].

Under **a clear sky**, the snow surface emits heat, in the form of longwave radiation, into the atmosphere and on into space. At night, or on north-facing slopes, which are exposed to only a little sunlight, even during the day, the snow's temperature drops sharply (unless the ambient air dominates the thermal balance). In these cases, net radiation is negative. On sunny slopes, shortwave radiation is intensive enough to heat up snow

[10] This, together with high longwave emissions, explains why powder snow often remains intact for several days in midwinter.

[11] Higher air temperature and humidity also increase longwave radiation.

during the day. Net radiation is positive in these cases (Fig. 2.7). This leads to major fluctuations in temperature in the top few centimeters of the snowpack (Fig. 2.6).

If the **sky is overcast**, the cloud cover reflects most of the snow's longwave radiation. At the same time, clouds radiate their own heat. Overall, the snow's surface emits less longwave radiation than it receives from the atmosphere, so the nighttime snow temperature barely drops at all. Net radiation totals 0 W/m². Combined with diffuse shortwave radiation, this often significantly heats up the snow during the day (Fig. 2.8). In this scenario, both longwave and shortwave radiation reach the snowpack, resulting in positive net radiation.

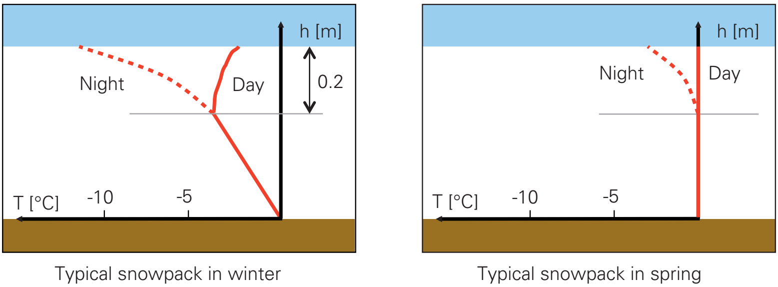


Fig. 2.6: Temperature changes in the snowpack during the day and night (dotted line). The daily cycle of air temperature and shortwave radiation only affects about the top 0.2 m of the snowpack.

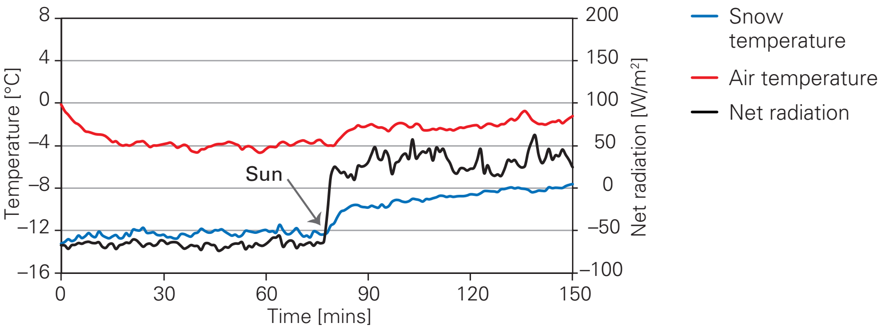


Fig. 2.7: Incoming sunshine increases net radiation, entailing a rapid, but only moderate, rise in snow temperature.

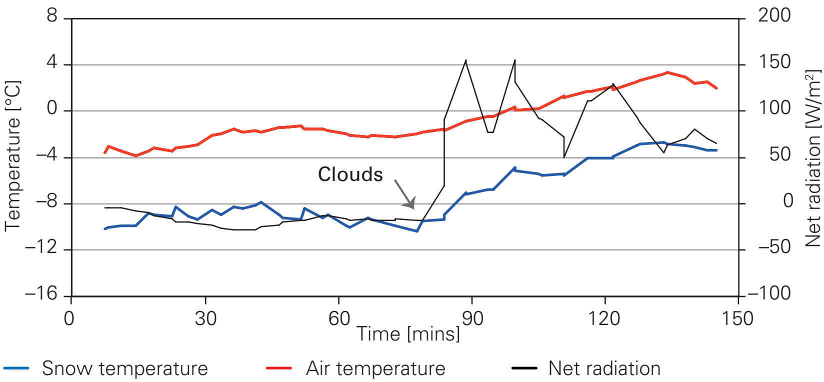


Fig. 2.8: When clouds appear, net radiation increases, leading to a quick and significant rise in snow temperature.

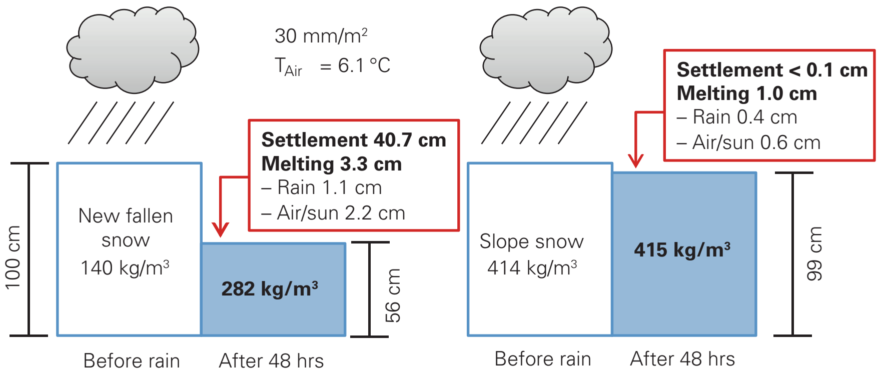


Fig. 2.9: If rain falls on 1 m of new fallen snow (left), melting reduces its depth by around 3 cm. Settlement, on the other hand, reduces the depth by around 41 cm. However, hardly any settlement occurs in compacted slope snow (calculated with snowpack Model, Section 8.3).

2.2.3 The Impact of Precipitation

Depending on both, the amount and temperature of precipitation, rain and snow transfer heat to the snow surface. The high temperature and heat transfer efficiency of free water in particular (wet snow or rain), rapidly heats up snow to 0 °C, prompting a small proportion of the surface cover to melt. However, compared to the heat transferred by radiation and ambient air, rain is not a major cause of snowmelt. In rainy weather, the high air temperature and humidity usually cause more snow to melt than the rainwater itself (WÜRZER 2017). Moreover, snow collapses as a result of settlement (see Section 1.3.3), which is subjectively perceived as melting and accounts for the biggest reductions in depth (Fig. 2.9).

2.2.4 Changes in the Properties of Snow

The **heat exchange** between a snowpack and the atmosphere significantly alters some of the properties of the snow surface in question:

- changes in **the snow's temperature** considerably alter the mechanical properties and, consequently, the workability of snow. Processes occurring within the snow are also affected (see Sections 1.3 and 1.4).
- if the snow **melts or freezes**, its basic structural properties change (see Section 1.1). If the snow continues to melt, the wetness level and strength of the surface gradually decrease (Figs. 2.10 and 2.11). A coarser structure and liquid water in the snow also decrease albedo (see Tab. 2.2 and 2.3).

The **mechanical effects of wind** also change the snow's properties. A surface of fresh snow is mainly **compressed** under the pressure of falling particles, and the crushing and rounding of original snow crystals (SOMMER 2018).

When the wind speed is low, high air humidity and a cold snow surface can lead to the **formation of hoarfrost and dew**, changing the basic structural properties of the snow surface (see Section 1.1).

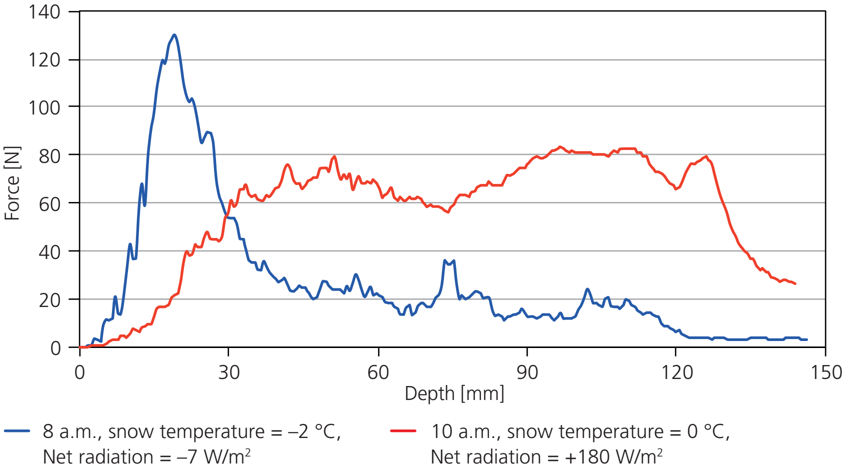


Fig. 2.10: At snow temperatures of around 0°C, fluctuations in radiation have a major impact on hardness. After 2 hours, the top 3 cm of snow will have softened. Deeper down, radiation has a lesser effect. However, slopes become harder when compressed by snowcats.

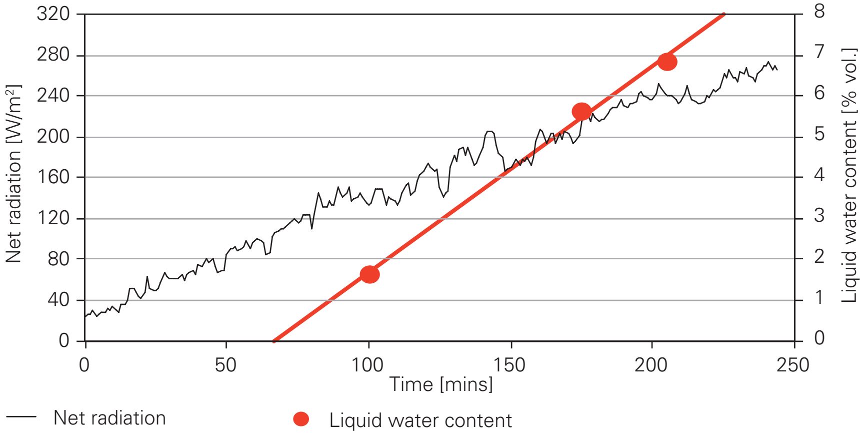


Fig. 2.11: At snow temperatures of 0°C, fluctuations in radiation affect wetness. Strong radiation increases the wetness of the snow surface.

3 Ski Slope Preparation and Grooming

Ski patrols bear a major share of the responsibility for winter sport safety. The **quality of the slope** is a key determinant of both safety and customer satisfaction. To be able to do their job, ski patrols need to consider two factors when using equipment and machinery: the **weather conditions** and their interactions with **natural processes in the snow**.

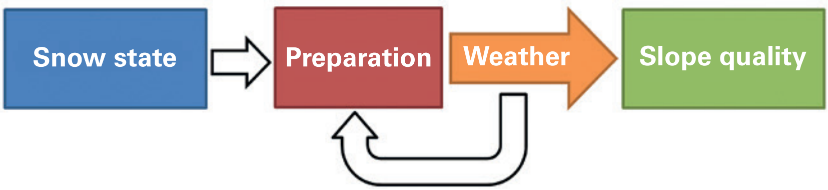


Fig. 3.1: Diagram of the interrelated factors in slope preparation. Weather and snow conditions should always be taken into account when preparing slopes.

3.1 The Optimal Slope

As sporting gear and slope grooming equipment have evolved, winter sport slopes have had to meet increasingly requirements. Means of compacting and leveling snow paved the way for the use of new sports equipment, such as snowboards and skis with deep sidecuts. This new equipment in turn necessitated conditions conducive to its use. It used to be mogul slopes that placed high demands on slope managers, but today users require wide, leveled areas with hard, grippy surfaces.
Ideally, slopes need to meet the **needs of winter sport enthusiasts** while also taking account of **ecological** and **economic requirements**.

Optimal slopes have to meet numerous requirements, depending on the **level of ability, discipline, and preferences of the groups using them.** Despite these different uses, all high-quality ski slopes share the following characteristics.

3.1.1 Demands on Snow as a Material

- **grippy:** enjoyable skiing without slipping
- **resistant:** less grooming required (lower running costs)
- **durable:** slope remains in optimal condition until the end of the season

Optimal strength and a certain minimum depth are crucial for determining snow's resistance and durability. Grip[1] is a highly subjective property that is heavily dependent on ski preparation and skiing dynamics. Slopes must be neither too soft, nor too hard, let alone icy.

3.1.2 Demands on the Snow Surface

- **homogeneous** (evenly groomed)
- **smooth**
- **visually appealing**
- **varied** (terrain)

The snow surface should be even, without undulations or coarse clumps of snow, so that skiers have no need to watch out for bumps or irregularities or worry about vibrations. The highest-quality slopes have a perfect, uniformly groomed surface.

3.1.3 Further Demands on Slopes

- **safe:** slope quality, danger zones, avalanche safety, markings
- **environmentally friendly:** slope preparation, protected areas (compliance with current structure plans).

[1] Ski racers sometimes (and usually disapprovingly) refer to excessively grippy snow as "aggressive snow." Slopes covered exclusively in machine-made snow tend to be more aggressive, resulting in a direct and highly dynamic energy transfer between skis and snow.

Managers bear particular responsibility for **slope safety** and must comply with the guidelines of the national and with International Ski Federation (FIS) rules. Having simple, high-quality slopes enables relaxed, controlled skiing, which also enhances their safety. There must be no **danger zones (rocks, areas with steep drops, etc.).** Also, **avalanche safety** must be guaranteed. Slopes' **intensity of use** can be controlled by opening alternative ski runs, widening them, and managing ski-lift capacity. Profitability has to be weighed up against the risks of collisions and less pleasurable skiing.

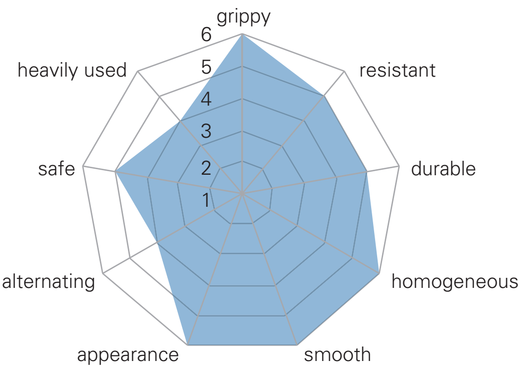
Well-compacted slopes are durable and stable, require less subsequent grooming, and therefore reduce both **diesel consumption and CO_2 emissions**. This yields both ecological and economic advantages. On the other hand, a thinner, compacted snowpack releases much more heat from the ground into the atmosphere, since it provides far poorer **insulation**. This can result in ground frost, damaging vegetation (Rixen 2003).

Having a sufficiently deep snow cover (at least around 40 cm of natural snow or 20 cm of machine-made snow) prevents **mechanical damage** to the vegetation and ground. Adding machine-made snow, however, and compacting the slope during its preparation **will delay ablation** in the spring (by up to four weeks), and **increase water infiltration**[2] into the ground, which can affect the plant population. In sensitive terrain (e.g. raised bogs, meadows), the route taken by the piste must take these factors into account. In particular, compliance with any structure plans and restrictions they impose is essential.

2 Snowmelt water has a higher mineral content and therefore adds nutrients to the ground. Like an increased water supply, this can also change plant composition (Rixen 2003).

3.1.4 Requirements to be met by Regular Ski Runs

Regular ski runs must be **comfortable to use** and **look good** if they are to fully meet customers' needs. Grip and a perfect surface of snow with homogeneous properties are particularly important for achieving this. High resistance and durability are not only essential for maintaining the quality of intensively used slopes, but also help to make ski resorts profitable.
A study conducted by the French Mountain Tourism Development and Research Department (SEATM) shows that 84 % of skiers said they preferred to spend time on simple, well-prepared, gently inclined slopes with



1 totally unimportant
2 unimportant
3 fairly unimportant
4 fairly important
5 important
6 extremely important

Fig. 3.2: Requirements to be met by regular ski runs.

Fig. 3.3: Optimal final state of a ski slope – photo: Josef Mallaun.

a gradient of less than 30 %. Even experienced winter sport enthusiasts spent only short periods, on average, on difficult runs (i.e. steep, icy slopes with humps or bumps). The most popular slopes only had gradients of between 25 and 30 %[3] (SEATM 1990). Accordingly, optimal preparation and grooming, particularly of intensively used, easy to intermediate slopes, is important.

3.1.5 Requirements to be met by Ski Racing Tracks

Since ski racing exerts greater stresses on slopes' surfaces, they need to be **highly resistant** and ensure maximally equivalent conditions and an equal level of difficulty for all competitors. Slopes must **last well**[4], withstanding the weather and stresses exerted by skiers. High strength is crucial in this regard, not just of surface snow, but also of deeper layers, to prevent the race track from breaking up (Fig. 3.5). For any such deterioration would prevent the athletes from competing under equal conditions and heighten their risk of injury. The extreme speeds reached in races make meeting **safety requirements** a top priority that should constantly be reassessed and checked for weak points.

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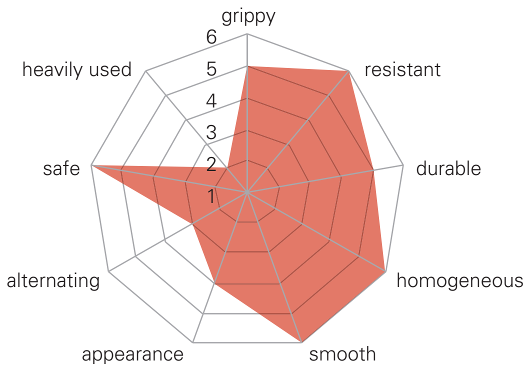

Fig. 3.4: Requirements to be met by ski racing tracks.

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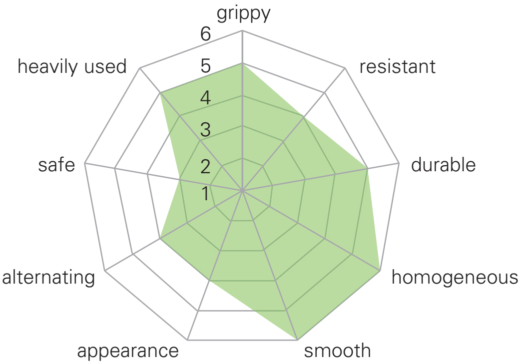
[3] Slopes are classified by difficulty, depending on their grade (i.e. percent slope). In Germany and Austria respectively, slopes are classified according to the DIN 32912 and ÖNORM S 4610 f standards as easy (blue, < 25 %, ca 14 °), intermediate (red, < 40 %, ca 22 °) and expert (black, > 40 %).

[4] Slopes need to withstand more than one race if used by various disciplines, for training runs, and for men's and women's competitions.

Fig. 3.5: Broken-up race track (2011 World Cup Giant Slalom, Val d'Isère, France).

3.1.6 Requirements to be met by Cross-Country Ski Trails

Cross-country skiing is primarily all about sliding, whereby the speeds and therefore forces involved during turning are lower than in racing. So fewer safety precautions need to be taken for cross-country trails. And resistance is not that important either, as such trails are subjected to less stress. Instead, the main focus is on **smoothness and homogeneity**, to help cross-country skiers balance and maneuver easily. Furthermore, regular cross-country trails should be neither too hard, nor too soft. This way they will give skiers sufficient support when they push off using the skate skiing technique.



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4 fairly important
5 important
6 extremely important

Fig. 3.6: Requirements to be met by cross-country ski trails.

Evenly prepared trails with firm pole tracks are particularly important for classic cross-country skiing. On descents, curve radii should be tailored to the speeds skiers reach, whereas ascents should not be too steep (see Chapter 5).
Competition courses are an exception, being subject to high stresses over longer periods, e.g. during World Championships. Consequently, the **snow on them needs to be significantly stronger**.

3.1.7 Requirements to be met by Parks

Meeting safety requirements[5] is, again, a prime concern for snow park operators. So it is absolutely essential that take-offs and landing surfaces have the right shape and proportions (see Chapter 6). Likewise, it is important for snow surfaces to be smooth and **not too hard**, to reduce the risk of injury. On the one hand, they have to be even and resistant enough to ensure smooth approaches, take-offs, and landings. On the other hand, the snow must not constitute a painfully hard surface for fallers. Another key safety consideration in this context is how snow's properties change throughout the day, as this can significantly affect approach speeds. Overly long or short jumps can result in injuries.

1 totally unimportant
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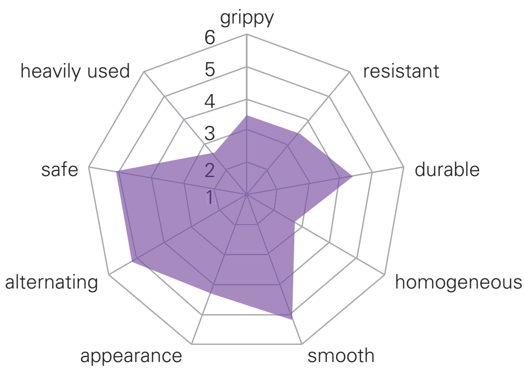

Fig. 3.7: Requirements to be met by parks.

[5] 76 % of all injuries in snow parks in Switzerland result from jumps. Collisions are much rarer than on slopes, accounting for just 3 % of injuries (bfu 2016).

3.2 From Snow to Slope: Principles of Snow Consolidation

New fallen snow is mechanically treated to **make it firmer** and thus provide a stable surface for snow sports activities. Snow is consolidated by **compacting** it and by **strengthening the bonds between grains (sintering)**.

3.2.1 Compaction

When preparing slopes, in principle there are three ways of **compacting new snow**:
- **compacting under pressure** (e.g. snowcat, skiers)
- **filling pore spaces with fine material** (tiller, front renovator)
- **filling pore spaces with water** (watering the slope)

Compaction by a snowcat reduces pore space in snow by compressing or filling air spaces. Added water almost completely fills pore spaces, making this method suitable for making very high-density snow.

3.2.1.1 Compacting Under Pressure

Snow is compressed under the weight of a snowcat and the contact pressure of a tiller. A **snowcat**[6] exerting a pressure of 3.5 to 5 kPa will break the snow's ice framework, compacting pore spaces and making the snow denser. How **deeply compacted the snow becomes** depends mainly on the initial properties of the snowpack: the denser the snow, the smaller the impact (Figs. 3.10 and 3.11). The density of the top 40 cm of a fresh, natural snowpack can more than double following a single pass by a snowcat. In the example in Fig. 3.9, snow depth decreases by up to 40 cm, and the compaction even significantly affects deeper layers. Once the snow has

[6] The large contact area of a snowcat means it exerts far less pressure on the snow surface than a skier (50–300 kPa).

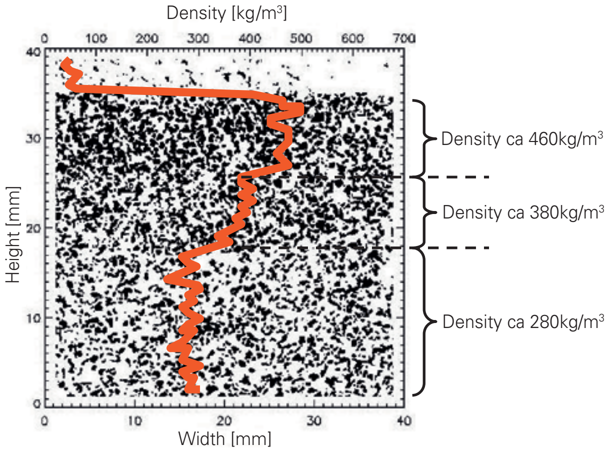

Fig. 3.8: Two-dimensional (2D) view (thin section) of a snow sample taken from the top 4 cm of a poorly prepared ski slope. Black structures show the ice framework, white areas the pores in the snow. The top 2 cm of snow have clearly been compacted by pressure exerted by skiers. Deeper down, snow density decreases as indicated by the red line.

been compressed, further passes by the snowcat will barely increase its density.

However, the additional contact pressure of a tiller and **finisher** can further compact the top 10 to 20 cm (finishing). The same principle applies here, however: the denser the original snowpack, the less impact a snowcat will have (Tab. 3.1).

3.2.1.2 Filling Pore Spaces with Fine Material

Using a tiller distributes grain sizes more widely in the snow, enabling minute particles to fill pore spaces. This increases snow density and improves sintering conditions (see Sections 3.2.2 and 1.3.2). Above snow densities of around 450 kg/m^3, additional slope preparation using a snowcat will not compact the snow any further (Fig. 3.10).

If there are different layers of snow – for example, if only the top 20 cm has been well compacted and deeper layers are not dense enough – an angle dozer blade or **front renovator** can be used to consolidate the snow down to a depth of 40 cm (see Section 3.4.7).

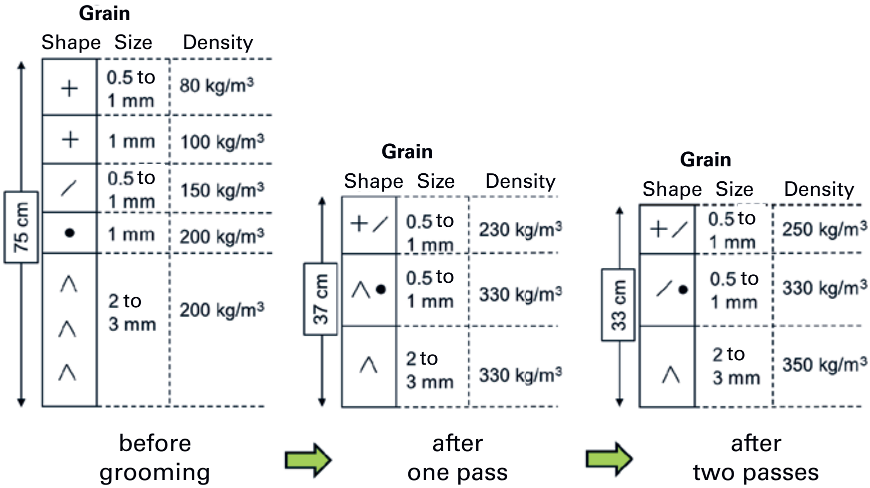

Fig. 3.9: Compaction and changes in grain size during the preparation of a slope covered in a 24-cm layer of new snow at –4 to –3 °C (after Guily 1991). No tiller or smoothing board were used.

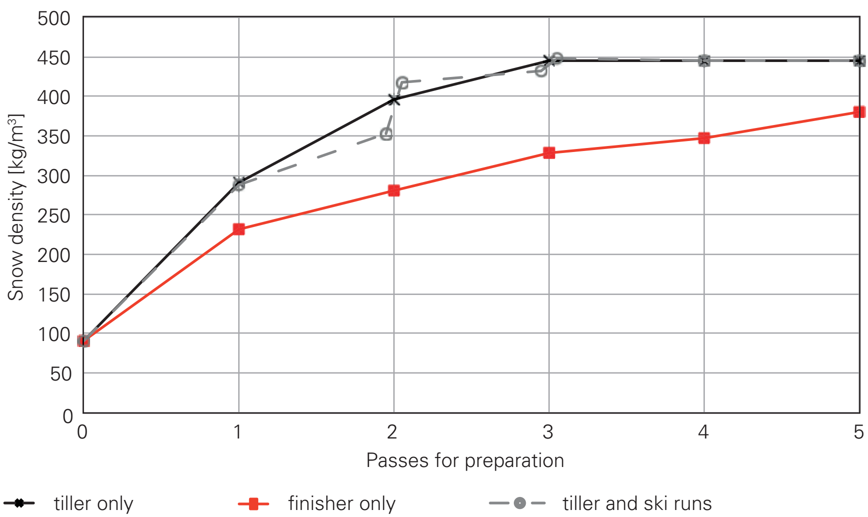

Fig. 3.10: How snow density increases with repeated passes made during slope preparation. The passes were made 24 hours apart (after Guily 1991).

Tab. 3.1: Various forms of compaction depending on the equipment used (after Guily 1991)

Unprocessed	**After a pass**		**After a pass with a smoothing board**		**After a pass with a tiller**	
Density [kg/m³]	Density [kg/m³]	Increase	Density [kg/m³]	Increase	Density [kg/m³]	Increase
89 (12 cm)	160	79%	230	158%	300	237%
120 (24 cm)	—	–	280	133%	350	191%

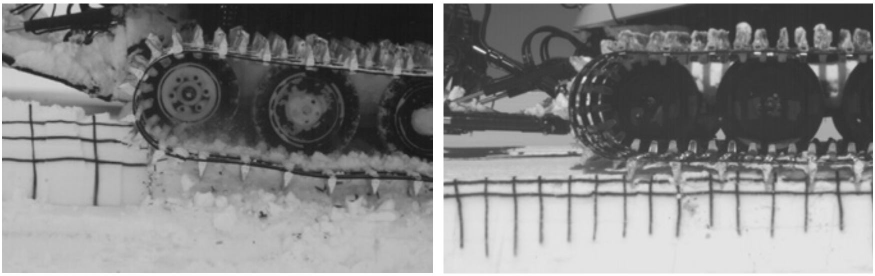

Fig. 3.11: Penetrates and deep effect of compaction of new fallen snow (left) and snow that has been prepared multiple times (right).

3.2.1.3 Filling Pore Spaces with Water

Once snow has a density higher than around 450 kg/m^3, it is so strong that insufficient pressure[7] can be applied to compress the ice framework and reduce the pore space. Even filling pores with very fine snow particles does not increase the strength any further, because the reduction in strength caused by tilling is no longer compensated by subsequent sintering.

The snow can only be further compacted by **adding water**. **Gravitation and capillary forces** ensure that the water penetrates the snow's pores. The finer the structure of the snow (small grains), the greater the capillary forces, which prevent the water from flowing down and away through pore spaces. Capillary forces also cause the water to spread out in all directions within the snow, like in a sponge.

[7] Even higher pressure can be exerted using special equipment.

If enough water can remain in the snow and freeze, the snow will be **compacted and consolidated**. The level of consolidation depends on how much water the capillary forces can keep in the snow and whether enough energy can be released into the environment to completely freeze the water. Since the added water freezes firstly at the bonds between grains, these **bonds grow steadily larger and stronger** (see Section 1.3.2). The various watering techniques, and how they are affected by **meteorological and snow-related factors** are described in Chapter 4 on Race Track Preparation and Grooming.

3.2.2 Strengthening Bonds between Grains (Dry Sintering)

Besides compaction, the main aim of slope preparation is to create **optimal sintering conditions**. The following aspects of using machines to work snow, facilitate sintering and hence also the speed and strength of snow consolidation:

- **compaction**
- **reduction in grain size**
- **formation of different grain sizes**
- **heating of the snow**
  - collisions between grains
  - mixing of snow layers with different temperatures
- **high temperature gradient**
- **respite period**

Working snow with a snowcat has the biggest impact on **precipitation particles**, greatly **compacting** them. Tillers accelerate the transformation of dendritic precipitation particles into rounded shapes, **improving grain size distribution** for sintering. This increases the number of contact points between grains, creating better sintering conditions.

Using a tiller on **old snow reduces particle sizes**, creating more contact points between them. Snow dust created during tilling acts as a filler material, increasing compaction. Fine particles also sublimate (see Section 1.3.1) very quickly, providing the material needed during the sintering process to **form new bonds between grains**.

The snow temperature and a **high temperature gradient** are particularly important for the dry sintering of compacted snow (Fig. 3.12). Temperature differences in the snowpack **improve vapor transport**, accelerating the **formation of bonds between grains**. Temperature gradients usually develop on clear nights, increasing until the morning. Working snow destroys any existing temperature gradients. Consequently, it is best to work snow before a temperature gradient occurs. Usually, this means shortly after a slope has closed.

3.2.3 Freezing (Liquid Sintering)

If thawing occurs, water initially collects at the bonds between grains. But an intensive snowmelt will completely fill pore spaces, until the snow can no longer retain the water, which then flows away (see Section 1.1.3). If the

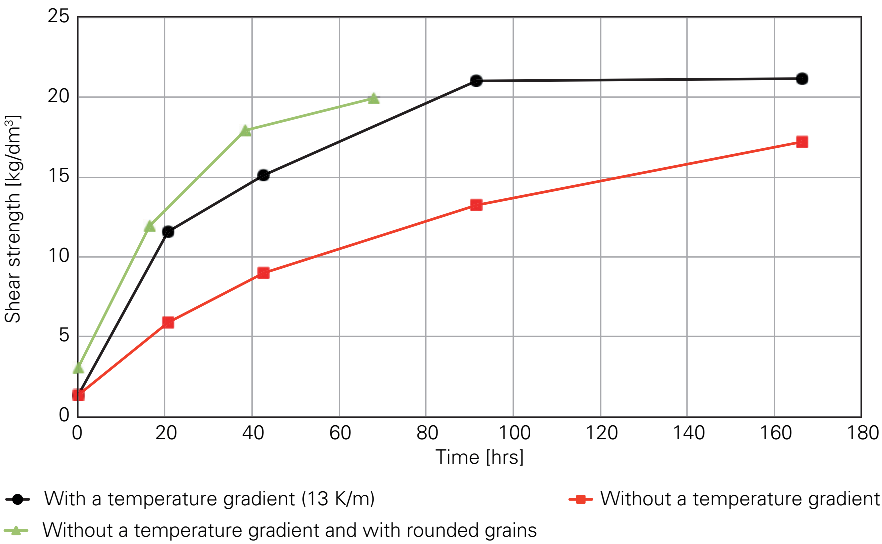

Fig. 3.12: Snow's shear strength increases significantly faster if a temperature gradient occurs after the slope has been prepared (T_{Snow} = –7 °C; grain size = 0.8 mm); rounded grains (grain size = 0.5 mm) also accelerate consolidation (after GUILY 1991).

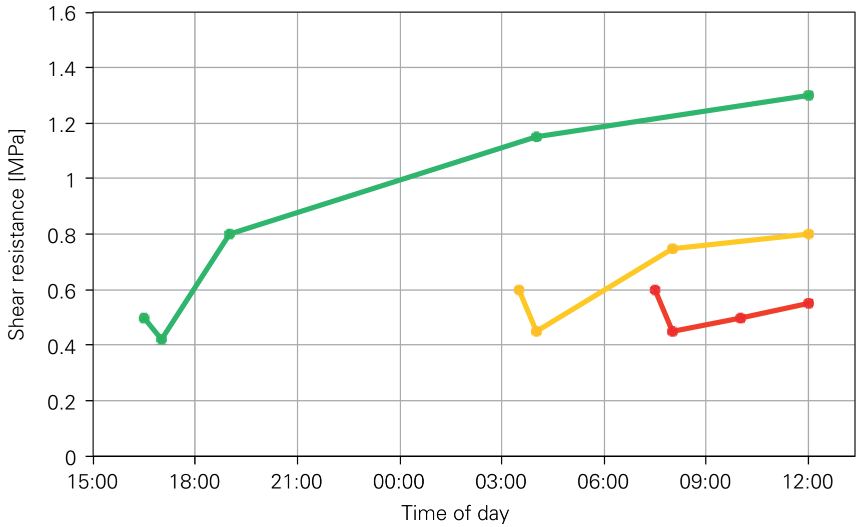

Fig. 3.13: Consolidation of the snow surface from shortly before preparation until the following noon. The slope prepared in the evening (green) is more than twice as resistant at opening time (9 a.m.) as the slope that was only prepared at 4 a.m. (orange). The slope prepared at 8 a.m. (red) does not even reach its initial strength before preparation began (after Guily 1991).

snowmelt subsequently refreezes, for example overnight, **considerable consolidation** takes place.

As described above, **frozen water in the pore spaces compacts the snow** because the same volume of snow now contains more ice and less air. Most ice freezes at the bonds between grains, because that is where the capillary forces are strongest. Accordingly, using water to compact snow always creates **larger, stronger bonds** (see Section 1.3.2.2).

But using this method for regular ski runs and snow parks makes the snow too strong early in the morning. This can prompt negative judgments by users because of the snow's low grip (icing up), and also increase their risk of injury.

The following factors are decisive for snow consolidation by freezing:

– **water in the snow** at the time of preparation
– weather conditions enabling **the snow to release energy** when it freezes

3.3 Slope Preparation: Working Snow in keeping with its State and the Weather

To create high-quality slopes at the lowest possible cost, it is important to **make optimal use of equipment**. To that end, slope preparation measures need to be aligned with **naturally effective processes**. Therefore, when choosing machine settings and timing the slope's preparation, its desired characteristics (required profile), the 24-hour weather forecast, and in particular the current condition of the snow should all be taken into account (Fig. 3.14).

An optimally prepared slope is more resistant, suffers less damage, and therefore requires less grooming. The work of a slope preparation team is divided up as follows (Fig. 3.15):

- **preparing** a resistant slope (basic preparation)
- **grooming and maintaining** the slope

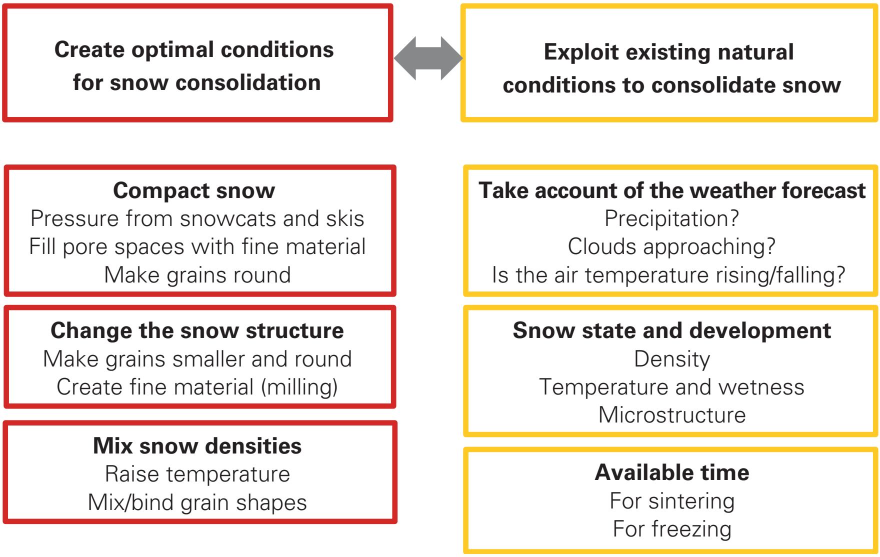

Fig. 3.14: Basic principles of slope preparation.

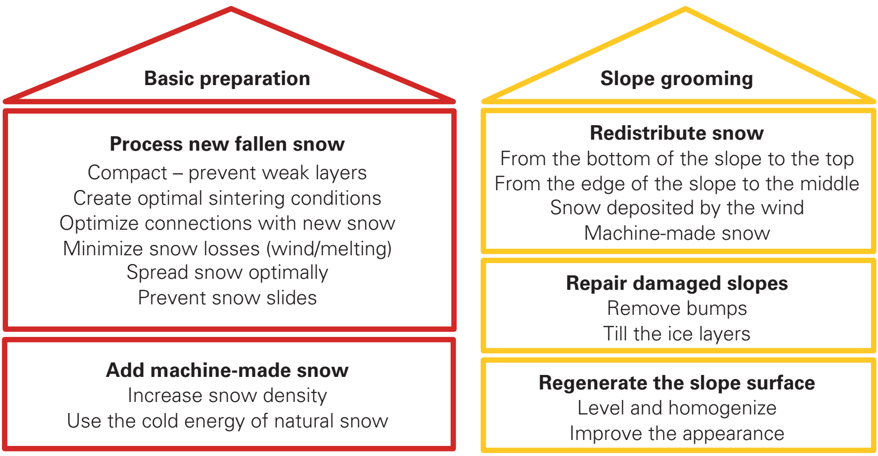

Fig. 3.15: Overview of the main tasks involved in slope preparation.

3.3.1 Preparing a Resistant Slope (Basic Preparation)

Laying **stable foundations** is crucial for preparing a resistant slope. To do this, the slope has to be prepared during the first snowfall, ideally **without tilling**, to produce a rough, coarse surface. This enables new surface snow to cool down better in winter conditions, enabling it to **bind better**[8] with the old snowpack. Only in very mild air temperatures (> 0 °C), for example when there is a strong foehn, is a maximally smooth surface beneficial for reducing melting.

Since, barring additional measures, **snowcats only penetrate** the top 20 to 40 cm of the surface, every new layer of snow must be compacted if at all possible. Compacting the snow down to the ground prevents loose **layers of depth hoar** from forming through constructive metamorphism (see Section 1.3.4.1). Moreover, compacting new fallen snow also accelerates sintering, thereby facilitating the desired consolidation. Continuous preparation in early winter also helps to ensure that less snow is carried off by the wind and eroded.

Machine-made snow does not need to be compacted because it is already very dense when produced (see Section 1.6.3.1). This makes it highly suitable for basic slope preparation. It can also reduce the amount of compaction work required for new snow if it is produced when that snow is falling and mixed with it. The natural snow's cold energy in turn helps to freeze the wet machine-made snow. Another aspect of basic slope preparation entails ensuring that **snow is optimally distributed**. For efficient slope preparation, it is important to match snowmaking with the weather conditions (especially the wind) and know exactly how deep the snow is and ought to be (see Chapter 7).

[8] Precipitation particles coalesce with particles at contact points in the old snow surface (see Section 1.3.2). Since this is a lengthy process, deposited snow crystals should not subsequently be moved.
It is therefore a good idea to make grooves in the surface to protect precipitation particles from being carried off by the wind.

3.3.2 Slope Grooming and Maintenance

Repair slope damage caused by the weather and skiers:
- remove humps and bumps
- till layers of ice

Redistribute the snow on the slope:
- shift snow that has been pushed to the bottom and edges of the slope
- shift machine-made snow
- shift snow deposited by the wind

Regenerate the slope surface to make it easier to ski on and more aesthetically pleasing:
- level the snow surface
- homogenize the properties of the snow
- improve the slope's appearance

Fig. 3.16: Typical slope damage: bump formation.

3.3.3 Principles and Rules of Thumb for Slope Grooming

3.3.3.1 Take Account of Topography and Stress Factors

Ski patrols need to know **the vulnerable parts of a resort**, prone to particularly high stress exerted by weather conditions and skiers. This enables damage to be predicted and even avoided under certain circumstances.

Examples of vulnerable areas susceptible to damage:
- **south-facing slopes** are exposed to strong sunshine, which can cause the surface to melt
- **steep slopes** facing east, south, and west are also exposed to strong sunshine in midwinter (solar angle). This causes humps or bumps to form and results in snow being pushed to the bottom of the slope. Such slopes cool down less overnight because they radiate less heat than flat slopes.
- **erosion zones**, where snow sports enthusiasts and the wind push snow to the bottom of the slope (Fig. 3.17)

3.3.3.2 Take Account of the Weather and the Condition of the Snow

When snow is worked, it should be readily **deformable**, i.e. have the lowest possible strength (see Section 1.4). A snow temperature close to 0 °C, the presence of liquid water (snow wetness), and snow that has been abraded and pushed down the slope all indicate good deformability.

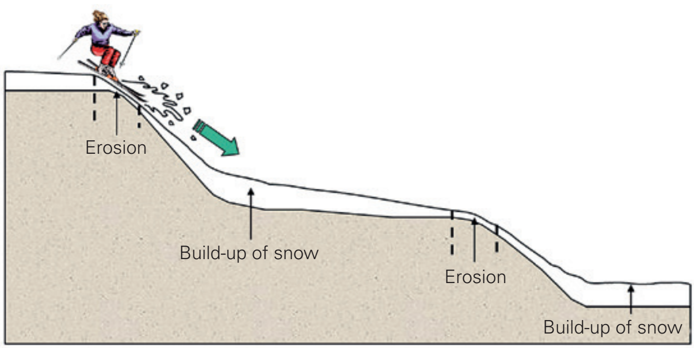

Fig. 3.17: Typical erosion zones at crests, and snow deposition zones at the bottom of slopes.

Fig. 3.18: Comparison of a slope's resistance after various respite periods based on the depth of a trace left by a snowboard curve.

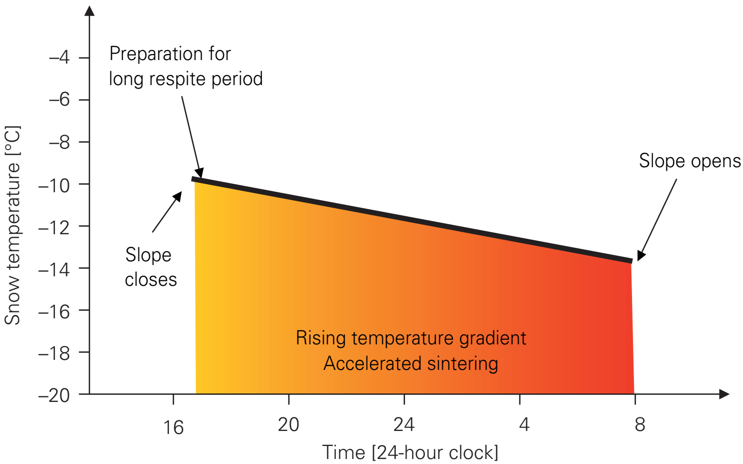

Fig. 3.19: The optimal time to work cold snow. Preparing the snow early gives it enough time to consolidate through sintering. Moreover, after it has been prepared, a temperature gradient can develop unhindered in the snowpack, accelerating the sintering process.

To choose the **best time to start working the snow**, its current state must be determined and its development over the following 12 hours predicted. The short-term weather forecast and knowledge about how weather impacts snow (see Chapter 2) are essential for this.

Respite periods between the slope's preparation and opening time also need to be as long as possible, to allow the snow to consolidate properly (Fig. 3.18 and Section 3.2.2). If the surface cools down overnight, a **high temperature gradient** develops in the snowpack. This accelerates consolidation, shortening the respite period. Snow structure also influences the respite period, for small rounded grains consolidate much faster than coarse grains (Fig. 3.12)

3.3.3.3 Derived Rules of Thumb

1. **Long respite periods – early slope grooming:** usually, the best time to groom slopes is shortly after they close, as the snow is still warm and easy to process (deformable). Moreover, this approach ensures a long respite period (Fig. 3.19). Long respite periods are particularly important in cloudy weather, when temperature gradients are low.

   If a clear winter sky turns cloudy in the afternoon, the snow will start to warm up. When such a sequence of weather occurs, sometimes it makes sense to postpone the preparation of individual sections of the slope until later, when snow temperatures will be higher (Fig. 3.20). However, the respite period should not fall below a minimum of around 8 hours. The basic rule of early preparation to maximize the respite period for consolidation applies particularly to heavily used sections of the slope.
2. **The higher the stress, the earlier the preparation:** since slopes cannot all be prepared simultaneously, the order of preparation must be prioritized. The more intensively a slope is used during the day, the earlier it should be prepared the evening before, to maximize both the respite period and consolidation. Flat and little-used sections of slopes are subjected to less stress than steep sections.
3. **Prepare south-facing slopes first:** in good winter weather with clear, cold nights, snow heats up during the day, particularly on south-facing slopes. These slopes should be groomed first, because warmed-up snow is easier to work.

4. **Prepare shady slopes slowly:** snow on shady slopes becomes very cold (below –25 °C) in good winter weather. Snowcats should be driven more slowly over such areas, to increase their effectiveness (see Tab. 3.2).
5. **Take account of temperature gradients:** if a cloudy sky only clears up at night, preparatory work on a slope's most important sections should have been completed by this time. This way, the temperature gradient can develop unhindered and the remaining respite period can be used efficiently for faster consolidation.
   When produced, machine-made snow has a relatively high temperature of close to 0°C. Whereas the lower layers of this man-made snowpack remain at this temperature, the surface snow cools down very quickly, depending on the weather. As a result, a high temperature gradient develops, accelerating consolidation through sintering, and speeding up the freezing process in wet snow (see Section 3.2.3).
6. **Take account of the quantity and density of new fallen snow:** if evening or nighttime snowfall is forecast, slope preparation should be postponed until a certain quantity of new snow has fallen. In the event

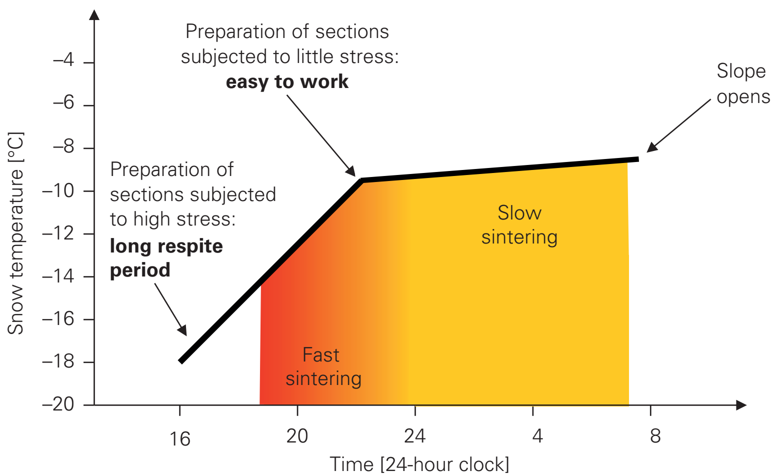

Fig. 3.20: The best time to start preparing a slope is when cold snow heats up in the evening. Although snow is easier to work at higher temperatures, sintering takes place more slowly. This is because the temperature gradient in the snowpack decreases, which affects the sintering process more strongly than being heated by 10 to 15°C.

of heavy snowfall, the slope should be prepared each time a new layer of 20 cm has fallen (but beware of avalanches!). If the density of the new fallen snow is very low (under 80 kg/m^3), it is a good idea to further postpone the onset of preparation, so that natural settlement can pre-compact the snow to a certain extent (see Section 1.3.3). This will make subsequent machine preparation of the slope more effective and more efficient. Machine-made snow can also be added if this is an option (see Section 3.3.1). Care must be taken to ensure that the new fallen and machine-made snow are thoroughly mixed, not deposited on top of each other in layers. Spreading machine-made snow on top of loose new snow on slopes with a gradient steeper than 30° can cause avalanches.

7. **Very wet snow necessitates optimal timing:** in spring, snow is often wet during the day and can refreeze overnight. Running machines over wet snow forces the water to the surface, where it can, under some circumstances, freeze to form a layer of ice that makes the slope very uncomfortable and dangerous to use. Furthermore, very wet snow hampers the maneuverability of snowcats and therefore their efficiency. On the other hand, if snow is worked when it has already frozen, large

Fig. 3.22: A prepared slope in spring. On the left, the slope was prepared in good time, before it froze. On the right, the snow was already partly frozen by the time it was prepared, which is why clumps of snow formed.

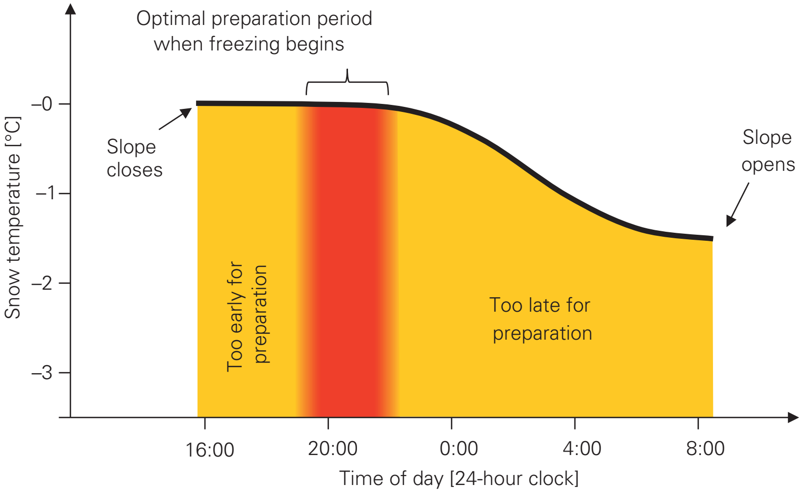

Fig. 3.21: The best time to process very wet snow.

grains and clusters are formed that are not conducive to good sintering. The snow surface remains loose, granular, and inhomogeneous (Fig. 3.22). The ideal time to groom wet snow is just as it starts to freeze (Fig. 3.21). Under heavy cloud cover, snow stays wet for longer, providing more time to work it.

3.4 Equipment: How Best to Use it

Equipment and machine settings are selected based on the preparatory work required (Tab. 3.3) and on the type and quantity of snow.

3.4.1 Snowcats (Cabin, Engine, and Propulsion System)

Various accessories can be attached to the front or rear of snowcats. The higher a snowcat's **speed**, the less compaction takes place and the more uneven the slope's hardness will be (Tab. 3.2). This especially applies to new fallen snow.

Tab. 3.2: Impact of snowcat speed on snow compaction (Guily 1991).

Initial density [kg/m³]	Density after working [kg/m³]		
	4.3 km/h	6.1 km/h	9 km/h
100	255	225	210
120	270	250	240
140	300	280	280

Manufacturers supply **various types of (caterpillar) tracks** made of different materials (rubber, metal) and chain blades of different shapes and sizes. The quantity of **snow churned up and ripped out of the surface** by a snowcat will depend on its track type, the snow's properties, and the vehicle's speed (Fig. 3.24). A tiller must be used to offset this impact. Except on hard slopes, a snowcat's speed should be selected to ensure that as little snow as possible is ripped out. Such losses can also be prevented by careful use of a winch.

Fig. 3.23: Snowcat with dozer blade, cable winch, and tiller with a yellow finisher.

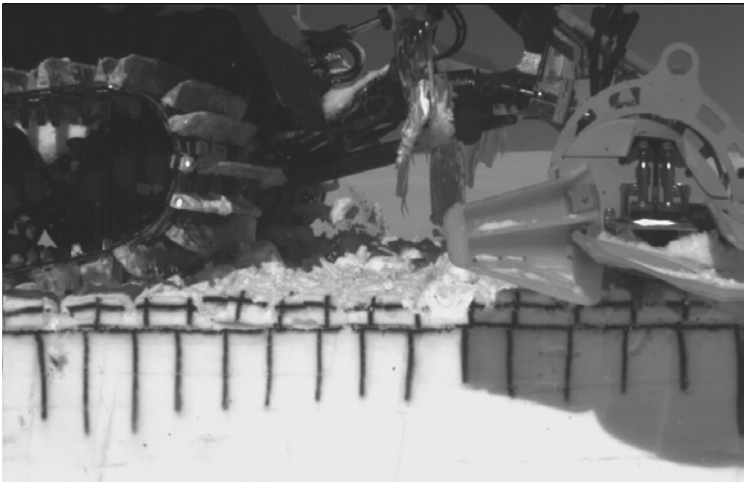

Fig. 3.24: Snow being churned up and torn out by track blades.

Fig. 3.25: Slope surface being leveled with a dozer blade.

3.4.2 Dozer Blades

Dozer blades are controlled by a hydraulic system. They shift snow from A to B, smooth out humps and bumps, **level slopes**, and regenerate their surface (Fig. 3.25). An angle dozer blade can be deployed like an agricultural plow to work deeper layers of snow (see Section 4.3 and Fig. 4.5).

3.4.3 Tillers and Finishers

Tillers are the equipment of choice for slope preparation. As explained above, they have a major impact on compacting snow and changing grain size distribution and grain shape. The **revs**, **contact pressure**, and **working depth** (blade angle) can be varied and tailored to the snow conditions. Increasing the revs and contact pressure improves compaction and creates better sintering conditions. Deeper tilling creates a more homogeneous

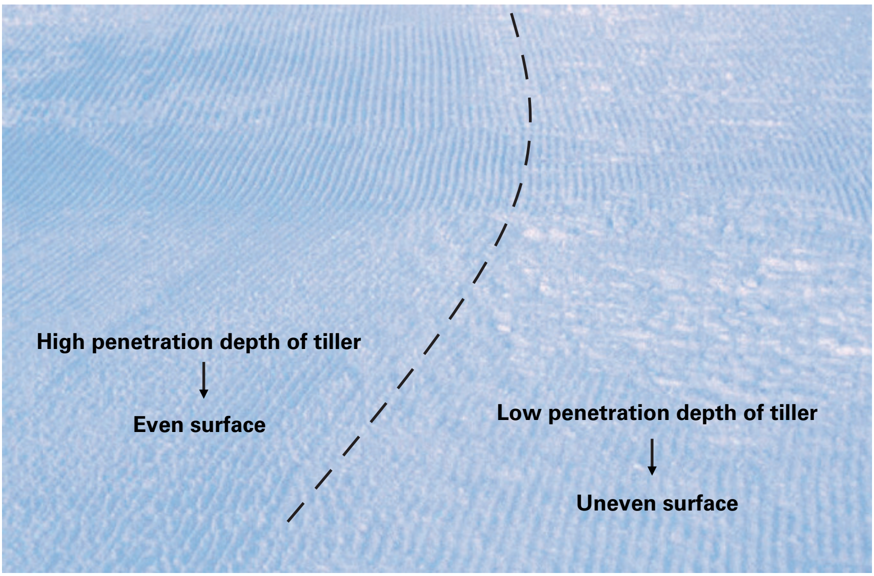

Fig. 3.26: The effect of different tilling depths on slope quality.

snow surface (Fig. 3.26). When finishers are used in combination with tillers, the tilled surface is smoothed out, giving it an aesthetically pleasing furrowed appearance.

3.4.4 Smoothing Boards

Smoothing boards gently pack, level, and structure the **surface of new fallen snow**, rather like finishers attached to tillers (Fig. 3.23). They can either be deployed on shallow snow (a snow shortage, pre-preparation) or serve for the straightforward, resource-efficient preparation of large quantities of new snow on flat terrain.

3.4.5 Cable Winches

Cable winches enable **the preparation of steep slopes**, making it possible to return snow that has been pushed to the bottom of a slope back up the run. Cable winches also improve tilling when driving uphill, because the greater pressure on the tiller compacts the snow to a greater depth. Furthermore, the caterpillar tracks on a snowcat pulled by a winch churn up and tear out less snow (Fig. 3.24).

3.4.6 Compactors

Compactors further **compress** a slope's topmost snow layers (< 20 cm). The strong **vibrations** they generate further compress pore spaces, making pores more likely to be filled with fine material. The working principle is based on cyclically increasing and decreasing the load on snow, which can repeatedly break up its grains and rearrange them more compactly. The weaker the bonds between the grains, the more effective the result. However, tilling snow to break up the bonds between its grains and create fine material, and compressing snow with a compactor are separate processes that cannot take place simultaneously. Accordingly, both tools cannot be used at the same time.

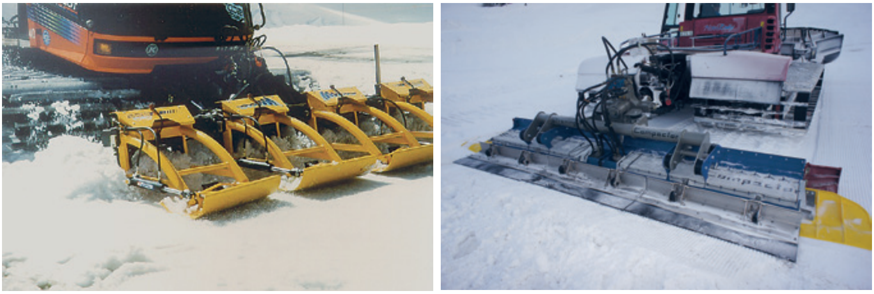

Fig. 3.27: Left: front renovator (www.bachler.ch). Right: compactor (www.straninger.com).

3.4.7 Front Renovators and Snow Cutters

A front renovator **mixes** the upper layers of snow (max. 40 cm). It works rather like an agricultural plow, thereby reaching a greater depth than a tiller, and can thus remove inhomogeneities, such as patches of surface ice or undercompacted layers just beneath the snow surface. This can be useful for creating a stable foundation, for example. Unlike tillers, however, front renovators do not create any fine material.
Snow cutters[9] are attached beneath dozer blades to tear up icy, crusted snow surfaces (max. 10 cm).

3.4.8 Front-Mounted Rotary Snowplows

Front-mounted rotary snowplows can move large quantities of snow. The displaced snow becomes heavily compacted.

3.4.9 Dozer Shovels

Unlike dozer blades, shovels (also called buckets) can transport snow (1–2 m^3) over longer distances.

9 www.pistenbully.com/fileadmin/content_pistenbully/modul_8_download/zubehoer_snow-cutter_DE.pdf

Tab. 3.3: Which equipment to use for various slope-grooming processes.

Process	Equipment
Leveling humps or bumps	Dozer blade Tiller
Distributing snow	Dozer blade Shovel Front-mounted rotary snowplow
Mixing different layers	Dozer blade Front renovator
Regenerating the snow surface e. g. destroying a layer of ice	Dozer blade Tiller Snow cutter
Finishing	Tiller (with finisher), smoothing board

4 Race Track Preparation and Grooming

4.1 Aims of Race Track Preparation

Race tracks are prepared to provide a durable, **extremely resistant** track capable of withstanding the high forces exerted by competitors. During competitions, snow conditions should be maximally **consistent** over the entire course, from start to finish. When asked, world cup athletes cited such consistency, the **evenness of the surface**, and **very firm snow**[1] as the key criteria determining race track quality (Wolfsperger 2015).

At least the **uppermost 30 cm** of snow on a race track must undergo additional consolidation to provide the required firmness. **Strong wear** caused by slipping or sliding[2] during track inspections or training runs means that having just a superficially firm, thin surface layer is not enough. To withstand the **forces exerted during races**, there should always remain a hardened layer at least 20 cm thick. The deeper down the snow is consolidated, the longer a completed race track will be able to withstand even

Fig. 4.1: Left: race track only superficially consolidated (World Cup Giant Slalom, Hinterstoder, Austria, 2011). Right: race track consolidated down to deeper layers, which withstood warm temperatures (World Cup Giant Slalom, Adelboden, Switzerland, 2011).

1 In the study, high fragility, equivalent to low firmness, was clearly negatively rated. Furthermore, aggressive snow conditions (see Section 3.1.3) were described as increasing the risk of injury in another study (Spörri 2012).

2 Depending on the ambient temperature, several centimeters of the surface are abraded every day. Records show that on downhill slopes at major events with very large numbers of participants, around 10 cm of snow can be worn away in the space of a single week.

heavy thawing in the run-up to a competition. It will also minimize the risk of a race track prepared well in advance suffering even greater damage before racing begins.

Heavy consolidation of the snow on a race track is key to giving it the firmness required. On sections of the race track subjected to less stress, such as the gliding sections of the fast downhill and super-G disciplines, the techniques used to prepare regular ski runs usually suffice. Here, snow densities of 450 kg/m^3 and above will meet firmness requirements. However, on technical sections (turns, jumps, etc.) and in technical disciplines like the slalom and giant slalom, the density must be no lower than around 600 kg/m^3. In such highly stressed areas, higher densities, even including icy snow, are less problematic than densities below 500 kg/m^3. However, high density alone does not generally guarantee great firmness. A coarse

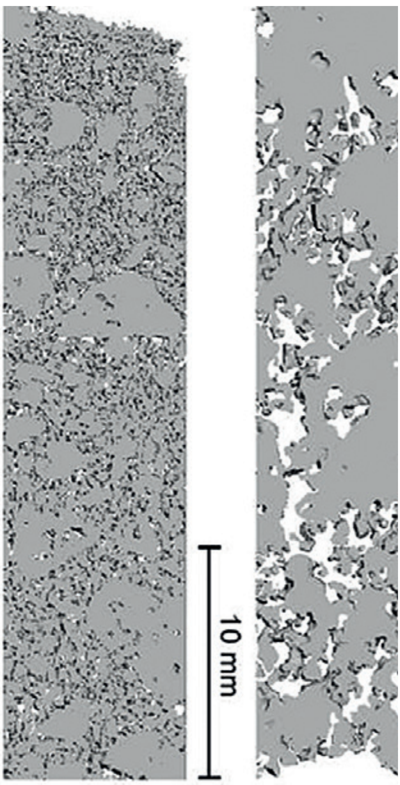

Fig. 4.2: Snow samples from the 2010 Beaver Creek (left) and 2011 Kitzbühel (right) downhill courses. Despite having similar densities, their snow strength differed (see Section 1.4). In the sample with rounded grains (left), small structures are held together by large numbers of bonds between grains. In the right-hand sample, there are few bonds to absorb the force exerted by skiers and distribute it across the ice framework. Furthermore, each bond is subjected to a clearly uneven level of stress, making the ice framework more fragile overall.

microstructure or high level of wetness makes snow much less firm (Fig. 4.2 and Section 1.4).

As explained in the previous chapter (Section 3.2.1), snowcats can only compact snow to about 450 kg/m^3 by exerting pressure and using fine material as a filler. The following methods may be used to prepare higher-density snow:

– **compressing at higher pressure** (vibrating plate, skiers)
– **using wet machine-made snow**
– **adding water** (watering the slope)

4.2 Basic Preparation (Starting Point)

Since race tracks are often used as regular ski runs before and after competitions, we will take a well-prepared regular ski run (see Section 3.3) as our starting point when describing how to prepare race tracks. If a slope is also going to be used as a race track, a **well-compacted foundation** is particularly important.

Using more or less **wet machine-made snow** can already help to achieve higher density (> 500 kg/m^3) and greater firmness. Another advantage of using machine-made snow for the foundation of a slope is that it is very homogeneous.

4.3 Watering Slopes

On downhill race tracks, slope watering is a widespread method of making snow **sufficiently resistant**. A well-watered slope remains intact for several days or even weeks. Its surface does gradually soften in mild, rainy weather, or when subjected to strong sunshine and warming, but if the slope has been watered to an optimal depth, this top layer can be removed. The lower layers thus exposed will still be firm enough for ski racing.
The aim of watering slopes is to add **enough water** to the snow to achieve the desired level of compaction. Furthermore, the water should penetrate **deep enough** into the snow to ensure that consolidation cannot merely take place on the surface. Finally, water should only be added when there is **enough time** and when weather conditions are suitable for it to **freeze**.

In principle, there are three "energy sources" capable of freezing water[3]:

- **snow**, when it is colder than 0 °C
- **ambient air[4],** when it is colder than 0 °C
- **net radiation** on the snow surface, when it is negative. This means that the snow surface emits more radiation energy than it absorbs (see Section 2.2.2.2).

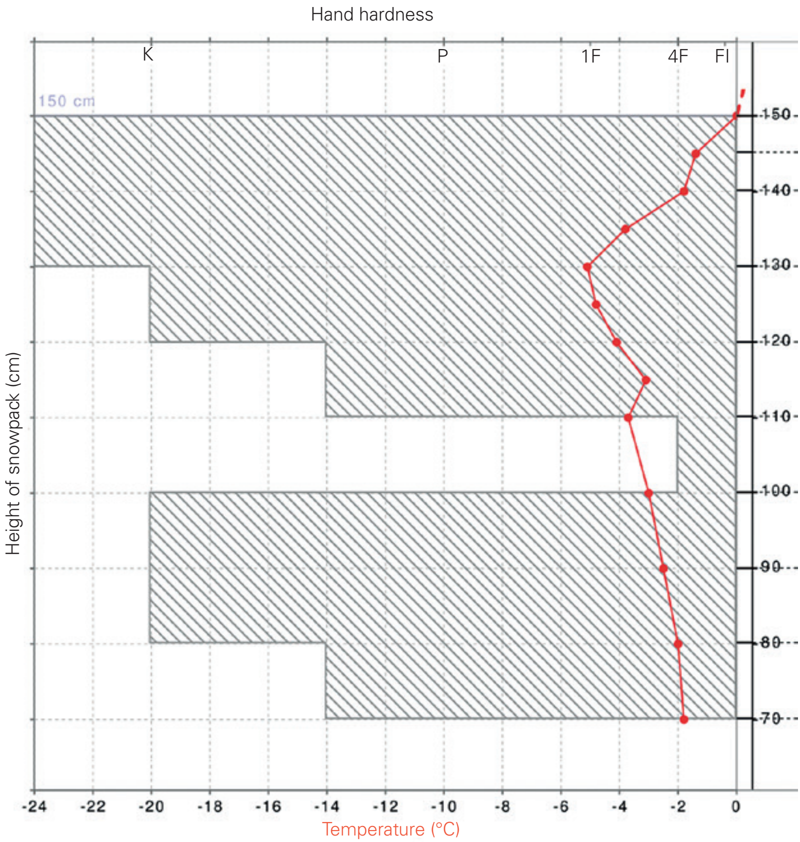

Fig. 4.3: Hardness (gray shading) and temperature (red line) profiles of a well-prepared slope without added water. The top 60 cm of this snowpack are very firm, but have no ice because no water was used. The temperature is 0 °C at the surface but between –4 °C and –6 °C deeper down. Hand hardness is based on whether a fist (FI), four fingers (4F), one finger (1F), a pencil (P), or just a knife (K) can be inserted into the snow.

When watering slopes, the following **key factors** should be taken into account:

- at **low snow temperatures**, water does not penetrate very far into the snowpack because it freezes before it can percolate down further. Accordingly, **more water** is needed to achieve the desired impact at the required depth (at least 30 cm). The additional water and the energy it contains prevent the snow near the surface from freezing prematurely (Fig. 4.4).
- by contrast, at **high snow temperatures** the water penetrates deeper into the snowpack, because it only freezes slowly. As a result, care should be taken not to add **too much water**, since only cold air and negative net radiation help it freeze.
- **fine-grained snow**, like those characteristic of machine-made snow, can absorb and hold more water than coarse grains. Consequently, here more water can usually be added.
- **coarse grains** cannot hold as much water. As a result, the water soaks in more quickly, penetrating deeper, or even percolating through to the ground. It will then take significantly longer to freeze completely. Coarse grains are also produced by the action of watering itself. When watering multiple times, larger grains must be taken into account, meaning less water should be applied.
- in **inhomogeneous snow layers**, for example shortly after the snowpack has been ripped up, water drains away irregularly, creating different levels of firmness.

Before watering a slope, the following **snow properties** and **weather parameters** over the next three to five days should be ascertained:

- **snow temperatures** at the surface and at depths of 10, 20, and 30 cm
- **snow density** at the surface and at depths of 10, 20, and 30 cm
- **snow structure** (grain shape and size)

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[3] Technically, "energy sinks" is the correct term to use here because energy is released into the environment (snow or atmosphere) during freezing (see Section 1.3.1).

[4] In addition, energy is released during freezing through evaporation and sublimation if the relative humidity is less than 100 %, whereby the air temperature may also be above 0 °C.

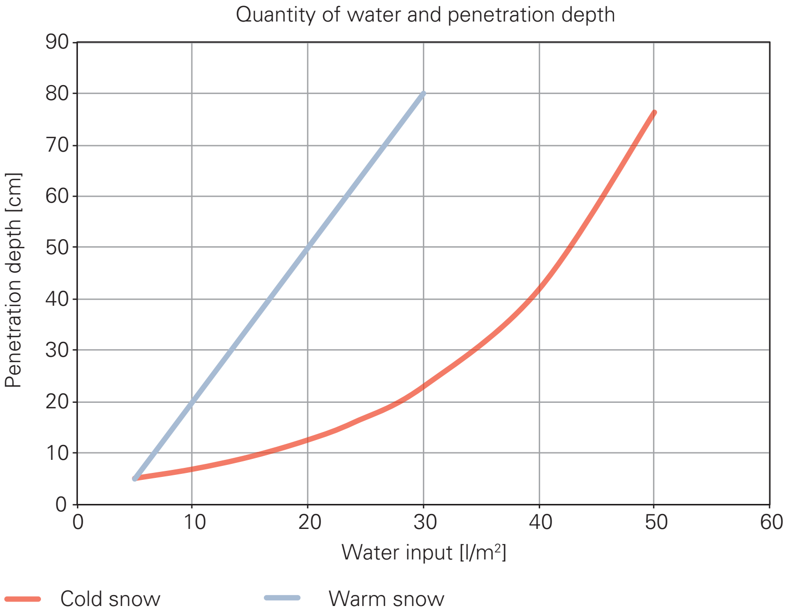

Fig. 4.4: Depth of penetration depending on the quantity of water in cold snow (well below –10 °C) and warm snow (well above –10 °C).

- **air temperature** and **wind speed:** for the colder and stronger the wind, the better added water will freeze.
- **air humidity:** the drier the air, the better the water will freeze.
- **net radiation:** clear nights considerably speed up the freezing process because the snow surface can give off heat (see Section 2.1.2).
- **precipitation:** new fallen snow forms an insulating layer (see Section 1.2.2), preventing the heat released during freezing from being emitted from the watered slope surface into the atmosphere. This greatly hinders the freezing of the added water. New snow should therefore be removed from watered slopes as quickly as possible.

4.3.1 Preparing Slopes for Watering

To prevent **water from draining away at the surface**, it is a good idea to prepare the surface (an exception being the injection method presented below). All that is required to do this is a snowcat with caterpillar tracks. There is no need to use a tiller. The snowcat creates a **rough surface** that holds the water in place so that it can percolate down into the snowpack. The roughness of the surface has almost no effect on the **depth to which the water penetrates**. If less water is used, for example at high snow temperatures, a smooth surface can also be watered.

All watering methods require the most homogeneous and densest possible snow on the slope (> 400 kg/m^3), so **thorough basic preparation** is important (see Sections 4.2 and 3.3.1). If the snow on a slope is inhomogeneously layered, a front renovator or an angle dozer blade similar to an agricultural plow can tear it up to a depth of around 40 cm to produce **more homogeneous compaction**. This should be done no later than two weeks before the completion of a race track, however. This way, before being watered, the snow will have enough time to consolidate through the

Fig. 4.5: A snowcat tearing up a slope with a dozer blade (St. Moritz, Switzerland, 2017).

Fig. 4.6: Left: a "torn up" slope before smoothing (St. Moritz, Switzerland, 2017). Right: the slope being smoothed (without a tiller) after being torn up.

growth of bonds between its grains, providing a good starting point for the slope's further preparation (see Section 3.2.2). Shoes or skis can be used to further compact areas subjected to particularly high levels of stress (e.g. jumps, steep turns).

Before any preparatory measures are taken, a suitable watering method, appropriate for the weather and snow conditions, should be chosen. The best-known methods and their advantages and disadvantages are described below:

- **hose watering**
- **injection bars or beams**
- **snowcat bars**
- **Norwegian sprinkler or fire-department sprinkler**

4.3.2 Hose Watering

Hose watering is probably the **oldest method** and involves using a snowmaking hose to spray water over the slope surface. The slope preparation team led by Greg Johnson, Chief of Course at the 2011 Ski World Cup in Beaver Creek, Colorado (USA), provided a good example of this approach. Their basic preparation involved using very wet machine-made snow that was processed while still wet. When watering, they used snow guns (without compressed air) to distribute the water more efficiently (Fig.4.7). In mild weather, the water could percolate about 20 cm down into the snowpack. In the afternoon, when air temperatures fell, the team were quick to start their multiple tilling operations (comprising 5 to 6 runs). As soon as the surface began to freeze, a finisher was used to smooth it. In total, around 5,700 m^3 of water was added to the slope.

Advantages of hose watering:
– a lot of water can be quickly applied by just a **few staff members**
– when performed correctly, this procedure produces a **grippy slope surface with little ice on it**

Disadvantages of hose watering:
– on steep terrain, some of the water flows over the surface, meaning it does not penetrate as far down. This can be prevented by using caterpillar tracks when **preparing the slope surface**, though if this is done, **watering must be followed by tilling**. It is therefore important to get the timing right (see Section 4.3.6).
– it is difficult to **estimate the correct quantity of water** to add

Fig. 4.7: The Birds of Prey World Cup course in Beaver Creek, USA, being watered with hoses (2011) – photo: Greg Johnson, Chief of Course.

4.3.3 Injection Bars

Injection bars[5] inject water at high pressure into the snow layer. The pressure level, which is set at the hydrant opening, can determine the **injection depth**. Water nozzles are spaced 10 cm apart on the bar, which two people gradually move forward, also 10 cm at a time, but each time shifting 5 cm to one side, creating a **grid** of columns of injected water measuring roughly 10 cm by 10 cm. The quantity of water used is determined by how long (in seconds) the bar remains in the same place on the slope.

Advantages of injection bars:

- the water quickly percolates into the snowpack
- less water is left on the surface than, for example, when using hoses
- **no preparation** of the snow surface is required
- consequently, no tilling is required after watering
- the **quantity of water can easily be determined and controlled**, though this depends on having highly experienced staff.
- **an unlimited quantity of water can be added**, so this method is particularly well-suited to low snow temperatures.
- a number of injection bars can be attached to each other, which increases efficiency.

Disadvantages of injection bars:

- in general, injection bars require large quantities of water. At snow temperatures higher than around –10°C, **too much water** is often injected. This unnecessarily softens the slope foundation and can result in water flowing over the ground. It also can lead to extremely icy surfaces lacking of grip if added water cannot percolate sufficiently.
- if the pressure exerted is too high for the type of snow (e.g. low density), water will be injected too deep down and **spread out too little horizontally** (Fig. 4.9). This leaves poorly consolidated areas between the water (ice) columns.
- it requires extensive human resources

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[5] Injection bars were developed by Christian Steinbach from Kitzbühel in the 1990s with a view to leaving less water on the surface and conveying more to deeper layers of the snowpack. Icy surfaces were frowned on at the time.

Fig. 4.8: Three connected injection bars being used to water a slope (St. Moritz, Switzerland, 2017)

4.3.4 Snowcat bar

Primarily in a bid to reduce the human resources needed to water slopes, various race organizers have developed bars that can be **attached to snowcats** (Fig. 4.11). As with conventional injection bars, water is supplied through a snowmaking hose and injected into the slope at high pressure through holes in the bar. When constructing such watering bars, care must be taken to ensure that roughly the same pressure is applied across the entire width of the bar. This can be done by varying the diameters of its pipes. The feed rate, and thus the quantity of water injected per area, is determined by the speed of the snowcat. As with injection bars, the quantity of water also depends on the diameter of the holes in the bar, on the hydrant opening, and on the pressure applied there. Unlike injection bars, snowcat bar do not create a grid of columns, but rather lines of water spaced 10 cm apart. The water can be distributed more evenly if the snowcat drives a subtle zigzag course.

Advantages of snowcat bars:
- The feed rate is regulated, guaranteeing the injection of a **specific quantity of water**
- **Smaller quantities of water** tend to be used, making this method more suited to snow temperatures above around –10 °C
- **fewer human resources are required**

Disadvantages of snowcat bars:
- slightly more water remains on the surface of the snow than when injection bars are deployed. To ensure that the water does not flow away across the surface, it is a good idea to **prepare the snow**, for example by tearing it up with caterpillar tracks.
- if the slope is prepared (with caterpillar tracks), it needs to be **tilled after watering** (timing is important)
- snowcat bars generally use less water than injection bars. At low snow temperatures, under certain circumstances **too little water** is added because the snowcat cannot travel sufficiently slowly.

Fig. 4.9: Injection tests on blocks of snow with different-sized grains (left: 0.4 mm; center: 1.5 mm; right: 0.25 mm) and densities (left: 455 kg/m^3; center: 306 kg/m^3; right: 435 kg/m^3). It is clear from the central block of snow that in coarse-grained snow water does not spread as well horizontally.

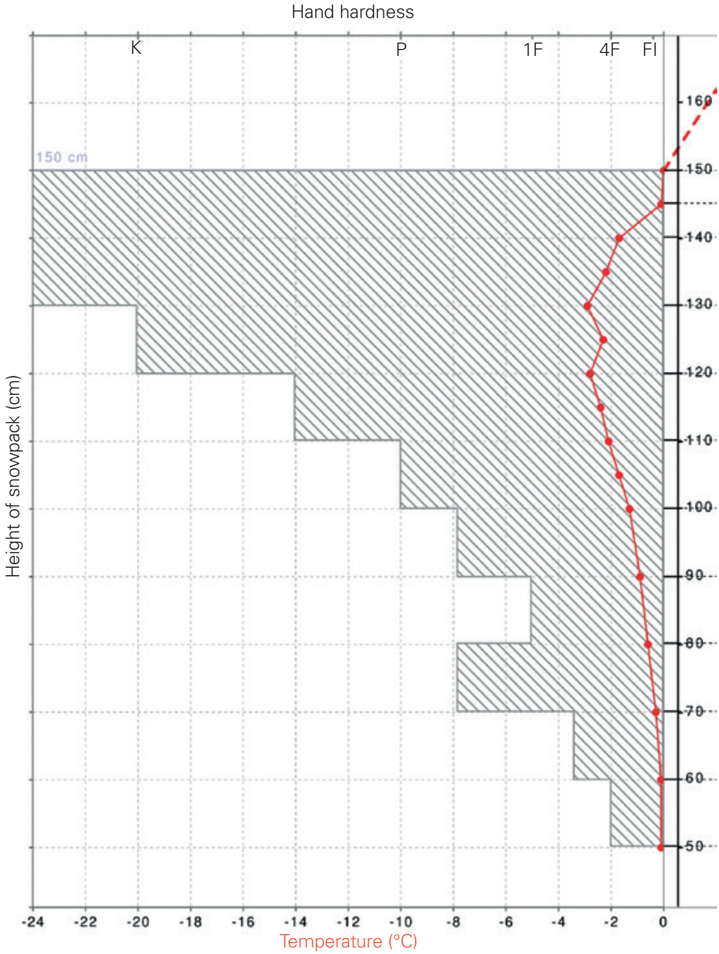

Fig. 4.10: Hardness (gray shading) and temperature (red line) profiles four days after slope watering using injection bars (St. Moritz, 2016). Note the sharp fall in firmness in the deeper layers due to the large quantity of water. Solar radiation brought the surface temperature to 0 °C. At a depth of between 10 and 30 cm, the temperature reached –3 °C as heat was lost overnight through radiation, and the slope was very firm. Further down, the snow was softened by the large quantity of water, and the temperature rose to 0 °C. At this depth, the snowpack consolidates very slowly.

Fig. 4.11: Slope watering using a snowcat bar (St. Moritz, Switzerland, 2017).

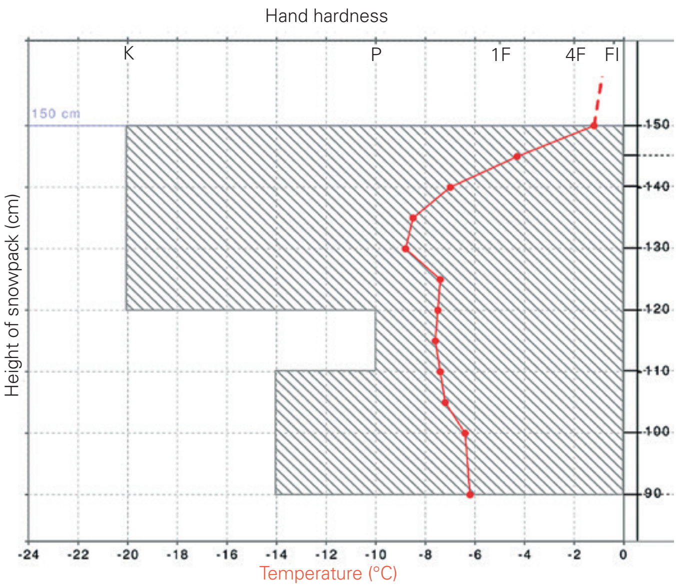

Fig. 4.12: Hardness (gray shading) and temperature (red line) profiles four days after the use of a mechanical bar to water a slope (St. Moritz, 2016). In this example, the top 30 cm were very firm and the deeper layers of snow were also sufficiently firm. A soft layer at a depth of 50 cm can be ignored, as long as the layers above it are firm enough. If need be, the soft layer can be removed by tearing up the slope. Water was visible to the depth of the profile (melt forms). Overall, less water was applied here than when injection bars were used (Fig. 4.10). Consequently it took less time to freeze, so the snow could consolidate faster.

4.3.5 Norwegian Sprinklers/Fire-Department Sprinklers

A type of sprinkler developed and deployed in Norway supposedly enables water to be spread evenly across the slope surface. Sprinklers like those used by fire departments are also used. Again, the water is delivered, in this case to sprinklers, by a snowmaking hydrant, where the pressure can be pre-set. The pressure can also be set at the sprinkler, operated by one person. The quantity of water is manually controlled by moving the sprinkler.

Advantages of sprinklers:

- their operation requires **few human resources**
- the pressure can be adjusted at the sprinkler
- sprinklers make it possible to work with **small quantities of water**

Fig. 4.13: Slope after watering and tilling (St. Moritz, Switzerland, 2017).

Disadvantages of sprinklers:
- the method is more suited to smaller areas
- the quantity of water required per area can only be determined/estimated manually
- more water remains at the surface than **percolates down to lower layers**
- when larger quantities of water need to be added (to penetrate further down), the **surface has to be prepared** (using caterpillar tracks).
- if a slope is prepared (by caterpillar tracks), it needs to be **tilled** after being watered (timing is important)
- as the **quantities of water tend to be small**, this method is only suitable for use at high snow temperatures

4.3.6 Tilling the Surface

A roughened surface has to be tilled after being watered. The **timing of tilling** is crucial here. The right time must be chosen depending on ambient temperatures and levels of solar radiation. Snow should be tilled when it is still only slightly wet (it must not stick to the tiller) and just about to freeze.

4.4 Chemical Hardening of Snow

In unfavorable **weather, when the temperature rises**, for example during a foehn event, intensive solar radiation, or rain, even optimally-prepared race tracks can soften considerably, making their surface no longer able to withstand the stresses exerted by athletes. Nonetheless, to enable races to take place in such **exceptional circumstances**, the snow can be **temporarily consolidated** using snow hardeners, both before and during the competition.

4.4.1 The Snow Hardening Process

Water-soluble substances such as common salt, ammonium nitrate, or urea are used as snow hardeners[6]. This is how snow is hardened:

- snow hardener is spread over a **wet snow surface** and dissolves in the water contained therein:
  - the snow cools slightly as the hardener **dissolves**[7] (Fig. 4.14 A)
  - the dissolved particles in the water **lower its melting point**. This means that water in which snow hardener has dissolved remains a liquid even at temperatures well below 0 °C (as does seawater, for example).
- subsequently, the snow's ice framework **melts further**, reducing its strength in these areas.
- **melting consumes heat** extracted from the surrounding ice framework, causing cooling (Fig. 4.14 B).
- **water** in which no hardener has dissolved and whose melting point has therefore not been lowered begins to **freeze**, thereby **consolidating** the snow. At the outset, therefore, the few centimeters below the surface are where the snow is most strongly consolidated (Fig. 4.15). But as the dissolved hardener seeps down, it is the deeper layers that become most strongly consolidated.

Snow quickly hardens at the surface (in roughly 30 minutes). After about 180 minutes, deeper layers of snow (up to 10 cm deep) are also consolidated by added snow hardeners (Fig. 4.15). However, by that point the strength of the layers near the surface has waned again, so they should be continuously **scraped away**. As the **snow hardener continues to seep in**, it becomes more evenly distributed, but increasingly less concentrated, in the snow. This phenomenon, as well as additional melting caused by the sun and warm air, means that the short-term consolidation of the snow is lost again after 3 to 4 hours at most[8] (Fig. 4.14 C).

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6 Under the product name PTX, Austrian company Gerema sells ammonium nitrate (PTX 311; NH_4N0_3) and common salt (PTX 312 speedy; NaCl) specifically as snow hardeners. These, and other usable substances such as urea ($CO(NH_2)_2$), are also available from chemical and food wholesalers.

7 When common salt, ammonium nitrate, or urea dissolve in water, a chemical reaction occurs, requiring heat, which is extracted from the surrounding area, thereby cooling it. This phenomenon is far more pronounced with ammonium nitrate (321 kJ/kg) and urea (234 kJ/kg) than with common salt (66 kJ/kg), but is negligible with all snow hardeners. This is because, as recommended by the manufacturer, small quantities are applied (1–4 g/m^3 of snow, penetrating to a depth of 2 cm; www.gerema.at). The energy absorbed in the reaction is therefore also low (< 0.3 kJ/ m^3 of snow).

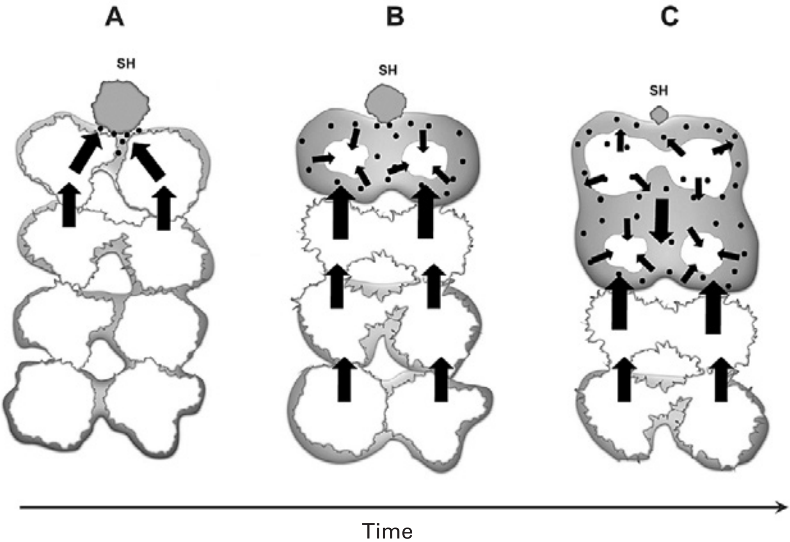

Fig. 4.14: Chemical snow hardening process. The dots represent dissolved snow hardener particles, which reduce the melting point of the water in the snow. The arrows indicate the strength and direction of the ensuing heat transport (MANI *et al.*, unpublished).

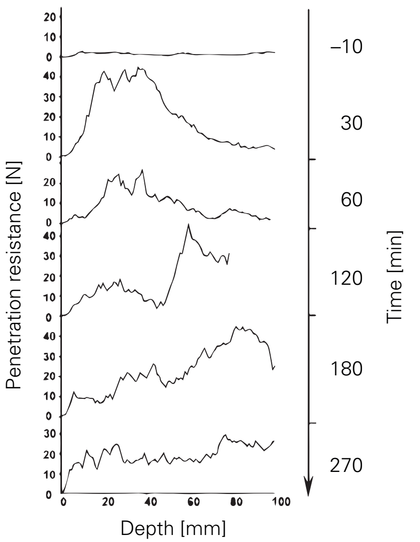

Fig. 4.15: In a laboratory experiment, 60 g/m² of ammonium nitrate was poured onto a block of snow (liquid water content = 1 vol. %), the hardness of which (see Chapter 8) was measured every 30 minutes. It is clear to see that the snow hardened quickly near the surface (10–40 mm), sinking down to a depth of around 90 mm after 3 hours. In the end, the block was moderately consolidated over its full depth, since under the laboratory conditions neither warm ambient air nor radiation could input any additional energy.

4.4.2 Practical Snow Hardening Tips

The following points should be taken into consideration when using snow hardeners:

- one prerequisite for their use is a **stable slope** of adequate thickness (at least 30 cm), constructed to withstand the intensified removal of soft surface layers
- **wet snow** – i.e. liquid water in the snow – is also required to enable the hardener to dissolve
- the manufacturers' instructions[9] regarding the **quantities to be deployed must be heeded** (100 to 200 g/m² of common salt; 50 g/m² of ammonium nitrate). Only relatively small quantities of snow hardener are needed to reach the required level of consolidation. If too much is used, the snow hardens less.
- the size of the grains of snow hardener also has a decisive influence: with larger grains, the snow hardens to a greater depth and remains hard for longer. However, the snow hardening process is relatively slow. Fine-grained hardeners, by contrast, work quickly and produce a harder surface, though it does not last very long.
- snow hardeners are very ineffective in snowfall and fog. The water in the snow does not freeze because the surface does not release any energy into the atmosphere (see Chapter 2). Moreover, the dendritic structure and low density of new fallen snow prevent effective heat conduction and impede water accumulation at the grain boundaries, a precondition for the hardening process.
- the tilling of snow hardeners is not recommended. Furthermore, once the hardening process has begun, the snow should no longer be worked in any way (e.g. tilled, compressed by caterpillar tracks).
- rainwater, however, is conducive to snow hardening, though it requires the continuous strewing of snow hardener

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[8] On the one hand, chemical hardening works because heat is transported through the snow much more quickly than hardener can dissolve and spread through the liquid water contained in that snow. On the other hand, hardener is not distributed evenly throughout the snow, causing major differences in its concentration.

[9] www.gerema.at; www.hanspierentopproducts.ch

Fig. 4.16: Snow hardener being applied using a blower spreader (left) and by hand (right) (Biathlon World Cup, 2017, Pyeongchang, South Korea).

- salt (common salt, ammonium nitrate) **works more quickly** and can therefore be added during races
- walking on a **softened slope while wearing crampons to roughen it** has in practice (Adelboden World Cup) been shown to improve the snow hardener's depth penetration
- once the hardener has been strewn, there should be a **respite period** to give it time to dissolve in the snow
- soft surface layers should be **removed** whenever possible
- all **sensitive areas** around the race track, such as nature reserves, bodies of water, and groundwater protection zones should be identified, as should the resulting environmentally relevant constraints arising from them. For example, nitrogen-based snow hardeners (ureas, ammonium nitrate) may not be spread on sensitive soils, such as nutrient-poor grassland or meadows used for biological purposes. Furthermore, the use (i.e. location and quantity) of snow hardeners in Switzerland has to be recorded[10].

[10] For Switzerland, further information can be found at www.bafu.admin.ch/bafu/de/home/themen/chemikalien/publikationen-studien/publikationen/ schnee-haerter-rennpisten-schneesportwettkaempfe.html.

– if weather windows enable **the snow surface to release energy** (negative energy balance), the use of hardeners should be adapted accordingly. Hardeners work particularly well when the sky clears up early in the morning, for example after nocturnal thawing, as long as the snow surface can radiate heat and there is no direct sunshine.
– **ammonium nitrate is an oxidizer** and highly explosive, so it needs to be stored far away from sources of ignition and heat

4.5 Removing Snow

Snowfall on a fully-prepared race track is every organizer's worst nightmare. Since new fallen snow cannot meet the firmness required by competitors, it must be removed wherever the steepness of the slope permits this to be done. New snow inevitably **piles up**, causing dangerous obstacles. New fallen snow can be removed from a slope by:
– **hand** (using a standard shovel, sleigh shovel, or broom)
– **using a hand tiller**
– **using a leaf blower**
– **sliding it off**
– **using a quad with rubber tracks** (with a tiller, broom, or dozer blade attached).

Only on very flat areas can it make more sense to till new snow, because it is very difficult to remove from them. It is important, however, to ensure that the snow has enough time to sinter.

4.5.1 Repairing Damage

Damage can often arise where there are minor **irregularities** in the race track due to the high level of stress exerted by users. Such unevenness or small **cracks** in the slope surface can be evened out using a **scraper**, a **shovel**, or by regularly sliding off the surface layers. If such weak spots are recognized early enough and continuously mended, more extensive damage can often be completely avoided or at least delayed. For example,

Fig. 4.17: Snow being removed by a quad with a front-mounted tiller (www.aebi-schmidt.ch).

if the entry to and exit from a forming hole in a turn is mended sufficiently early and regularly using a scraper, the high stress exerted by the competitors will be spread over a larger area, alleviating the problem.

Turns and **steep sections** also have to be **slipped over with skies** constantly, so that the wear on the slope surface becomes more even and more dynamic. There should be no skidding on flat (gliding) sections. Skidding causes varyingly loose snow particles to form during the race, which leads to inconsistent skiing conditions.

5 Cross-Country Ski Trail Preparation and Grooming

Section 3.1.6 above described how cross-country ski trails and downhill slopes both have to meet similar requirements. Above all, they must have an **even, homogeneous** surface. But many cross-country trails do not need to be as resistant as downhill slopes.

The preparation and grooming of trails does not differ fundamentally from the procedures followed for downhill slopes. Basic preparations entail **building a stable foundation** in the same way as with downhill slopes. Similarly, topography, stress, weather, and snow conditions (see Chapter 3) all need to be taken into account for trails, too. Trail grooming essentially involves **surface regeneration** work. There is rarely need to repair damage or redistribute snow. But the **track grooves** on classic cross-country ski trails also need to be prepared. Competition courses are an exception, as they sometimes necessitate special measures.

Fig. 5.1: Sandra Wagenführ using the skate skiing technique at the 2017 Engadin Ski Marathon – photo: Jürg Marugg.

5.1 Preparing Tracks for Classic Cross-Country Ski Trails

Setting a good track is essential for creating a high-quality classic cross-country trail. When doing this, the following points should be taken on board:

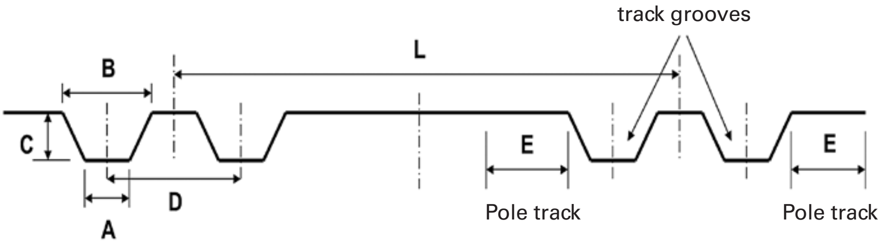
- prepare an even track, i. e. one with a consistent depth and no undulations
- make the track as deep as possible (5 cm) to improve its durability
- drive the snowcat slowly (< 8 km/h)
- (if possible) do not make ascents/descents too steep
- tailor curve radii on descents to the speed at which skiers will be traveling

Tracks are prepared using devices or plates mounted on the rear of a snowcat (Fig. 5.2). Track devices are equipped with small cutting tools that tear up the hard surface to make it easier for the track profiles behind them

Fig. 5.2: A snowcat making a trail, with a tiller, finisher, and three track-setting plates attached.

to penetrate the snow. Where the **ski track's geometry** (Fig. 5.3) is imprinted, the **snow is compacted**. But the track-setting device only lightly compresses the pole track.

Optimal preparation involves the simultaneous use of **a tiller and track-setting plates**. Track profiles penetrate freshly-tilled snow better. Furthermore, using a tiller positively impacts snow consolidation (see Section 3.2). This is particularly important for **consolidating pole tracks**, as the snow there is less firmly compressed by the track profiles. As well as using a tiller, it is also essential to **drive slowly** to maximize **homogeneity** and therefore optimize track quality (Fig. 5.4 tracks grooves).



A = 52– 60 mm
B = 130–160 mm
C = 40– 50 mm
D = 170– 250 mm
E = 80– 120 mm
L = 1,000–1,200 mm

Fig. 5.3: Profile of two pairs of cross-country tracks.

Fig. 5.4: A comparison of two cross-country tracks. Track A was prepared applying low contact pressure, with penetration to a depth of 40 mm, and driving at a speed of 8 km/h. Track B was prepared applying maximum contact pressure, with penetration to a depth of 60 mm, and driving at a speed of 5 km/h.

Fig. 5.5: Left: tiller with front-mounted cutter (Kratzus, Bächler Top Track AG, Switzerland). Right: narrow track tillers (Nordic Liner, Prinoth AG, IT; photo: www.prinoth.com). Both devices improve track preparation, even of hard and icy surfaces.

To improve track quality in hard snow (an icy trail), an additional cutting device or track tiller can be mounted in front of the tiller (Fig. 5.5). Unlike the main tiller, these devices only tear up the snow where the track is, but penetrate deeper there. This facilitates the preparation of icy tracks. The main tiller can also be used at a shallower depth.

If higher speeds are reached on **descents**, **tracks should not be prepared**, especially in sharp turns. To ensure that trail users can control their slides and/or change of footing when skiing through turns, the trail must be even and grippy across its entire width. Depending on the snow conditions, the outside of the turn can be banked (bobsled turn) to facilitate the change in direction.

Ideally, trails should be prepared in the evening, as this will provide a **sufficiently long respite period** for the snow to consolidate through sintering (see Section 3.2.2). Only in exceptional cases (e.g. heavy snowfall) should cross-country trails be prepared while skiers are using them.

5.2 Grooming Cross-Country Ski Trails

Trails must be groomed throughout the winter season. In general, the tasks this involves are the same as those for downhill slopes (see Section 3.3.2). The main focus, however, is more on **regenerating the trail's surface** (leveling, homogenization), **reconstructing destroyed tracks**, and compressing and **leveling new fallen snow.** Frequent snowfall necessitates daily trail grooming. Under stable high-pressure weather conditions, an optimally prepared trail can be left for a few days without needing to be groomed. Icy patches should be torn up and removed, especially in turns and on descents. Snow will also need to be moved in places.

5.3 Preparation and Grooming of Competition Trails

Competition courses are subject to far **greater stresses** than regular trails. This is partly because races entail many athletes completing the course in a short space of time, usually over several consecutive days. But it is also because professional skiers make much deeper indentations with their skis and poles than recreational skiers.

Fig. 5.6: Roller and light track-setting device to be used on a snowmobile. Snowmobiles are particularly useful for leveling the surface when there is insufficient snow and/or very warm weather has softened the snow, because snowcats would sink in too deeply (www.yellowstonetrack.com).

To ensure that competition courses can **withstand these exceptional stresses**, their basic preparation must leave them with a higher density, for example through the use of machine-made snow. The focus here should be on steep sections that are exposed to the sun, to prevent or limit significant softening in the event of sudden warm weather.

Furthermore, the trail's preparation with a snowcat needs to be optimally tailored to the snow conditions (see Chapter 3) by:

- ensuring the longest possible **respite periods** after preparation (closure)
- preparing wet snow early, **before it starts to freeze**
- preparing dry snow **slowly**, **making maximum use of a tiller**
- preparing new fallen snow **multiple times**, **making maximum use of a tiller**

Other measures can include **covering**[1] sections of the trail (Fig. 5.7); applying **snow hardener** (see Section 4.4); or, if the foundation of the trail is deep and dense enough, **removing soft surface layers or fresh snow**.

Competition courses may also be insufficiently firm if **snow stored** over the summer is used (see Section 7.4), because such coarse, round-grained old snow does not consolidate as effectively through sintering (see Section 1.3.2). In this scenario, it is particularly important to drive the snowcat slowly, applying a high contact pressure, and tilling at high speed. If the temperatures are low enough, **slope watering methods** can be used (see Section 4.3).

[1] Any covers must be removed in good time as soon as the snow can once again release more energy through radiation loss and/or evaporation than it absorbs from the sun and warm air (see Section 7.4). Meteorological measurements and snowpack simulations can help in this regard (see Chapter 8).

Fig. 5.7: Covered ascent at the 2017 Biathlon World Cup in South Korea. Covering a course reduces softening and melting in the middle of the day and ensures better competitive conditions in the late afternoon and evening.

6 Snow Park Construction, Maintenance, and Management

Meeting **growing customer needs** entails more than just optimizing slope preparation. It is also worthwhile introducing additional **attractions at a ski resort** to offer guests fun, variety, and new sporting challenges. Furthermore, **staging competitions** in spectacular Olympic skiing and snowboarding disciplines like slopestyle, cross, and halfpipe attracts visitors, and can prove valuable for **marketing** purposes. Nowadays, the term snow park encompasses a **wide variety of very different facilities**, from children's parks to superpipes (Fig. 6.1). This has made it increasingly difficult for ski resort managers to choose and build the right snow park facilities.

Although typical features like jumps, banked turns, and undulations are most popular with younger users, if the right know-how is applied, parks can be made to appeal to **young and old** alike, from **beginners to skilled** snow sports enthusiasts. Ski resorts' expensive facilities will only turn a profit if a maximum number of visitors is induced to actually use them.

If visitors are to **enjoy snow parks and use them safely**, they must be expertly constructed and properly maintained. This chapter gives a rough overview of some potential features and construction and maintenance methods, as well as of the most important safety principles. The content below is based on the Swiss Competence Centre for Accident Prevention

Attraction park	Cross course	Freestyle park	Halfpipe
Airbag jump Photo jump Speed track Toboggan/tubing run Snow playground …	**Ski-/boardercross** (professional)	**Slopestyle** (professional)	**Superpipe** (professional)
	Freeride cross	**Freestyle park** – Large – Medium – Small	**Medium pipe** – Wall < 4 m
	Funline	Kids' park	Small pipe – Wall < 1.5 m

Fig. 6.1: Overview of different types of snow parks.

(BFU) guide on snow parks (Weiler 2013 - only available in French and German), which presents further information. A professional snow park designer[1] may also be consulted, to develop facilities that best suit the specific features of the ski resort.

Fig. 6.2: Freestyle park with super and medium pipes (Laax, Switzerland, 2016). Left: large and medium step-down jumps. Adjacent: medium line with rails, tabletops and wallride – photo: Roger Heid.

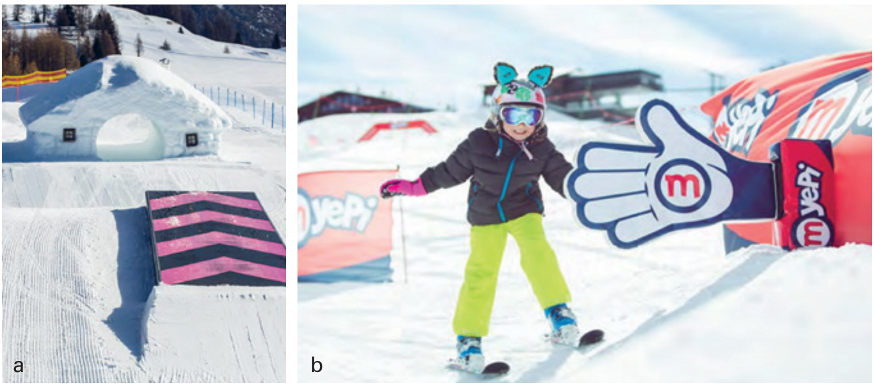


Fig. 6.3: a) Fun line with box and snow tunnel. b) Fun line high-five feature (Livigno, Italy, 2016) – photos: www.schneestern.com.

6.1 Freestyle Parks[2]

A good freestyle park consists of **jumps** built out of snow[3], and **jibs**. One example of a jib might be a table creatively integrated into the snow surface for users to glide over, push off from, or tap (Fig. 6.11). Series of jumps and/or jibs of similar difficulty are positioned in so-called lines, which users pass through in sequence from top to bottom (Figs. 6.2 and 6.4). Table 6.1 lists typical freestyle park features, though there are virtually no limits on the creativity of park builders. Freestyle parks must be clearly separated from slopes.

Fig. 6.4: Left: small freestyle park with two lines. Right: freestyle park with a medium line, and a large line on the right with an extra-large step-down jump at the start (Les Deux Alpes, France, 2006).

1 Larger facilities, e.g. at the Olympic Games, are only built by park construction companies (e.g. whiteindustriesltd.com; schneestern.com; shape-academy.com; f-tech.bz).

2 Usually they are simply referred to as parks, or as snow, fun, terrain, or slopestyle parks.

3 Earthworks can help to reduce the quantity of snow needed to construct larger jumps. In Switzerland, earthworks require authorization and often have an environmental impact (see Section 7.5.2).

As when constructing slopes, users' different **levels of ability** must be taken into account. Yet whereas slopes can be relatively easily categorized based on their gradient, making it easy to give users reliable information, it is not as easy to **grade the difficulty of park features**. For above all, it is users' personal preferences, rather than just the size and type of a feature, that determine its degree of difficulty.

Table 6.1: Typical freestyle park features. Also see the following figures.

Jumps	**Jibs**	**Others**
Tabletop	Box – flat, bow, curved	Quarterpipe
Step-down	Rail – straight, kinked, bow, curved	Airbag jump
Step-up	Tube	Seating area
Roller	Picnic table	Snow bar
Drop	Wallride	
Gap	Bonks – e.g. barrels or logs	
Corner (hip) or spine		

a

b

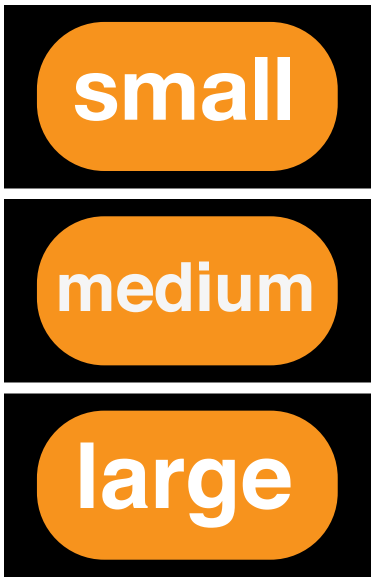


Fig. 6.5: a) Official placard from the Swiss Commission for the Prevention of Accidents on Snowsport Runs (SKUS) with the rules for safe behavior, displayed at snow park entrances. b) SKUS labels for snow park features (www.bfu.ch).

For this reason, the **smart-style concept** is recommended, which involves **park-specific difficulty grading** and standardized **signage**, but on top of that focuses above all on promoting **safe behavior in snow parks** (Fig. 6.5). The colors blue, red, and black, used to indicate slope safety, should not be used to signal the difficulty of park features, because this can lead to misjudgments. After all, not everyone who can ski down a black slope will automatically be capable of tackling "black" jumps in a park (WEILER 2013).

Grading difficulty based on feature size:
- **SMALL:** beginners should be able to negotiate the easiest features without any previous park experience, and without even having to jump. Clearing an obstacle should never require jumping higher than 0.5 m off the ground
- **MEDIUM:** intermediate obstacles with jump distances of between 5 and 12 m, for experienced park users
- **LARGE:** difficult obstacles with jump distances of 10 m and above, for experts. X-LARGE or PRO labels may serve to indicate extra-large features primarily used by competitive athletes.

6.1.1 Jumps[4]

A jump is determined by the size (height and length) and shape (curvature and gradient) of the inrun, transition, take-off, table, and landing (or landing slope) (Fig. 6.6).

The shape and proportions of the different parts of a jump have to match. For example, the longer and larger the take-off area, the wider and longer the landing zone should be. Although **no standardized jump geometries** are desired by all those involved in park construction, the following key points should be taken into account:
- an **inrun** should lead straight to the kicker and have the most invariable gradient possible

[4] Also called kickers and ramps.

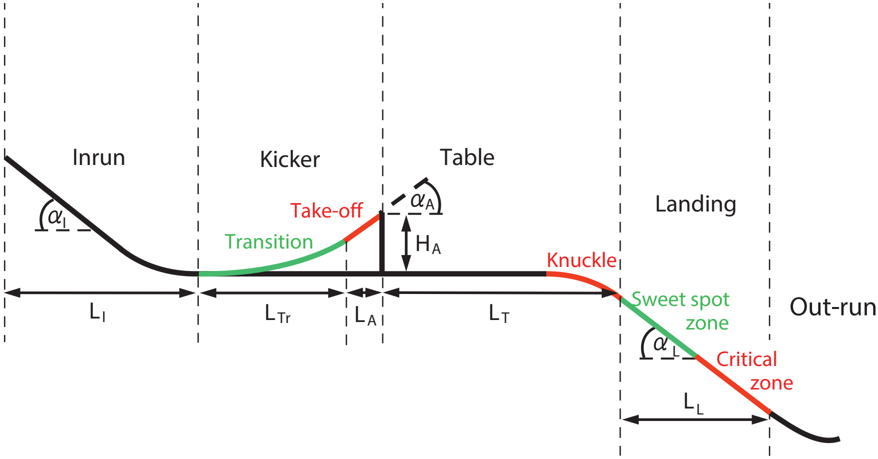


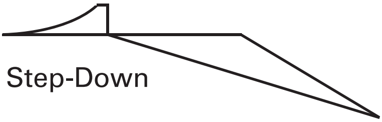
Fig. 6.6: The various parameters of a jump, describing its size and shape. The take-off is also sometimes called the transition.

– the **shape of the kicker** (height H_{TO}, length L_{TO}, gradient α_{TO}, curvature) should depend on the type of jump and always be tailored to the landing (Fig. 6.7):
  - the wider and longer the landing zone, the larger the kicker can be
  - the transition from inrun to take-off must be smooth, i.e. allow plenty of space for a **long transition** (L_{Tr})[5]
  - the take-off is the straight, non-curved end of the kicker[5]: the larger the jump, the faster the approach speed, and the longer the straight take-off needs to be (about 0.5–2 m)
  - the steeper the landing (α_L), the steeper the angle of take-off needs to be (α_{TO})
  - for large jumps the landing should be a few degrees steeper than the take-off

[5] Due to the curvature of the transition, angular momentum is generated as users pass through, which would cause them to rotate backward if they did not compensate by shifting their weight. If they lose their balance because the transition is abrupt and strongly curved, they can suffer a bad fall. Long transitions and straight take-offs are therefore safer.

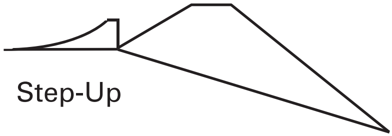
  - flat (take-off < 20 °) kickers that are only slightly curved are easier to jump off from and are more quickly passed over
  - steep, highly curved kickers require experience and precision on the part of builders and jumpers alike
  - kickers should be at least as wide as a snowcat, as this makes them easier to groom and is also beneficial to jumpers
- a **table** should be at least three snowcats wide, allowing free passage around the jump during its preparation
- the **landing zone** should be at least twice as long as the table and widen out toward the bottom
- there is a **lower risk of injury**[6] with tabletop, roller, and step-up jumps than with gaps and drops. With step-down jumps, the risk of injury can be minimized by building the table slightly uphill so that the landing zone starts higher up, lowering the fall height, similar to the geometry of a step-up jump (Fig. 6.9). The **tabletops** of SMALL jumps should preferably be built with flat take-offs so that users have the option of sliding right over them without taking off.

[6] When jumping, the fall height refers to the user's distance above the ground. In the event of an accident, a higher fall height often increases the **seriousness of the injury** (= injury hazard). The same is true of a higher landing speed, whereas a higher take-off speed increases the **likelihood of a fall**, as it is harder get the timing right. Likelihood of falling plus injury hazard equals actual risk of injury.



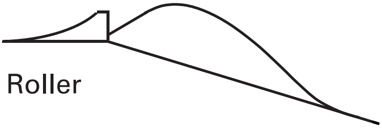
Step-Down

Steep take-off (up to around 32°), whereby the landing area begins far below the take-off point.
+ easy to build
– high fall height and landing speed[6]



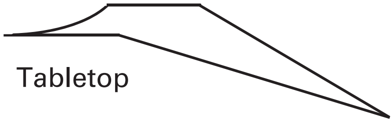
Step-Up

Very steep take-off with a steep landing area that begins above the take-off point.
+ low fall height and landing speed
– high take-off speed
– a lot of snow required/rare shape of terrain



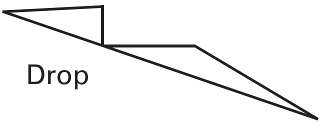
Roller

Steep take-off with a curved landing area that is adapted to the jumper's trajectory and begins at roughly the same height as the take-off point.
+ low fall height
+ is forgiving of excessively fast or slow approach speeds
– elaborate construction



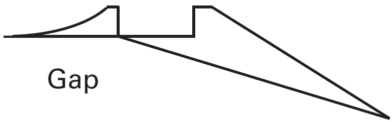
Tabletop

Take-off and landing are connected by the tabletop. The landing area begins at the same height as the take-off point.
+ low fall height and can be skied over
+ variable feature/also together with jibs
– expensive to build and maintain when large



Drop

Flat take-off (< 5°). The landing area starts well below the jump.
+ low take-off speed
- highest fall height
- elaborate construction/rare shape of terrain



Gap

Steep take-off. The landing area begins at the same height as the take-off. In between is a gap.
+ spectacular
– very high injury hazard

Fig. 6.7: Different types of jump. There are not always clear boundaries between step-down, roller, and step-up jumps. In reality, the transitions from table to landing area are rounded off.

Fig. 6.8: In the foreground, a medium-line roller (table ca 8 m high). In the background, two small-line tabletop jumps (ca 3 m high; Davos, Switzerland, 2014).

Fig. 6.9: Large-line step-up/down jump (table ca 15 m high; Davos, Switzerland, 2014).

Fig. 6.10: Step-down jump (table ca 15-20 m high) in Olympic slopestyle (Rosa Khutor, Russia, 2014).

Fig. 6.11: Various jibs (Laax and Davos, Switzerland). a) Rainbow box – photo: Marc Stal. b) Rainbow rail – photo: Roger Heid. c) Tree bonk for tapping, jumping over, or resting on.

6.1.2 Jibs

Jibs are artificial metal, plastic, or wooden features that users normally glide over. **Boxes and rails** (Fig. 6.11) are among the standard jibs found in freestyle parks. Unlike rails, boxes provide a surface to slide on that makes it easier for users to maintain their balance. Nowadays, there are also especially wide, flat, and short boxes for beginners, with no metal tube surround. The longer, higher, and steeper boxes and rails are, the harder it is to glide over them. The most difficult features are also curved (rainbow) or kinked as well.

There are no prescribed quality standards for jib features either. Nevertheless, to increase safety and comply with due diligence obligations, park operators should meet the following **minimum requirements** when installing jib features (Weiler 2013):

- the manner of construction and choice of material must make them **unbreakable** and **weatherproof** (resistant to corrosion and UV radiation)
- features must be **stable** and firmly anchored in the snow
- features must be **closed structures** that rule out straddling or snagging
- **any connections**, e.g. from sliding surfaces or pipes, must be **level**. Joints should never be more than 5 mm wide. Welding seams must be sanded down.
- all **edges must be rounded** (radius = 5 mm) and deburred. There must be no protruding screws or sharp parts.

To ensure the safest possible use of jibs, it is also vital that they are securely anchored in the snow surface. As with jumps, the inrun, transition, take-off, and landing of jibs must all be built to suit their size and shape (see Section 6.1.3).

6.1.3 Planning and Constructing Freestyle Parks

If a ski resort decides to build a freestyle park, it should first ascertain whether the available resources will suffice to achieve its goal. The following questions are important in this connection (Weiler 2013).

- **Who is the target group?** Which features of which size should therefore be considered for inclusion? What form should the communication and marketing strategy take? How will event planning be organized?
- **What's the park's planned location?** Is the terrain suitable? Is any snowmaking infrastructure available?
- **Who will build and maintain the park?** Are resources (workers, machines and infrastructure, know-how) available? Does the preparation team need to be enlarged, or will external park designers be commissioned[7]?
- **Who will finance the park?** How much is it expected to cost? What is the available budget? How much revenue will the park generate?

Once the basic concept behind the park has been identified, a design is produced to specify the work to be done to build it. This design comprises a simple sketch indicating the proposed park's various lines and features and their rough configuration. Particular attention should be paid to the following points:
- if possible, **avoid north and west-facing locations and sites exposed to wind[8]**;
- take account of the existing **inrun length and gradient** when determining the number and size of features. On average, the park's terrain should be no steeper than 22° in most places (red slope). Blue slopes (< 14°) are ideal for parks catering for beginners.
- incorporate **natural terrain** (humps, cornices, trails, undulations, and rocks) to reduce the workload and the quantity of snow required.

[7] The BFU recommends that ski resorts only build small snow parks themselves, and involve external designers in the construction of larger parks. The BFU snow park guide provides planning and building checklists (Weiler 2013).

[8] With south-facing jumps, although the required inrun height varies as the snow conditions change (see Section 6.1.4), the upside is that landing areas soften throughout the day, while the shaded take-offs remain stable. North-facing slopes produce the most stable conditions and require the least maintenance. That said, constant shade is unattractive. West-facing locations are also not ideal, as take-offs soften considerably while landings tend to remain hard.

[9] The operating costs incurred by snowmaking systems are lower than those incurred by the time-consuming piling up and compacting of natural snow. If, despite this, you choose to work with natural snow, snowcats should compact layers with a maximum thickness of 30 cm.

Fig. 6.12: A jump's landing hill under construction (Stelvio, Italy, 2017).

In the final step, individual features (type, size, shape, workload, quantity of snow required, cost) are **specified in detail**, including barriers, signs, seating, and so on. The aim is to draw up the most exhaustive list possible of everything needed for the park. Furthermore, drawings should be produced of every feature of every jib or jump, specifying their exact dimensions, to serve as a basis for their actual construction.

In principle, the **landing zone of any feature is always built first.** The take-off zone is then constructed to match the size of that landing area. **Machine-made snow**[9] is an ideal building material because it is very dense and consolidates quickly. Moreover, it can also already be piled up wherever it is needed. During construction, once the snow has been placed in position, there should be a fairly **long respite period** (of more than 16 hours) before final shaping, so that the grains can coalesce and the snow can consolidate again (see Section 3.2.2).

If **snow is wet to very wet when produced**, it should be used immediately. If it is only used after lengthy storage, it will not consolidate well when the planned features are built. The main reason for this is that the grains in wet snow coalesce into larger clusters (see Section 1.3.4.2). If this snow is then used for further work, these coarse-grained structures will seriously hamper consolidation induced by sintering. Adding water is then often the only solution when that snow is used for construction. But it is vital that the take-off and landing zones should not ice over, as that would increase the injury hazard.

When **building jumps**, experts recommend proceeding as follows (WEILER 2013):

- **produce the snow and move it** to where the feature is to be built
- use poles to **mark out** the landing slope from beginning to end
- use a dozer blade to **heap up the snow** at the end of the landing to prevent snow from sliding away during the jump's construction
- **construct the table and landing slope**, working downward from the top (Fig. 6.12)
- **build the take-off**
- **create the curvature of the transition** and take-off (also with a dozer blade)
- **cut out** the sides and front
- use a finisher and tiller to **smooth out** the take-off and landing, working from top to bottom (Fig. 6.13). Use shaping tools to do precision work by hand (Figs. 6.14 and 6.15).

Fig. 6.13: A tabletop landing being smoothed out with a tiller and finisher (Stelvio, Italy, 2017). When constructing and maintaining snow park features, snowcats should be small and maneuverable. Moreover, tillers and dozer blades should be extremely mobile. Flexible tillers need to be fixed in place when preparing landings and take-offs to prevent lateral curvature of the snow surface.

Rails and boxes are constructed as follows (WEILER 2013):
- use poles to **mark out** the fall line and length of the feature (including the landing, etc.)
- **build** a wide shelf of snow (table) with the desired inclination and landing zone
- **anchor** the feature to the table
- **build the take-off** (at least 1 m wide)
- **shift** the side walls of the table to match the width of the take-off
- use a snowcat to **smooth out** the landing and lateral fall zones. Add the finishing touches to the take-off by hand using shaping tools.

6.1.4 Maintaining and Running Freestyle Parks

Features need to be **maintained on a daily basis** to keep freestyle parks attractive and safe. Just like slopes, parks should be groomed when the snow is soft and easy to work with, which is usually the case immediately after the facility's closure (see Section 3.3). The **main tasks of park maintenance teams** include:
- **regenerating** inruns, take-offs, and landings (using a snowcat or shaping by hand; see Section 3.3.2). A winch should be used when working on steep landing slopes, working from bottom to top (WEILER 2013).
- **repairing damage** (using a snowcat or hand-held shaping tools):
  - softening landing zones (tilling hard layers of snow or ice)
  - filling in depressions, e. g. tracks in the transition; removing bumps
  - fixing slanting jib features, loose parts, broken sliding surfaces, etc.
- **checking** barriers and signs
- **closing off** features in dangerous conditions (strong wind, fog, snow that is too hard or too slow)
- **sliding away** large quantities of new fallen snow
- using snow hardener (see Section 4.4) and/or covers (see Section 5.3) to prevent the snow on the inrun or take-off from softening during **competitions**, e.g. during thawing

Fig. 6.14: A kicker being shaped (smoothed) – photo: www.schneestern.com

Fig. 6.15: a) A rail take-off being shaped (Kitzbühel, Austria, 2015) – photo: Roland Haschka.
b) A shaping tool for cutting through walls of snow, e.g. in halfpipes – photo: shapetools.ch.

Further safety measures:

- in poor visibility, **slope safety colors should be used to mark take-offs and landing zones** (Fig. 6.19)
- if a jump only requires a low approach speed, a small **barrier should be installed to shorten the inrun**
- with large jumps in particular, fluctuating snow and/or wind conditions can significantly alter the approach speed[10]. This can result in serious injuries if the jump onto the table is too short or the jumper overshoots the landing zone. **Wind vanes and speed indicators** at the start of a transition help jumpers to assess prevailing conditions more accurately.
- the snow's hardness in the landing zone, which depends mainly on the weather and the position of the sun, is another factor determining the injury hazard posed by jumping. As well as the measures listed above, notice boards at park entrances should **warn of foreseeable dangerous conditions** (e.g. in the morning during spring weather or if natural snow is in short supply).
- **any changes in jumps' geometry** during a season caused by snowfall, melting, and preparation (e.g. a landing that has become too flat), should be **spotted and rectified**. Having experienced, knowledgeable shapers is essential

[10] To reduce the danger of excessively long or short jumps, US scientists have calculated special landing geometries with which the vertical landing impact for various distances of jump always remains constant (McNeil 2012).

6.2 Cross Courses

Cross courses are downhill runs separate from slopes, with various **obstacles made of snow**, e.g. jumps, undulations, banked turns, and terrain drops. A cross track has a defined **start and finish**, and is taken on by up to six competitors at once. Cross courses vary enormously, ranging from world cup tracks for top athletes, and sporty freeride cross for anyone, to fun trails for children (fun lines) with snow tunnels, high-fives, and so-called rainbow bridges (Fig. 6.3 and 6.16). Competitive cross tracks cannot be constructed without experienced park designers[1]. Assuming the right choice of terrain, however, **family-friendly beginners' tracks** can be built without external supervision by slope preparation teams, with an acceptable amount of effort.

The **smart-style concept** should also be applied to cross courses, to alert users to dangers and encourage safe behavior (see Section 6.1). Just like lines in a freestyle park, the obstacles in a cross courses should have a similar level of difficulty. Cross courses must also imperatively be cordoned off at the sides, so that users can only enter them at the start. It is especially important for cross courses to be designed to **flow freely, without requiring significant braking** (Weiler 2013). Their users must be able to glide over or, if possible, bypass obstacles.

Fig. 6.16: a) Fun line with rainbow bridge. b) Freeride cross with two drops (Montafon, Austria, 2016) – photo: www.schneestern.com.

Fig. 6.17: a) Beginners' cross course with small tabletop jumps, banked turns, and series of dips and undulations (Laax, Switzerland, 2016) – photo: Roger Heid. b) Fun line with banked turns, snow tunnels, and other features – photo: www.schneestern.com.

6.2.1 Cross Course Features

Jumps

Jumps on regular cross tracks should have **flat** (< 20°), **low take-offs** (H_{TO}). Accordingly, **landings should also be flat and long**, so that users can jump or glide over them either quickly or slowly. **Tabletops** or **step-down jumps** without cutaway fronts that users can glide over and with a low take-off height are the most suitable features (Fig. 6.19).

In principle, there must be no risk of the speeds reached on the track being so high that users can **overshoot the landing zone**, and the take-off must be flat enough to prevent them from losing balance in the air. To guarantee this, the stretch of track leading up to the jump as well as the jump itself can be adjusted.

Dips and undulations

Series of dips and undulations are fun and also challenging for snow sports enthusiasts at all levels of ability. Runs containing these features should be laid out so that they can be **negotiated** at full speed **without losing contact with the ground** (and crashing into the next rise). To ensure this,

Fig. 6.18: Four features on the ski cross course at the 2014 Winter Olympic Games (Rosa Khutor, Russia): a hill of dips and undulations, sloping turn, step-down jump, and banked turn.

Fig. 6.19: Three features (step-down jump out of a banked turn, double undulation, jump) from the boardercross course at the 2014 Winter Olympic Games (Rosa Khutor, Russia).

Fig. 6.20: a) Dips and undulations followed by a jump. b) A steep tabletop jump shortly after the start that can be taken at low speed. c) A flat step-up jump with a medium jump distance that becomes a step-down when jumped over completely. The feature can also be slid over without jumping (Stelvio, Italy, 2017).

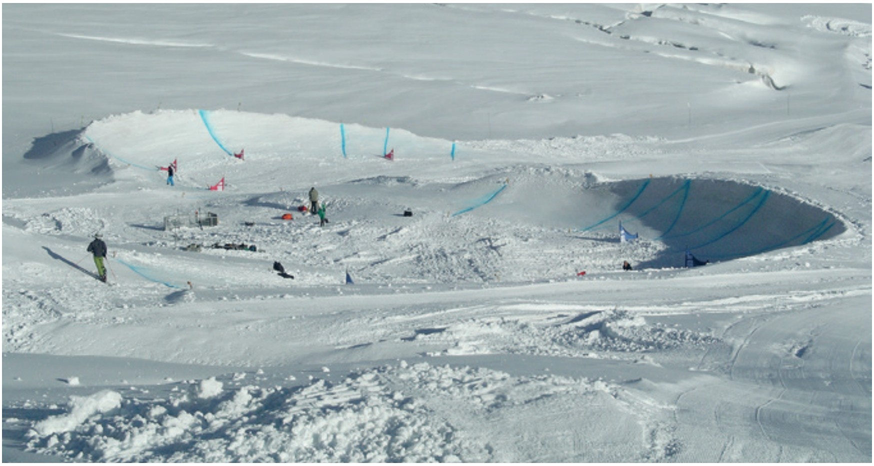


Fig. 6.21: Banked turns (Saas Fee, Switzerland, 2009) – photo: Matthias Gilgien.

Fig. 6.22: Construction of a banked turn for a regular boardercross track (Stelvio, Italy, 2017). The snow is pushed upward and outward in a radial direction from the inner side of the turn. Finishing can take place once the snow has been left to consolidate, this time in the direction that users will be traveling. Unlike with landings, take-offs, and undulations, a flexible tiller that can adapt to the curvature of a bend must be used for banked turns.

the **distance between successive undulations** should be at least one-and-a-half times the length of a snowcat. This also makes it easier to groom the track with a snowcat, because if the undulations are too small and steep, the tiller and dozer blade will rise off the ground. Ideally, dips and undulations should be created on flat terrain. Since speed increases when traveling downhill, undulations near the end of the run should be positioned further apart.

Banked turns

Steeply banked turns are an integral part of cross courses (Fig. 6.21). They should **not be too tight**, to ensure that compressive forces are kept within tolerable limits. Banked turns on regular cross courses should not be too steep either (< 40°), so that they can still be groomed by a snowcat (Fig. 6.22). What is more, their position on the track should rule out the possibility of entering the turn at too high a speed. This will reduce the risk of traveling too fast and **flying out of the turn**, which is to be avoided at all costs! Should these precautionary measures prove impossible, it is wiser to build a normal turn (Weiler 2013).

6.2.2 Planning, Constructing, Maintaining, and Operating Cross Courses

The planning and construction of cross courses is in many respects similar to the approach taken for freestyle parks (see Section 6.1), but there are differences regarding the choice of terrain. On cross tracks, the **average gradient should be no more than 10 degrees**[11]. There must also be enough space for the track to run sideways, across the slope. If the site is too steep, more money, effort, and snow will be required to build such lateral sections or construct obstacles facing up-slope to make the track's users slow down.

Once the site has been selected, the precise track (line) is determined. An optical inclinometer is a big help in this regard[11]. Beginning at the start, it can be used to plan the objective of the next section and provide infor-

[11] The gradient can be determined using good maps or measuring devices (see Chapter 8).

mation about its gradient and length, preventing the choice of an overly steep line. In general, **the steeper the section, the shorter it should be**, to prevent the track's users from reaching excessively high speeds. Once the line has been determined, the edges of the track are marked out (it should be at least equivalent to two snowcats wide), and the features to be built are outlined in a rough plan.

Features are constructed in the same way as for freestyle parks (see Section 6.1.3). If maintenance is to be efficient and require a minimum of manual labor, **it must be possible to drive a snowcat over all the track's features**. To ensure that larger quantities of new fallen snow can be removed, it must also be possible to drive onto and off the track between its features. When finishing features, the sides and areas beside the track should also be leveled, to minimize the threat of injury in the event of a fall. Edges that break away, unleveled snow surfaces with holes and clumps of snow, and other hazards must be remedied or removed. Other **maintenance and management** measures are equivalent to those applicable to ski slopes (see Section 3.3) and freestyle parks (see Section 6.1.4).

6.3 Halfpipes

As the name suggests, a halfpipe (often shortened to pipe) looks like half a pipe scooped out of the snow. Nowadays, competition pipes are up to 7 m high. Their size and shape need to meet the specifications of the International Ski Federation (FIS; Tab. 6.2).

It is fundamentally important when building a halfpipe to be mindful of the **target group** who will be using it. **Smaller halfpipes** are better suited to recreational sport. Medium pipes (1.5–4 m) or small pipes (under 1.5 m) are not as high and are constructed on flatter terrain (e.g. the Laax medium pipe: 13—15°). Moreover, small pipe walls have no vertical section (often abbreviated to “vert"). Halfpipe sizes are also limited by which tillers are available (Fig. 6.27).

Halfpipes should ideally **be either north- or south-facing** so that their walls are exposed to equal radiation and have virtually the same properties. North-facing locations are particularly suited to pipes that will still be used well into the summer months.

Tab. 6.2: FIS specifications for competition halfpipes (FIS, 2016).

Category (size)		Level A (22 ft)	Level B (18 ft)	Level C (15 ft)
Wall height [m]		6.7	5.3	3.5
Skiable length [m]	Minimum	150	120	100
	Recommended	170	150	120
Width [m]	Minimum	19	17	15
	Recommended	22	19	17
Inclination [°]	Minimum	17	16	14
	Recommended	18	17	15
Vert		top of wall	top of wall	0.2 m @ 82–83°
Competition categories		OWG, WC, WSC	OC, UVS, WJC, YOG	NC, FIS, JUN

Fig. 6.23: Olympic halfpipe (Rosa Khutor, Russia, 2014). The wall, or more specifically the passage from flat to vertical, is also called the transition.

6.3.1 Construction and Maintenance of Halfpipes

It is recommended to construct halfpipes (see Section 6.1.3) **using only machine-made snow**. Large competition pipes require huge volumes of snow. Despite considerable ground profiling, around 60,000 m^3 of machine-made snow is required for the superpipe in Laax, Switzerland (Fig. 6.24). **Shapers' know-how** and years of experience are key to ensuring a high-quality halfpipe.

Halfpipes are constructed as follows (Weiler 2013):
- **produce several piles of snow** where the pipe walls will be (Fig. 6.25)
- use a dozer blade to make two **snow walls** parallel to the fall line, creating banks, with a lot of snow accumulating in the middle (Fig. 6.27) (take account of snow consolidation; see Section 6.1.3)
- make the **snow walls** the **same height** (Fig. 6.26)
- use a laser or cord to **mark out** the centerlines and **the two copings** depending on how wide the halfpipe is meant to be
- **chainsaw off the verts** along the coping markings (about 0.5 m deep at an angle of around 80 °)
- **push snow out of the pipe** in one-meter layers to initially create a trapezoid shape with tiered walls

Fig. 6.24: Ground profiling to reduce the quantity of snow required when constructing a pipe (Laax, Switzerland, 2017).

Fig. 6.25: Snow being produced to construct a halfpipe (Davos, Switzerland, 2016).

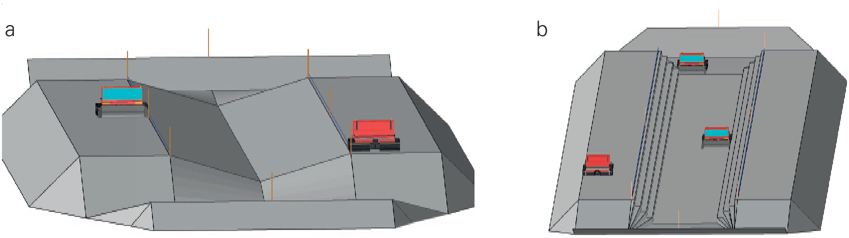


Fig. 6.26: a) Snow walls being created. b) Tiered walls being tilled (after WEILER 2013) – image: www.schneestern.com.

Fig. 6.27: Construction of pipe walls – photo: www.schneestern.com.

– gradually remove the tiered walls using a **pipe tiller** to form the halfpipe shape (Fig. 6.26, right)
– remove the **tilled snow** using a rotary snowplow or dozer blade (Fig. 6.28)
– **smooth out** the flat bottom and platforms with a finisher and tiller
– **once completed**, leave the halfpipe untouched for some time (at least 8 hours) to give the snow surface time to consolidate (see Section 1.3.2)

Halfpipes in poor condition are no good for users and can also prove dangerous, so it is very important to **maintain them** throughout the entire season. This mainly involves:
– **using a pipe tiller** to smooth out and reprofile **eroded walls**. As much snow as necessary, but as little as possible should be tilled away, to avoid any significant change to the halfpipe's dimensions. Minor damage can be repaired by hand using a **chiseling tool** or **snow rake.**

Fig. 6.28: Snowcat with pipe tiller (Laax, Switzerland, 2016): tiller blades and a finisher shape the surface of the pipe. The integrated rotary snowplow sprays the snow out of the pipe (Zaugg AG, Switzerland) – photo: Roger Heid.

- repairing **holes or chipped areas**, which is tricky. One option is to try to spray newly-produced wet snow directly onto the damaged area using a fan gun and then till it.
- using a dozer blade to push **drifted snow or large quantities of new fallen snow from the flat bottom** out of the pipe. If the new layer of snow is less than 5 cm deep, it can be compressed in the halfpipe.
- using hardener on the flat to temporarily consolidate **snow that is too soft for competition use**. Covering the walls with geotextiles can also slow down the softening process (see Sections 4.4 and 5.3).

7 Snow Management

Snow management is the term used to refer to the **planned and forward-looking handling of snow** in the context of snow sports applications and tourism. Identifying potential ways of optimizing snow management at ski resorts requires knowledge of the factors affecting slope quality and how they are interrelated (Fig. 7.1). Knowledge of microclimates and quantities of snow on various slope sections can, for example, be used to manage snowmaking equipment or calculate when ablation is expected to start on an existing slope.

The prime concern of snow management is to **efficiently handle the resources used in** snowmaking and slope preparation (e.g. energy, water, labor). A huge variety of technical and organizational measures and tools are deployed for this purpose, such as measurement and software systems to ascertain and visualize snow depths. Managing snow helps to reduce costs while improving the **quality of snow sports facilities**, which increases **customer satisfaction** and boosts the **resort's profitability**.

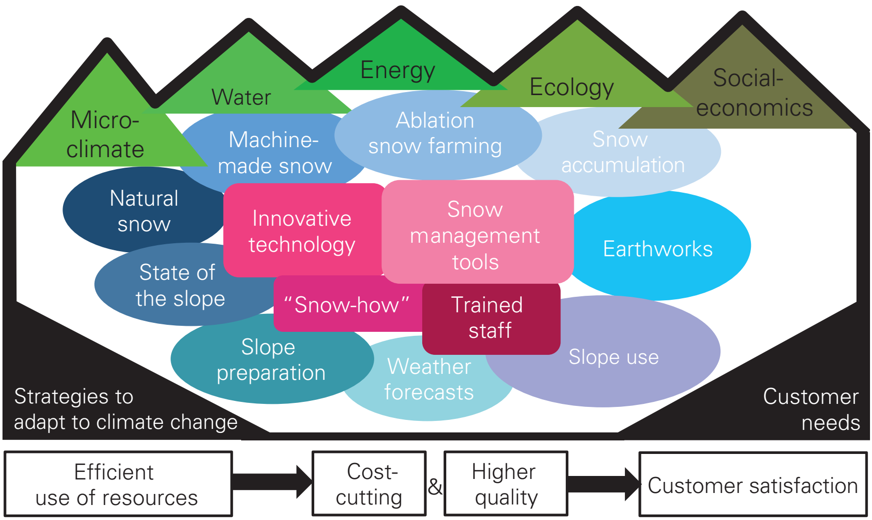


Fig. 7.1: Snow management: general conditions (green and black), components (blue and red), and interactions.

Every ski resort practices snow management to a certain extent. To facilitate the expansion of these activities, this chapter briefly describes state-of-the-art methods and the benefits of modern snow management.

Successful snow management above all requires the **collaboration of organized, motivated, skilled personnel**. Consequently, when purchasing technical systems, ski resorts should ensure that there is close cooperation with the supplier[1], who will also help them to roll out and establish the system in the day-to-day running of the ski resort. The Mayrhofner Bergbahnen resort identified the following keys to success when introducing a comprehensive snow management system (Schneider 2015):

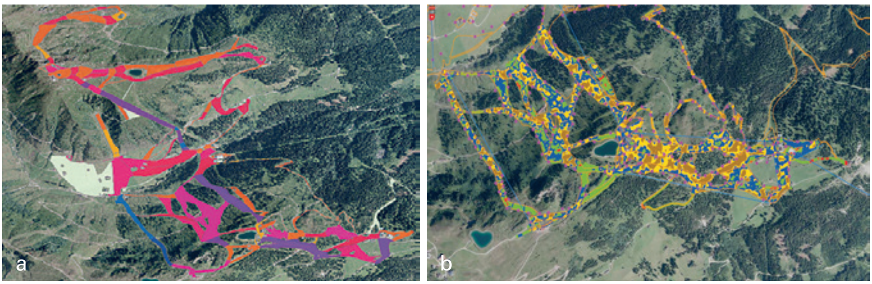
- set **goals**: break down the overall objective into interim goals and work packages:
  - e.g. start-of-season strategy – open as early as possible or focus on seasonal vacationers?
  - e.g. when should which slopes be opened?
- set up **project organization** (e.g. project manager, project team)
- ensure good **communication**, with regular meetings
- develop and introduce **tools** and **instruments**:
  - e.g. to plan, measure, and manage the quantities of snow produced, the quantity of water required, pump capacity, and so on per slope section (Fig. 7.2).
  - e.g. to determine slope quality
  - e.g. to ascertain how snowcats are driven (routes, consumption etc.)
- draw on the **experience of all employees**
- make snow management an integral part of the **day-to-day running** of the resort
- share and learn from experience
- keep permanent **records**

[1] e.g. www.pistenmanagement.at

7.1 Standardized Work Processes

Successful snow management begins with **clearly defining ski resort management tasks in terms of an objective. Work processes are then developed** and adopted for these tasks, with a view to optimizing goal attainment. In this respect, it is important to continuously monitor and record whether the objectives are being met and the processes are being implemented correctly (e.g. comparing the desired and actual depth of the snow on a slope on a daily basis; Fig. 7.2).

This will ensure consistent high quality, regardless of who does the work. If any staff member identifies weaknesses, these can be systematically rectified by **adjusting standardized work processes** for all their colleagues. This joint optimization boosts the efficiency of the entire operation. Although processes are predetermined, a successful outcome can only be ensured if personnel actively and critically implement their various tasks and openly discuss their views with managers. In other words, a process for ensuring continuous improvement must be firmly established in the company.



Gebiet	Schneehöhe Soll	Schneehöhe Ist	Fläche (Schneedaten)	Schneevolumen
FIS Steilhang	70 cm	73 cm	10.822 m² (86%)	6.775 m³
FIS oben	70 cm	71 cm	14.963 m² (80%)	8.566 m³
Familienabfahrt	50 cm	95 cm	3.547 m² (88%)	2.964 m³
Gschößalm Abfahrt	70 cm	90 cm	30.307 m² (83%)	22.774 m³
Gschößalm Abfahrt	90 cm	96 cm	26.735 m² (92%)	23.592 m³
Gschößalm Abfahrt	50 cm	63 cm	10.563 m² (87%)	5.780 m³
Harakiri	150 cm	92 cm	11.312 m² (87%)	9.099 m³
Harakiri	120 cm	88 cm	21.178 m² (85%)	15.790 m³
Harakiri	80 cm	51 cm	6.290 m² (72%)	2.307 m³

Fig. 7.2: a) Slopes divided into sections, with the desired snow depth specified.
b) Measured actual snow depths. Below: table overview of slope sections, indicating desired and actual snow depths, surface areas, and snow volumes (Schneider 2015).

7.2 Snowmaking and Microclimates

To optimize technical snowmaking, **rules** should be set, based on the following factors:

- **the intended purpose/use of snowmaking:** foundation, regular ski run, race course, park, etc.
- **time:** when during the day snow can be made, depending on the presence of skiers, electricity and other costs, and the stage of the season (available time for achieving the intended snow depth)
- **weather:** snowmaking productivity and efficiency, depending on wet-bulb temperature, wind speed, wind direction, and precipitation (see Section 1.6)
- **condition of the snow:** depth, density, and wetness (compacting/bonding of new snow by adding/mixing machine-made snow)
- **resources:** the availability and price of water, electricity rates, and snow-water factor

Automated snowmaking equipment[2] can then make many decisions independently, based on current weather data. It is important to have a dense network of reliable weather stations that can provide accurate information about the microclimate. Like decisions made during slope preparation, however, decisions regarding the quantity and type of snow to be produced also depend on logistical and other factors that are not covered by the control system.

7.3 Slope Preparation

For the purposes of snow management, **slope preparation processes** should be optimized based on the following points:

- decide on and monitor **intended snow depths** for each slope section
- **prioritize** slopes and slope sections

[2] Snowmaker manufacturers provide software (control systems) that can be used to fully or partly automatically operate individual snow guns and pump stations. Temperature and humidity sensors tailor the water flow and compressed air supply to the ambient conditions to produce snow that meets pre-set quality requirements (regarding its liquid water content).

- accurately **ascertain** the **movements of a snowcat with caterpillar tracks**, diesel consumption, speed range, winch and tiller settings, and how to reduce unnecessary driving
- determine the **optimal preparation time,** based on typical weather patterns and the condition of the snow
- **optimize machine settings** according to the condition of the slope and the snow
- **coordinate this with snowmaking**
- adjust the **areas available for skiing** (slope width and sections) depending on the availability of snow and the number of users

Since slope preparation always depends on current snow and weather conditions (see Chapter 3) and on the stresses exerted by skiers, it makes no sense to define fixed work processes. Nonetheless, an effort should be made to identify typical **snow and weather patterns**. This information can serve as a basis for establishing a set of different work processes to choose between based on the respective situation.

Measurement and software systems that record snow depths and snowcat performance indicators provide the technical data required for optimized slope preparations.

7.3.1 Measuring Snow Depth

Many snowcats already use automatic **snow-depth measurement systems**[3] . Information on slope snow depths can be used to determine where snow guns need to be employed or where additional snow is required, where there is already enough, or even where there are reserves of snow. Moreover, hotspots with little snow during preparation can be identified early enough, preventing snowcats from eroding the soil and contaminating the snow (Fig. 7.3).

3 GNSS-based snow-depth measurement systems determine snow depth based on the difference image between the current position measured by a receiver on a snowcat and the altitude of snow-free terrain. Consequently, ski resorts' terrain should be modeled as accurately as possible, and if earthworks during the summer alter that terrain, the model needs to be updated.

Collecting snow depth measurements over an entire season can also **prove useful in the long term**. The aim is to use these data to estimate the minimum snow depth required at various slope sections to ensure that slopes are optimally prepared and groomed right up to the end of the season. As a result, snowmaking in the following years will be better able to adhere to this guiding principle: **only produce as much snow as necessary** (for an optimal slope) **and as little as possible.** Not only will this lower costs, it will also cause the snow to melt more quickly after the season ends, causing less disruption to the terrain's use by farmers or summer tourists.

7.3.2 Fleet Management

Snow management software packages were originally designed to evaluate snow depth measurements, but they are continuously being developed to optimize slope quality and snowcat deployment. Since a snowcat's position is recorded when it is used to determine snow depth, the **routes it takes and its speed profiles** can also be analyzed, and in the

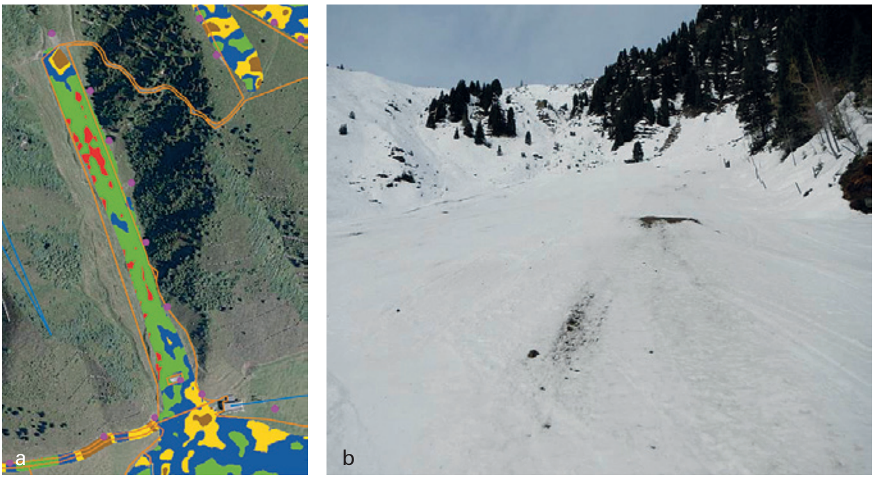


Fig. 7.3: a) Red areas show where the snow was found to be below the minimum depth required for that slope section. b) Photo of a slope section with grass poking through (Schneider 2015).

best-case scenario resources can be saved. Furthermore, digital tachometers collect engine and vehicle data, such as engine speed, fuel consumption, and tiller settings. Current systems, however, do not incorporate information about the **current or forecast condition of snow**[4] or about **skiers' movements**, which would provide data about the stresses exerted on different parts of the slope.

The components of snow management are intricately interrelated with a ski resort's overall resource management system (Fig. 7.4).

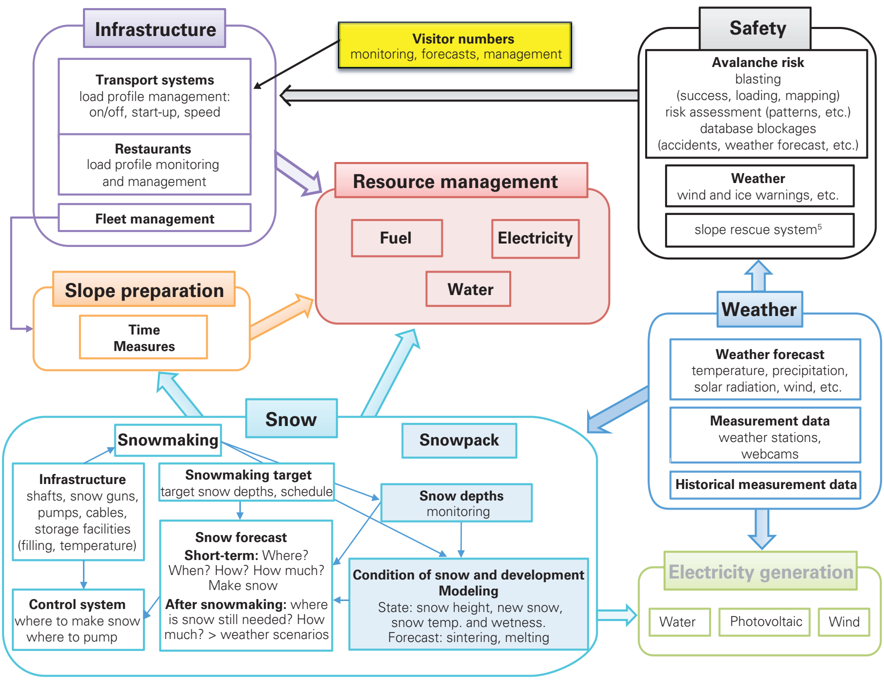


Fig. 7.4: Potential components and their interactions in ski resorts' complex resource management systems

4 The issue is currently the subject of an EU project: http://prosnow.org/.
5 A system for coordinating and recording on-slope rescues with additional functions for inspection runs to check slope quality and safety in situ.

7.4 Snow Farming[6]

Snow farming entails **preserving large quantities of snow** over the warm summer months. To minimize melting, stored snow needs to be **covered, for thermal insulation purposes**. The type of cover should be selected based on climatic conditions, technical and logistical feasibility, and the storage site's location.

Although the basic idea of snow farming has been around for a long time[7], the snow sports and tourism industries only rediscovered it in the last 10 to 20 years. In the 1990s, glacier ski resorts in particular began using bright covers (e.g. under ski lift pylons or access routes to lifts) to prevent areas of snow and ice from melting. More and more ski resorts and municipalities are now using snow farming to overcome **snow shortages,** particularly in early winter. As a result, **some snow sports can be offered** even if no snow can be produced and not enough natural snow is available.

So far, apart from at glacier resorts, snow farming has mainly been employed to ensure that Nordic skiing competitions can be held (cross-country skiing, ski jumping). There has recently been a trend towards increasingly larger storage sites that are big enough to enable the preparation of even smallish downhill slopes (Fig. 7.8 a). A recent SLF survey (Wolfsperger 2018) in the German-speaking Alpine region and Scandinavia confirms the **growing interest in snow farming:** around half of ski resort managers view it positively, whereas only 14 % are critical of it. Table 7.1 provides an overview of known snow farming projects.

6 In the Alps, snow farming (also called snow storage) has become an established method of using various insulating materials to cover and thus preserve snow during the summer months.

7 Until the start of the 20th century, snow and ice were mainly preserved for use as refrigerants over the summer. Even today, they are still used for this purpose, e.g. to cool buildings (Skogsberg 2005).

Fig. 7.5: A fleece cover in Snowpark Kaunertal (Austria, 2015) – photo: Rosi Walder.

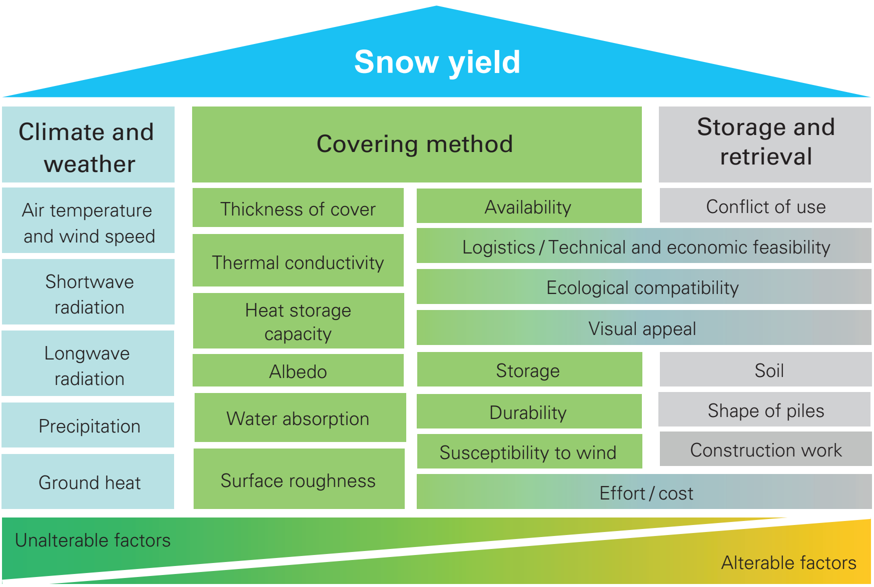


Fig. 7.6: An overview of the factors affecting snow farming. Climate and weather conditions and the choice of covering are the biggest factors determining snow loss through melting. Technical and logistical factors determine further losses incurred when covers are removed and the stored snow is spread.

Fig. 7.7: Examples of snow farming: a) Davos (Switzerland, 2017), sawdust cover. b) Val Martello (Italy, 2015), woodchip cover. c) Livigno (Italy, 2017), sawdust and fleece cover.

Tab. 7.1: Overview of known snow farming projects[8].

Location			Cover	Yield	
Country	**Municipality**	**m.a.s.l.**	**Material**	**Volume [m³]**	**Loss [%]**
AUT	St. Jakob im Walde	1,150	sawdust	2,700	26
AUT	Ramsau	1,100	woodchips/truck tarpaulin	20,000	40
AUT	St. Gallenkirch (Montafon)	2,080	film	15,000	80
AUT	Seefeld (Tirol)	1,200	woodchips	5,000	40
AUT	Hochfilzen	960	fleece	8,000	no data
AUT	Reiteralm	2,100	straw	no data	no data
AUT	Saalbach-Hinterglemm	1,000	woodchips/fleece/film	15,000	17
AUT	Hermagor	1,200	straw	400	25
AUT	Kitzbühel	1,900	insulation slabs/silage film/fleece	25,000	20
CAN	Canmore Nordic Centre	1,380	sawdust	no data	no data
CHE	Davos (old storage site)	1,650	sawdust	6,900	22
CHE	Davos	1,650	sawdust	16,000	16
CHE	Disentis	2,600	fleece	no data	no data
CHE	Davos Jakobshorn	2,600	fleece	20,500	57
CHE	Engelberg	1,050	woodchips	600	no data
DEU	Ruhpolding	700	insulation slabs/silage film/tape	10,850	30
DEU	Neustadt	820	insulation slabs/film	10,000	20
DEU	Klingenthal	569	sawdust	16,000	no data
DEU	Oberhof	815	insulation slabs/film	10,000	no data
FIN	Ruka	400	sawdust/fleece	30,000*	no data
FIN	Vuokatti	ca 100	sawdust	20,000	20
ITA	Livigno	1,800	sawdust/fleece	70,000	25
ITA	Corvara	1,900	Steinbach S500T-550	6,000	50
ITA	Martell	1,700	woodchips	7,140	33
ITA	Watles	2,300	insulation slabs/silage film/fleece	25,000	20
NOR	Söderhamn	ca 100	tree bark	no data	no data
NOR	Dovre	700	woodchips	10,000	no data
NOR	Beitostølen	820	sawdust	18,000	22
NOR	Trondheim	180	insulation slabs	18,000	22
NOR	Geilo	ca 1,000	fleece/sawdust or straw	no data	no data
RUS	Rosa Khutor	1,600	fleece/insulating mat	800,000*	20–50
SWE	Östersund	372	sawdust	55,200*	24
SWE	Orsa	ca 100	tree bark	5,000	no data
SWE	Piteå	ca 100	tree bark/fleece	3,400	30
SWE	Arjeplog	ca 100	tree bark/fleece	1,600	60

* Total volume, split into several piles

[8] Glacier covers are not listed here but they are intensively deployed in the Alps (e.g. in Kaunertal, Pitztal, Sölden, Diavolezza, Gemsstock, Saas Fee, and on the Vorab Glacier).

Fig. 7.8: Snow farming examples: a) Kitzbühel (Austria, 2016), insulation slabs (10 cm, XPS), silage film, and fleece – photo: Bergbahnen Kitzbühel. b) Jakobshorn, two layers of fleece – photo: Bergbahnen Davos. c) Neustadt (Germany, 2014), insulation slabs (20 cm, EPS) and film – photo: Markus Feser.

7.4.1 Impact of Climate and Weather

The climate and weather at the storage location determines how much energy is available to melt the snow. To select the optimal cover method, it is important to understand the contribution of the various energy inputs to the total snow melt.

Heat transmitted from the **air** and **shortwave radiation** is generally the biggest contributor to snowmelt (Fig. 7.9, blue bars). Whereas air temperatures will often drop below freezing overnight during winter thaws, in summer months the air is usually warmer than the snow, even at medium altitudes in the Alps. As a result, the air continuously transports heat to the snow, greatly accelerating the snowmelt.

By contrast, energy inputs from **rain[9] and ground heat[10]** are **negligible** (Fig. 7.9). The heat flow from the ground may be continuous, but remains minimal, even when viewed as a total over the entire storage period. Even rain has a negligible effect on snowmelt over the storage period as a whole, since the total duration of rainfall (at Switzerland's latitude) is very short compared to the duration of the storage period. A bigger problem is posed by stored snow becoming **icy and contaminated** by rainwater and the material used to cover the snow, which the rain flushes into the snow pile.

As well as absorbing energy, snow can also **release it** (see Section 2.2), mainly through **longwave radiation**. To reduce snowmelt as far as possible during snow farming, an insulating cover has to be used to minimize the energy input into the snow pile while maximizing the energy released into the atmosphere.

9 Because rain is always accompanied by temperatures above zero, heavy cloud cover, and wind, it causes considerable snowmelt. Mild temperatures and longwave radiation trigger much more snowmelt than the rainwater itself. Furthermore, a large proportion of the decrease in snow depth is caused by settlement rather than melting (see Sections 1.3.3 and 2.2.3).

10 Even in areas of Switzerland with high levels of geothermal heat flow (0.14 W/m^2), the energy input from ground heat is far below 1 % of the total energy input (Bodmer 1982).

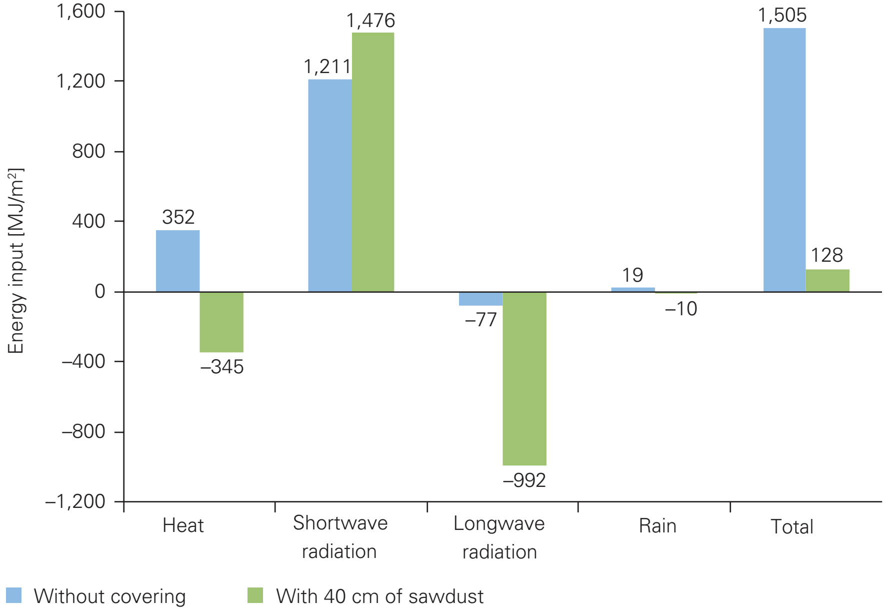


Fig. 7.9: Energy input into snow without a cover and snow covered by 40 cm of sawdust stored between April 29 and October 8, 2015 in Flüela Valley (Davos, Switzerland, 1,650 m.a.s.l.; GRÜNEWALD 2018).

7.4.2 Covering Methods

To ensure that a cover prevents energy from being conveyed from the atmosphere into the snow pile, thereby hindering snowmelt, the following **criteria** should be fulfilled:

– **a closed cover should be used** so that the air does not directly transfer heat to the snow (convective heat transfer; see Section 2.1.3)
– the **thicker the cover** and the lower the **heat conductivity** of the material, the less heat can penetrate the snow through it (thermal conduction; see Sections 2.1.3 and 1.2.2)

- the air transfers slightly less heat to **smooth-surfaced** covering materials than to materials with a rough surface
- materials with a high **heat storage capacity** (= high density and heat capacity; see Sections 1.3.1 and 1.1.1) absorb heat during the day **without transmitting it to the snow,** and release it back into the atmosphere at night
- materials that **absorb water** release heat into the atmosphere when the water evaporates (evaporative cooling). Covers also prevent the snow from absorbing additional heat from rainwater.
- highly reflective surfaces (albedo) prevent energy from being transferred by **shortwave radiation,** so covering surfaces should be as light as possible and resistant to contamination
- by contrast, where **longwave radiation** (thermal radiation) is concerned, high emissivity[11] is an advantage (see Section 2.1.2) because after being heated during the day the cover can then emit maximum heat overnight, and thereby cool down. Reflective metal film's very low emissivity therefore makes it unsuitable.

The Davos example proves that not all criteria need to be met for snow farming to be successful. Figure 7.9 shows that although **sawdust covers** absorb more shortwave radiation than the snow surface or white fleece, the fact that they are good at storing and releasing energy leads to a much lower (overall) net energy input. This is largely (74 %) due to the strong longwave heat radiation from the heated surface of the sawdust. Sawdust also releases heat into the ambient air (20 %) because its surface is often warmer than the air in the evening and at night (see Section 2.2.1). Water evaporating from the sawdust into the air also releases heat, albeit a smaller volume (6 %) (Grünewald 2018).
Suitable materials are selected based on the **availability** of materials and the **logistical feasibility** of covering the snow at the respective location (Tab. 7.2). **Climatic conditions** should also be taken into account. For example, since geotextiles, which are only a few millimeters thick, are poor heat insulators, they are only suitable for areas with low air temperatures

[11] A material surface's ability to radiate heat. The emissivity and reflectivity of opaque materials always correlate with each other.

(daily average of less than 6 °C), such as on glaciers (Rinderer 2008). Moreover, because geotextiles have a higher albedo than the surface of a glacier, they absorb less shortwave radiation, reducing melting rates by up to 60 % (at around 2,900 m.a.s.l.)[12]. Furthermore, it would barely be feasible to transport and apply, say, a woodchip covering to snow stored in a glacier depot.

Fig. 7.10: Glacier fleece cover along a ski lift route (Disentis, Switzerland, 2,400 m.a.s.l.). Snow preservation enables ski lifts on rocky slopes to remain in use even when there is very little new fallen snow. It is clear from where individual fleeces overlap that doubling up layers slightly reduces melting – photo: Otmar Venzin.

Tab. 7.2: Snow farming: covering methods.

Category	Cover	Advantages	Disadvantages
films and fleeces	geotextiles silage film truck tarpaulin	– less effort	– high snow loss – reduced albedo[12] – prone to tearing
natural materials	sawdust woodchips bark mulch straw	– less snow loss – water absorption	– more effort – winter storage – snow contamination
insulating materials	insulation slabs insulating mats[13]	– less snow loss – no snow contamination	– more effort – winter storage – decreasing insulating effect due to gradual formation of gaps (Fig. 7.12)
combinations	sawdust + fleece woodchips + truck tarpaulin insulation slabs + fleece + silage film etc.	– higher albedo – protection from water – protection from wind	– additional effort and costs

12 Olefs (2008 and 2010) identified albedo values of around 20 % for dirty glacier ice, around 40 % for clean glacier ice (Fig. 7.5), and ranging from 92 % (when new) to 46 % (after 75 days) for geotextiles. It has also been demonstrated that air pockets underneath geotextiles (also called glacier fleece) significantly boost thermal insulation. Adding a second layer has been shown to further reduce melting by around 10 %. But regular use of a snowcat to compact seasonal new fallen snow barely reduced the melting of glacier ice in the summer. Even adding water to the compacted snow did not significantly affect melting.

13 Thin (1–2 cm) plastic foam mats do not provide sufficient insulation, so their use results in significant losses through melting (as in Ruhpolding). Thicker mats are less practical than slabs.

7.4.3 Planning and Implementation

According to surveys, the availability of a suitable **snow storage site** poses a major problem for snow farming (Wolfsperger 2018). The main requirements regarding a snow storage site concern logistics, the microclimate, environmental protection, and nature conservation.

Another key criterion for their viability is the local **snow production potential** in winter. Consequently, at the planning stage, weather data spanning several years should be used to assess how much snow can be produced at the site in unfavorable conditions (Fig. 7.11). This information, together with the intended application, target quantities, and estimated losses, can then be used to evaluate the site's feasibility.

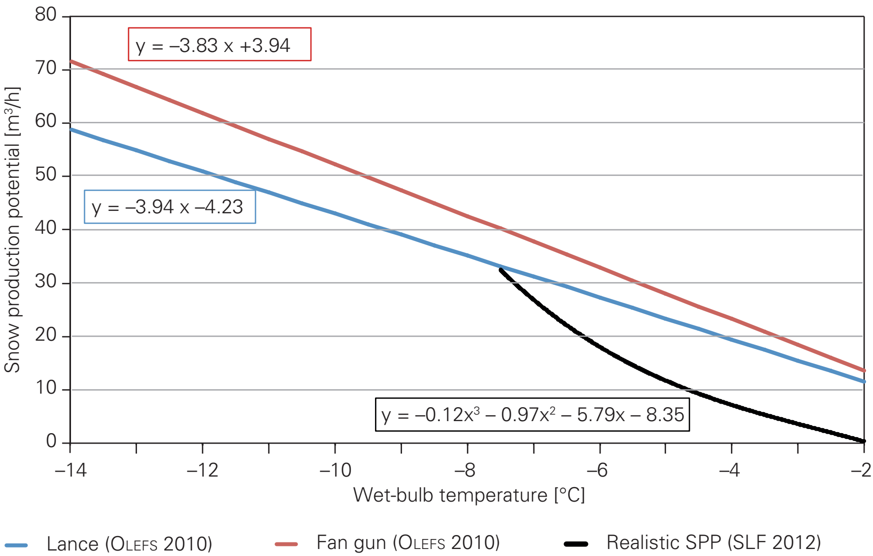


Fig. 7.11: Snow production potential (SPP) depending on wet-bulb temperature. The curves taken from Olefs (2010) are based on water flow data from snow guns, assuming a constant snow density (400 kg/m³) and no losses of any kind (see Section 1.6.1). SPP can be measured more realistically by taking account of increasing snow wetness and density in the marginal temperature range, and of a minimum loss of 15 % (SLF 2012).

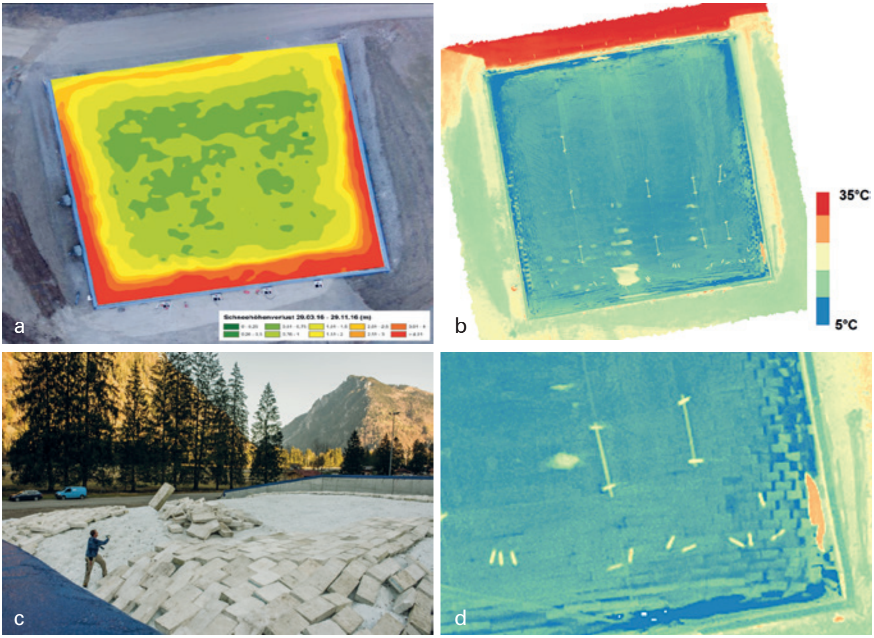


Fig. 7.12: a) Significant snow loss (red area, around 30%) due to the heat radiated from the concrete walls of a snow storage site covered with insulation slabs (20 cm, polystyrene) and silage film in Ruhpolding (700 m.a.s.l., Germany, 2016). b) and d) Shots from a thermal imaging camera show how gaps open up between the insulation slabs due to extensive melting at the edges, allowing additional heat to penetrate the snow. c) Removal of a cover in the fall – photo: Alois Reiter; thermal imaging shots/snow loss analyses: Krämer 2017 (www.wwl-web.de).

If a storage site only meets some requirements, **structural measures** can be taken to improve the situation. Logistical and technical measures are most common, such as building access roads, reinforcing the storage site's subsoil, providing drainage, or installing silo-like wall mountings. It is imperative to make sure that these structural measures do not unintentionally increase snow loss by causing the piles of stored snow to absorb more energy (Fig. 7.12).

The following points should be taken into account when **planning and implementing** a snow farming project:

1) Planning:

- define the **use and requirements**, i. e. the purpose and demand, the time when snow will be made available, the quantity of snow required[14], the duration of use, budget, resources (equipment, personnel), revenue, marketing.
- select a **site**:
  - snowmaking infrastructure, availability of water, microclimate, and snowmaking potential (Fig. 7.11)
  - conflicts of use: summer tourism, agriculture, water overflow zones, nature and landscape conservation (e.g. water conservation areas), danger zones
  - watercourses and extraneous waterlogging[15]: drainage must be ensured. Groundwater and other inflows during the snowmelt must be taken into account, especially on sites with troughs
  - storage site subsoil, access, and transport routes to the target area: stable, dry, and level subsoil that work machines can drive over is needed to minimize contamination and loss when snow is distributed (Fig. 7.20)
  - the microclimate at the storage site in summer: low radiation and wind; take account of heat radiation from buildings and roads
  - the site's potential for expansion

- **select the most suitable covering method:**
  - good insulation, suited to the storage site
  - good availability, with low transport and material costs
  - environmental compatibility (e. g. bark mulch adds acid to the ground)
  - anchorage and low susceptibility to wind
  - visual compatibility with the landscape
  - durability, low-cost recyclability
  - space-saving storage[16], low susceptibility to contamination and/or rotting

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14 Each kilometer of a cross-country trail requires around 3,000-5,000 m^3 of snow, depending on the subsoil, width, and losses incurred during spreading.

15 Extraneous waterlogging: when the ground contains extraneous (slope or ground) water as well as precipitation water. Any potential site should be assessed during the natural snowmelt in spring.

16 The storage of natural materials can generate heat. Fire-prevention guidelines must be met when storing biomass (Ferrero 2009).

2) Structural measures (Fig. 7.13):

- **storage site soil:** reinforcement (e.g. graveling, asphalting), run-off (slight gradient, drainage)
- **storage troughs, supporting walls,** awnings, snowmaking infrastructure, or similar, considering the filling of the site, snow removal, and the covering of the site in particular. Concrete walls should be entirely subterranean. Heating through solar radiation and the air must be avoided at all costs, so that the energy stored in the concrete is not transferred to the snow (thermal conduction and thermal radiation; Fig. 7.12).
- reinforcement of **access roads** to the area where the snow is stored or spread out, including to reduce the need for snow (e.g. rutted, muddy roads, Fig. 7.21)

Fig. 7.13: Structural measures to optimize snow storage: a) Snow silo with a concrete wall on three sides (Ruhpolding, Germany) – photo: Alois Reiter. b) Graveling of the storage site's subsoil in Val Martello (Italy, 2014). c, d) Asphalted snow trough with drainage, surrounded by grass pavers; wooden wall and ground reinforcement to store sawdust in winter (Davos, Switzerland, 2016).

3) Snowmaking[17]/shaping snow piles:

- the site's **snow production potential** (Fig. 7.11) must be sufficient to meet quantitative storage targets[18]
- low temperatures facilitate **efficient snowmaking**
- **highly productive snow guns** should be used (flow rates)
- when snow is being produced in the winter, **snow piles** can be **put to other uses**, e.g. serving as vantage points or toboggan runs. Snow may also be accumulated on slopes on a large scale throughout the season and only be formed into piles at the end of the season.
- **the shapes of piles** should enable their covers to be fitted as easily as possible:
  - when using insulation slabs, surfaces should not be curved
  - the angle of repose should remain below 45° for natural materials[19]. When applying sawdust with a rotary snowplow, piles should have a limited height (about 9 m), and preferably a pointed shape, because blowing sawdust onto a flat surface is not easy (Fig. 7.17).
  - large, spherical piles lose less snow, since their energy input directly depends on their surface area. The larger and more spherical a pile, the smaller its surface area will be in relation to its volume (specific surface area; Fig. 7.14). Losses will therefore be noticeably greater for piles less than 10,000 m³ in size.

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[17] Sometimes at the end of winter, existing snow is gathered up. However, this is far more expensive than efficient snowmaking.

[18] If the desired quantity cannot be produced in winter, the snow can be made elsewhere, though this will push up transport costs.

[19] Sawdust and woodchips have an angle of repose of between around 30 and 40° (Pfeifer 1977; Ima 2007). The wetter the sawdust, the more acute the angle (Stasiak 2015). Steeper piles can be built (e.g. with an angle of around 45° at snow farming sites in Davos), but this causes the sawdust on the surface to gradually slide down and accumulate at the bottom.

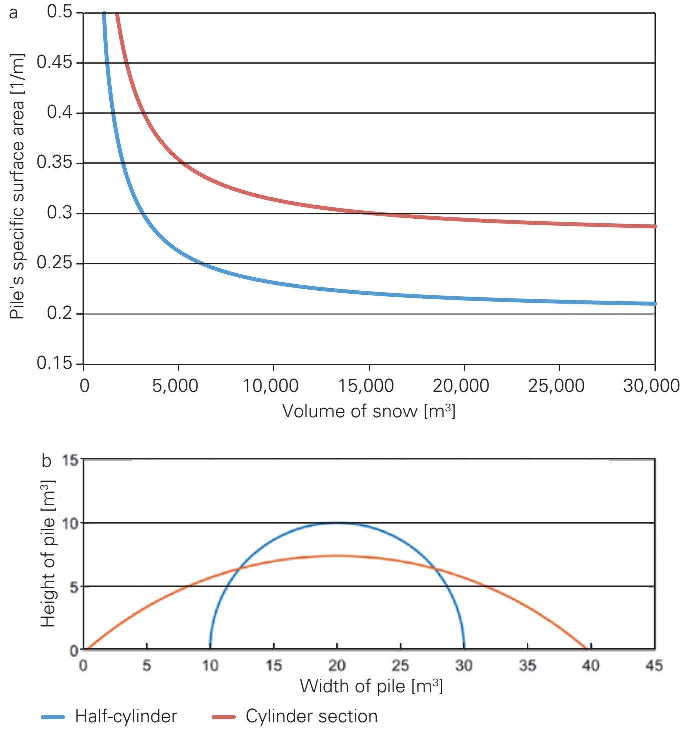

Fig. 7.14: a) The effect of pile size b) and shape (cross-sections) on the specific surface area, which directly impacts the energy input.

4) Applying the cover:

- **apply the cover early** to minimize snow loss. Shortwave radiation is already very high in April.
- apply natural materials evenly and in **sufficiently thick layers** (min. 30 cm; Fig. 7.15). A snow blower can only spread sawdust that is wet.
- **fit** insulation slabs with film and/or slats. Attach the film to the edge of the pile using carabiners or by burying it.
- prevent **water from penetrating** by properly (depending on the gradient) overlapping the sheets of film
- **join together the sheets of fleece or film** (e.g. by sewing them or applying velcro or adhesive tape)

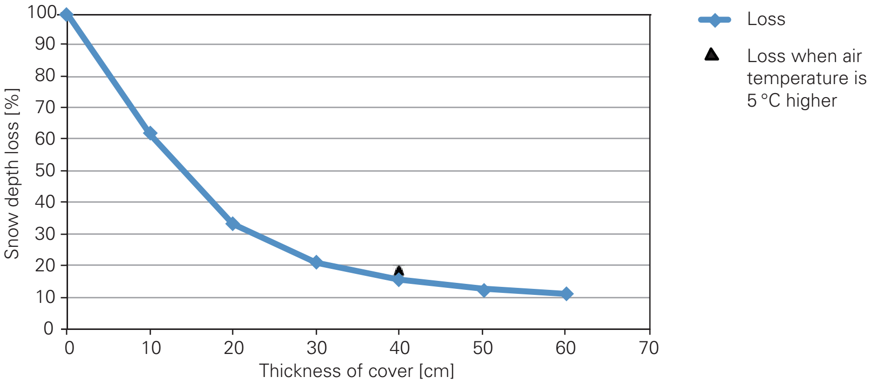

Fig. 7.15: Impact of the thickness of a sawdust cover on snow volume loss, based on a computer simulation from 2015 (T_{Air} = 11.3 °C, Flüela Valley, Davos, Switzerland) (GRÜNEWALD 2018). The study also shows that a sufficiently thick cover layer (40 cm) can preserve snow with relatively little loss, even at much higher temperatures.

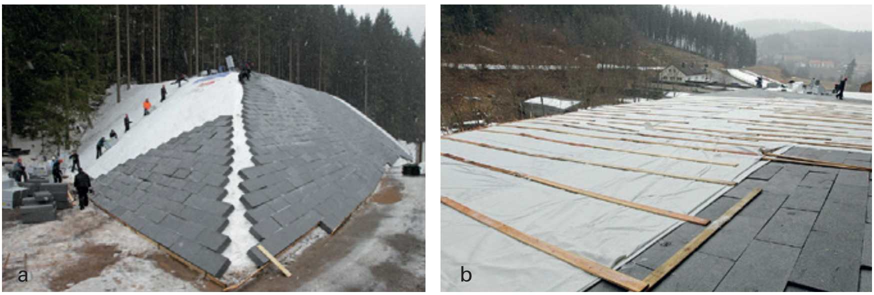

Fig. 7.16: a) Laying expanded polystyrene (EPS) insulation slabs. b) Fixing them in place (Neustadt, Germany, 2014) – photos: Markus Feser.

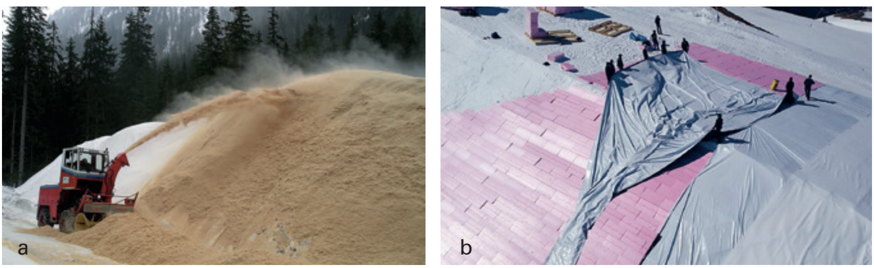

Fig. 7.17: a) A scrapped rotary snowplow spraying sawdust onto a heap of snow (Davos, Switzerland). b) Fixing 10-cm extruded polystyrene (XPS) insulation slabs in place with silage film and fleece (KITZBÜHEL 2015) – photo: Bergbahnen Kitzbühel.

5) Storage:

- **inspect and repair the cover:** damage can be caused by weather, wild or domestic animals (e.g. nest-making birds, rodents, dogs, etc.). Water tightness can be impaired (film and insulation slabs), puddles and drain funnels can form (natural material), or the cover can slip down badly and tear. Puddles increase the quantity of energy input into the cover.
- a cover made of natural material should not be allowed to **dry out completely**, otherwise more heat will penetrate the pile. In very dry conditions, it is a good idea to lightly water the cover.
- some snow melts during storage, but some decrease in volume (around 5 %) is due to settlement, i.e. the **compaction of snow** (GRÜNEWALD 2018; see Section 1.3.3 and Fig. 7.18). Wet metamorphism also increases grain size, which can negatively impact consolidation when the snow is spread out (Fig. 7.19).

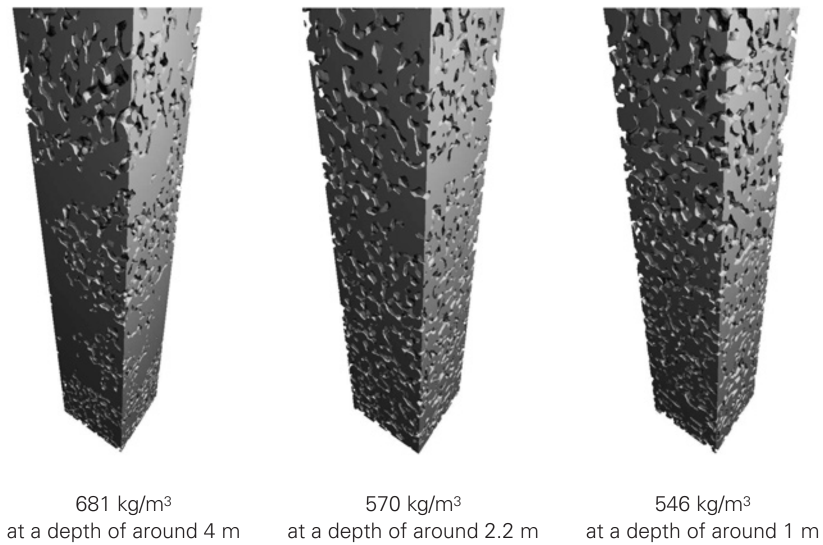

Fig. 7.18: Snow samples (11.4 x 11.4 x 59.3 mm) taken at different depths from a heap of snow roughly 9 m high that was stored for half a year (Davos, Switzerland, 2015). The snow in question was primarily machine-made.

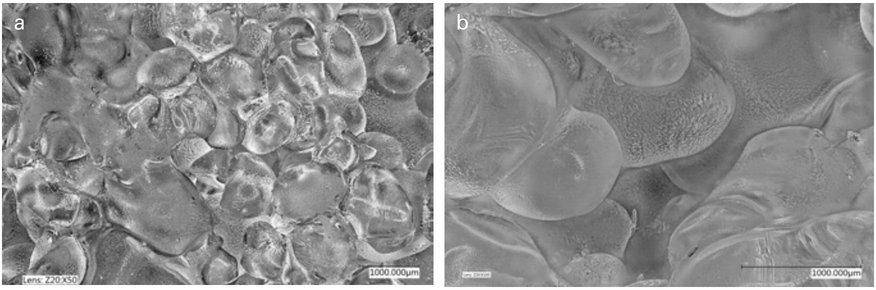

Fig. 7.19: Strongly sintered (liquid) machine-made snow with coarse, rounded grains after storage for half a year (Davos, Switzerland, 2015), magnified a) 50 and b) 100 times.

Fig. 7.20: Sawdust and woodchip covers being removed by excavators (a: Davos, Switzerland, 2015; b: Ruhpolding, Germany, 2016 – photo b: Elias Walser).

6) Removing the cover:

– **the cover can be removed** relatively early. Snow loss is low in the fall as long as the snow has not been spread out, but if snow falls on a covered pile, the workload will increase significantly.
– **the covering material should be cleanly separated from the snow** (natural materials, Fig. 7.20). Having experienced staff is essential in this context.

7) Spreading and preparing the snow:

– to ensure that **spread snow is optimally consolidated**, a work plan should be drawn up that can be pushed back a few days if necessary, to ensure that this operation takes place in optimal weather conditions. Clear nights are important, so that the spread out wet snow can freeze and thereby consolidate.

- if there is no water left in the coarse-grained snow **when it is spread out** (see Section 1.1.3), it will consolidate very poorly (see Section 3.2.2). Long respite periods or the use of water or wet machine-made snow will then be required.
- **contamination** can be minimized by transporting the snow in clean vehicles
- to **minimize loss** when spreading out snow, supporting walls can be erected at the sides of cross-country trails. Smoothing out the rough sloping sides of trails also reduces melting.
- boggy sections of the track should be the last to be covered with snow. In this scenario, **icy snow** from lower down in the storage pile can be used as a bottom layer.

8) Storing coverings:

- it may be wise to sift very dirty natural materials **before storing them**
- **contamination** during storage should be avoided if at all possible
- estimate both the quantity and quality and **consider further purchases**

Fig. 7.21: Snow being moved (Davos, Switzerland, 2014). The vehicles used to transport snow are chosen based on the access roads. Bumpy surfaces and dirt increase the quantity of snow required.

– to **avoid storage,** woodchip coverings may be bought back by the supplier at a reduced price after a single use (as in Ramsau, Austria, for example)

7.4.4 Costs

Ski resort managers cite excessively **high costs** as the second biggest barrier to snow farming after the availability of a suitable storage site (Wolfsperger 2018). That said, 50% of respondents are convinced that storing snow over the summer is profitable, as opposed to just 31% who consider it uneconomical.

It is not possible to make any **general assertion about snow farming costs** because technical and logistical solutions, the outlay on equipment and personnel, snowmaking costs, and the extent of snow loss can vary from place to place. However, a cover with a long lifespan reduces costs

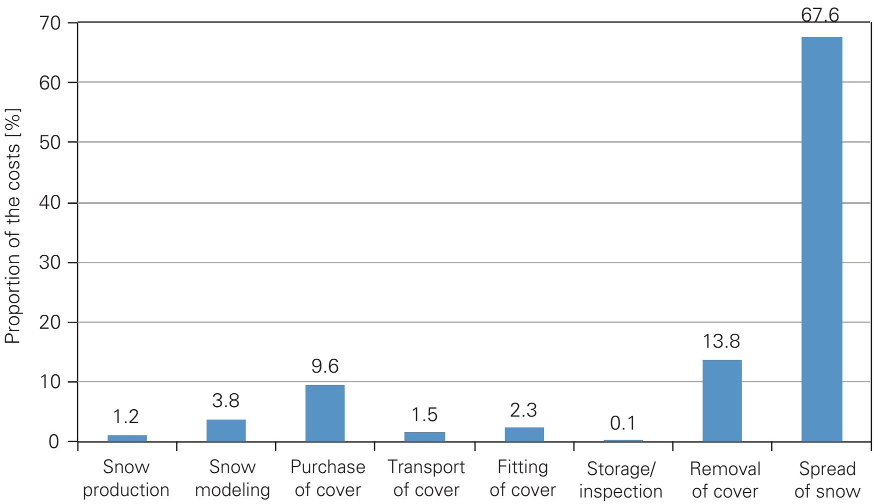

Fig. 7.22: Distribution of costs, taking Davos 2016 as an example (a site storing ca 16,000 m³, with a 16 % loss, a sawdust cover with a 5-year lifespan, and stored snow spread onto a roughly 4-km-long cross-country trail). Investment costs (structural measures, snowmaking equipment) are not taken into account.

drastically, as the acquisition costs are spread over a number of snow storage years.

It is just as difficult to determine how profitable snow farming is (Dreier 2010). Whether – and how – **advertising value** through additional media attention, or **safeguards against the cancellation** of snow sport events are taken into account considerably affects the economic evaluation of a snow farming project.

Taking **Davos' snow farming project** for example, the operational costs are between around **CHF 9 and 12 per m³** (Grünewald 2018). The **spreading and preparation** of snow on cross-country trails in the fall accounts for by far the lion's share of these costs, whereas snow production plays only a tiny role (Fig. 7.22). Such allocations of costs are often typical for snow storage sites at higher altitudes, because although snow can be made at any time of winter, being able to wait until conditions are perfect enables very efficient snowmaking. Spreading snow, by contrast, is very **time-intensive and takes a lot of equipment.** How much this costs will depend on the use to which the snow is put and also on the logistics involved. Costs drop especially when the snow does not need to be loaded and transported, but can be shifted by snowcats directly to the desired location (e.g. for downhill ski runs).

7.5 Other Measures

7.5.1 Accumulation of Snow

Snowmaking is not the only way of accumulating snow. Alternative methods are of special interest in areas where snow cannot be machine-made.

7.5.1.1 Snow Fences and Gates

Where and how much snow is deposited can be determined by putting up snow fences or gates, or barriers made of snow in strategic places. The quantity of snow that accumulates behind a fence will depend on the structure's height, shape, and porosity (air permeability). Fences with a porosity of around 50% store the most snow (Tabler 2003).

Fig. 7.23: a) Snow accumulated by a fence (picture courtesy of the Ebenalp-Horn ski resort). b) Snow formed into banks to accelerate deposits of wind-driven snow in the slope area (Tignes, France, 2016 – photo: Stéphane Mougin).

7.5.1.2 Shifting and Storing Snow

In glacier ski resorts, **shifting snow from ice-free to glaciated substrate** at the end of the season is an effective way of reducing the melting of glacier ice (OLEFS 2010). Conversely, avalanche snow deposited on glaciers should not necessarily be amassed for snow storage sites. Although in the short term this may mean more snow could be stored over the summer, in the medium term it would accelerate glacial retreat, because glaciers use natural snow replenishment as a basis for growth.

Fig. 7.24: Chute for transporting snow – photo: Edi Zihlmann.

Snow often needs to be moved on a short-term basis to ensure that there is enough for competitions and other events. This can be made easier by **creating in advance small storage sites** near tracks, and efficient snow transport systems (Fig. 7.24).

7.5.2 Earthworks and High-Altitude Revegetation

Expensive **earthworks** or ski resort redevelopments are sometimes carried out to **minimize** the **need for snow** on slopes and in snow parks (Fig. 7.25). Such human interference in some places substantially **changes** the **vegetation** and the chemical and physical **properties of the soil** (Roux-Fouillet 2011). Furthermore, it is well known that alpine vegetation barely recovers from such interference of its own accord: once damaged by earthworks, it continues suffering the consequences for a very long time.

In the last 20 years, however, **great progress** has been made on revegetation at subalpine and alpine altitudes (Krautzer 2012a). If upland revegetation is to be successful, the **process used must be right for the location** and be expertly planned and implemented (Krautzer 2006). More

Fig. 7.25: Terraces created to reduce the demand for snow in a terrain park (Laax, Switzerland, 2017).

detailed information can be found in the "Richtlinien Hochlagenbegrünung/ Directives pour la végétalisation en altitude", a set of guidelines for high-altitude revegetation drawn up in German and French (Locher-Oberholzer 2008). In principle, the following points should be borne in mind:

– set a **revegetation target** and identify the **environmental factors**
– correctly **reuse the topsoil**, together with plant sod, by carefully removing it and putting it into appropriate temporary storage
– use a **suitable seed mix for the location**[20], as well as existing vegetation
– **sow seeds as early as possible** in the growing season, or in the fall as so-called "sleeping" (dormant) seeds
– **protect against erosion** during the first two growing seasons using mulch or geotextile covers
– use (organic) **fertilizers** that have a slow, but long-lasting effect (Krautzer 2012b)
– define **plant management measures**

[20] Plant material and seeds should come from the area surrounding the project plot, or be similar. Seeds can be bought to suit different altitudes, bedrocks, and uses (Krautzer 2012b).

Fig. 7.26: a) Development of the Tauplitzalm ski resort (Mitterstein, 1,750–2,000 m.a.s.l., Austria, 2011). Clearly visible is the topsoil that was neatly separated into piles for temporary storage and then spread out again towards the bottom of the slope. b) Successful upland revegetation 2 years later – photos: Bernhard Krautzer.

7.6 Climate Change and Snow Reliability

Climate change will have a considerable impact on the future of alpine winter sports because **less favorable conditions for snowmaking,** substantially less natural snow (SCHMUCKI 2017), and glacial melting will directly impact ski resort management. The climate is definitely warming (IPCC 2013). Switzerland is already around 1.8°C warmer now than it was at the start of the 20th century (Swiss Academies of Arts and Sciences 2016; Fig. 7.27).

In each decade over the last 50 years, temperatures in Switzerland have risen by an average of **0.38 °C** (MeteoSwiss, 2017). This phenomenon is most pronounced in spring and summer (0.47 and 0.49 °C per decade respectively, compared to 0.24 and 0.3 °C in fall and winter) (MeteoSwiss, 2017). Weather records for Davos, Engelberg, and Säntis in recent decades show a **temperature increase** over the winter months (October–April),

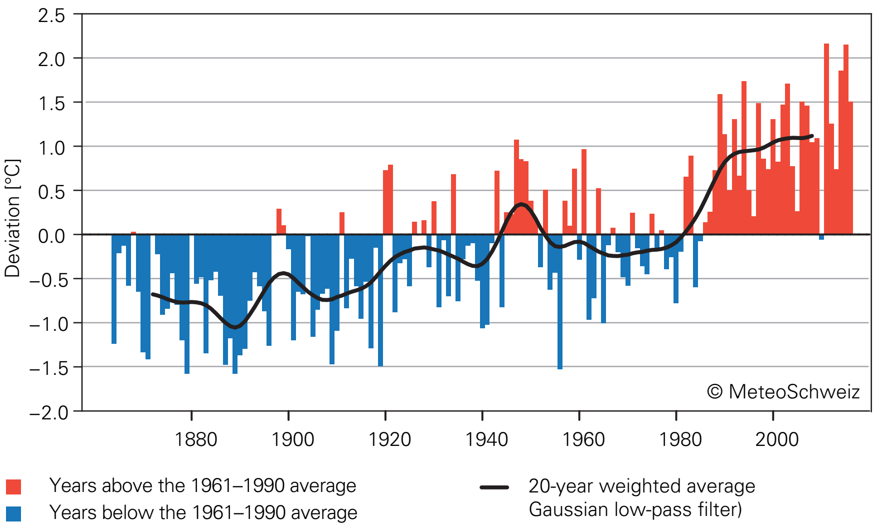

Fig. 7.27: Deviation of average annual temperatures from the mean temperature between 1961 and 1990 in northern Switzerland at altitudes above 1,000 m.

including in the two months most suitable for snowmaking: **November and December** (Fig. 7.28). A similar trend applies at all altitudes. However, the climate has not warmed continuously. Rather, the trend has repeatedly been interrupted by periods of stagnation or slight cooling, for example between 1990 and 2010 (Bader 2015). There have also clearly been **strong fluctuations** between individual years. The picture regarding precipitation is hazier. Over the last 50 years, there have been no changes in annual and seasonal precipitation levels in Switzerland. But records from further back (from 1901 to 2016) show a slight increase in winter of 1.7 % per decade (MeteoSwiss, 2017).

Forecasts suggest that **further warming** is to be expected. Between 2020 and 2049, **average winter temperatures in the Swiss Alps** will be around **0.6 to 2 °C** higher than the mean for the reference period of 1980 to 2009 (Fischer 2015). The temperature increase in the latter half of the 21st century will depend heavily on whether CO_2 emissions can be substantially cut worldwide. If not, winters between 2045 and 2074 will be

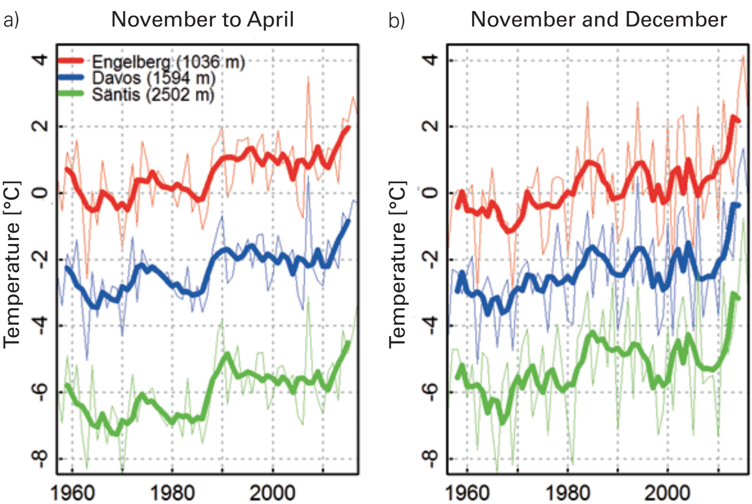

Fig. 7.28: a) Average air temperatures at three weather stations between 1956 and 2016 for winter months and b) the main snowmaking months, November and December. Thin lines show mean values for individual years; thick lines show the moving average over 5 years – source: MeteoSwiss.

around 1.6 to 3.4 °C warmer on average than they were at the start of the millennium (Fischer 2015).

Various studies focusing on the Swiss Alps indicate how the expected temperature increase will **affect** snow conditions and **winter tourism**:

- **less snow** is expected at all altitudes, as rain will more often fall instead, and the snowmelt will be more pronounced and start earlier in the year (Marty 2017).
- the snow situation will deteriorate most at **medium altitudes (1,000 to 1,700 m)** and below (Schmucki 2017). In particular, the thinner snowpack at medium altitudes, where a wide variety of snow sports are currently still on offer, will pose a problem for winter tourism. Over the next three decades, **snow depths will already decrease by up to 40 %** unless CO_2 emissions are significantly reduced (Schmucki 2017; Fig. 7.29). At the same time, the winter season will become much briefer (around 20 % shorter). Even continuous snow cover at least 5 cm deep will no longer be guaranteed above 1,000 m in many places (Schmucki 2017). The sharp drop in the number of snow days[21] in towns and cities could also make winter sports less popular.
- climate warming will initially have little impact on **high-altitude alpine areas**. But here too, by the end of the century average snow depths will decrease by up to 25 % (Schmucki 2017).
- over the next three decades, only **areas above around 1,900 m will be snow reliable** [22]. Barring a sharp cut in CO_2 emissions, from the **middle of the century** onwards, this snow-sure altitude will start rising even further, to around **2,200 m** (Marty 2017).

[21] Days on which there is 5 cm or more of snow on the ground. In cities like Chur (593 m) or Bern (542 m), the number of snow days will fall by nearly 70% over the next three decades, to only around 13 days each winter.

[22] The term snow reliability is said to apply to any ski resort where, for at least 100 days a season, 80% of the slope surface area has enough natural snow (> 30 cm) to enable skiing to take place, and thereby make the facility's operation financially viable (Elsasser 2002; Scott 2008; Steiger 2013). Between 1999 and 2012, areas in the Swiss Alps above around 1,600 m were considered reliable to have snow (Marty 2017).

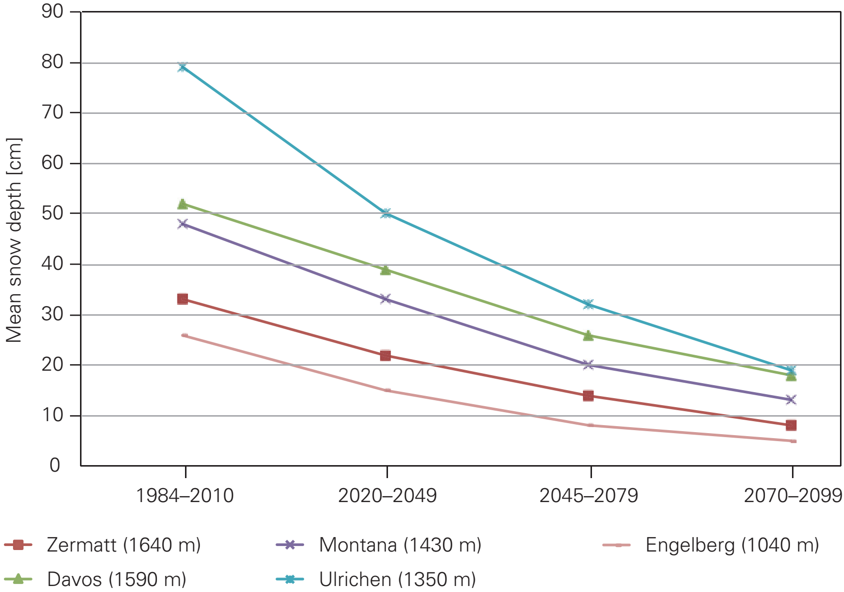

Fig. 7.29: Average snow depths in winter (December, January, and February) in the 21st century at medium altitude at various Swiss winter sports destinations (after Schmucki 2017). Naturally, snow depth varies tremendously (> 100 %). Some days there may be no snow at all; on others it may be more than twice as deep as the indicated mean value.

– although optimal conditions for productive and efficient snowmaking will become rarer, **machine-made snow** will mostly be able to **compensate for deteriorating snow conditions** in the decades to come. Assuming that **snow can be produced everywhere**[23], almost all ski resorts in Grisons can expect to remain snow-sure for at least 7 out of 10 winters up to the middle of the century (Abegg 2013). This will still apply to 95 % of resorts in Grisons from the middle of the century onwards, and to around 80 % by the end of the century, even without any major reduction in CO_2 emissions (Abegg 2013). This is mainly due

[23] For this to happen, snowmaking capacities (snow guns, water available from reservoirs) need to be greatly expanded (Abegg 2013; Steiger 2013). This will not only impact the environment, but the high investment and energy costs involved will also make skiing more expensive.

to the **high altitudes of ski resorts**. By the 2050s, only around 80 % of ski resorts in regions with a larger proportion of facilities at lower altitudes, e.g. the Tyrol, will be snow-sure (in at least 7 out of 10 winters) (Steiger 2013).

- technical snowmaking is less effective at compensating for **snow shortages over the economically important Christmas period** (Steiger 2013; Scott 2008). So in the 2050s, only some 55 % of Tyrol's current ski resorts will be open for skiing over Christmas (in at least 7 out of 10 years)[24]. Therefore, based on the current business model[25], a key criterion for the sustainability of a ski resort is the snow production potential in November and December, which depends on the altitude, characteristics of the region and microclimate, and, above all, on the number and productivity of available snow guns.

[24] The study assesses the technical snow reliability of an entire ski resort based on climatic conditions at medium-altitude sites. However, when actually deciding how to expand a resort's snowmaking equipment, each slope's snow production potential should be considered separately. There are different scenarios: for example, a resort may just lose its downhill run in the long term, or technical snowmaking may prove insufficient to guarantee snow at higher-altitude slopes as well.

[25] Winter sports destinations like the Tyrol typically generate some 30% of their revenue over the Christmas and New Year period (Steiger 2013). Nevertheless, it is entirely conceivable that smaller resorts, in particular, could be profitably run based on alternative business models.

8 Measurement Methods and Tools

Optimal slope preparation and grooming requires in-depth knowledge of weather and snow parameters. This chapter presents methods and devices that can be used to quickly and easily analyze snow and meteorological conditions. It also describes useful **tools** that facilitate **snowmaking** and the **construction of snow parks**.

8.1 Snow Measurements

The most important snow parameters for a slope's preparation are:
- **temperature**
- **density**
- **wetness** (liquid water content)
- **structure** (specific surface area, and grain size and shape)
- **mechanical properties**

8.1.1 Snow Temperature

There are two ways of measuring temperature: **contactless** measurement (infrared thermometers) and methods involving **contact between a sensor and the snow** (thermocouples, resistance thermometers, which are also called resistance temperature detectors (RTDs)). In general, it is important to regularly test the device's **measurement errors** (calibration) in ice water, which has a constant temperature of 0 °C. Snow that is just beginning to melt also always has a temperature of 0 °C, as it also contains liquid water.

The use of contactless **infrared thermometers** is not suitable for measurements taken by hand, because, if a thermometer is carried in a jacket pocket, for example, body heat will seriously distort the measurement. Liquid water content, surface condition, and angle of incidence also affect measurements. Moreover, even some expensive devices sometimes yield inaccurate measurements, even when used correctly. That said, for continuous measurements of snow surface temperature, e.g. at **weather stations**, only infrared thermometers are used, because they are well protected against solar radiation and thus do not heat up.

By contrast, even very inexpensive **contact sensors** are up to the job. Measurements are always taken at the tip of a sensor. To measure the surface temperature, the sensor should be inserted less than 1 cm into the snow and be shielded from solar radiation.

8.1.2 Snow Density

Snow density provides information about **slope firmness.** It also indicates which **preparation methods** can be used to further compact the snow (see Chapters 3 and 4). If its density is low, a set **volume** can be dug out and **weighed** (Fig. 8.1). Since higher-density snow is virtually impossible to cut, a larger chunk of snow can be broken off and trimmed with a saw blade so that its volume can be calculated by measuring its edge lengths.

The **dielectric method,** however, is better suited to determining snow density (see Section 1.1.3 and Fig. 8.2). This involves placing a sensor on the snow surface and using an electric field to measure its density. The surface of the snow must be as level as possible, so that the sensor lies flush with it.

Fig. 8.1: A set volume being weighed to measure snow density.

Fig. 8.2: Snow density being measured (dielectric method) using a snow sensor developed by FPGA Company GmbH and the SLF.

8.1.3 Snow Wetness

The **dielectric method** is also suitable for determining snow wetness. An electric field is used to measure the snow's dielectric constant. The dielectric constant of air is 1, that of pore-free ice is around 3, and that of water around 81. Snow measurements therefore largely depend on how much air, ice, and water the snow contains. Once the air and ice content, i.e. the **dry snow density,** is known, snow wetness can be calculated based on the dielectric number (see Section 1.1.3; Denoth 1989). If the dry snow density is unknown, it must be estimated.

Measuring snow wetness is time-consuming, but crucial for ensuring accurate analyses. Knowledge of local temperatures and net radiation can help to estimate wetness. Devices that do not indicate 0 % wetness when the snow temperature is below zero are clearly mismeasuring.

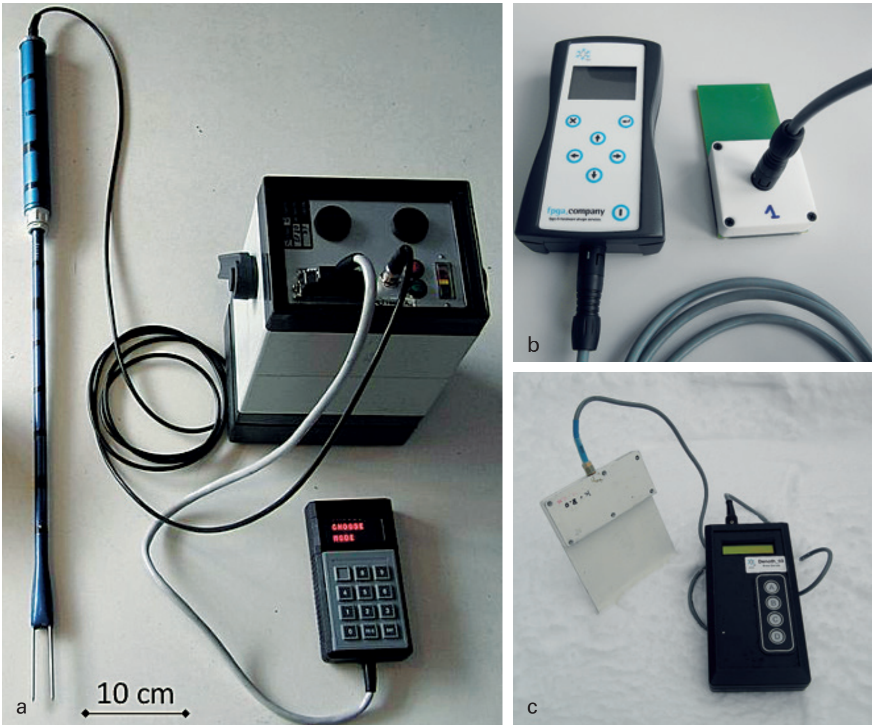

Fig. 8.3: Snow wetness measuring devices a) Snow fork (www.toikkaoy.com) (after TECHEL 2011). b) Denoth meter (DENOTH 1994). c) Snow sensor to measure density and wetness (SLF and www.fpga-company.com).

8.1.4 Snow Structure

Grain size and shape, and connections between grains – i.e. the snow's microstructure – should be taken into account when **choosing slope preparation methods** and **snowcat settings**. The conventional method for examining the structure of snow, using a magnifying glass, breaks up the sintered snow structure to assess and describe the size and shape of its grains. Inexpensive, portable **USB microscopes** make this method more objective (Fig. 8.4). Although more accurate measurement methods exist, they are usually set aside for research (SCHNEEBELI 2009; GALLET 2009), since the serial production of measuring devices is rarely financially viable.

Fig. 8.4: a) Grain shape and size being objectively observed using a grid, and a magnifying glass or USB microscope. b, c) Measuring devices for determining microstructure based on the snow's reflectivity (b: InfraSnow, SLF; c: IceCube, www.A2PhotonicSensors.com).

8.1.5 Mechanical Properties

Evaluating the result of slope preperation measures necessitates **taking direct measurements of firmness, and assessing layer structure and homogeneity**. A simple, subjective method is the resistance felt when using a snow drill. A **snow ram penetrometer** can provide a rough measurement of hardness, both at the surface and down to a depth of 15 cm (Bruhin 2018). **High-resolution snow penetrometers,** such as the SnowMicroPen developed by the SLF or the SnowSpike slope penetrometer (Fig. 8.5), can be used to gain very accurate measurements of snow hardness (also called penetration resistance). However, such devices can only penetrate deeply into slopes covered in low-density snow. Analyses of harder snow are limited to the surface (down to a depth of around 30 mm).

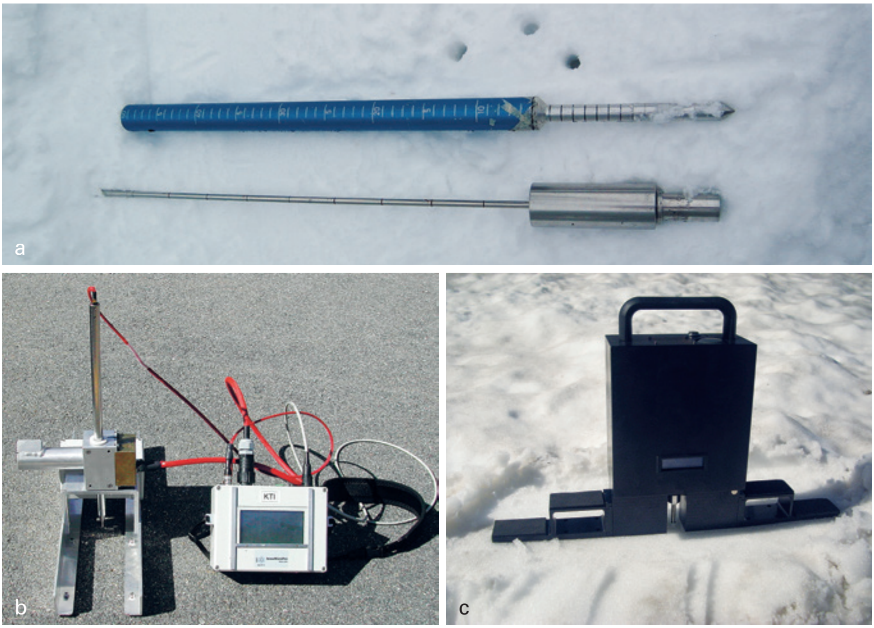

Fig. 8.5: a) Snow ram penetrometer. b, c) Penetrometer (b: SnowMicroPen; c: SnowSpike) for measuring snow hardness.

8.2 Measuring Meteorological Parameters

The heat and mass exchange between the snow surface and the atmosphere depends on the following weather parameters (see Chapter 2):

- **air temperature and humidity**
- **wind speed and direction**
- **snow temperature**
- **net radiation**

For Ski patrols it is hugely useful to measure and forecast these parameters. Whereas **snow guns** usually record air temperature, air humidity, and wind measurements, ski patrols are usually unaware of radiation levels and snow temperatures. It is therefore advisable to purchase a few **additional weather stations**. Various manufacturers[1] now offer affordable, simple, high-quality solutions to automatically record weather parameters and make data available online (Fig. 8.6).

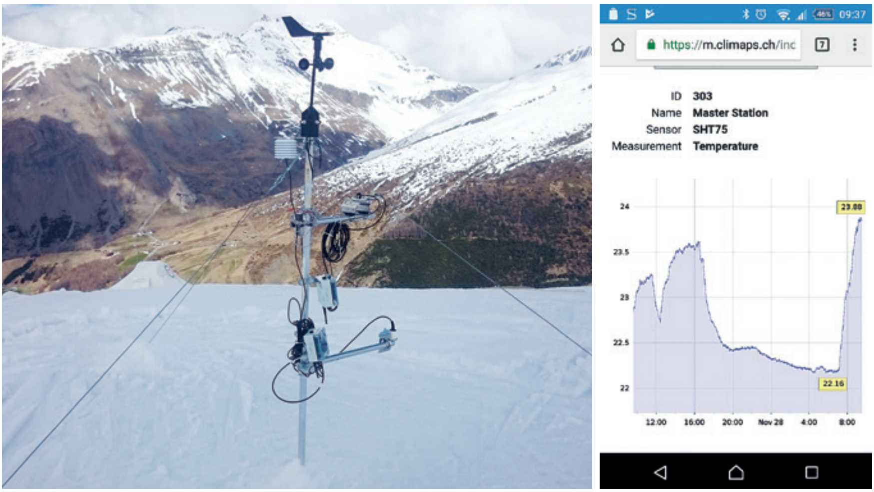

Fig. 8.6: Mobile weather station that can store and post data online using mobile telephony (www.climaps.ch).

1 www.sensorscope.ch; www.decagon.com; www.davisnet.com; www.apogeedigital.com.

8.3 Snowpack Models

When preparing slopes, it is useful to know the weather forecast and **how snow conditions will develop**. For example, knowing what the snow temperature will be in 4 hours makes it easier to decide the best **time to prepare the slope**.

Snowpack models[2] can be used to calculate snow temperature, wetness, and density, grain size, and other parameters for the next few hours or days (Figs. 8.7 and 8.8). This information helps to **optimize the deployment of snowcat fleets** based on the snow conditions on various slope sections. Furthermore, when **watering slopes**, such data can be used to calculate freezing times and water penetration depth. Snowpack models

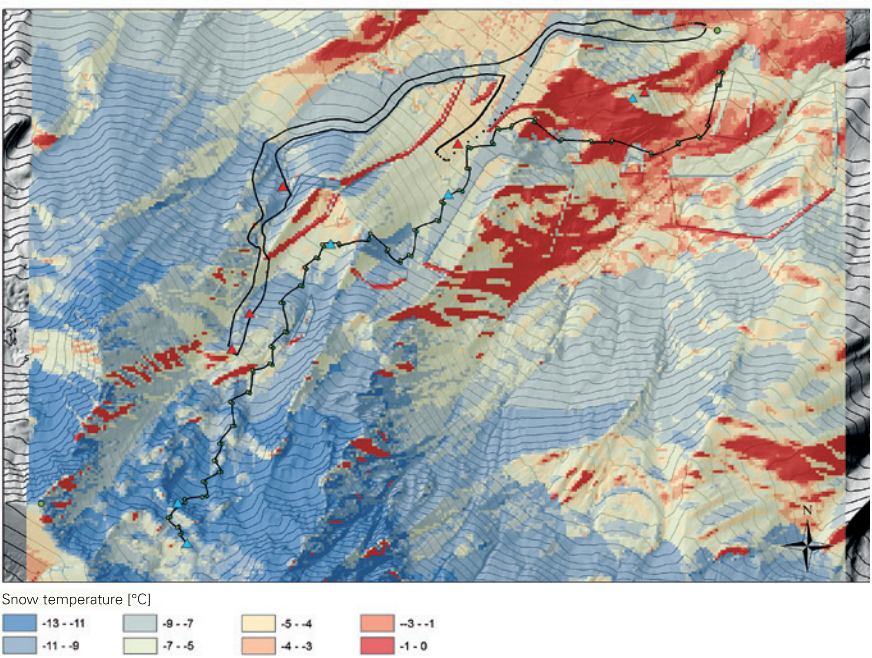

Fig. 8.7: Alpine3D simulation for forecasting snow temperatures (11:00) on downhill slopes at the 2014 Olympic Games (Rosa Khutor, Russia).

2 https://models.slf.ch
3 www.slf.ch/de/services-und-produkte/alpine-3d.html

are also used to accurately forecast ski run **ablation dates**, and calculate quantities of meltwater.

The development of snow properties can be determined for a specific spot using the **SNOWPACK model** (LEHNING 2002), or for an entire area using the **Alpine3D model**[3] (LEHNING 2006), both of which require current snow data and weather forecasts. If the snow properties for an entire area are to be calculated in advance, a digital terrain model, among other things, is also needed, to take account of factors like shade caused by the topography or vegetation (Fig. 8.9).

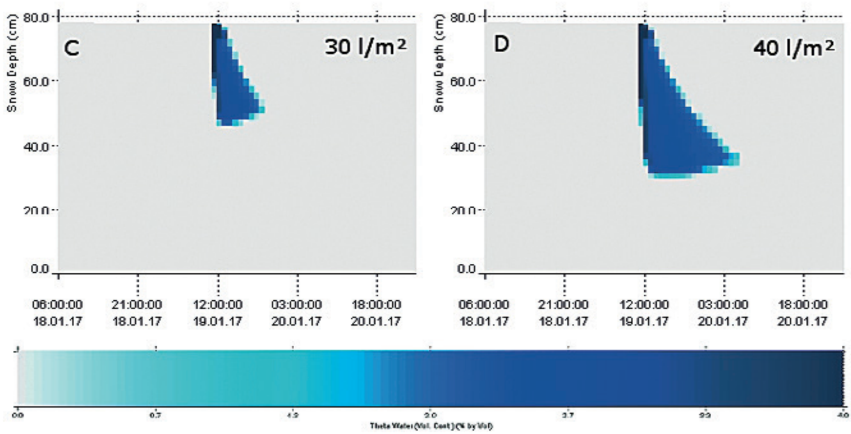

Fig. 8.8: SNOWPACK simulations of race track watering, with different quantities of water.

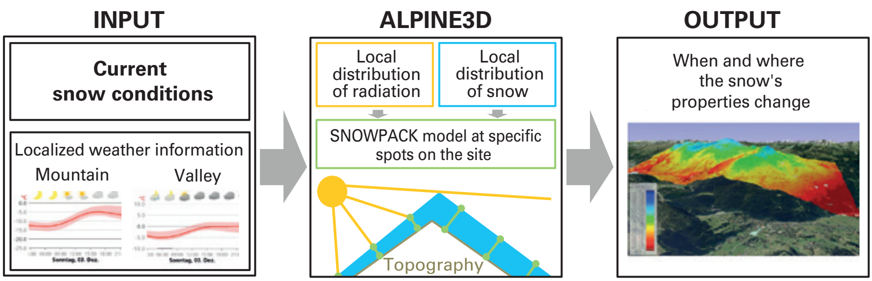

Fig. 8.9: Simplified representation of the Alpine3D model with the three modules – SNOWPACK (snowpack, ground, and vegetation), Ebalance (radiation dictated by the topography, etc.), and SnowDrift (snow transport and distribution) – as well as the required input and possible output variables.

Fig. 8.10: The SLF's snowmaking app (only in German).

8.4 Snowmaking App

The SLF has developed a snowmaking app for smartphones, which can be used to calculate **snow wetness,** productivity, and the snow-water ratio (see Section 1.6.1) depending on **weather factors** (wet-bulb temperature, wind), water temperature, and water flow (Fig. 8.10). It can also be used to determine the **freezing time** of wet machine-made snow on the ground. The **knowledge section** provides background information on machine-made snow and explains how it is produced.

8.5 Tools for Snow Park Construction

When constructing freestyle parks and cross courses, the **distances between and gradients** of potential track sections, inruns, and landing zones should be known at the planning stage. **Maps** only help to determine the average gradient of large slope areas. For more detailed analyses, high-resolution **geographic information** is now available online for many countries[4]. Moreover, open-source **GIS software**[5] provides various options for displaying, analyzing, and processing terrain data.

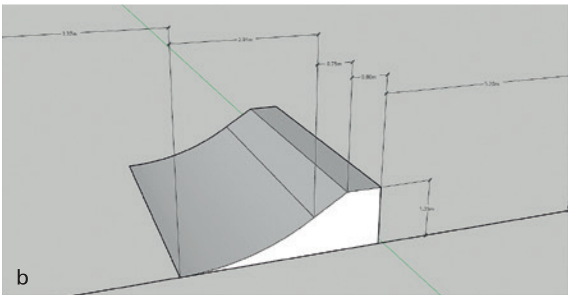

Fig. 8.11: a) Rangefinder and inclinometer. b) Simple 3D model of a kicker, with dimensions specified, created by the SketchUp software program.

[4] E.g. https://map.geo.admin.ch; www.geoland.at

[5] www.qgis.org/de/site

Another helpful tool when planning and constructing snow parks is an **optical rangefinder and inclinometer.** When this device is aimed at a visible obstacle or snow surface, it indicates the distance and gradient measured from the current location. When planning the route of a cross course, it can be used to estimate how fast competitors will be traveling by the end of a section and thus how the following obstacle must be designed.

Before constructing jumps, jibs, or other **snow park features**, the **dimensions should be fixed in drawings**. **Free software**[6] is also now available for simple 2D drawings and 3D models, enabling the quick and easy construction of snow park features.

6 www.sketchup.com/de; www.freecadweb.org

Bibliography

Abegg, B.; Steiger, R.; Walser, R., 2013: Herausforderung Klimawandel. Chancen und Risiken für den Tourismus in Graubünden. Aktuelle und zukünftige Schneesicherheit der Bündner Skigebiete. Hrsg. Bergbahnen Graubünden. Accessed on 16/01/2018 at https://www.uibk.ac.at/geographie/personal/steiger/awt_bbgr_klimabericht2013.pdf

Akademien der Wissenschaften Schweiz, 2016: Brennpunkt Klima Schweiz. Grundlagen, Folgen und Perspektiven. Swiss Academies Reports 11: 5.

Armstrong, R.L.; Brun, E. (eds.), 2008: Snow and climate: physical processes, surface energy exchange and modelling. Cambridge. Cambridge University Press. 256 pp. ISBN-10: 0-521854-54-7, ISBN-13: 978-0-52185-454-7, hardback.

Bächler Top Track Ag, 2018: Accessed on 16/01/2018 at www.bachler.ch/ProdukteBeschneiung/SnoTek/tabid/1732/Default.aspx

Bader, S.; Fukutome, S., 2015: Milde und kalte Bergwinter, Fachbericht MeteoSchweiz, 254: 10 pp.

BAFU – Bundesamt für Umwelt, 2007: Verwendung von Schneehärtern für Betreiber von Rennpisten und Veranstalter von Schneesportwettkämpfen. Accessed on 18/01/2018 at https://www.bafu.admin.ch/bafu/de/home/themen/chemikalien/publikationen-studien/publikationen/schneehaerter-rennpisten-schneesportwettkaempfe.html

Bavay, M.; Grünewald, T.; Lehning, M., 2013: Response of snow cover and runoff to climate change in high Alpine catchments of Eastern Switzerland. Advances in Water Resources, 55: 4–16. doi: 10.1016/j.advwatres.2012.12.009

bfu – Beratungsstelle für Unfallverhütung, 2016: Statistik der Nichtberufsunfälle und des Sicherheitsniveaus in der Schweiz, Strassenverkehr, Sport, Haus und Freizeit. Bern. ISSN 1663.7828; DOI 10.13100/bfu.2.275.01.

Bodmer, P., 1982: Geothermische Karte der Schweiz 1: 500000 (Papierkarte). Bundesamt für Landestopografie Swisstopo, SGPK.

Breiling, M.; Bacher, M.; Sokratov, S.; Best, F.G., 2016: Method and device for producing snow. US Patent 9429348 B2.

Bruhin, B.; Senn, I.; Flury, S.; Wolfsperger, F.; Boffi, G.; Lorenzetti, S., 2018: A systematic race course analysis and a description of men's race performance in paralympic alpine skiing world cup slalom and giant slalom races of the seasons 2014/15 and 2015/16. In: Science and Skiing VII, 52–59. Maidenhead: Meyer & Meyer Spor(UK) Ltd. ISBN: 978-1-78255-124-9.

Calonne, N.; Flin, F.; Morin, S.; Lesaffre, B.; Rolland du Roscoat, S.; Geindreau, C., 2011: Numerical and experimental investigations of the effective thermal conductivity of snow, Geophys. Res. Lett. 38, L23501, doi:10.1029/2011GL049234.

Ceppi, P.; Scherrer, S.C.; Fischer, A.M.; Appenzeller, C., 2012: Revisiting Swiss temperature trends 1959–2008. Int. J. Climatol. 32: 203–213. doi:10.1002/joc.2260

CIPRA SCHWEIZ (Hrsg.) 2007: Gletscherabdeckungen und Schneebewirtschaftung. Positionspapier der CIPRA Schweiz. Zürich.

Clulow, M., 2006: Indoor Snowmaking, ASHRAE Journal, No. 48.

Conway, H.; Gades, A.; Raymond, C.F., 1996: Albedo of dirty snow during conditions of melt, Water Resour. Res. 32: 6, 1713–1718, doi:10.1029/96WR00712.

Demaclenko Ltd., 2018. Accessed on 16/1/2018 at http://www.demaclenko.com/en/fan-guns/titan-2-0/41-1168.html

Denoth, A., 1989: Snow dielectric measurements. Adv. Space Res. 9: 233–243.

DENOTH, A., 1994: An electronic device for long-term snow wetness recording. Ann. Glaciol. 19: 104–106.

DREIER, J.-A., 2010: Economic benefits and ecological consequences of Snow Farming in Davos. Bachelor Thesis. HTW Chur.

ELSASSER, H.; BÜRKI, R., 2002: Climate change as a threat to tourism in the Alps. Climate Research 20, 3: 253–257. DOI 10.3354/cr020253.

ENZENHOFER, U.; BACHER, M.; SOKRATEV, S.; MAHR, C.; MÜLLER, J.; WORTHMANN, U.; REINWEGER, I., 2016: Producing nature like snow in a supercooled cloud for laboratory experiments. ISSW conference proceedings, Breckenridge, Colardo.

FAUVE, M., 1997: Influence of sintering and temperature on snow penetration and compressive strength of snow. Diploma Thesis. Eidgenössisches Institut für Schnee- und Lawinenforschung SLF.

FERRERO, F.; MALOW, M.; SCHMIDT, M.; KRAUSE, U., 2009: Leitfaden zur Brandvermeidung bei der Lagerung von Biomasse. Bundesanstalt für Materialforschung und -prüfung (BAM) Berlin. Berlin (Deutschland) Selbstverlag, 22 S., ISBN: 978-3-9812354-1-8.

FIERZ, C.; ARMSTRONG, R.L.; DURAND, Y.; ETCHEVERS, P.; GREENE, E.; MCCLUNG, D.M.; NISHIMURA, K.; SATYAWALI, P.K.; SOKRATOV, S.A., 2009: The International Classification for Seasonal Snow on the Ground. IHP-VII Technical Documents in Hydrology No. 83, IACS Contribution No. 1, UNESCO-IHP, Paris.

FIS – Internationaler Skiverband, 2016: The international freestyle skiing competition rules (ICR) Book V. Joint regulations for freestyle skiing. 50th international ski congress, Cancun (Mex). P.101. Accessed on 18/10/2018 at http://www.fis-ski.com/mm/Document/documentlibrary/FreestyleSkiing/02/03/28/FS_FIS_FreestyleICRmarkedup201602.08.16_English.pdf

FISCHER, A.M.; LINIGER, M.; APPENZELLER, C., 2015: Climate scenarios of seasonal means: extensions in time and space, CH2011 Extension Series No. 2, Zurich, 18 pp. Accessed on 16/01/2018 at http://www.ch2011.ch/pdf/CH2011plus_No2_Fischer_etal_2015.pdf

FUKUE, M., 1979: Mechanical Performance of Snow Under Loading; Tokai University Press.

FURUKAWA, Y., 1997: Faszination der Schneekristalle: wie ihre bezaubernden Formen entstehen, Chem. unserer Zeit, 2: 58–65.

GALLET, J.-C.; DOMINE, F.; ZENDER, C.S.; PICARD, G., 2009: Rapid and accurate measurement of the specific surface area of snow using infrared reflectance at 1310 and 1550 nm. The Cryosphere 3: 167–182.

GERGELY, M.; WOLFSPERGER, F.; SCHNEEBELI, M., 2013: Simulation and Validation of the InfraSnow: An Instrument to Measure Snow Optically Equivalent Grain Size. IEEE Trans. Geosci. Remote Sens. 52, 7. DOI: 10.1109/TGRS.2013.2280502.

GUILY, L., 1991: L'Exploitation technique des pistes de ski alpin dans le domaine skiable français. Doktorarbeit. Université Jospeh Fournier Grenoble.

GRÜNEWALD, T.; LEHNING, M.; WOLFSPERGER, F., 2018: Snow farming: Conserving snow over the summer season. The Cryosphere, 12, 1.

HÄCHLER, P., 2002: Schneegrenze und Schneefallgrenze. Bearbeitet und ergänzt 2016 von Kaufmann G. und Gerstgrasser, D. MeteoSchweiz. Accessed on 18/01/18 at http://www.meteoschweiz.admin.ch/home/wetter/wetterbegriffe/schneegrenze-schneefallgrenze.html.

HAGENMULLER, P.; THEILE, T.; SCHNEEBELI, M., 2014: Numerical simulation of microstructural damage and tensile strength of snow. Geophysical Research Letters 41, 1: 86–89. doi: 10.1002/2013GL058078.

HERWIJNEN, A.; MILLER, D. (n.d.), 2013: Experimental and numerical investigation of the sintering rate of snow. Journal of Glaciology 59, 214: 269–274. doi:10.3189/2013JoG12J094.

IMA, C.S.; MANN, D.D., 2007: Physical Properties of Woodchip: Compost Mixtures used as Biofilter Media. Agricultural Engineering International: the CIGR Ejournal. Manuscript BC 07 005. Vol. IX.

IPCC, 2013: Summary for Policymakers. In: STOCKER, T.F.; QIN, D.; PLATTNER, G.-K.;TIGNOR, M.; ALLEN, S.K.; BOSCHUNG, J.; NAUELS, A.; XIA, Y.; BEX, V.; MIDGLEY, P.M. (eds.). Climate Change 2013: The Physical Science Basis.Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

KAEMPFER, T.U.; SCHNEEBELI, M., 2007: Observation of isothermal metamorphism of new snow and interpretation as a sintering process. J. Geophys. Res. 112, D24101, doi:10.1029/2007JD009047.

KINDSCHI, J., 2012: Machbarkeitsstudie zur Erweiterung des Loipennetzes in Davos durch Snowfarming. Bachelor Thesis. HTW Chur. ESHM.

KOTLARSKY, S., 2012: Wärmer und weniger Schneefall. In: Der Klimawandel in den Alpen. Die Alpen 6: 48–49.

KRÄMER, A.; GAVELMANN, J.; WOLFSPERGER, F.; RHYNER, H., 2017: Wissenschaftliche Untersuchungen zum Snowfarming und Schneemanagement am Beispiel der Chiemgau Arena Ruhpolding im Sommer 2016 – Projektbericht herausgegeben von der Stiftung Sicherheit im Skisport SIS.

KRAUTZER, B., GRAISS, W., 2006: Techniken zur Begrünung in Hochlagen. Seilbahnen International 4: 67–68.

KRAUTZER, B.; GRAISS, W., 2012b: Die richtige Düngung von Schipisten. Seilbahn International 3: 21–22.

KRAUTZER, B.; PARTL, C.; GRAISS, W., 2012a: Hochlagenbegrünung in Österreich, Stand des Wissens und aktuelle Herausforderungen. Seilbahn International 3: 21–22.

KUROIWA, D., 1975: Metarmorphism of snow and ice sintering observed by time lapse cinephotomicrography. Snow Mechnics (Pro. Grindelwald Symposium, April 1974). IAHS Publication 114: 82–88. IAHS Press, Wallingford, Oxfordshire, UK.

LEHNING, M.; BARTELT, P.; BROWN, R.L.; FIERZ, C., 2002: A physical SNOWPACK model for the Swiss avalanche warning, Part III: meteorological forcing, thin layer formation and evaluation, Cold Regions Science and Technology 35: 169–184.

LEHNING, M.; BARTELT, P.; BROWN, R.L.; FIERZ, C.; SATYAWALI, P.K., 2002: A physical SNOWPACK model for the Swiss avalanche warning, Part II. Snow microstructure, Cold Regions Science and Technology 35: 147–167.

LEHNING, M.; VÖLKSCH, I.; GUSTAFSSON, D.; NGUYEN, T.A.; STÄHLI, M.; ZAPPA, M., 2006: ALPINE3D: a detailed model of mountain surface processes and its application to snow hydrology. Hydrological Processes 20, 10: 2111–2128. http://doi.org/10.1002/hyp.6204.

LIBBRECHT, K.G., 2005: The physics of snow crystals, Rep. Prog. Phys. 14: 599–895.

LIMACHER-LEHNER, D.; FAUVE, M., 2009: Abschlussbericht NESSy. Interner Bericht. Fachhochschule Nordwestschweiz, WSL – Institut für Schnee- und Lawinenforschung SLF.

LINTZEN, N.; EDESKÄR, T., 2014: Uniaxial Strength and Deformation Properties of Machine-Made Snow. J. Cold Reg. Eng. 29: 4. Accessed on 16/01/2018 at https://doi.org/10.1061/(ASCE)CR.1943-5495.0000090.

LOCHER-OBERHOLZER, N.; STREIT, M.; FREI, M.; ANDREY, C.; BLASER, R.; MEYER, J.; MÜLLER, U.; REIDY, B.; SCHUTZ, M.; SCHWAGER, M.; STOLL, M.; WYTTENBACH, M.; RIXEN, C., 2008a: Richtlinien Hochlagenbegrünung. Kurzfassung für die Baustelle.

LOCHER-OBERHOLZER, N.; STREIT, M.; FREI, M.; ANDREY, C.; BLASER, R.; MEYER, J.; MÜLLER, U.; REIDY, B.; SCHUTZ, M.; SCHWAGER, M.; STOLL, M.; WYTTENBACH, M.; RIXEN, C., 2008: Richtlinien Hochlagenbegrünung. Ingenieurbiologie, 2: 3–33.

MANI, O.; SCHNEEBELI, M.; MICHLMAYR, G.; RHYNER, H.; RIXEN C.: Unpublished Mausscript: Mechanism of snow hardeners on the snow cover of a ski piste. WSL – Institut für Schnee- und Lawinenforschung SLF.

MARTY, C.; BAVAY, M., 2012: Schneegrenze steigt um 500 Meter, In: Der Klimawandel in den Alpen. Die Alpen 6: 50–51.

MARTY, C.; SCHLÖGL, S.; BAVAY, M.; LEHNING, M., 2017: How much can we save? Impact of different emission scenarios on future snow cover in the Alps. Cryosphere 11, 1: 517–529. http://doi.org/10.5194/tc-11-517-2017.

MCNEIL, J.A.; HUBBARD, M.; SWEDBERG, A.D., 2012: Designing tomorrow's snow park jump. Sports Eng 15: 1–20. DOI 10.1007/s12283-012-0083-x. ISSN 1369-7072.

MEIER, F. 2012: Kunst- und Naturschnee im Vergleich. Maturaarbeit Bündner Kantonsschule Chur / SLF.

MeteoSwiss, 2014: Klimaszenarien Schweiz – eine regionale Übersicht, Fachbericht MeteoSchweiz, 243: 36 pp.

MeteoSwiss, 2017: Klimareport 2016. Bundesamt für Meteorologie und Klimatologie MeteoSchweiz, Zürich. 80 S.

NAKAMURA, H., 1978: A new apparatus to produce fresh snow. Rep. Natl Res. Cent. Disaster Prev. 19: 229–237 [in Japanese with English summary].

OLEFS, M.; FISCHER, A., 2008: Comparative study of technical measures to reduce snow and ice ablation in Alpine glacier ski resorts. Cold Regions Science and Technology 52 (2008) 371–384. https://doi.org/10.1016/j.coldregions.2007.04.021

OLEFS, M.; LEHNING. M., 2010: Textile protection of snow and ice: Measured and simulated effects on the energy and mass balance. Cold Regions Science and Technology 62: 126–141. http://doi.org/10.1016/j.coldregions.2010.03.011.

OLEFS, M., 2009: Intentionally modified mass balance of snow and ice. Dissertation. Institute of Meteorology and Geophysics. LeopoldFranzens Universität Innsbruck.

PETROVIC, J.J., 2003: Review Mechanical properties of ice and snow. J. Mater. Sci. 38: 1. https://doi.org/10.1023/A: 1021134128038

PFEIFER, H., 1977: Grundlagen der Fördertechnik. Vieweg+Teubner Verlag Braunschweig. DOI 10.1007/978-3-322-85675-3.

PINZER, B.R.; SCHNEEBELI, M.; KAEMPFER, T.U., 2012: Vapor flux and recrystallization during dry snow metamorphism under a steady temperature gradient as observed by time-lapse micro-tomography, Cryosph. 6, 5: 1141–1155, doi:10.5194/tc-6-1141-2012.

PROKSCH, M.; SCHNEEBELI, M., 2016: Schneemetamorphose. Bergundsteigen #94 / Frühling 16.

PRUPPACHER, H.R.; KLETT, J.D., 2010: Microphysics of Clouds and Precipitation. Springer, Dordrecht. https://doi.org/10.1007/978-0-306-48100-0.

RHODE, R.A., 2007: Global Warming Art. Accessed on 18/01/2018 at https://en.wikipedia.org/w/index.php?title=Image:Solar_Spectrum.png&redirect=no&oldid=137131966

RICHE, F.; SCHNEEBELI, M., 2013: Thermal conductivity of snow measured by three independent methods and anisotropy considerations. Cryosphere 7, 1: 217–227. doi: 10.5194/tc-7-217-2013.

RINDERER, T., 2008: Snowfarming – Experimenteller Vergleich und numerische Modellierung zweier Isoliermethoden zur Konservierung von Schnee. Diplomarbeit. TU München. WSL-Institut für Schnee- und Lawinforschung SLF.

RIXEN, C.; STÖCKLI, V.; AMMANN, W., 2003: Does artificial snow production affect the soil and vegetation of ski pistes? A review. Perspectives in Plant Ecology, Evolution and Systematics 5, 4: 219–230.

ROGSTAM, J.; DAHLBERG, M., 2011: A review of the energy use of mobile snowmaking at Swedish ski resorts. Internal Project Report. Accessed on 16/01/2018 at: http://bachler.cms1.ch/Portals/41/docs/energy_usage_for_snowmaking.pdf

ROUX-FOUILLET, P.; WIPF, S.; RIXEN, C., 2011: Long-term impacts of ski piste management on alpine vegetation and soils Journal of Applied Ecology, 48: 906–915, doi: 10.1111/j.1365-2664.2011.01964.x

SCHLEEF, S., 2014: X-ray microtomography analysis of isothermal new snow densification. DISS. ETH NO. 21856. Doktorarbeit.

SCHMUCKI, E.; MARTY, C.; FIERZ, C.; WEINGARTNER, R.; LEHNING, M., 2017: Impact of climate change in Switzerland on socioeconomic snow indices. Theoretical and Applied Climatology, 127 (3), 875-889. http://doi.org/10.1007/s00704-015-1676-7

SCHNEEBELI, M., 2015: Warum alter Schnee jung ist, Phys. unserer Zeit 46, 3: 126–130, doi:10.1002/piuz.201401397.

SCHNEEBELI, M.; TRUNZ, S.; HUG, M.; JÜTZ, J.; STAUDENMANN, M., 2009: Verfahren und Gerät zur Messung der Schneebeschaffenheit, Swiss Patent 698 701, 2009.

SCHNEIDER, R., 2015: Pistenmanagement. Präsentation beim Pistenmanagement Workshop der Bergbahnen Mayrhofen.

SCOTT, D.; DAWSON, J.; JONES, B., 2008: Climate change vulnerability of the US Northeast winter recreation – tourism sector, Mitigation and Adaptation Strategies for Global Change 13: 577–596.

SEATM – Service d'Etudes et d'Aménagement Touristique de la Montagne, 1990: Aménagement des pistes de ski alpin. Ministere de l'Equipment.

SHAPIRO, L.; JOHNSON, J.B.; STURM, M.; BLASIDELL, G.L., 1997: Snow mechanics. Review of state of the knowledge and applications. CRREL Report 97–3.

SIHVOLA, A.; TIURI, M., 1986: Snow fork for field determination of the density and wetness profiles of a snow pack. IEEE Trans. Geosci. Remote Sens. Vol. GE-24, 5: 717–721.

SKOGSBERG, K., 2005: Seasonal Snow Storage for Space and Process Cooling. Luela Universtity of Sweden. Dissertation.

SOMMER, C.G.; LEHNING, M.; FIERZ, C., 2018: Wind tunnel experiments: influence of erosion and deposition on wind-packing of new snow. Frontiers in Earth Science 6, 4: 11. doi: 10.3389/feart.2018.00004

SPANDRE, P.; FRANÇOIS, H.; THIBERT, E.; MORIN, S.; GEORGE-MARCELPOIL, E., 2017: Determination of snowmaking efficiency on a ski slope from observations and modelling of snowmaking events and seasonal snow accumulation, The Cryosphere 11, 891–909, https://doi.org/10.5194/tc-11-891-2017.

SPÖRRI, J.; KRÖLL, J.; AMESBERGER, G.; BLAKE, M.O.; MÜLLER, E., 2012: Perceived key injury risk factors in WC alpine ski racing – an explorative qualitative study with ex-pert stakeholders. BJSM. 1–7.

STASIAK, M.; MOLENDA, M.; BAN, M., 2015: Mechanical properties of sawdust and woodchips. Fuel 159: 900–908, ISSN 0016-2361, https://doi.org/10.1016/j.fuel.2015.07.044.

STEIGER, R.; STÖTTER, J., 2013: Climate Change Impact Assessment of Ski Tourism in Tyrol, Tourism Geographies 15, 4: 577–600, DOI: 10.1080/14616688.2012.762539.

STEINKOGLER, W.; GAUME, J.; LÖWE, H.; SOVILLA, B.; LEHNING, M., 2015: Granulation of snow: From tumbler experiments to discrete element simulations. J. Geophys. Res. F: Earth Surface 120, 6: 1107–1126.

STURM, M.; HOLMGREN, J.; KONIG, M.; MORRIS, K., 1997: The thermal conductivity of seasonal snow. 3 Glacial., 43, 143: 26–41.

Szabo, D.; Schneebeli, M., 2007: Subsecond sintering of ice, Appl. Phys. Lett. 90, 15: 151916, doi:151916 10.1063/1.2721391.

Tabler, R., 2003: Controlling blowing and drifting snow with snow fences and road design. Final report prepared for National cooperative highway research program, transportation research board of the national academies, Niwot, Colorado.

Techel, F.; Pielmeier, C., 2011: Point observations of liquid water content in wet snow – investigating methodical, spatial and temporal aspects. The Cryosphere, 5, 405–418, https://doi.org/10.5194/tc-5-405-2011.

Theile, T.; Szabo, D.; Lüthi, A.; Rhyner, H.; Schneebeli, M., 2009: Mechanics of the Ski-Snow Contact. Tribology Letters 36: 223–231.

Vanicek, K.; Frei, T.; Zenobia, L.; Schmalwieser, A., 2000: UV Index for the public: A guide for publication and interpretation of solar UV Index forecasts for the public prepared by the Working Group 4 of the COST 713 Action 'UVB. Accessed on 16/01/2018 at http://www.temis.nl/uvradiation/info/Vanicek_et_al_COST-713_2000.pdf

Weiler M., 2013: Snowparks: Leitfaden für Planung, Bau und Betrieb. Bern: bfu – Beratungsstelle für Unfallverhütung. bfu-Fachdokumentation 2.081.

Wolfsperger, F.; Hinterberger, B.; Christian, J.; Matzl, M.; Jahnel, R.; Spörri, J.; Kröll, J.; Gilgien, M.; Rhyner, H.; Schneebeli, M.; Müller, E., 2015: Quantifying Snow Conditions of World Cup Alpine Ski Racing Tracks. In: Science and Skiing VI, 330–339. Maidenhead: Meyer & Meyer Spor(UK) Ltd. ISBN: 978-1-78255-066-2.

Wolfsperger, F.; Grünewald, T., 2018: Snow farming (storage) in the Alps and Scandinavia: today's and future activities. Book of Abstracts ISSW 2018.

Würzer, S.; Wever, N.; Juras, R.; Lehning, M.; Jonas, T., 2017: Modelling liquid water transport in snow under rain-on-snow conditions – considering preferential flow. Hydrology and Earth System Sciences 21, 3: 1741–1756. doi: 10.5194/hess-21-1741-2017

Zmarsly, E.; Kuttler, W.; Pethe, H., 2007: Meteorologisches-klimatologisches Grundwissen. Verlag Eugen Ulmer UTB.

Snow is one of the most complex materials on our planet, as demonstrated by the fact that many languages have more than one word for it. Scots English alone has 421 words for it! Snow is highly variable and constantly changing. There are many reasons for this, such as air and snow temperature, air humidity, snow conditions, composition (natural or machine-made snow), age, grain size and shape, compaction, slope exposure and gradient, solar radiation, longwave radiation, clouds, and wind.
This book contains more than 200 pages full of practical examples to explain the scientific and multifaceted interrelations between these parameters, providing a wealth of information for any operational manager, chief of course, race director, or snowcat driver. The knowledge presented should help to enhance the quality of slopes and cross-country trails and also facilitate more efficient cooperation, thereby cutting the costs of facility operators and lowering competition budgets. I also found the discussions with Fabian Wolfsperger incredibly interesting and useful.
The key to successful slope preparation is: "know-how, sound planning based on weather forecasts, use of the right tools, and optimal timing".

I hope you all enjoy reading the book and continuing to learn about snow, a never-ending task!

Hans Pieren

World Cup Race Director in Adelboden,
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