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Review

Snow Cover Studies: a Review on the Intensity of Human Pressure

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Abstract

Snow cover should be treated as a highly dynamic medium. A variety of physical and chemical processes interact to alter its chemical composition and affect the metamorphism of its individual crystals and layers; this, in turn, has a direct influence on their mutual adhesion, and ultimately on the stability of the entire snow cover.

The literature data here reported provide basic information on the forms of solid precipitation, the types of snow and their generation, as well as the formation, stability, and chemical composition of snow cover in terms of a broad spectrum of inorganic compounds and of the levels of certain organic compounds in snowpit sampled in mountain regions in Poland and elsewhere in the world.

Keywords: snow, snowpit, snow cover, deposition of contaminants, snow cover stability

Introduction

Snow on the ground is a veritable storehouse of atmospheric contaminants. The chemical composition of subsequent meltwater is not merely the sum of all chemical components accumulating in snow cover after each successive precipitation and deposition. As long as snow cover persists, it is subject to numerous processes: deposition of contaminants and also rime on its surface, wind erosion and accumulation from different areas, partial top-down or bottom-up thawing, and related possible seepage of meltwater into the ground. As a result, the chemistry of snow on the ground is continually changing. If the snow does not melt, the overall contaminant load builds up with each succeeding snowfall.

The reason for studying the chemistry of snow is the considerable influence of snow cover on the deposition rate of contaminants. Assays of the chemical composition of atmospheric precipitation within 24 h do not reflect the real rate of pollutant deposition. When conditions for evaporation are unfavourable, precipitation increases the amount of water in the snow cover and the contaminant load 'stored' in.

This condition is particularly enhanced in mountain regions where, given favourable weather, the snow on the ground can persist for several months. Only once the thaw sets in are pollutants released from the snow cover, from where they pass into the soil and surface/ground waters [1]. The result is that in the space of a very short time (a few days), a large amount of the accumulated chemical load of contaminants is released from the snow cover, leading to intense environmental stress.

Research programmes and projects for evaluating the state/composition of snow cover and the processes occur-

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ring in it are crucial not only from meteorological and climatic points of view, but also from hydrological and applied ones. The role played by snow in nature is tremendously important, particularly in relation to the balance between incoming solar radiation and outcoming from the Earth's surface, to the heat balance between the atmosphere and the lithosphere, and also in conditioning weather, climate, and human health [2].

Solid Atmospheric Precipitation

Atmospheric precipitation, both liquid and solid, are formed above the condensation level, that is the altitude at which water vapour becomes saturated. Clouds (from which precipitation falls) can be divided into those containing water, ice, and a mixture of water and ice. Water clouds form at temperatures above 0ºC, mixed ones between 0ºC and 40ºC. Ice clouds form only at very low temperatures. Snow occurs from the following types of clouds: *Altostratus*, *Nimbostratus*, *Stratocumulus*, *Stratus* (granular snow only), *Cumulus*, and *Cumulonimbus*.

The microphysical processes taking place within clouds and leading to the formation of water droplets and ice crystals are complex. Most or nearly all the incipient crystals are formed around ice nuclei, which are outcoming agents, e.g. mineral, artificial, or smoke particles carried upwards to considerable heights from the Earth's surface by convection. In the upper part of the cloud, the film of water adhering to the nucleus forms droplets or incipient ice crystals. A snowflake is formed as a result of sublimation (the direct transition from ice to water vapour driven by surrounding heat) or coagulation (the coalescing of water droplets into larger drops as a result of collisions between them during gravitational freefall or turbulent air movements). Overcoming the force of the ascending air currents, the largest flakes fall to the base of the cloud, where supercooled water droplets are prevalent. The snowflake becomes larger by sublimation. Its convex parts most distant from the centre grow most quickly, and a six-beam star grows out of a hexagonal flake [3].

Once snow flakes have escaped from the cloud, they begin their journey toward the Earth's surface. Depending on the altitude of the cloud from which the snow is falling, the distance to be covered may range from 500 to 5,000 m. The forces of gravitation, floating, and air resistance together act on a falling snowflake. The rate of fall of a snowflake is known as its hydraulic velocity and depends mainly on its mass, shape and size, and air density. In frosty weather, snow in the shape of small needles and columns usually falls with speeds up to 0.5 m/s, flakes and stars 0.5-1.0 m/s, graupel (snow pellets and ice pellets) at 1.0-2.7 m/s. The velocity of a snowflake and the distance it travels depend mainly on the speed of the wind during the fall [4].

Snow is solid precipitation in the form of fine ice crystals, often joined together in various shapes (snowflakes). On the ground these crystals form a porous cover of low density. The shapes, sizes and concentrations of snow crystals vary considerably, depending on the temperature at which they were created and the conditions prevailing during their development. Snow is not the only kind of solid precipitation. On their way down through a cloud, snowflakes collide with supercooled droplets of water and become granular, the large drops enveloping and freezing on them transform them into ice/freezing rain or hail [4-9].

According to the classification of the International Commission on Snow and Ice (ICSI), the following forms of precipitation particles can be distinguished (Table 1) [9].

The Formation of Snow

During a single fall of snow a great number of different types of crystal are usually identifiable; in nature, however, these crystal types may be considered infinite in number. International classifications have been developed in an attempt to categorize snow crystal forms. One of the earliest, compiled by Professor U. Nakaya from the University of Hokkaido, was the "Classification of snow crystals" [7]. This classification describes 41 different morphological types divided into several groups (Table 1):

- needle-shaped crystals
- columnar crystals
- planar crystals
- aggregates (combinations) of columnar and flat crystals
- columnar crystals with extensive facets
- crystals with surface hoar, and graupel (depending on cloud temperatures and physical processes in the cloud)
- irregular snow particles

An extension of Nakaya's classification is the one by Magono and Lee [8]; in fact, it is the most widely ramified classification of snow crystals in existence, covering 80 separate morphological types.

The structure of a snowflake results from the sum of the process of its formation: this begins when ice condenses on a nucleus. Initially, a hexagonal or planar crystal is formed, a fraction of a millimetre in size. At temperatures between -3ºC and -8ºC and below -30ºC conditions favour the deposition of ice on the crystal's edges, from which six branches (arms) grow out. At temperatures between -3ºC and -5ºC and below -60ºC, ice is deposited on the facets, and the crystal grows vertically, forming needles. At random places along the needle the crystallization of a new needle begins at an initial angle of 60º. Other shapes occur when, during the crystal growth, the ambient conditions change (Table 1) [4, 9].

Most snow crystals are planar and have six, more or less identical, branches (arms). Depending on the temperature, humidity and pressure of the air, other forms like columns, needles, plates and pellets may appear.

The Formation of a Snow Cover

Snow cover is a natural body with specific properties that is subject to continual change under the influence of external and internal factors (Fig. 1).

Table 1. The main forms of precipitation particles (ICSI) – basic information [9].

Form of precipitation particles	Temperature of formation (physical process)	Brief description (shape)
Columns	Growth from water vapour at -3 to -8ºC and below -30ºC	Prismatic crystal, solid or hollow
Needles	Growth from water vapour at high super-saturation at -3 to -5ºC and below -60ºC	Very thin snow particles, approximately cylindrical in shape
Plates	Growth from water vapour at 0 to -3ºC and -8 to -70ºC	Plate-like, mostly hexagonal structure
Stellars, Dendrites	Growth from water vapour at high super-saturation at 0 to -3ºC and at -12 to -16ºC	Planar or spatial crystals resembling patterned stars, usually with 6 branches.
Irregular crystals	Polycrystals growing in varying environmental conditions	Clusters of very small crystals.
Graupel	Heavy riming of particles by acceretion of supercooled water droplets	Heavily rimed particles, spherical, conical, hexagonal, or irregular in shape (size: ≤5 mm)
Hail	Growth by acceration of supercooled water	Laminar internal structure, translucent or milky glazed surface (size: >5mm)
Ice pellets	Freezing of raindrops or refreezing of largely melted snow crystals or snowflakes. Graupel or snow pellets encased in thin ice layer (small hail)	Tansparent surface, mostly small spheroids, white core (size: ≤5 mm)
Rime	Formed onto surfaces as well as on freely exposed objects	Acceration of small, supercooled fog droplets frozen in place. Thin breakable crust forms on snow surface if process continues long enough.

Table 2. Classification of the main types of snow [10, 11].

Type of snow	Conditions of formation
Fresh	Powdery snow crystals falling at temperatures <-10ºC do not coalesce, and form a light, fluffy layer not bound to the substrate.
Loose, graupel-like	Snow formed from falls of graupel and fine granular snow
Settled, wind-blown	Dry snow, at temperatures from -10ºC to -3ºC, displays only a slight tendency to coalesce. The cover of powdery snow begins to settle. An important feature of such snow is the ease with which its is blown by the wind.
Compressed, dry	Packed powder is patchy in occurrence and consists of heavy but not wet snow, well compressed due to the action of the wind and its own weight.
Wet snow	At temperatures at and above -3ºC falling snow crystals are wet, which facilitates their coalescence. A layer of such snow easily attaches to the substrate. This snow has quite a high specific gravity (up to 200 kg/m^3) and considerable plasticity. It has a fairly high liquid water content. The greater the plasticity of the snow, the more resistant the snow cover is to forces tending to detach it from the substrate. With their high coherence and weight, damp or wet snows are wind-resistant.
Crust	Snow with an icy surface, breakable under the icy surface, the snow is mostly dry
Ice crust	Snow with a supportable icy surface
Granular snow	A cover of granular snow consists of large, hard crystals formed as a result of recrystallization.
Firn	Consists of large, irregular grains, not coalesced, always wet. The interstices between the grains are air-filled. This is the final phase in the metamorphosis of snow

Snow derived from precipitation and lying for some time on the ground as a layer no thinner than 0.5 cm constitutes snow cover. Once on the ground, snow crystals retain their original form for only a short time, after which they are transformed into different shapes, depending on temperature, humidity, wind, time on the ground, crystal form, and the thickness of the snow cover. As the snow cover thickens, the contaminants contained in the particles of precipitation gradually accumulate within it, but when it melts, the contaminants are released along with the meltwater, which seeps into the soil and surface/ground waters.

Depending on the duration of the interval between two falls of snow and on the weather during such intervals, the layers of snow are transformed both on the surface and within. Different types of snow begin to form. The snow cover changes under the influence of melting, wind, evaporation, recrystallization, and pressure. In the Polish mountains nine types of snow occur during winter (Table 2) [10].

Three states of matter can be distinguished in snow forming a cover:

solid – in which ice takes the form of crystals or grains;

liquid – when at temperatures around the melting point water forms a coating around the grains of snow;

gas – formed by water vapour or air present in the interstices between the snow crystals.

The variations in the proportions of each of these phases and the metamorphism taking place within the snow directly affect the properties of a snow cover.

The Processes Taking Place within a Snow Cover

Both on the surface and within, a cover of snow is subject to continual change as a result of the physical processes taking place in it. Both external and internal factors affect these processes and the time when they occur. External factors include temperature, wind, radiation, and air humidity, while internal factors include the pressure of successive layers of snow, and the temperature within the snow cover.

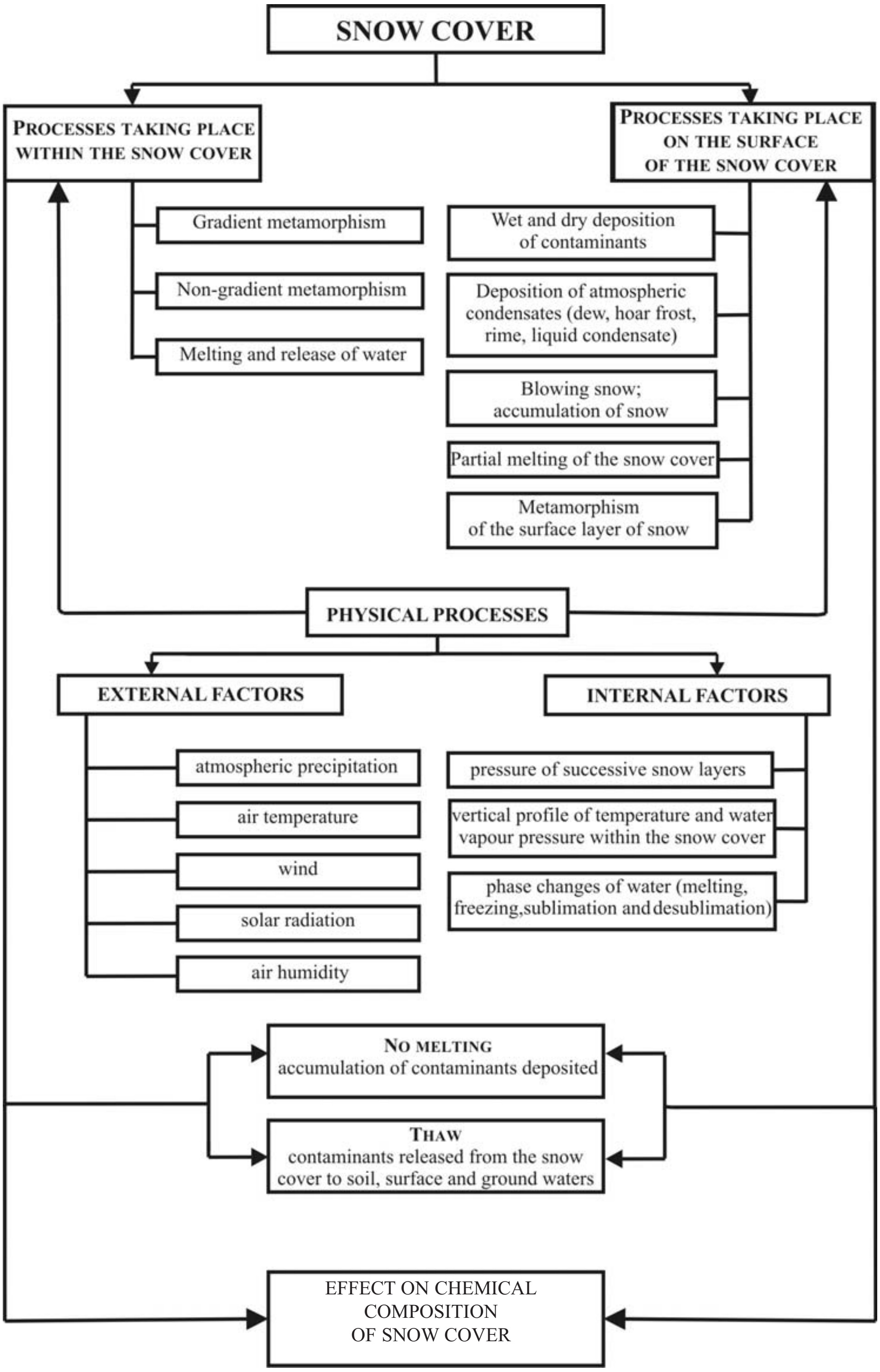


Fig. 1. Processes causing changes in the physical/chemical texture of snow cover.

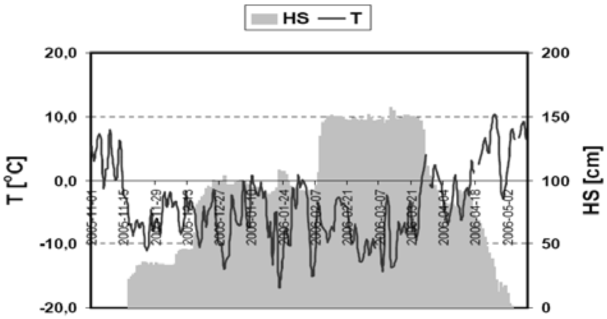


Fig. 2. The changes in height of snow cover (HS) and air temperature (T) in winter 2005-06 at Szrenica in the Giant Mountains (Poland).

An important aspect, affecting the way individual snow crystals join together is their morphology (shape) and the processes of sublimation and recrystallization taking place within the snow cover. The interaction of these factors leads to changes in the properties of the snow as a result of:

a) the constant-temperature metamorphism of snow – i.e. **destructive metamorphism** – that occurs in all crystals throughout the snow cover at temperatures <0ºC, most rapidly just below 0ºC, and which declines at -15ºC and ceases altogether at -40ºC; and
b) the metamorphism of snow under the influence of a temperature gradient – i.e. **constructive metamorphism** – that takes place when there is a temperature difference between the bottom layer of snow (usually 0ºC) and the snow surface; highly unstable, cup-shaped crystals then appear, a process that takes place rapidly when there is a big difference in temperature [4].

The metamorphosis of snow oscillates between melting and refreezing when temperatures change from above-zero to sub-zero, and vice versa. The effect of 24 h changes in temperature and the melting and refreezing give rise to the fact that the melting snow grains become larger and more spherical; the end result is a stable snow cover layer. The degree of metamorphosis of the various layers has a direct influence on mutual adhesion, and by extension, on the stability of the snow cover as a whole.

The potential causes of deviations of height and duration of a snow cover from the hypsometric profile include:

- exposure to the sun (insolation)
- total winter precipitation
- air temperature
- the extent to which snow is wind-blown
- surface vegetation

Both temperatures, of air and within snow cover, are main factors affecting the metamorposis of snow. Snow has low thermal conductivity, so temperature within snow cover changes slowly, far more than the corresponding temperature changes in the atmosphere. Temperatures are usually highest in the deepest layers, so water vapour diffuses from the lower layers to the surface. The consequence of this is a loss of crystals in the lower part and a loose texture of the lower layers, which eventually disturbs the equilibrium of the snow cover. When above-zero temperatures act on the snow cover for a longer period of time, the water penetrating down into the bulk of the snow gives rise to wet snow. When air temperature is low, snow mass contraction takes place, leading to the appearance of cracks and crevices. The surface layers are also subject to metamorphosis, changing the type of snow from which they were

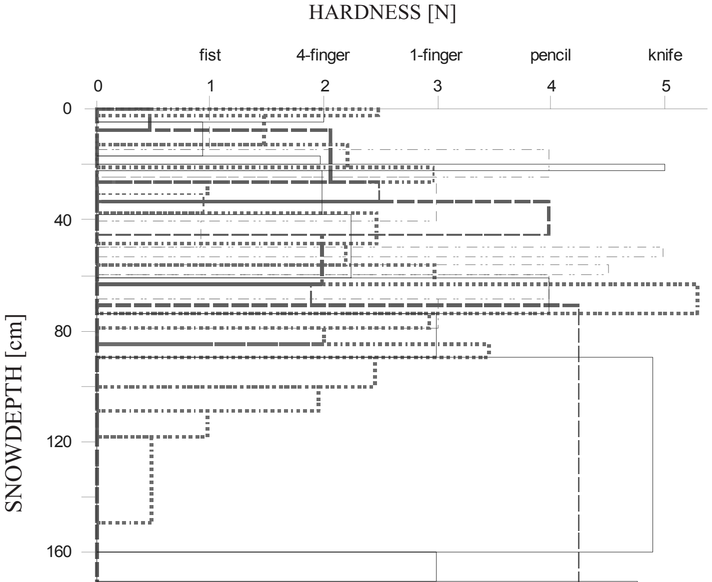


Fig. 3. Snowpit hardness from: 1. Greenland Ice Core (2005) [20], 2. The Summit of Nevado Illimani, Bolivia (1999) [21], 3. Pika Glacier – Alaska Range (2001) [22], 4. The Swiss Alps [23].

Table 3. Primary physical characteristics of deposited snow (ICSI-2009) [9].

Snow cover measurements		Method of measurement			
Grain shape		1.	Precipitation particles		(Fig. 5)
		2.	Machine-made snow		
		3.	Decomposing and fragmented precipitation particles		
		4.	Rounded grains		
		5.	Faceted crystals		
		6.	Depth hoar		
		7.	Surface hoar		
		8.	Melt forms		
		9.	Ice formations		
Grain size		very fine	<0.2 mm		(Fig. 6)
		fine	0.2-0.5 mm		
		medium	0.5-1.0 mm		
		coarse	1.0-2.0 mm		
		very coarse	2.0-5.0 mm		
		extreme	>5 mm		
Snow density [kg/m³]	Determined by weighing snow of a known volume				(Fig. 7)
Snow hardness (Figs. 3, 4)	HH index	Hand-hardness test		Ram resistance [N]	
				Range	Mean
	1.	very soft	Fist	0-50	20
	2.	soft	Four fingers	50-175	100
	3.	medium	One finger	175-390	250
	4.	hard	Pencil	390-715	500
	5.	very hard	Knife blade	715-1,200	1,000
	6.	ice formations	Ice	>1200	>1,200
Liquid water content		Wetness index		Range	
		1.	dry	0% water	
		2.	moist	< 3% water	
		3.	wet	3-8% water	
		4.	very wet	8-15% water	
		5.	slush	> 15% water	
Temperature [°C]	Measuring air temperature, temperature at the snow surface, ground temperature, snow profile temperature: 5 cm above the ground, and 5 cm below the surface				(Fig. 8)
Impurities	It cover those cases where the type and amount of an impurity influence physical characteristics of the snow				
Thickness of layers [cm]	An essential parameter when chracterizing the current state of snowpack. Usually measured vertically				

formed. When water vapour rises from the warmer grains of snow near the ground to the upper layers, where it condenses in the colder air, a crust is formed. Firn is formed when heat entering the snow pack from above initiates the melting and refreezing of snow crystals. In contrast, an ice crust is formed when after a period of prolonged insolation, during which the surface layer of the snow cover melts, there is a sudden drop in temperature at the surface (Table 2) [1, 11]. The wind also affects the nature of the surface layer of snow. Wind breaks up and comminutes the snow crystals as they are blown about by the wind. On windward slopes the snow is blown away and compacted, it is deposited on ridges forming cornices, and on leeward slopes, it forms wind slabs.

Table 4. Additional measurements of snow cover [9].

Snow cover measurements	Units	Method of measurement
Height	cm	Height is the coordinate measured vertically (line of plumb) from the base. Ground surface is usually taken as the base, but on firn fields and glaciers it refers to the level of either the firn surface or glacier ice.
Thickness	cm	Used when measurements are taken perpendicularly, i.e., at a right angle to the slope on inclined snow covers. It is measured from the base and the same comments apply as for height.
Height of snowpack	cm	Total height of the snowpack, i.e., the vertical distance from base to snow surface.
Height of new snow	cm	The thickness of freshly fallen snow that accumulated on a snow board during a standard observation period of 24 hours.
Snow water equivalent	mm w.e.* kg/m^2	Snow water equivalent is the depth of water that would result if the mass of snow melted completely. It is the product of the snow height in metres and the vertically-integrated density in kilograms per cubic metre. It can be describe by: snow water equivalent of snow cover (SWE, HSW), water equivalent from the base up to the height H (HW), water equivalent of a single layer of thickness L (LW), and water equivalent of snowfall (HNW).
Water equivalent of snowfall	mm w.e.* kg/m^2	Typically measured for a standard observation period of 24 hours.
Snow strength	Pa	Snow strength can be regarded as the maximum or failure stress on a stress-strain curve. It is the maximum stress snow can withstand without failing or fracturing.
Penetrability of snow surface	cm	The depth that an object penetrates into the snow from the surface.
Surface features	cm	Described more generally in terms of roughness elements that are not related to snow microstructure: smooth, wavy, concave furrows, convex furrows, random furrows.
Snow-covered area	1%	The areal extent of snow-covered ground, usually expressed as a fraction (%) of the total area investigated.
Slope angle	^{o}	The acute angle measured from the horizontal to the plane of a slope. Slope angle is measured with a clinometer.
Aspect of slope	^{o}	Aspect is the compass direction toward which a slope faces. The direction is taken downslope and normal to the contours of elevation, i.e., along the fall line.
Time	s, min, h, d, week, month, year	Usually given in seconds

Fig. 2 shows a continuous record of snow cover height and air temperature.

Progressive deforestation in the last 20 years has also had a significant influence on snow cover formation. In the Jizera Mountains (west part of Western Sudetes), where the rate of deforestation has been even faster than in the Giant Mts. (a central part of the Western Sudetes), the snow cover remains on the ground for a good three weeks less in clear-felled areas than in the adjoining forest. During the first half of winter the height of the snow cover and the supply of water it contains are similar both within the forest and beyond it. But when the thaw sets in, the snow cover in the open ground melts far more rapidly, and the pH and contaminant load of the resulting meltwaters are correspondingly high [12]. The same scenario was repeated in the Polish part of the Giant Mts and in the Jizera Mts in 1998, when the thawing period in the catchment area of the Kamienna River was 25 days shorter than normal and the largest masses of meltwater flowed downstream already in April rather than in May [13].

Measurement of Snow Cover

The standard observations of snow cover do not take into account its internal structure and properties to any great extent. Obtaining full information on the current structure of a snow layer and the processes occurring within it enable its stability to be analyzed, which is a crucial factor in assessing and forecasting avalanche hazards. For this purpose meteorologists carry out features and additional measurements of the snow cover (Tables 3 and 4) [9]. Figs. 3-8 illustrate measurements of the hardness, density and temperature of snow, and crystal sizes and grain forms.

If a pit is dug in the snow cover and one of its sides cut vertically, its stratified structure is revealed. The sediment accumulated in the surface layers of snow is known as *snowpit*. The layers making up a cover of snow differ in their physical and mechanical properties, depending on the weather conditions and time when they were formed, and also on how long they have been in existence. With a com-

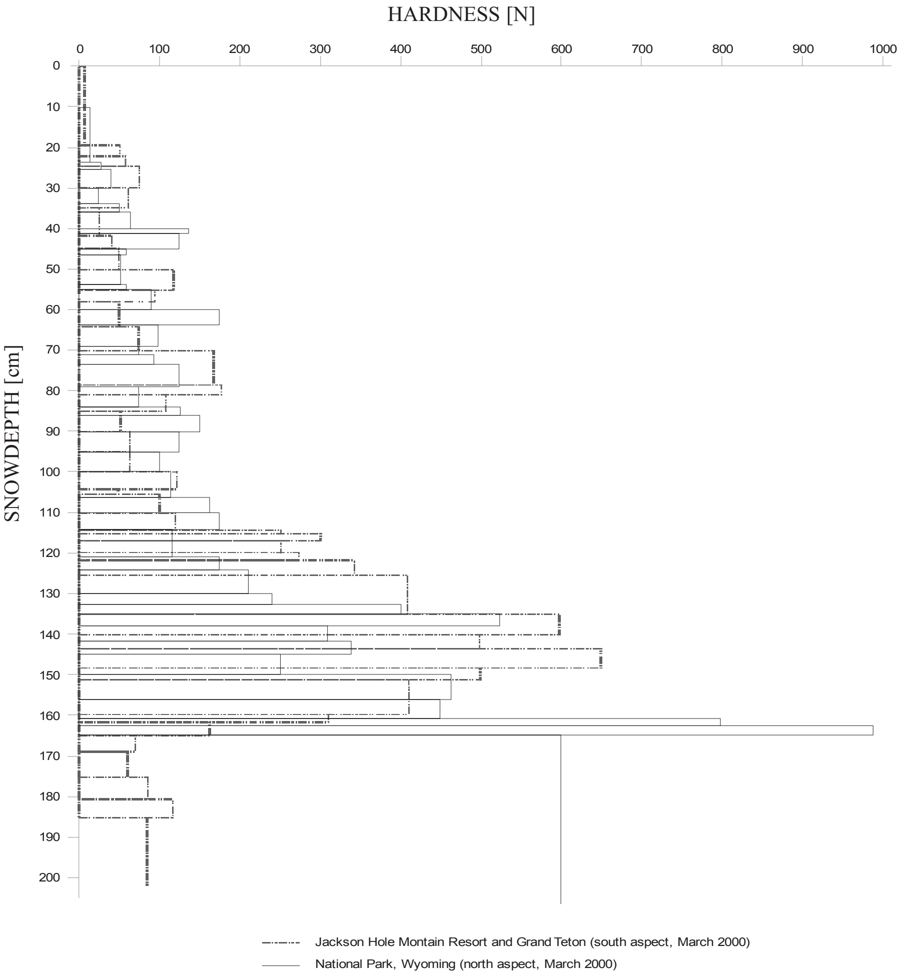


Fig. 4. Ram penetrometer profile of southern and northern aspects in March 2000 (Jackson Hole Mountain Resort and Grand Teton National Park, Wyoming) [24].

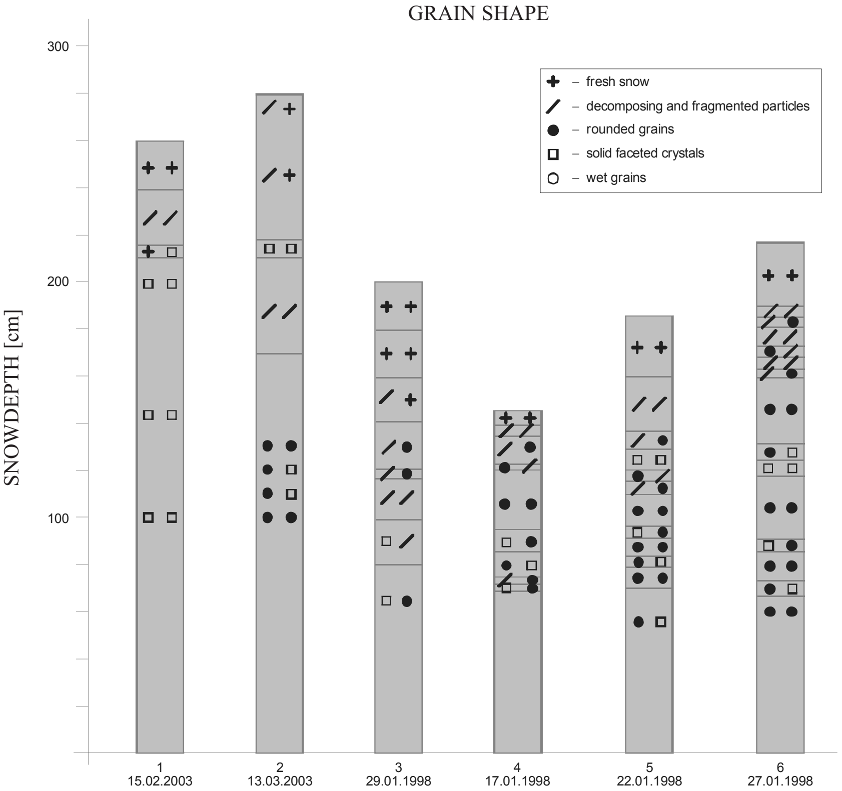


Fig. 5. Grain profile measured at sites A and B at Niseko, Japan, in January 1998 [24], and February and March 2003 [26].

Table 5. Classification of ram hardness profiles [14, 17, 25, 27].

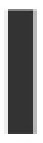
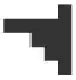
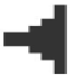
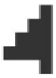
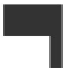
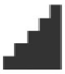
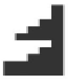
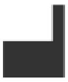
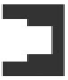
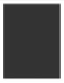
Type	Profile	Base	Stability
1		weak	unstable
2			depends on other conditions
3			
4			
5			unstable
6		strong	stable
7			unstable
8			depends on other conditions
9			unstable
10			stable

Table 6. Relative importance of parameters for interpretation of profiles and the RB (Rutschblock test) [14-19, 30, 31].

Profile interpretation	Importance	RB interpretation	Importance
Ram hardness profile	1	Slab thickness	0.9
Weak layers	1	Type of fracture plane	0.9
Rutschblock	0.9	RB score	0.8
Grain type and size	0.7	Type of failure	0.8
Snow temperature	0.5	Slope angle	0.7
Hand hardness	0.4	Snow depth	0.6
Liquid water content	0.1	Slab hardness	0.4

plete set of measurements for a given profile at hand, and having entered these data into the relevant computer program, we obtain a graphic picture of the snow cover and the vertical distribution of its parameters; this is known as a description of the stratigraphic profile.

Weak layers are mostly soft, usually 'fist' or '4-fingers' in the hand-hardness scale. It is important to search for differences in hardness, as they are often associated with weaker layers. Increasing hardness with decreasing depth

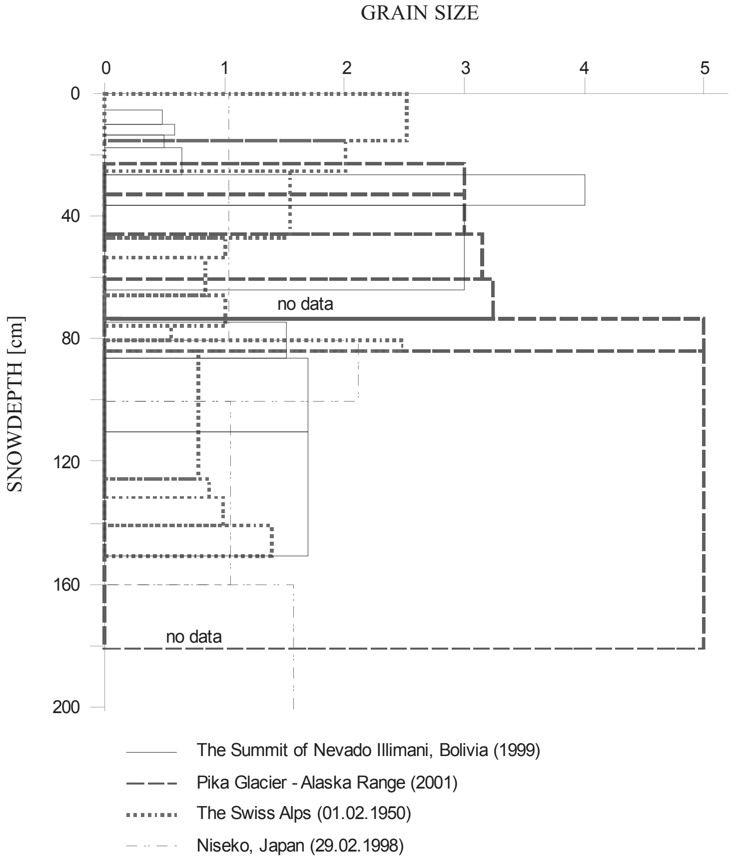


Fig. 6. Snowpit grain size from: 1. Pika Glacier – Alaska Range (2001) [22], 2. The Summit of Nevado Illimani, Bolivia (1999) [21], 3. the Swiss Alps [23], 4. Site A – Niseko, Japan – January 1998 [24].

may indicate that the snowpack is unstable. Weak layers responsible for snowpack instability are often found between two hard layers. Frequent small changes in hardness in the snowpack profile are not as critical as a large difference between two layers [5, 14, 17, 27].

The vertical distribution of a snowpack's penetration resistance can be illustrated by a ram profile. The main disadvantage, however, is that because of low resolution, hard or soft thin layers cannot be detected. The ram hardness profile can be presented in different ways (see Table 5 – the wider the darkened area, the harder the snowpack layer). The fact that the base may be weak does not necessarily mean that the snowpack is unstable [5, 14].

Surface hoar, faceted grains, or depth hoar are usually present in the weak layers of skier-triggered avalanches. These grains are coarse and have plane surfaces, so the bonding is weaker and hence the grain types are weaker, too. If the grains are buried they become rounded in shape and thus are less critical. The snowpack is stabilized by the ice crust created by the melting and refreezing of surface snow layer. On the other hand, they may provide surfaces over which new, upper snow layers can slip. Wetting the crust layer may reduce the friction and instability of a snowpack [5, 14].

The strength of a snow layer depends on grain size. There is negative correlation between grain size and number of bonds per unit volume. The dependence of grain size on snow depth is presented in Fig. 6 [5, 14].

The density of a snow layer does not directly indicate its instability, but critical layers are often less dense than the surrounding ones. Generally, a dense snow layer overlying a low-density layer may be dangerous. Obtaining more information about stability, strength, hardness, and grain size measurements is necessary, not just density measurements [5, 14].

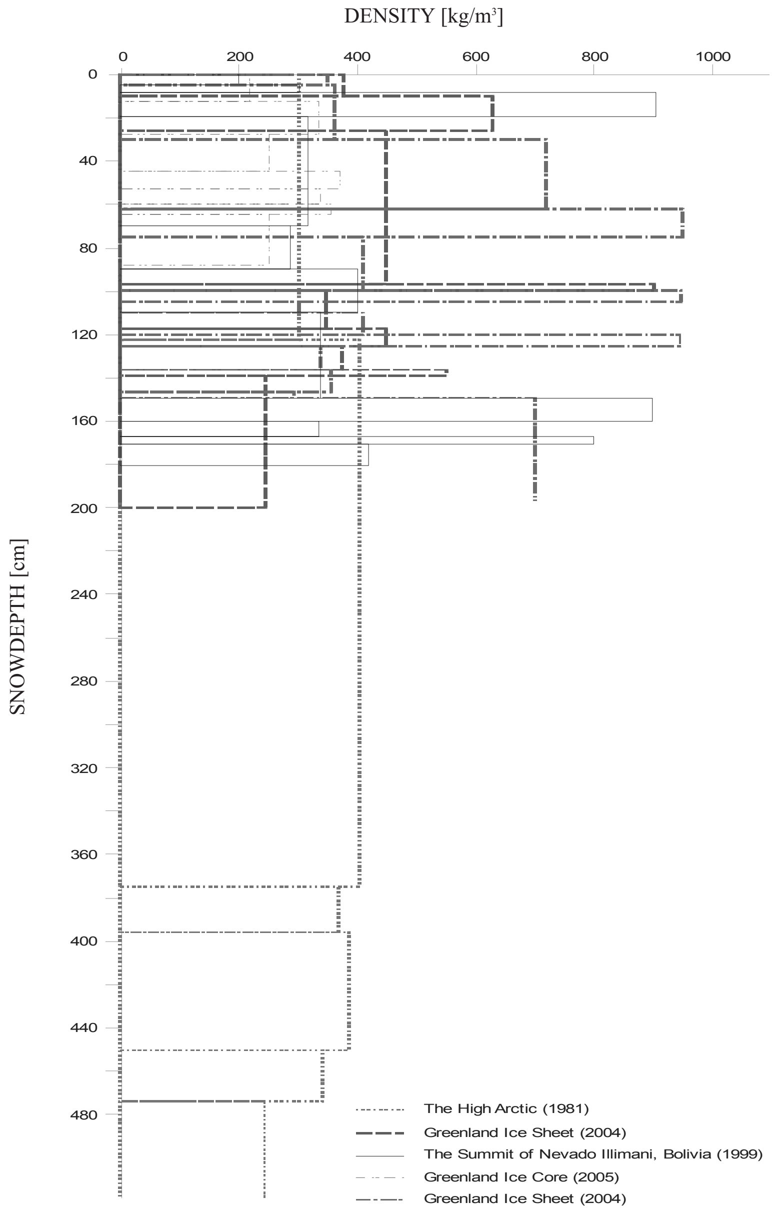


Fig. 7. Snowpit density from 1. The High Arctic (1981) [28], 2.,5. Greenland Ice Core (2004) [29], 3. The Summit of Nevado Illimani, Bolivia (1999) [21], 4. Greenland Ice Core (2005) [20].

For establishing the stability of a snow layer, temperature seems to be a parameter of little value. There are no clear rules about how snow temperature should be evaluated [5, 14-16].

Table 6 provides information on the importance of the various parameters determined in snow samples taken from a snowpit profile (1: very important, 0: not important).

A snow cover is a highly dynamic medium. Both physical and chemical processes can cause its chemical composition to change, so comprehensive tests should be carried out to ascertain the contaminant content in snow. The chemical composition of snow layers reflects the composition of native atmospheric aerosols, dry precipitation, and the nature of the adsorbent surface. The accumulation of components in snow cover present in the atmosphere depends on the weather and on the properties of the surface covered by the snow. The chemical composition of snow can provide a great deal of useful information on the levels of contaminants in the atmosphere, the changes in these levels over time, and the mechanism of their transport and deposition. Changes in the chemical composition of the atmosphere are reflected in changes in the chemical composition of snow and should be associated with various sources and transport pathways (Fig. 1).

The Chemistry of Snow Cover

Reliable information on the chemistry of snow cover is provided by the assay of representative samples collected using the appropriate equipment and correctly prepared for their analysis for target components and parameters characterizing the chemical composition and the processes taking place within the snow cover.

A number of problems and challenges crop up with this type of analysis, which the analysts involved in this type of assay have to solve. The most important of these include:

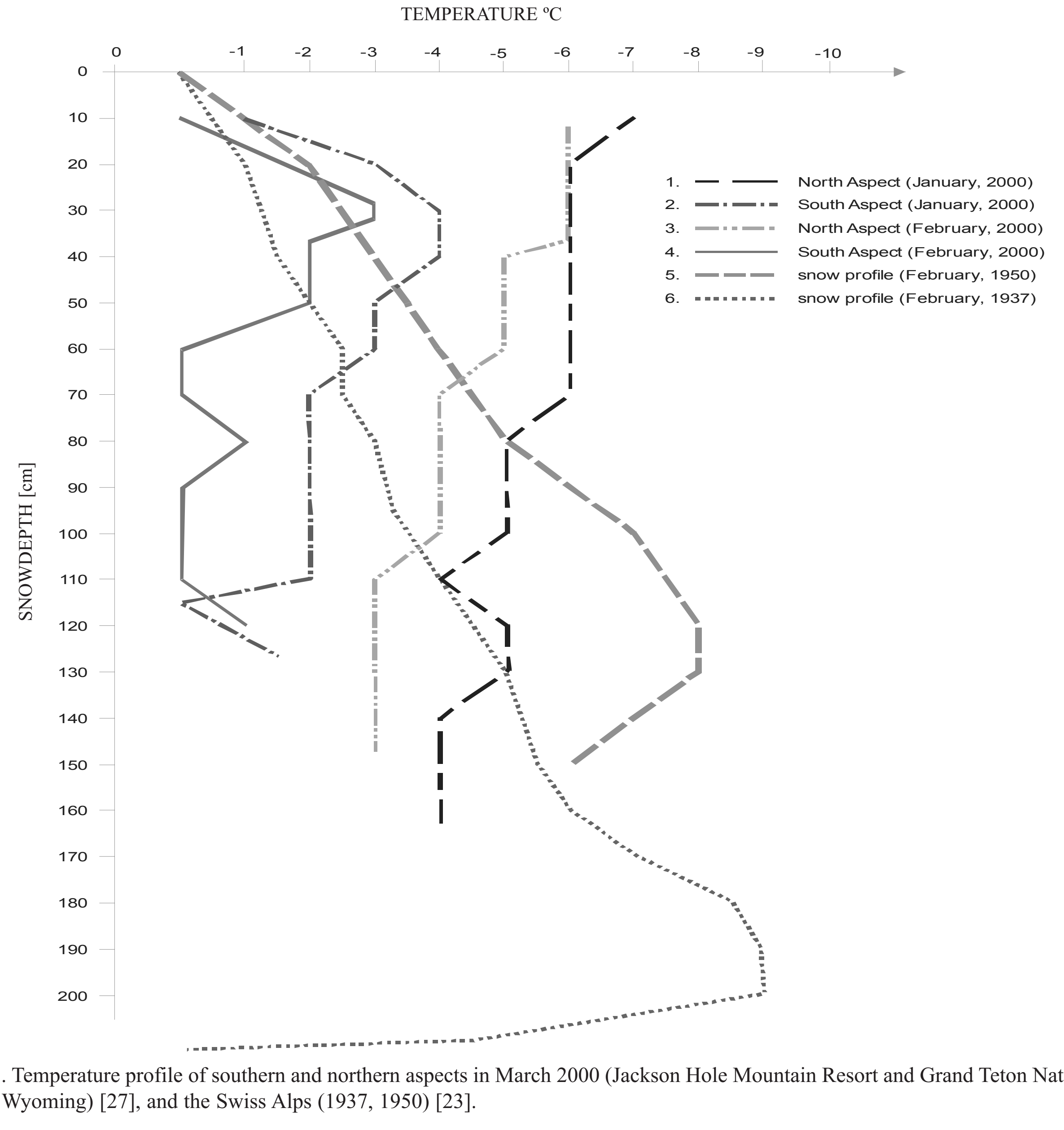


Fig. 8. Temperature profile of southern and northern aspects in March 2000 (Jackson Hole Mountain Resort and Grand Teton National Park, Wyoming) [27], and the Swiss Alps (1937, 1950) [23].

Table 7. Results of snowpit sample analyses: a review of literature data

Sampling area	Sampling period	Features of the sampling site	Analytes	Concentration ranges	References
Himalayas – Mt. Everest	1998-2002	The East Rongbuk glacier on the northern slopes of Mt. Everest (27º59'N, 86º55'E). Three snowpit samples were taken at altitudes of 6,400 m and 6,500 m.	NO_3^-	0.18-1.37 [μeq/l]	[33]
			Cl^-	0.55-1.29	
			SO_4^{2-}	0.69-0.80	
			NH4+	nd – 1.41	
			Ca^{2+}	2.79-8.26	
			Na^+	0.54-0.75	
			K^+	0.24-0.46	
			Mg^{2+}	0.21-0.49	
China	1996	Glacier at the head of the River Ürümqi, Tien Shan, altitude 4,230 m	NO_3^-	0-0.85 [10^{-6} g/g]	[31]
			Cl^-	0.06-1.11	
			SO_4^{2-}	0.1-2.3	
Greenland	1988-89	A sampler was placed at the summit of Dye 3 in the southern part of the ice cover at latitude 65º11N, longitude 43º50W, and altitude 2,479 m	Al^{3+}	1.82-6.82 [μg/l]	[34]
			Fe^{2+}	1.10-3.02	
	1991-92	Summit of the Greenland Ice Sheet – samples taken at latitude 72º20N, longitude 38º45W and altitude 3,240 m	Na^+	0.1-3.8	[35]
			Mg^{2+}	0.1-8.1	
			K^+	0.05-6.9	
	1996	Summit of the Greenland Ice Sheet – the snowpit was located in the SW part of the Greenland Ice Sheet. The camp was sited at latitude 72º58N, longitude 38º48W and altitude 3,207 m	PHE	1295-4,536 [pg/kg H_2O]	[36]
			FLU	685-5718	
			PYR	449-4,069	
			BaA	nd – 1081	
			CHR	nd – 1697	
			BeP	nd – 1310	
			BaP	nd – 2540	
			InP	nd – 781	
			BgP	nd – 919	
			RET	57-399	
Alps	1991	Summit of the Sonnblick (Austria)	NO_3^-	0-0.13 [ppm]	[37]
			Cl^-	0-0.09	
			SO_4^{2-}	0-0.31	
			NH_4^+	0-0.08	
			Na^+	0-0.94	
			K^+	0-0.15	
	1992	Summit of the Sonnblick (Austria)	NO_3^-	0.461-0.618	
			Cl^-	0.047-0.111	
			SO_4^{2-}	0.298-0.372	
			NH_4^+	0.048-0.08	
			Na^+	0.027-0.074	
			Mg^{2+}	0.021-0.03	
			Ca^{2+}	0.056-0.149	

Table 7. Continued.

Sampling area	Sampling period	Features of the sampling site	Analytes	Concentration ranges	References
Alps	1994	Jungfraujoch (Switzerland) – latitude 46.55ºN , longitude 7.98ºE , altitude 3,400 m	NO_3^-	2.8-7.1 [µeq/l]	[38]
			Cl^-	0.7-5.6	
			SO_4^{2-}	2.5-8.1	
	1992-95	The Stubai glacier in the Tyrolean Alps, altitude 2,950 m, latitude 46º59'N, longitude 11º6'E	average value [µeq/l]		[30]
			NO_3^-	5.3	
			Cl^-	1.1	
			SO_4^{2-}	3.4	
			NH_4^+	2.3	
			Na^+	1.0	
			Mg^{2+}	0.5	
			Ca^{2+}	2.1	
			K^+	0.4	
Poland	1993	Jakuszyce	NO_3	0.339-18.301	[46]
			SO_4	2.550-8.212	
			Mg	0.105-0.224	
			Na	0.405-0.577	
			Pb	0.008-0.028	
			Zn	0.035-0.063	
		Łabski Szczyt	NO_3	0.281-9.390	
			SO_4	0.838-7.510	
			Mg	0.049-0.198	
			Na	0.257-0.625	
			Pb	0.001-0.047	
			Zn	0.048-0.385	
		Szrenica	NO_3	0.266-2.730	
			SO_4	1.390-2.301	
			Mg	0.058-0.165	
			Na	0.324-0.495	
			Pb	0.004-0.019	
			Zn	0.037-0.061	
		Odrodzenie	NO_3	0.595-1.880	
			SO_4	0.970-3.270	
			Mg	0.035-0.221	
			Na	0.201-0.527	
			Pb	0.001-0.024	
			Zn	0.009-0.058	
		Śnieżka	NO_3	0.319-1.220	
			SO_4	1.320-2.190	
			Mg	0.039-0.151	
			Na	0.129-0.578	
			Pb	0.008-0.130	
			Zn	0.019-0.066	

- limited access to the appropriate equipment for collecting samples of the different types of solid precipitation and snow cover layers
- the requirement to apply appropriate procedures during the transport and sample preparation stages, prior to the final determination stage
- the lack of reference materials essential for validating the analytical procedures applied, ensuring the appropriate level of control and assuring the quality of the analytical results

It is clear from an analysis of literature data that more and more results are becoming available from analyses of snowpit samples carried out to determine the levels of different components. Such research has been carried out using snowpit samples collected in very different parts of the world (Greenland, the Alps, the Andes, the Himalayas, Antarctica, the Sudeten Mountains) [21, 32-40]. Levels of the following components were assayed in these samples:

- anions: Cl^-, NO^{3-}, SO_4^{2-};
- cations: H^+, Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+};
- PAHs: phenanthrene, fluoroanthene, pyrene, benz[a]anthracene, chrysene, benzo[e]pyrene, benzo[a]pyrene, indeno[1,2,3-cd]pyrene, benzo[ghi]perylene, retene (1-methyl-7-isopropylphenanthrene);
- metals.

Table 7 presents information on the results of studies performed so far. It gives the features of the sites from which the snow/snowpit samples were taken, the maximum and minimum concentrations determined, and in some cases the mean concentrations of the analytes.

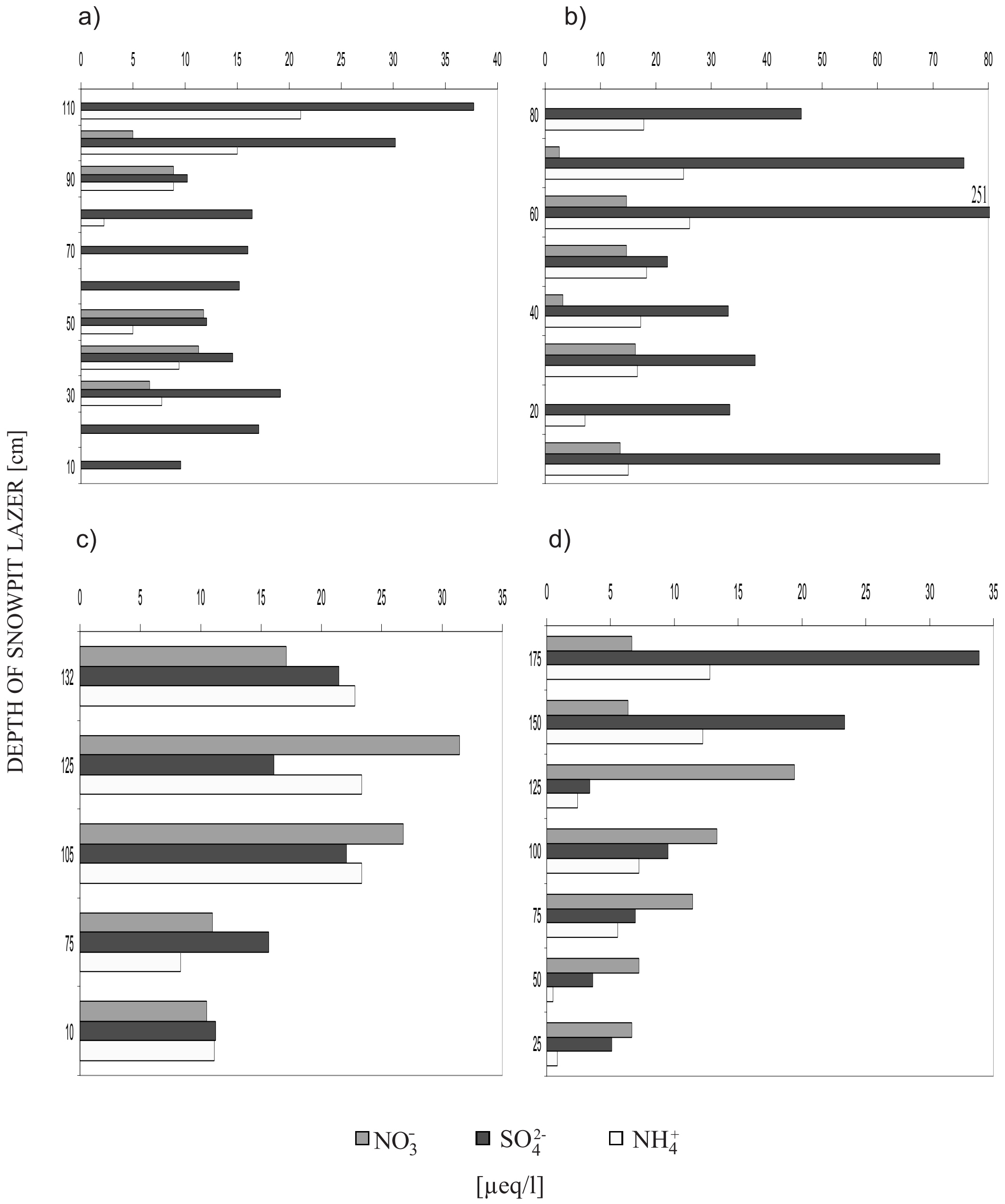


Fig. 9. Mean concentrations of nitrate, sulphate, and ammonium ions in samples of snow collected at a) Śnieżnik, b) Orle, c) Szrenica in January 2008 (author's own results), and d) the Alps (April 1994) [32].

Attention has been drawn to the part played by snow cover in the pollution of mountain ecosystems in Poland (the Sudeten and Carpathian Mountains) since the mid-1990s [41, 42]. This problem takes on particular urgency in the Giant and Jizera Mountains (western Sudetes), where the buffering ability of the bedrock is limited.

Numerous papers have been written on the spatial conditions governing the decomposition of the snow cover in the Western Sudetes. They all emphasise that the snow cover is thicker and lies on the ground longer, the greater the absolute altitude [43-47]. They also draw attention to the influence of the local relief and vegetation on the thickness and duration of the snow cover.

Fig. 9 shows the mean concentrations of ammonium, nitrate and sulphate ions determined in samples of snow collected at Śnieżnik, Orle, and Szrenica in 2008 (author's own results) and in the Alps [32].

Comparison of the diagrams in Fig. 9 indicates that levels of nitrate, sulphate, and ammonium ions are the highest in the surface layers of snow cover.

In contrast, Fig. 10 presents the mean concentrations of sodium, potassium and magnesium ions determined in snow samples collected at Śnieżnik, Orle, and Szrenica in 2008 (author's own results) and from the East Rongbuk glacier, on the northern slopes of Mt. Everest [35].

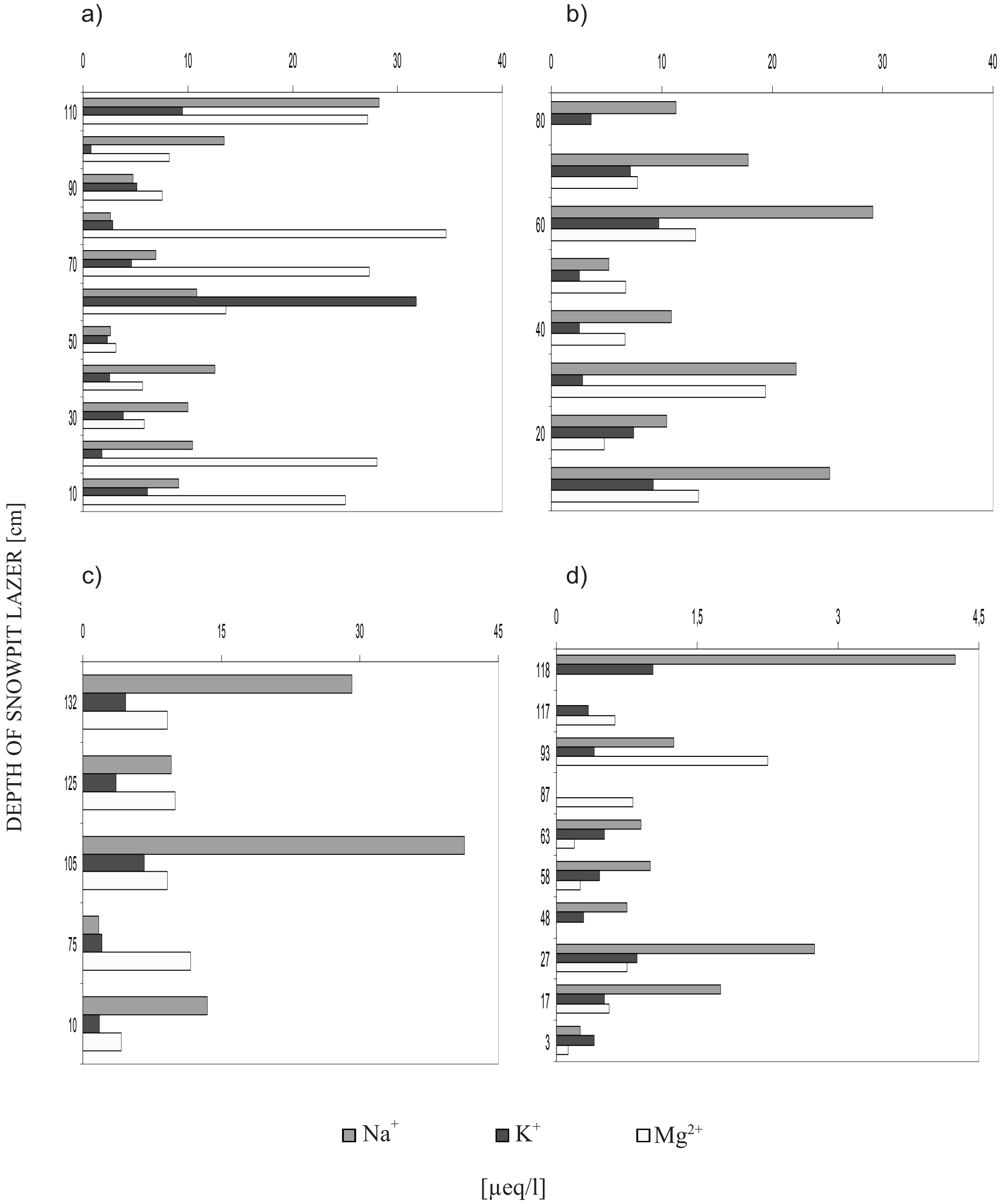


Fig. 10. Mean concentrations of sodium, potassium, and magnesium ions determined in snow samples collected at a) Śnieżnik, b) Orle, c) Szrenica in January 2008 (author's own results), and d) from the East Rongbuk glacier, on the northern slopes of Mt. Everest (May 2000) [35].

Levels of sodium, potassium, and magnesium ions were the highest in the surface layers of the snow cover. The levels of these ions were much higher in the snow samples collected in Poland.

Fig. 11 shows the mean concentrations of selected metals (cadmium, lead, zinc, copper) determined in snow samples collected at Śnieżnik, Orle, and Szrenica in 2008 (author's own results) and in central Greenland (1992) [49].

There is considerable similarity between the highest concentrations of zinc and copper determined in surface layers of snow in both Poland and Greenland. The concentrations of Zn and Cu in the snow samples from Poland were much higher.

Fig. 12 shows histograms of the mean levels of nitrate, sulphate and ammonium ions in snow samples taken from snowpits at different stations in the Polish Sudeten Mountains (author's own results), the Alps [32, 39, 40], and the Himalayas [35].

The highest levels of nitrate, sulphate and ammonium ions were recorded in the snow samples from Orle (Poland). The other Polish samples did not differ much in their ionic composition. The concentrations of these ions in the Alps and the Himalayas were 6-7 times smaller.

Fig. 13 illustrates the mean levels of the polyaromatic hydrocarbons fluoroanthene, pyrene, and retene in snow samples taken from snowpits in Greenland [50].

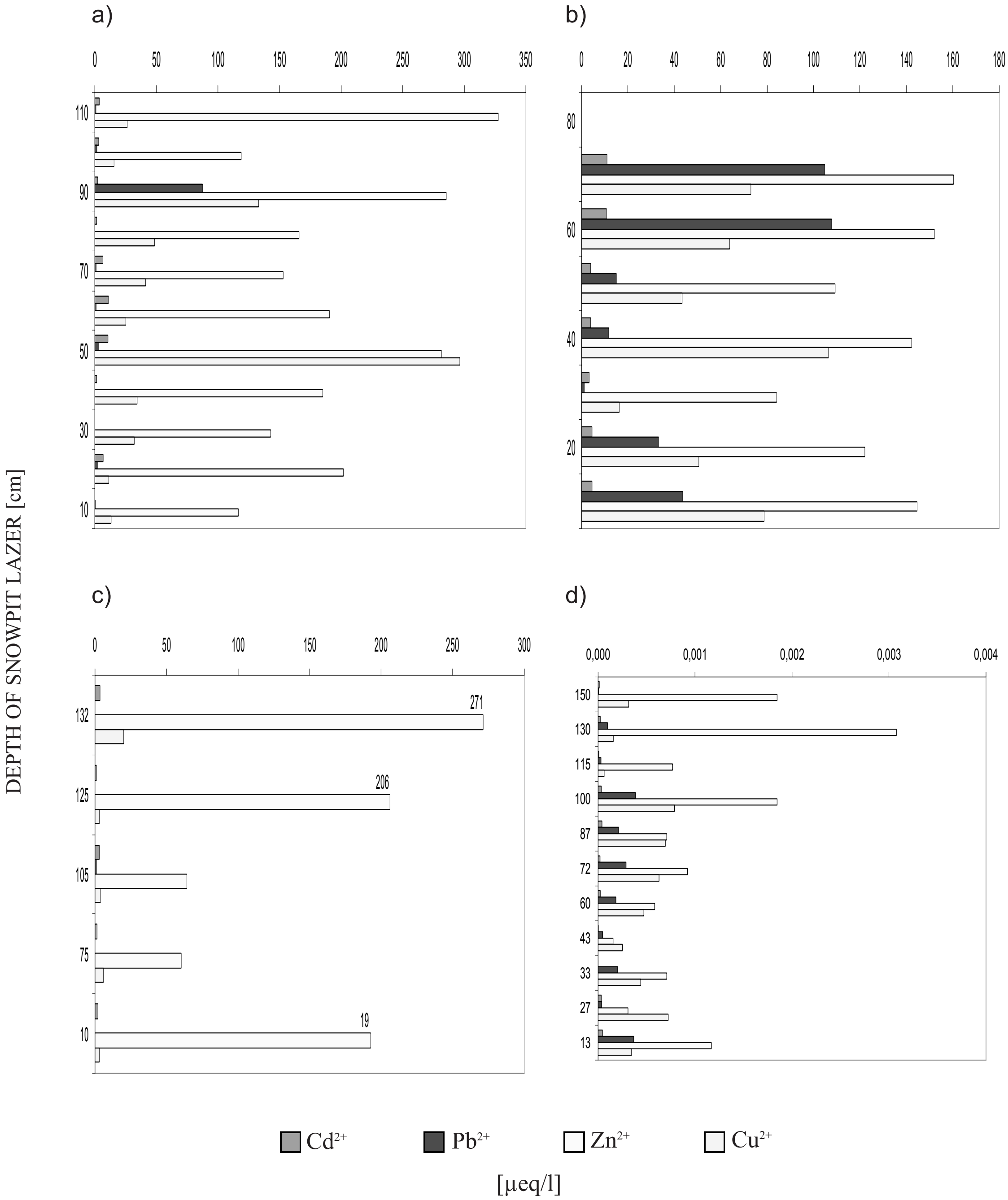


Fig. 11. Mean concentrations of cadmium, lead, zinc, and copper ions in snow samples collected at a) Śnieżnik, b) Orle, c) Szrenica in January 2008 (author's own results – concentrations of Zn^{2+} and Cu^{2+} x 10), d) the Greenland ice sheet (July 1992) [49].

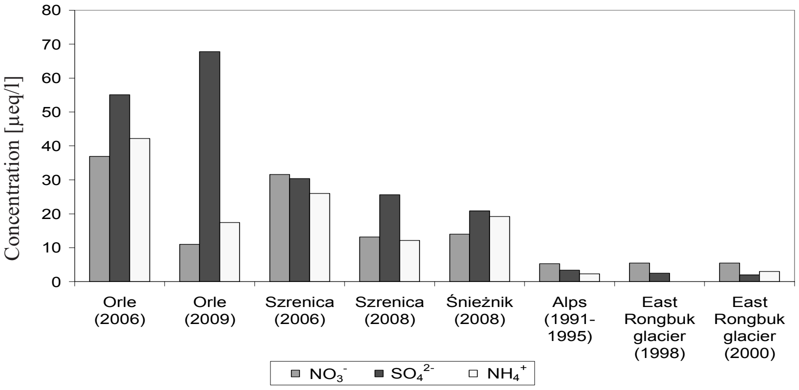


Fig. 12. Mean concentrations of nitrate, sulphate, and ammonium ions in snow samples collected from snowpits at different stations in the Polish Sudeten Mountains, the Alps, and the Himalayas.

These studies have shown that PAH concentrations are seasonally dependent: they are highest in winter and early spring. Identical results were obtained from snowpit samples collected in earlier years [51].

Anthropogenic PAH discharges are greater in winter in the industrialized countries, which are most often the source areas (Eastern Europe, Russia, and Northern America). Photochemical degradation of PAHs is minimal in winter because the low luminosity leads to a reduced production of OH radicals, the main photochemical aggressors of PAHs [52].

Conclusions

Analysis of snow cover supplies a complete set of information on its current structure and the processes taking place within it; this, in turn, enables its stability to be assessed, a key factor in assessing and forecasting avalanche hazards [53].

A crucial aspect of the assessment of snow cover stability is the correct interpretation of the snow profile, which requires a great deal of experience on the part of the person performing the profile. No precisely defined methods are in use, so the following parameters are normally assessed: the depth of the snow cover and the thickness of its constituent layers, the type and size of snow crystals, the hardness of the snow cover, and the water content, temperature, and density of the snow. The vertical hardness profile and the stability test of the snow cover (for the presence of slip layers) are additional crucial factors [14]. This means of assessing the stability of a snow cover is used all over the world, as testified by the numerous publications and other information on research being carried out in different parts of the world (Greenland, Austria, Italy, Switzerland, South America, the Himalayas, Antarctica, Poland) [21, 32-40].

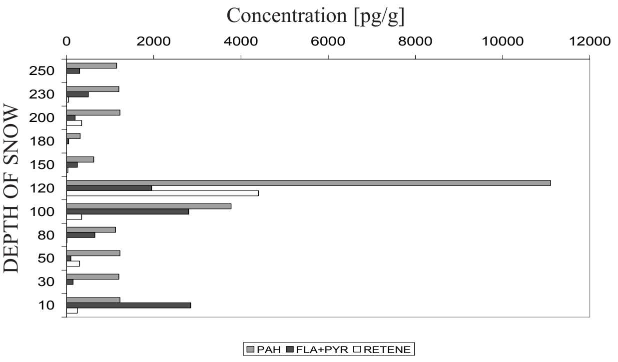


Fig. 13. Dating the strata of superficial snow (correlation of PAHs, fluoranthene, pyrene, and retene) [50].

Studies of snow cover, including specially-dug snowpits, can supply valuable information not only about the chemistry of snow, but above all about the state of the atmosphere and the processes taking place in it. Measurements of the chemical composition of 24 h portions of winter precipitation do not reflect the actual rate of contaminant deposition. This applies to mountain regions in particular, where contaminants are not released from the snow cover to seep into the soil, and surface and ground waters until the spring thaw sets in. The 'frontal wave' that then appears removes a large proportion of the accumulated contaminant load in a very short time.

By defining the composition of contaminants present in snowpit samples we can learn much about the parts played by the most important factors governing the chemical composition of snow cover in a given area and also about the balance in the total load of contaminants present in snow cover that will eventually find its way into the environment.

The contaminant composition of the various snow layers depends on the duration of the snow cover. This, in turn, depends not only on the amounts of contaminants discharged into the atmosphere, but also on meteorological conditions such as the direction of flow of air masses, temperature, wind, humidity, pressure, and the frequency of precipitation. Such investigations enable us to monitor environmental degradation, and their results can provide a starting point for taking measures to counteract it.

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