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SNOW LITHOSTRATIGRAPHIC COMPLEXES

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The concept of snow lithostratigraphic complexes, with snow considered as a monomineral rock, has been suggested based on studies at 2530 snow pits in 1979 through 2017, in different regions of Russia (Sakhalin Island, Kuriles, Transbaikalia, Kola and Yamal peninsulas, Western and Northern Caucasus, West and East Siberia, Moscow and Arkhangelsk regions). Snow complexes with similar stratification, snow microstructure, and physical properties form in geographically dispersed regions which have similar landscape, weather, and physical conditions of snow deposition and metamorphism. The suggested classification of snow lithostratigraphic complexes includes five hierarchic levels. The degree of changes in snowpack structure and snow microstructure is described quantitatively by coefficients of secondary stratification and recrystallization. Size and shape changes in ice crystals have constant rates and are thus predictable. In most of regions in Russia, ice crystals acquire skeletal shapes (depth hoar) in 20 to 60 days after snowfall, depending on landscape.

Snow lithostratigraphic complex, snowpack structure, snow microstructure

INTRODUCTION

Snow is most often considered phenomenologically in terms of classical thermodynamics as a three-phase porous material prone to irreversible viscous deformation. The snowpack structure is commonly characterized on the basis of grain sizes, mainly in the context of continuum properties and boundaries of grains while their shapes remain overlooked [*Moskalev, 1965; Gray and Male, 1981; Kotlyakov et al., 1984; Bozhinskiy and Losev, 1987; Bartlett et al., 2008*]. Basic snow properties have been quite well studied [*Voitkovskiy, 1977; Gray and Male, 1981*]. There exist many physical and mathematical models of snowpacks [*Voitkovskiy, 1977; Bolov, 1981, 1984; Bozhinskiy and Losev, 1987*], which have important theoretical and practical implications. However, the modeling has made no reference to the percentages of ice crystals of different shapes in a snowpack and the evolution of the latter towards a more complex structure and respective changes in physical properties.

The theory of snow evolution was developed by *Kolomyts* [*1976, 1977*] after the fundamentals had been formulated by *Tushinskiy* [*1950*] whose ideas have been unfairly forgotten.

Snowpacks from different landscapes differ in their structure [*Kolomyts, 1976*], i.e., their physical properties controlled by snowpack stratification and snow microstructure largely depend on landscape even within a single climate zone.

CONCEPT OF A SNOW LITHOSTRATIGRAPHIC COMPLEX

The present study is based on snow data from 1430 pits we documented, as well as published reports of 1979–2017 from 1100 pits in different regions: Sakhalin Island, the Kuriles, Transbaikalia, the Kola and Yamal peninsulas, the Arkhangelsk and Moscow areas, the Western and Northern Caucasus, West and East Siberia. Snowpacks existing in landscapes of the same type, with similar moisture regime and winter weather conditions, have been found out to be similar irrespective of the climate zone. The landscape control of processes responsible for the formation of snowpacks allows classifying them in the same way as rock complexes.

The crucially important theory of snow evolution [*Tushinskiy, 1950; Kolomyts, 2013*] views it as a deterministic process leading to snowpack deposition, growth, and subsequent metamorphism under joint action of weather and geophysical effects. Snowpacks acquire different structure, stratification, and snow microstructure at different evolution stages, which control their physical properties, including mechanic strength.

A snowpack has been traditionally considered as a geographic object in snow science, but it may be also interpreted as a monomineral rock, with ice as the principal rock-forming mineral, and as a set of layers having different ages and physical properties. It was suggested in a number of earlier publications [*Tushinskiy, 1949; Rikhter, 1955; Saveliev, 1980; Kotlyakov, 2002*] to characterize snow in geological terms. Thus, the methods and approaches used for lithological classification of rocks can be reasonably applied to snow studies.

In this respect, a snowpack is a kind of a lithostratigraphic complex [*Paffengholts, 1978*] existing in a certain landscape where it undergoes metamorphism after deposition under certain weather and geophysical conditions, develops certain stratification (number and thickness of layers) and snow microstructure, and has its specific physical properties [*Kazakov et al., 2012*]. Snow lithostratigraphic complexes originate and evolve under a joint effect of physical, geological, and physiographic processes (ac-

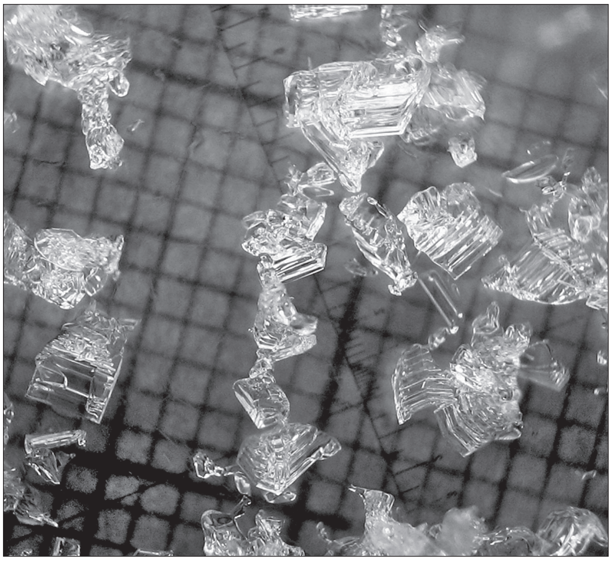


Fig. 1. Shape and size of skeletal ice crystals in a snow layer.

Bar scale 1 mm. Photograph by N. Kazakov.

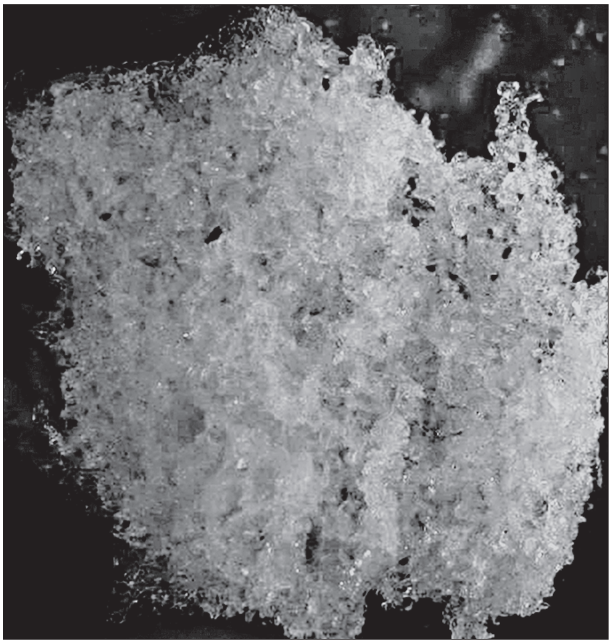


Fig. 2. Ice crystals and pores in a layer of fibrous snow.

Photograph by N. Kazakov.

cording to the classical definition of a landscape) [*Shchukin, 1980*]). Thus, deterministic evolution produces snowpacks with predictable structure, microstructure, and physical properties controlled by weather and geophysical factors.

Snow lithostratigraphic complexes have similar parameters if they form in similar landscapes, even in geographically dispersed regions, but differ in stratification and microstructure in different landscapes, even under similar winter weather conditions. Any complex physical object or a group of physically related objects (including natural ones) can be described as a physical system. This approach allowed *Sochava* [*1978*] to create the theory of geosystems. A snowpack is a geosystem or a set of several geosystems, with sybsystem levels corresponding to lithostratigraphic complexes. Snow microstructure (shape and size of ice crystals, Fig. 1) and texture (relative position of ice crystals and pores in a snow layer and crystallographic orientations, Fig. 2) are the principal govern parameters in the physical system of a snowpack.

METHODS

Lithostratigraphic division of snow in terms of structural snow science [*Kolomyts, 2013*] is based on quantitative description of snow structure and microstructure using crystal morphology approaches.

The existing classifications of snow [*Moskalev, 1965; Kotlyakov et al., 1984; Gray and Male, 1981; Bozhinskiy and Losev, 1987*] overlook systematic successive size and shape changes in ice crystals in a snowpack (Fig. 3). The shapes of ice crystals changing in the course of metamorphism are never described as a genetic series of related shapes, while the ice crystal size averaged over a snow layer and the predominant crystal shapes are estimated at random rather than by processing statistical samples. Furthermore, there are only three grades of crystal sizes (fine, medium, and coarse) and two shape classes (granular and depth hoar); the age of a snowpack is commonly neglected as well. Therefore, even the most perfect *International Classification for Seasonal Snow on the Ground* [*2009, 2012*] is unsuitable to predict crystal size and shape changes and respective changes in snowpack properties [*Sokratov and Kazakov, 2012*]. Furthermore, the existing classifications use neither crystallographic approach nor data quantification. The methodology for snow observation and documentation according to *International Classification* [*2009, 2012*] can provide only partial solution to the problem.

The morphogenetic classification of *Kolomyts* [*1976, 1977, 2013*] and its modifications [*Kazakov et al., 2012*] are advantageous as they focus on snow evolution and allow predicting possible changes in snow microstructure from estimated rates of successive transformations of ice crystals from one shape class ("crystal form class" according to Kolomyts) to another and the respective changes in snow physics, especially strength.

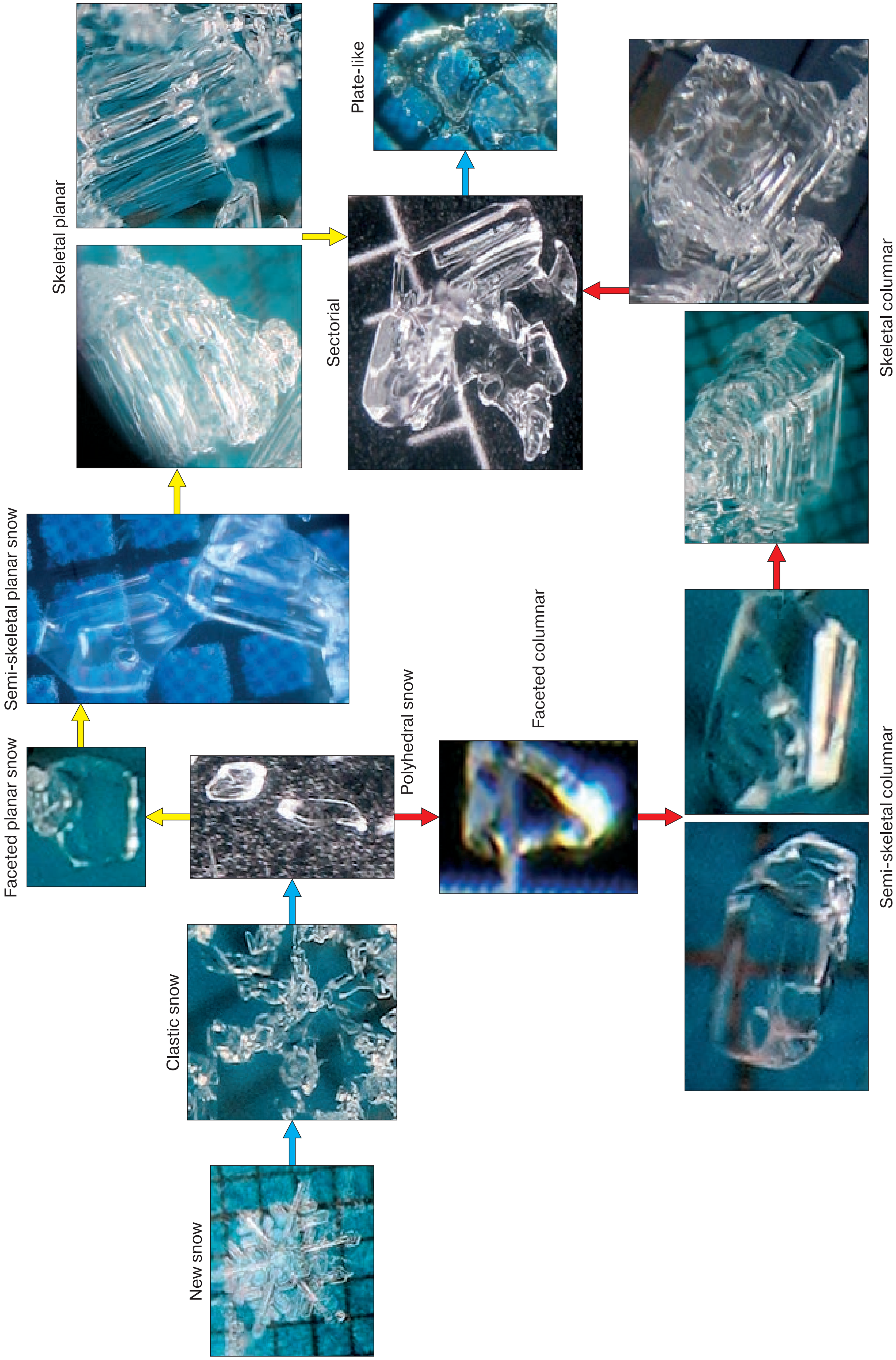


Fig. 3. Shape changes in ice crystals during snow evolution.

Table 1. **Legend to snow stratigraphy**

1. Snow structure. Snow type and crystal shape class**			2. Texture of secondary idiomorphic snow	
Symbol	Snow type and crystal shape	Type and phase of metamorphism		Monolith
				Columnar
1.1. Primary idiomorphic				Fibrous
*	New fallen*		3. Snow water content*	
	Corrasion-polyhedral			Dry
	Clastic	Destructive		Moisty
• •	Regelation-polyhedral	Regelation		Wet
	Sublimation-polyhedral	Rounding		Very wet
1.2. Secondary idiomorphic (metamorphosed, depth hoar)		Sublimation	4. Hardness of primary idiomorphic snow*, kg/m^2	
	Faceted planar	Constructive		Very soft
	Faceted columnar			Soft
	Semi-skeletal planar			Average
	Semi-skeletal columnar			Hard
	Skeletal planar			Very hard
	Skeletal columnar			Ice
	Sectorial	Regressive	5. Surface under snow	
	Plate-like			
1.3. Crusts and inclusions				Dwarf pine
	Regelation crust			*Sasa kurilensis*
	Ice crust			Grass
	Undivided clusters of regelation crystals			
si	Snow ice			

*Note: Structure of new (precipitation) and recrystallized snow is according to [*The International Classification for Seasonal Snow on the Ground, 2009*].

**Crystal shapes are classified according to crystal form classes of E. Kolomyts, here and in all figures and tables below.

Snowpack modeling should base on quantifying snow structure and microstructure in terms of crystallography [*Kolomyts, 1977, 2013*]. Note that our description approach based on the classification of Kolomyts has been included into the Russian version of *International Classification* [*2012*].

In the current practice, the knowledge of snowpack structure is an expert judgment based on visual examination. However, objective description of this structure, modeling of physical processes, and avalanche hazard prediction require statistical data on percentages of ice crystals of certain sizes and shapes. The work begins with macro-photographing of ice crystals from each snow layer in pits (Fig. 1) followed by laboratory identification of crystal shape classes in recrystallized snow (depth hoar) according to the classification of *Kolomyts* [*1977*] (Table 1), as well as estimation of average and maximum crystal sizes and percentages of different shape classes in a snow layer. The statistical samples include at least 20 crystals (Table 2), and special software for automatic snow stratigraphy studies in snow pits [*Kononov and Kazakov, 2011; Kononov, 2012, 2014*] can process statistical samples of 100 or more crystals in each snow layer. Photographs of ice crystals attached to stratigraphic charts can provide reference useful for other reseacrhers.

The ordering degree of ice crystal clusters in a snow layer is estimated for three successive types (monolith, columnar, and fibrous) of evolving snow (Fig. 4) evident from visual examination.

Other parameters for describing snow lithostratigraphic complexes are: the number, thickness, density, hardness, and age of snow layers (Table 3);

Table 2.

Sizes and shape of ice crystals

Layer 10	Layer thickness 49–52 cm				Date 09.01.2013					Layer deposition date 31.12.2012							Layer age, days 10				Sum of sizes, mm	Ice crystal size, mm		Percentage of ice crystals		Sum of ice crystals of different shapes		Monotriclinic coefficient	Metamorphism type
Crystal shape class	Ice crystal diameter, mm																					av.	max.	unit	%	Planar	Columnar		
	Ice crystal number																												
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20									
	0.2	0.5	0.5	0.5		0.6	0.6	0.6		0.6	0.4	0.5	0.5	0.3	0.3	0.2	0.5	0.5			7.3	0.5	0.6	16.0	0.8				
																					0.0		0.0	0.0	0				
					0.6				1.1										1.0	1.0	3.7	0.9	1.1	4.0	0.2				
																					0.0		0.0	0.0	0	0.0	20.0	0.00	Columnar
																					0.0		0.0	0.0	0				
																					0.0		0.0	0.0	0				
																					0.0		0.0	0.0	0				
																					0.0		0.0	0.0	0				
																					11.0	0.6	1.1	20.0	1				

age is used to estimate the rate of evolutionary changes.

PARAMETERS OF SNOW RECRYSTALLIZATION

A snowpack is commonly described qualitatively as an object with a certain structure and microstructure [*Moskalev, 1965; Bozhinskiy and Losev, 1987; The International Classification, 2009, 2012*]. However, systematic lithostratigrpahic division requires quantitative estimates of parameters that represent the snowpack structure and degree of microstructure changes in ice crystals.

We suggest to use the coefficients of snow rercrystallization (K_{rcr}), secondary stratification (K_{ss}) [*Kolomyts, 1977*] and structuring (K_{st}) [*Kazakov et al., 2012*]:

$$K_{rcr} = H_1/H,$$

$$K_{ss} = \Sigma N_1 \cdot H_2 / \Sigma N_1 \cdot H_1,$$

$$K_{st} = H_{fb}/H,$$

where H is the total snow depth; H_1 is the total thickness of recrystallized snow (depth hoar) layers; H_2 is the total thickness of snow consisitng of skeletal crystals; H_{fb} is the total thickness of fibrous snow; ΣN_2 and ΣN_1 are, respectively, the total percentages of skeletal and depth hoar crystals, %.

The snowpack structure can be described with a combination of these coefficients (Table 4) for any period of winters of four types: with small, medium, and large total amounts of snow (all frozen precipitation) and with thaw excursions. The parameters for lithostratigraphic complexes from the studied areas can provide reference for estimating the respective parameters in similar complexes of unexplored areas.

CLASSIFICATION OF SNOW LITHOSTRATIGRAPHIC COMPLEXES

A snow lithostratigraphic complex, as a subsystem of the landscape system, can be described following general taxonomic principles for complex systems. A unified scale for classification of these complexes and an algorithm for their hierarchic description are based on the respective theory of classification and systematization. The principles of classification and multilevel description of complex systems [*Chereshkin et al., 1999*] imply, respectively, that the values of system parameters are classified and that an object is an element of a larger system; a complex structure as an integrate phenomenon should be described to a sufficient level of detail.

Thus, the problem in our case is to choose criteria for division into areas with similar parameters that characterize processes in a snowpack. These processes

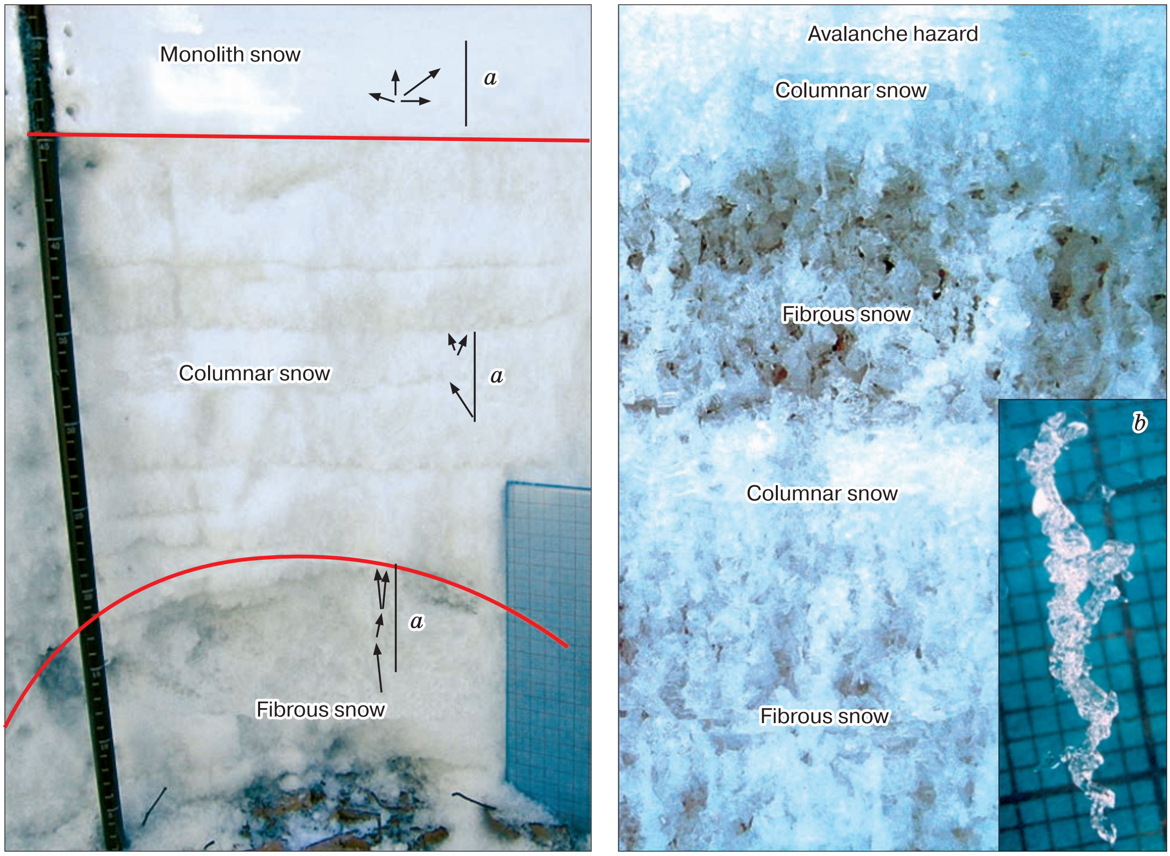


Fig. 4. Snow changes during evolution.

a: preferred orientations of ice crystal clusters in snow layers; *b*: cluster of skeletal ice crystals in fibrous snow. Red lines are boundaries of snow layers.

are controlled by weather, moisture, terrain, and geophysical landscape conditions, and lithostratigraphic division on their basis consists in contouring areas with similar conditions of snow deposition and metamorphism (Table 5).

The hierarchic scale of snow complexes includes five levels:

(1) *class:* regional-scale factors; territory division into physiographic provinces and climate zones according to general conditions of snow deposition and evolution;

(2) *subclass:* weather and altitude zoning factors (air temperature, precipitation, winds and air circulation, etc.); division according to climate conditions for snow deposition and alteration;

(3) *type:* geomorphic factors (terrain, slope angle and aspect, etc.); division according to geomorphic conditions of snow occurrence;

(4) *subtype:* geobotanic factors (grass, shrub, and tree vegetation); division according to vegetation-controlled depth and distribution of snow and respective local evolution patterns;

(5) *species:* landscape factors (microtopography, grass and moss vegetation, moisture regime, etc.); division according to snow recrystallization conditions that control ice crystal morphology.

SNOW LITHOSTRATIGRAPHIC COMPLEXES: MAPPING AND USE FOR SNOW CHARACTERIZATION IN UNEXPLORED REGIONS

The hierarchic scale of snow lithostratigraphic complexes (Table 5) based on landscape classification principles, as well as quantitative estimation of snow evolution (Table 4), allow mapping for four types of winters [*Drevilo, 1981, 2001; Kazakov, 2000*], with the following principles.

1. The style and rate of snow metamorphism depend on landscape conditions. Landscape-controlled properties of snow can be used as reference to predict snow deposition and evolution patterns in unexplored areas, including the formation time of fibrous snow composed of skeletal ice crystals. The scope of possible snow stratigraphy patterns [*Drevilo et al.,*

Table 3. **Snow stratigraphy and processed results of field observations (Kola Peninsula, March 2017)**

Pit 9. Location: Kola Peninsula. Bog; sporadic birch and pine trees. Date: 02.03.2017. Time: 15:00. Latitude 68°35′22.16″ N Longitude 31°37′45.80″ E

Site description		Weather conditions	
Elevation asl, m	111	Weather	Sun and clouds
Slope aspect	0	Air temperature, °C	–4.0
Slope angle, grad	0	Clouds (total/lower), grade	7/0
Subsnow substrate	Bog-berry, sphagnum, sedge, moss, lichen	Wind	Calm air
Vegetation	Sporadic pines, birches, up to 1.5 m	Air humidity, %	31
Soil state	Frozen		

Layer number	Layer boundary depth, cm	Layer thickness, cm	Snow type and ice crystal shape class; layer structure and texture	Density, g/cm³	Water content, mm	Ice crystal diameter, mm		Percentage of crystal shape class, %																	Temperature, °C	Layer deposition date	Layer age, days	Porosity, %
						av.	max.	▭	↔	⊙	*	v	ʄ	▲	⟁	∀	/	⁄ ⁄	¤	▮ ▬	◩ ◪	▯ ▭	⌂	=				
12	64	3	*	0.03	0.90						1.00														–6.0	01.03.17	1	96.7
11	61	5	⁄ ⁄	0.13	6.50	0.50	0.70											1.00							–4.2	25–27.02.17	3–4	85.8
10	56	5	▮ ◩ ▬ ʃ	0.17	8.50	0.60	0.92														0.86	0.14			–5.2	17.02.17	13	81.4
9	51	4	▮ ◩ ▬ ⫽⫽	0.25	10.00	0.60	0.96														0.81	0.19			–5.5	15.02.17	15	72.7
8	48	1	▬	0.32	3.20																				–6.2	14.02.17	16	65.1
7	47	3	▮ ◩ ʃ	0.39	11.70	0.72	1.04														0.69	0.31			–5.6	26.01–1.02.17	29–35	57.4
6	44	4	▮ ◩ ʃ	0.46	18.40	1.04	1.52														0.61	0.39			–5.5	18–19.01.17	42–43	49.8
5	40	5	▮ ◩ ʃ	0.53	26.50	0.74	1.00														0.80	0.20			–5.5	11–12.01.17	49–50	42.1
4	35	8	▮ ◩ ▯ ʃ	0.60	48.00	1.87	3.09														0.27	0.23	0.50		–5.0	31.12.16–2.01.17	59–61	34.5
3	27	1	▬	0.67	6.70																				–4.5	20.12.2016	72	26.9
2	26	19	▮ ◩ ▯ ʃʃ	0.74	140.60	1.92	3.25														0.26	0.25	0.49		–4.0	10.11–19.12.16	73–112	19.2
1	7	7	moss																						–0.2			
	0																											

Total water amount	281.0	Snow depth, cm, according to snow survey											Coefficients	
Average density, g/cm³	0.40												Recrystallization	0.82
Average snow depth, cm, according to snow survey	70	N/S	60	75	70	72	60	71	82	73	73	71	Secondary stratification	0.38
Water content, mm, according to snow survey	280	W/E	64	64	63	63	63	71	59	70	85	84	Structuring	0.33

Table 4. **Parameters of snow lithostratigraphic complexes**

Secondary stratification coefficient	Recrystallization degree	Structuring coefficient	Loosening degree
>0.5	High	>0.3	High
0.3–0.5	Moderately high	0.2–0.3	Moderately high
0.1–0.3	Medium	0.1–0.2	Medium
⩽0.1	Low	⩽0.1	Low

Table 5. **Classification of snow lithostratigraphic complexes and hierarchy of taxonomic levels, as a basis for map legends**

Hierarchic levels	Factors of snow processes	Units and parameters	Snowpack structure	Snow stratification and microstructure
Class	Regional factors	Physiographic province; climate zone	Snow formation conditions	Regional snow deposition and metamorphism patterns
Subclass	Meteorology and altitude zoning	Climate region (temperature, precipitation, winds)	Snow deposition and metamorphism	Snowpack structure
Type	Geomorphology and geology	Terrain and lithology (macro-topography, slope aspect and angle, type of material under snow)	Snowpack occurrence	Snow facies
Subtype	Geobotanics	Vegetation (shrubs and trees)	Snow depth and distribution	Snowpack with local features of metamorphism
Species	Landscape	Landscape (micro-topography, sub-snow surface, grass and moss cover, moisture regime)	Degree of changes in snow microstructure	Snowpack with certain crystallography and morphology of ice crystals

2000; Drevilo, 2001; Gensiorovskiy et al., 2011] depends on the landscape structure [*Kolomyts, 1977, 2013*], moisture regime [*Kazakov et al., 2012; Lobkina, 2012*], and winter weather conditions. This knowledge has implications for snowpack parameters in the case of field data shortage.

2. Snow lithostratigraphic complexes in unexplored areas can be typified assuming that snow evolves in a deterministic way according to landscape conditions of deposition and metamorphism, with the values of snowpack parameters predicted proceeding from snow properties in explored areas.

At the levels of *type* and *subtype*, snow complexes are mapped to high and medium resolution (Fig. 5) based on field observations (Fig. 6) and landscape maps [*Durov, 1971*], for any period of dry, medium, snowy, and thawy winters, for theoretical and practical applications.

At the level of *species*, snow complexes are mapped to a scale of 1:25 000 [*Gensiorovskiy, 2007*] using landscape maps [*Komsomolskiy and Siryk, 1967; Litenko, 1992*] and field data (Fig. 7).

Maps of typical snow lithostratigraphic complexes in unexplored areas are compiled with reference to field data from explored areas, using landscape and vegetation maps.

SNOW EVOLUTION IN THE ARCTIC

It is interesting to analyze evolutionary changes in the snow structure and microstructure in the Arctic. Snow in this region is often dense and has low rates of metamorphism because of strong drifting and low air temperatures. However, observations of snow stratigraphy by N. Kazakov in 1985–1988 in the Kuniyok and Wudiyavrjok river valleys (Khibiny Mountains) revealed mechanically weak layers composed of 2–4 mm semi-skeletal and skeletal ice crystals (Fig. 8) which appeared in 60 to 90 days depending on prewinter weather and initial snow deposition conditions, in spite of slow recrystallization of the compacted blown (0.32–0.50 g/cm^3) or regeleation (0.50 g/cm^3) snow.

We logged 82 pits in three winter seasons (1985–1988), at elevations of 370–720 m asl, including 35 pits in zones of avalanche catchments (Nos. 101, 102, 104–107, 109, 122, and 125 in the eastern slopes of the Poachvumchorr Range; No. 227 in the western slope of the Kukisvumchorr Range; and 6 pits along the avalanche fracture line). Snow stratigraphic planes in avalanche catchments originated above the forest line, at slope angles of 42–45°, upon bedrock surfaces. The earliest and latest pits were done on 10.11.1987 and 19.05.1988, respectively. The snow depth was 40 to 130 cm and the ground temperature in December–January (at a snow depth of 100 cm) was in the range –6.6 to –0.1 °C. The density of snow, depending on the origin and age of snow layers, was 0.20–0.55 g/cm^3, 0.22–0.42 g/cm^3, and 0.26–0.40 g/cm^3 in the case of faceted, semi-skeletal, and skeletal ice crystals, respectively. The first semi-skeletal crystals appeared in mid-December; skeletal crystals generally formed after 10 January (with a di-

Index	Snow lithostratigraphic complex	Elevation asl, m	Recrystallization and loosening degree of snow (March, I decade). Snowy winter			Long-term annual mean, cm (March, I decade)
			K_{rcr}	K_{ss}	K_{st}	
I	Low-degree recrystallization and loosening; shrub tundra	10–200	0.74	0.07	0.00	19
II	Moderately high-degree recrystallization, high-degree loosening; grass, grass-moss, and hillock bog	100–300	0.82	0.38	0.33	50
III	Medium-degree recrystallization and loosening; lichen-dwarf birch and dwarf birch-lichen tundra	200–300	0.78	0.10	0.13	37
IV	Medium-degree recrystallization, low-degree loosening; sparse and crooked birch forest tundra	20–300	0.82	0.10	0.00	62
V	Low-degree recrystallization, medium-degree loosening; northern taiga pine-birch forest	50–250	0.91	0.03	0.11	58
VI	Low-degree recrystallization, medium-degree loosening; northern taiga spruce-birch forest	50–150	0.89	0.03	0.14	60
VII	Medium-degree recrystallization, moderately high-degree loosening; highland forest tundra of sparse and crooked birch forest	250–400	0.95	0.21	0.26	136
VIII	Medium-degree recrystallization and loosening; highland tundra	250–700	1.00	0.20	0.16	58
IX	Medium-degree recrystallization, moderately high-degree loosening; highland Arctic deserts	higher 700	0.93	0.14	0.23	60

Note: *K* are coefficients of recrystallization (K_{rcr}), secondary stratification (K_{ss}), and structuring (K_{st}).

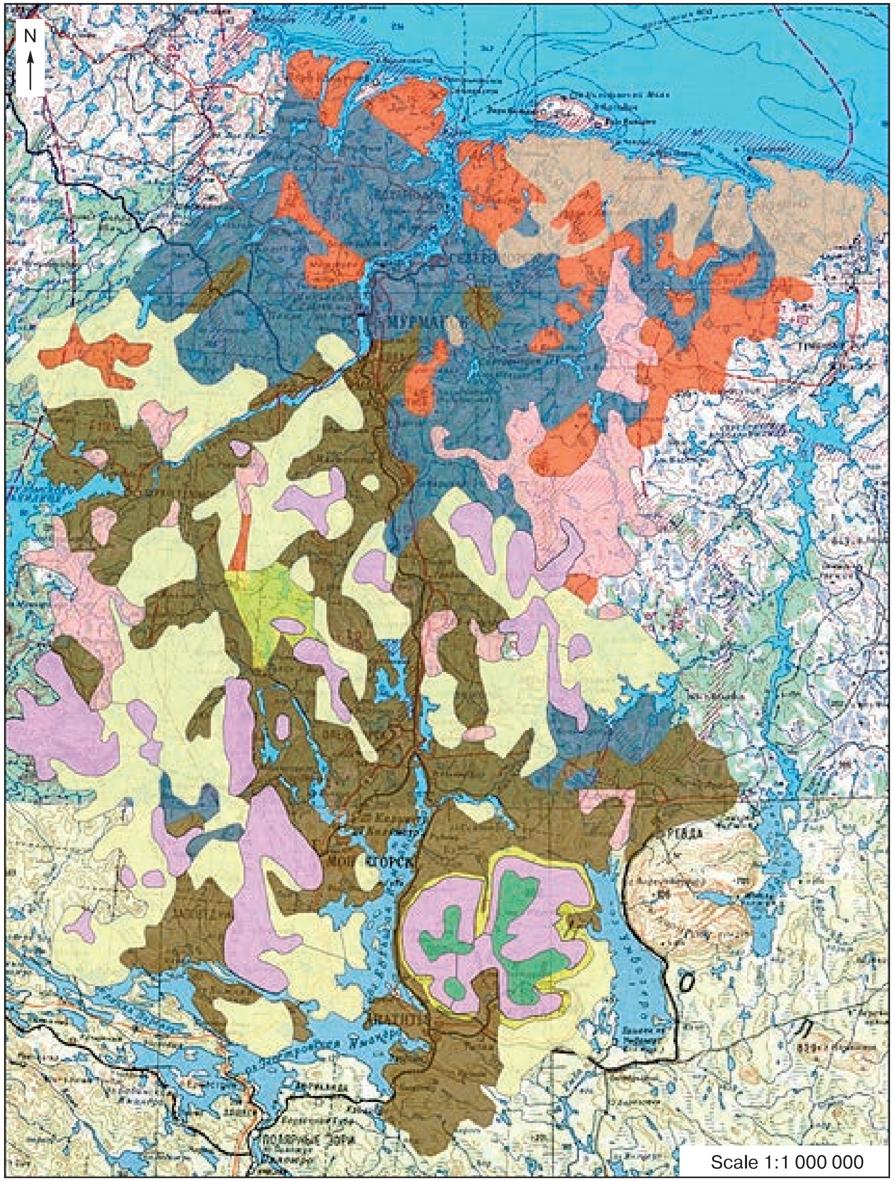


Fig. 5. Map of snow lithostratigraphic complexes in the central Kola Peninsula. Subtype level.
Snowy winter.

a

Layer boundary depth, cm	Snow type and crystal shape class; layer structure	Density, g/cm³	Crystal diameter, mm		Percentage of crystal shape class, %			
			ave-rage	max				
27		0.05	0.5	2.0	0.68	0.29	0.03	
26		0.29	0.5	1.0	0.50	0.50		
23		0.34						
22		0.34	0.5	1.3	0.67	0.25	0.08	
13		0.38	0.4	1.0	0.55	0.45		
11		0.24	0.7	1.4	0.62	0.35	0.03	
6		0.29	1.5	4.0	0.23	0.25	0.51	0.01
4								
0								

b

Layer boundary depth, cm	Snow type and crystal shape class; layer structure	Density, g/cm³	Crystal diameter, mm		Percentage of crystal shape class, %			
			ave-rage	max				
50		0.17	0.68	1.30	0.36	0.62	0.17	
45		0.19	0.73	1.44	0.50	0.50		
38		0.28						
35		0.27	0.75	1.31	0.42	0.52	0.06	
27		0.26	1.04	2.21	0.30	0.55	0.15	
22		0.27						
19		0.24	1.75	4.00	0.17	0.38	0.43	0.02
0								

c

Layer boundary depth, cm	Snow type and crystal shape class; layer structure	Density, g/cm³	Crystal diameter, mm		Percentage of crystal shape class, %		
			ave-rage	max			
75		0.08					
74		0.15	0.7	1.7	0.58	0.30	0.12
72		0.26	0.6	1.2	0.87	0.13	
69		0.24	0.5	1.0	0.79	0.21	
65		0.24	0.5	1.3	0.64	0.34	0.02
57		0.28	0.5	0.7	0.90	0.10	
50		0.29	0.9	1.8	0.69	0.26	0.05
43		0.26	1.3	2.2	0.44	0.28	0.28
37		0.26	1.3	2.3	0.33	0.34	0.33
29		0.34	1.0	2.0	0.29	0.56	0.15
25		0.35	0.7	1.3	0.73	0.22	0.05
21		0.30	0.9	1.7	0.59	0.36	0.05
19		0.27	1.3	2.8	0.46	0.33	0.21
13		0.27	1.2	2.1	0.48	0.39	0.13
7		0.26	1.3	2.6	0.17	0.58	0.25
4		0.20	1.6	3.0	0.30	0.19	0.52
0							

Fig. 6. Snow stratigraphy in different complexes of the Kola Peninsula (March 2016).

a: shrub tundra; *b*: spruce and crooked birch forest tundra; *c*: north taiga pine forest. Horizontal surface. Observations by N. Kazakov, E. Kazakova, A. Muzychenko, G. Popov.

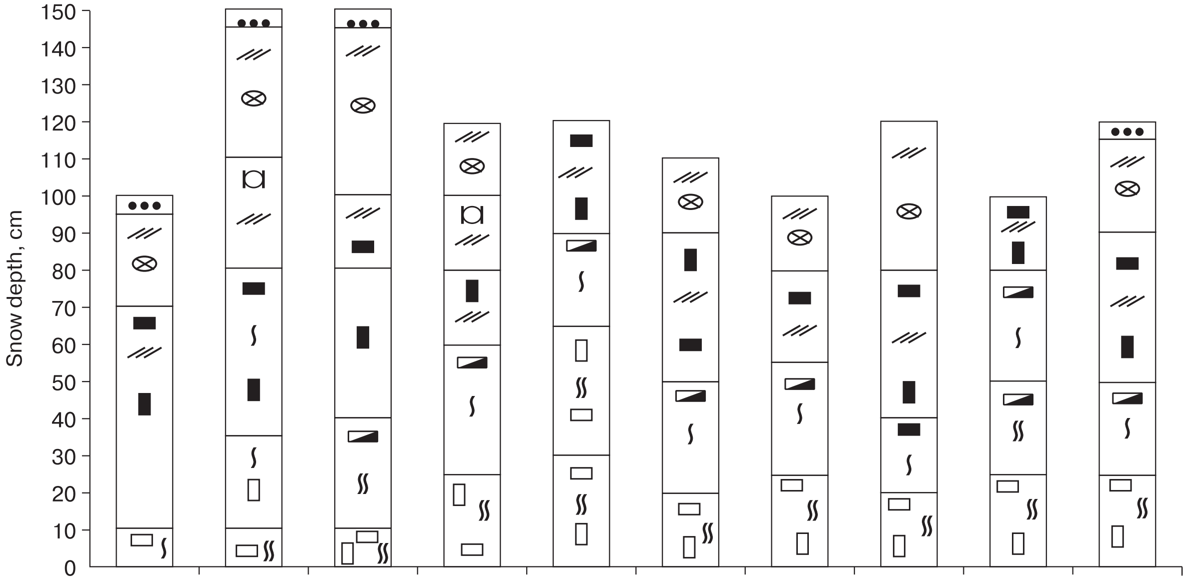


Fig. 7. Snow stratigraphy in different complexes of the Rogatka River basin (Southern Sakhalin) in season of maximum snow storage.

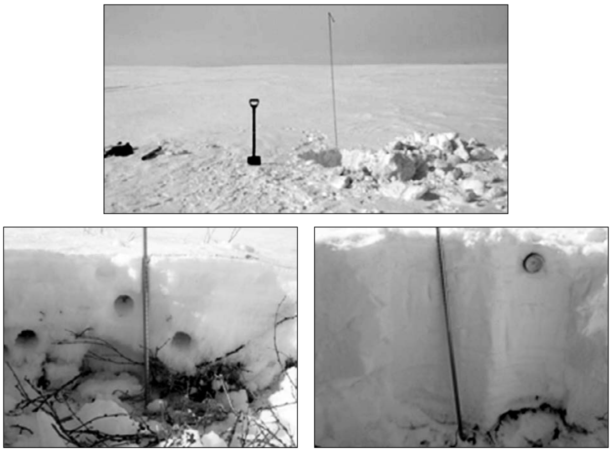
ameter of 2 mm on average and 4 mm the largest) but appeared already after 20 November in the floor of the Kuniyok and Vudiyvrjok valleys (elevations 370–380 m asl).

Recrystallization, although being slow, was very active because the snow layers were originally deposited as dense drift snow (0.32–0.40 g/cm^3) or as regelation snow early in the winter (to 0.50 g/cm^3). The

Layer boundary depth, cm	Snow type and crystal shape class; layer structure	Density, g/cm^3	Crystal diameter, mm		Percentage of crystal shape class, %			Temperature, °C
			average	max				
								–8.8
94		0.18						–6.7
85		0.40	0.3					–7.7
80		0.40	0.3					–7.3
75		0.44	0.5					–7.3
63		0.50	0.5					–5.9
60		0.47	0.5					–6.3
50		0.45	0.5					–6.5
41		0.33	1.0					–6.3
38		0.38	1.6	2.0	0.20	0.70	0.10	–5.7
29		0.32	2.9	4.0		0.10	0.90	–5.5
20		0.36	3.0					–5.3
16		0.43	1.5					–5.3
3		0.40	3.0					–5.0
0								

Fig. 8. Snow complex of highland tundra.

Strongly recrystallized and loosened snow. Dry winter. Kola Peninsula, Khibiny Mountains, Poachvumchorr Range (elevation 580 m asl, eastern slope, slope angle 38°, 18.03.1987). Observations by N. Kazakov.



a

Layer boundary depth, cm	Snow type and crystal shape class; layer structure	Density, g/cm^3	Crystal diameter, mm	
			ave-rage	max
37	······	0.50		
35	◪ ◩ ⫽⫽	0.37	1.5	2.0
30	▬	0.50	3.0	3.5
29	□ ʃ	0.34	2.5	4.0
21	□ ʃʃ	0.27	2.5	4.0
14	□ ʃʃ si	0.26	2.5	4.0
0				

b

Layer boundary depth, cm	Snow type and crystal shape class; layer structure	Density, g/cm^3	Crystal diameter, mm	
			ave-rage	max
84	······	0.50		
81	◘	0.32	1.2	1.5
79	• •	0.50		
73	• •	0.34	1.5	2.0
71	• •	0.50		
65	◩ ⫽⫽	0.34	1.5	2.0
56	◪ ◩ ʃ	0.34	1.5	2.3
48	□ ʃ	0.37	2.0	2.5
35	□ ʃʃ	0.26	1.8	2.7
28	□ ʃʃ	0.38	1.9	2.8
20	□ ʃʃ	0.34	2.0	3.0
9	□ ʃʃ si	0.26	2.3	4.0
0				

Fig. 9. Snow complex of dwarf-birch tundra.

Strongly recrystallized and loosened snow, Yamal Peninsula. *a*: 270-th km, railway station Obskaya–Bovanenkovo, north of Khralovo loop, 21.04.2009; *b*: 332-th km, railway station Obskaya–Bovanenkovo, right side of Yuribei River, 17.04.2009. Observations by V. Okopnyi.

avalanche hazard was associated with layers of skeletal and semi-skeletal ice crystals, 3 mm and 2–4 mm in diameter, respectively, that formed in 60 to 90 days, depending on weather in prewinter time and early during snow deposition, most often in mid-January. Generally, snow evolution in the Kuniyok and Vudiyvrjok valleys did not differ from that in snow lithostratigraphic complexes of the same type elsewhere in Eurasia.

Snow metamorphism is an important agent in the formation of avalanches (including those of wet snow) in the Khibiny Mountains. For instance, many avalanches that moved down the Poachvumchorr Range in 1986–1987 after 20 April were of mixed origin; they slid along 0.32–0.34 g/cm^3 layers of 3 mm skeletal crystals at the base of 20–110 cm thick layers of wet snow.

Field studies of snow microstructure, stratification, and physical properties we performed in different landscapes of the Kola Peninsula in March of 2016 and 2017 (Fig. 6) showed the snow evolution in the central part of the peninsula to be the same as in other cold regions. The formation of weak fibrous snow composed of semi-skeletal and skeletal ice crystals 2–5 mm in diameter takes 70 to 80 days depending on weather in prewinter time and soon after snow deposition. Fibrous and columnar snow makes up to 80 % of snowpack volume by the middle of snowy winters. Snow develops 1.3–2.2 mm skeletal crystals already 12–20 days after deposition, while 2.4 mm sectorial and plate-like crystals form at the stage of regressive metamorphism in 85–100 days, even in snowy winters.

In the same way, 2–4 mm skeletal crystals in fibrous snow make up to 80 % of snowpack by the middle of winter in dwarf birch tundra (zone of strong snow drifting) in the Yamal Peninsula (Fig. 9).

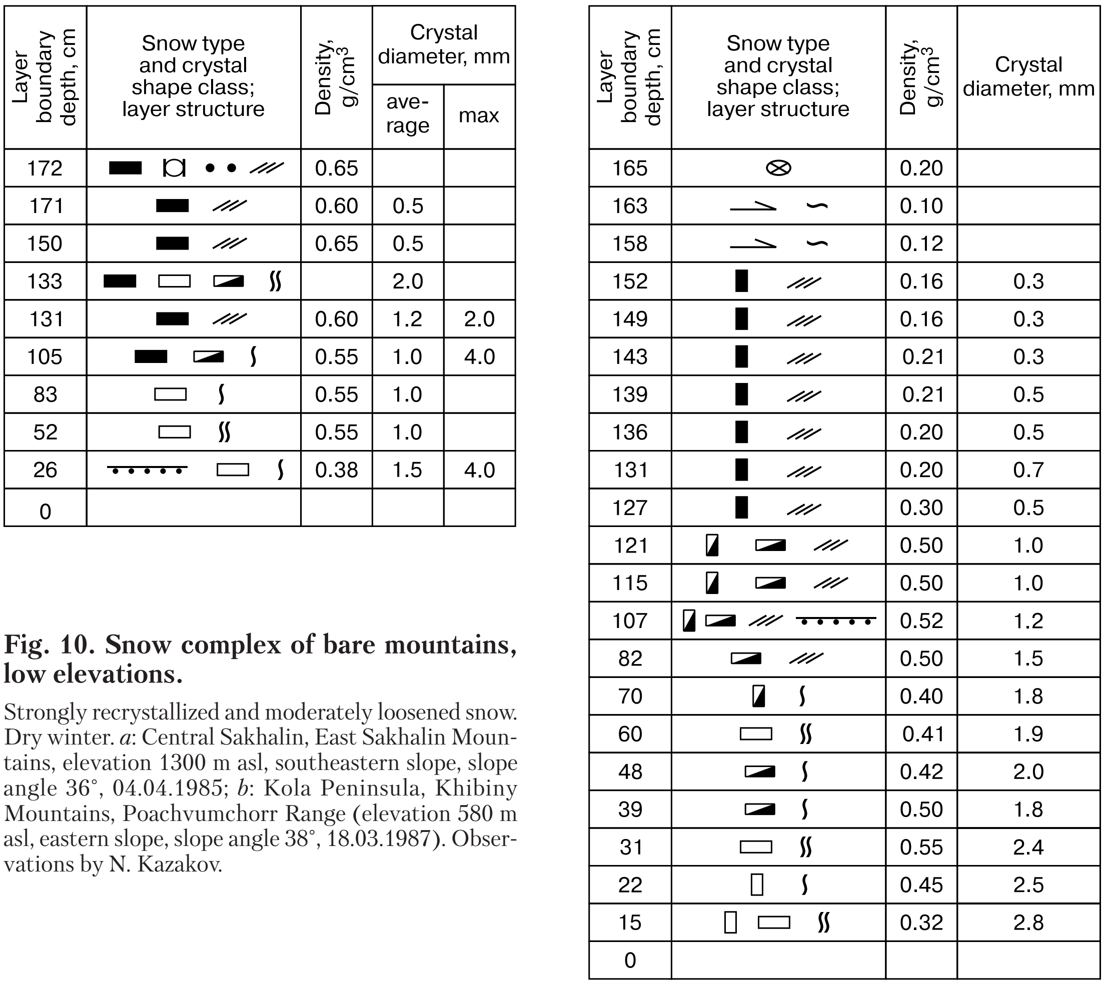
PREDICTION OF CHANGES IN MECHANIC PROPERTIES OF A SNOWPACK

Field data from 2530 pits in different regions of Russia show that ice crystals change in shape and size at similar rates within similar snow complexes and in winters of the same types. For instance, ice crystals in Sakhalin Island reach semi-skeletal shapes and 1.5–2.2 mm sizes in 35–45 days in the absence of thaw excursions. Skeletal shapes of crystals in central and southern Sakhalin Island appear in 45–55 days after snow fall [*Kazakov, 2009a; Lobkina and Mihalev, 2011; Lobkina, 2013*].

Table 6. **Rates of snowpack structure changes for predicting the deposition time of avalanche-prone snow layers**

Phase of snow metamorphism Crystal shapes	Age of crystals after snow deposition (snowfall, snow blowing, thaw), days		
Types of primary idiomorphic snow	New snow	Corrosion-polyhedral	Regelation-polyhedral
Original snow density, g/cm^3	0.06–0.08	0.40–0.50	0.30–0.35
	Primary idiomorphic snow		
Old snow	1	–	–
Sublimation-polyhedral snow	2–3	5–10	–
	Secondary idiomorphic snow (depth hoar)		
Ice crystal shapes			
Faceted	3–5	10–20	20–25
Semi-skeletal	5–15	30–50	30–45
Skeletal	15–25	40 – 70	40–55
Sectorial	30–45	100–110	80 – 100
Plate-like	95–110	–	–

N o t e. Calculations performed for air temperature ranges of −10 to −25 °C (night) and −4 до −10 °C (day). Average recrystallization time estimated for snow depths from 55 to 160 cm (Southern and Central Sakhalin).



a

Layer boundary depth, cm	Snow type and crystal shape class; layer structure	Density, g/cm^3	Crystal diameter, mm: average	Crystal diameter, mm: max
172		0.65		
171		0.60	0.5	
150		0.65	0.5	
133			2.0	
131		0.60	1.2	2.0
105		0.55	1.0	4.0
83		0.55	1.0	
52		0.55	1.0	
26		0.38	1.5	4.0
0				

b

Layer boundary depth, cm	Snow type and crystal shape class; layer structure	Density, g/cm^3	Crystal diameter, mm
165		0.20	
163		0.10	
158		0.12	
152		0.16	0.3
149		0.16	0.3
143		0.21	0.3
139		0.21	0.5
136		0.20	0.5
131		0.20	0.7
127		0.30	0.5
121		0.50	1.0
115		0.50	1.0
107		0.52	1.2
82		0.50	1.5
70		0.40	1.8
60		0.41	1.9
48		0.42	2.0
39		0.50	1.8
31		0.55	2.4
22		0.45	2.5
15		0.32	2.8
0			

Fig. 10. Snow complex of bare mountains, low elevations.

Strongly recrystallized and moderately loosened snow. Dry winter. *a*: Central Sakhalin, East Sakhalin Mountains, elevation 1300 m asl, southeastern slope, slope angle 36°, 04.04.1985; *b*: Kola Peninsula, Khibiny Mountains, Poachvumchorr Range (elevation 580 m asl, eastern slope, slope angle 38°, 18.03.1987). Observations by N. Kazakov.

Recrystallization in 0.40–0.50 g/cm^3 wind-blown snowpacks, at 1000–1200 m asl, in the zone of Siberian dwarf pine zone, is very slow: skeletal crystals usually form as late as March–April, in 90 to 115 days after snow deposition. In the area of bare mountains above 1200 m, ice crystals most often acquire faceted shapes and are within 1.5 mm in diameter. Generally, avalanche-prone snow layers composed of fibrous skeletal and semi-skeletal ice crystals form in 30–45 days after snow deposition in Sakhalin Island and in the Kuriles.

Lithostratigraphic division of avalanche catchment areas can reveal zones with the fastest recrystallization rates and lowest mechanic strength of snowpacks, which pose the greatest avalanche risks. Snowpacks in these zones will collapse the most easily during avalanching.

The revealed general patterns of snowpack evolution allow

– estimating the peak time of snow metamorphism (Table 6) and predicting changes in snow structure and microstructure and related physical properties (especially, bearing capacity);

– choosing stratigraphic surfaces that characterize the snowpack state in a group of avalanche catchments of the same type proceeding from lithostratigraphic division. This facilitates, without quality loss, the collection of data from avalanche starting zones required for prediciton;

– distinguishing snow lithostratigraphic complexes of the same type in different regions and predicting snow properties in unexplored regions proceeding from stratigraphy of respective complexes in documented regions.

For instance, the stratigraphic patterns of snow (Fig. 10) at elevations of 500–700 m asl in the Poachvumchorr Range (Kola Peninsula, Khibiny Mountains) are similar to those from bare mountains in Sakhalin Island (East Sakhalin mountains, 1400–1500 m asl) and southern Sakhalin (Susunai Range, 950–1000 m asl), where physiographic conditions are similar.

a

Layer boundary depth, cm	Snow type and crystal shape class; layer structure	Density, g/cm^3	Crystal diameter, mm
57	• •	0.33	
50	▮ ⫽⫽	0.28	1.0
44	▮ ⫽⫽	0.34	1.0
40	▮ ▬ ∫	0.35	0.8
36	◩ ∫	0.27	2.0
30	▯ ∫	0.26	2.5
25	▯ ∫	0.24	3.0
21	▯ ⏏ ∬	0.27	3.0
14	▯ ⏏ ∬	0.25	5.0; 4.0
10	▯ ●● ⏏ ∬ si	0.30	7.0; 5.0
8	●● ⏏ ∬ si	0.36	3.0
2	⏏ ═ ∬	0.25	5.0
0			

b

Layer boundary depth, cm	Snow type and crystal shape class; layer structure	Density, g/cm^3	Crystal diameter, mm		Percentage of crystal shape class, %			
			average	max	▮ ▬	◩ ◩	▯ ▭	⏏
45	• • │ • •	0.22						
39	◩ ▮ ∫ ••••••	0.28	0.8	1.2	0.55	0.45		
35	◩ ▮ ∬ ••••••	0.23	0.8	1.8	0.45	0.55		
30	▯ ◩ ▮ ∬	0.31	1.5	2.4	0.35	0.55	0.10	
24	si ▯ ∫	0.24	2.2	3.1			1.00	
15	▯ ∬	0.26	2.1	4.0			1.00	
11	▯ ⏏ ∬	0.25	2.6	3.1			0.95	0.05
6	▯ ⏏ ∬	0.21	3.2	4.5			0.90	0.10
0								

Fig. 11. Snow complex of valley birch-willow forest.

Strongly recrystallized and loosened snow. *a*: Susunai valley, Southern Sakhalin, 23.03.2005; *b*: Moscow area, 3 km north of Lake Trostenskoye, 21.03.2010. Observations by N. Kazakov.

PREDICTION OF AVALANCHES ASSOCIATED WITH SNOW METAMORPHISM

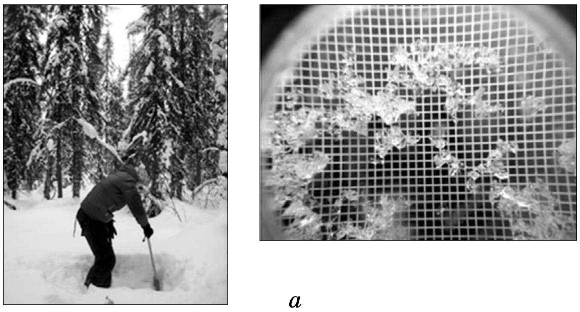
The theory of snow evolution makes basis for short- and long-term prediction of changes in snow mechanic strength and appearance of avalanche-prone weak layers of columnar and fibrous snow composed of semi-skeletal and skeletal ice crystals. Predicting the formation time of such layers is a key prerequisite for avalanche risk prediction and mitigation (active control of avalanche processes, including preventive triggering). This time can be inferred from the avergae rate of shape and size changes in ice crystals in Central and Southern Sakahlin (Table 6). Thus, the onset of large-scale avalanche formation can be predicted 15–90 days in advance, since the precipitation of snow (assuming its small or moderate amounts).

We practiced such prediction for avalanche saftey in roadways between Kirovsk and Novyi Rudnik towns (Kola Peninsula, Khibiny Mountains, 1987–1988), Yasnoye village and Zagornyi pass (Sakhalin Island, East Sakhalin Mountains, 1989–1996), as well as in roads of Southern Sakhalin (2000–2013). The percentage of true long-term predictions reached 85–90 % and increased to 92–95 % in the case of updates based on short-term prediction.

According to our experience of prediction based on ideas of snow evolution in avalanche catchments [*Kazakov, 2009b*], the approach is the most efficient in protection of roadways where the traffic is planned long in advance, which reduces considerably the economic losses.

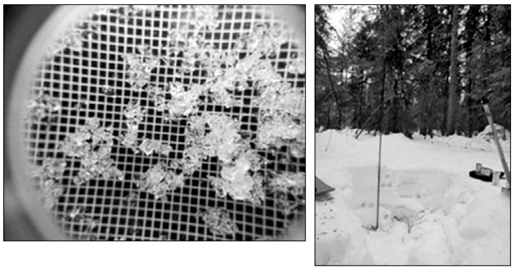
RESULTS AND DISCUSSION

The reported studies of snow in the territory of Russia show that snow stratigraphy patterns are the same in landscapes of the same type, with similar weather conditions and moisture regime that control the conditions of snow deposition and subsequent metamorphism, in geographically dispersed regions. This inference is confirmed by comparison of snow stratigraphy in similar landscapes from several regions: Sakhalin Island (Fig. 7; 10, *a*; 11, *a*), the Kuriles, Transbaikalia, the Kola (Figs. 6; 8; 10, *b*; 12, *a*; Table 3) and Yamal (Fig. 9) peninsulas, the Moscow area (Fig. 11, *b*), the lower reaches of the Severnaya Dvina River (Fig. 12, *b*), the Western (Fig. 13) and



a

Layer boundary depth, cm	Snow type and crystal shape class; layer structure	Density, g/cm^3	Crystal diameter, mm		Percentage of crystal shape class, %		
			average	max	▮ ▬	◪ ◩	▯ ▭
56	▮ ◪ ▬ ʃ	0.16	0.6	1.0	0.80	0.20	
52	▮ ◪ ▯ ▬ ʃ	0.20	0.7	1.3	0.50	0.46	0.04
44	• • • • •	0.26					
42	▮ ◪ ▯ ▬ ʃ	0.27	0.9	1.5	0.31	0.55	0.14
26	▮ ◪ ▯ ◩ ʃʃ	0.22	1.3	2.4	0.37	0.42	0.21
11	▮ ◪ ▯ ʃʃ	0.26	1.2	2.5	0.35	0.48	0.17
9	▮ ◪ ▯ ʃʃ	0.28	2.0	3.1	0.03	0.47	0.50
0							



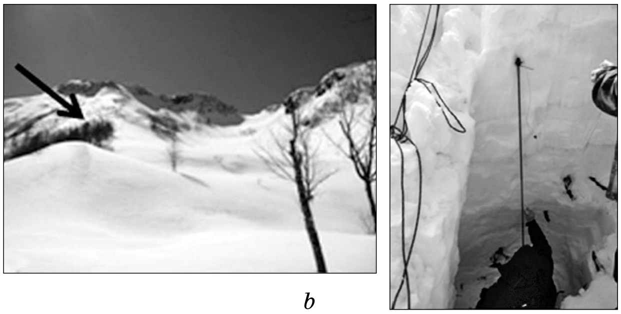
b

Layer boundary depth, cm	Snow type and crystal shape class; layer structure		Density, g/cm^3	Crystal diameter, mm	
				average	max
62	si	• •	0.32		
60	▮	ʃ	0.25	0.3	
54	▮	ʃ	0.25	0.5	
46	▮	ʃ	0.27	0.4	0.8
38.2	▬		0.80		
38	◩	ʃʃ	0.25	1.2	
28	◩	ʃʃ	0.29	1.5	2.0
20	◩ ▭	ʃʃ	0.25	1.8	
12	▭	ʃʃ	0.24	2.2	
0					

Fig. 12. Snow complex of spruce and spruce-pine forests.

Strongly recrystallized and loosened snow. *a*: Kola Peninsula (left side of Tuloma River, Verkhnetuloma Village, 05.03.2016); *b*: Arkhangelsk region (right side of Severnaya Dvina River, Malaya Korela River, 15.02.2015). Observations by N. Kazakov, E. Kazakova, A. Muzychenko.

a



b

Layer boundary depth, cm	Snow type and crystal shape class; layer structure	Density, g/cm³	Crystal diameter, mm	
			average	max
145		0.18		
136		0.34		
125				
122		0.39		
118		0.34	1.0	1.2
107		0.37	0.5	0.8
94		0.26	1.0	1.1
88		0.28	2.0	2.2
84		0.37	1.5	2.0
79		0.34		
70		0.34	1.2	1.5
60		0.39	2.8	3.0
55		0.27	2.0	2.4
50		0.34	2.0	2.4
44		0.37	2.4	3.0
32		0.34	2.2	2.5
22	si	0.34	2.4	3.0
16	si	0.45	2.2	2.7
0				

Layer boundary depth, cm	Snow type and crystal shape class; layer structure		Density, g/cm³	Crystal diameter, mm	
				average	max
332			0.10	0.3	
320	si		0.27	0.6	1.0
310			0.32	0.5	0.8
265	si		0.32	1.1	1.5
259			0.32		
246	si		0.32		
244			0.29	1.6	3.0
229			0.40	2.2	4.0
224			0.39	2.2	4.0
179			0.42		
166			0.37	2.0	3.8
152			0.39	1.2	2.4
135			0.42	1.2	2.8
111			0.39		
101			0.42	1.5	2.4
90			0.34	2.4	4.0
50			0.29	2.0	3.0
32			0.29	2.2	3.6
19			0.32	2.4	4.2
0					

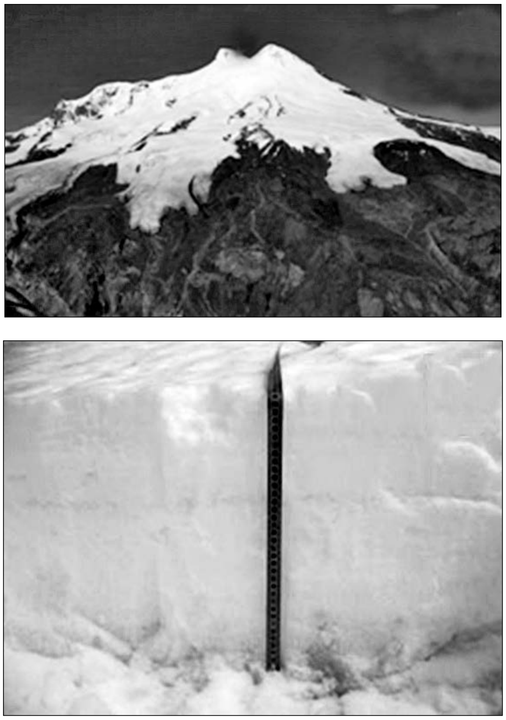
Fig. 13. Snow complex of medium mountains (Western Caucasus).

a: strongly recrystallized and medium loosened snow in divides of Aibga Range, Shumikkha cirque (elevation 2230 m asl., 03.04.2009); *b*: strongly recrystallized and moderately loosened snow of larch forests on hill slopes (Aibga Range, Tobias Creek catchment, elevation 1862 m asl, 04.04.2009). Observations by N. Kazakov, Yu. Gensiorovskiy, E. Kazakova, V. Okopnyi, D. Bobrov, S. Rybalchenko.

Northern (Fig. 14) Caucasus (Elbrus Mt., 5000–5200 m asl), and West Siberia.

Snow evolution in different terrain (high and medium mountains, lowlands and plainlands) and climate conditions (except for regions of short snow season, <40–50 days) leads to the formation of snow layers composed of skeletal crystals. This result is consistent with published evidence [*Saveliev, 1980; Kotlyakov, 2004; Lobkina and Mikhalev, 2011; Lobkina, 2013*].

Over the greatest part of Russia, ice crystals acquire skeletal shapes (depth hoar) in 20 to 60 days after snow fall, depending on landscape.



a

Layer boundary depth, cm	Snow type and crystal shape class; layer structure	Density, g/cm^3	Water content, mm	Crystal diameter, mm	
				ave-rage	max
36	⊗ ⇁ ///	0.40	16.0		
32	▬ ◩ ∫	0.34	23.8	1.0	1.5
25	▬ ///	0.50	15.0	0.5	0.8
22	◪ ▯ ⌒ ∬	0.27	59.0	1.5	3.0
0	Total water content, mm		113.8		

Fig. 14. Snow complexes of highliands.

a: strongly recrystallized and loosened snow in near-divide slope parts (northwestern Elbrus, elevation 5200 m asl, 08.09.2009); *b*: strongly recrystallized and weakly loosened snow of ice plateau (western ice plateau, Elbrus Mt., elevation 5111 m asl., 07.09.2009). Observations by V. Okopnyi.

b

Layer boundary depth, cm	Snow type and crystal shape class; layer structure	Density, g/cm^3	Water content, mm	Crystal diameter, mm	
				ave-rage	max
227	⊗ ⇁ ///	0.34	20.4		
221	◘ ▬ ∽	0.23	27.6		
209	⊗ ▬ ///	0.50	20.0		
205	▬ ▮ ///	0.29	23.2	0.4	0.8
197	▬ ///	0.32	32.0	0.3	0.6
187	▬ ◪ ///	0.33	16.5	0.5	1.0
182	▬ ///	0.50	5.0	0.4	0.6
181	▬ ///	0.35	42.0	0.5	0.8
169	▬ ◪ ///	0.33	6.6	0.5	0.8
167	▬ ///	0.35	10.5	0.5	0.8
164	▬ ///	0.50	15.0	0.6	1.0
161	▬ ///	0.35	10.5	0.6	1.0
158	▬ ///	0.35	14.0	0.4	0.6
154	▬ ◪ ∫	0.33	6.6	0.6	1.0
152	▬	0.88	17.6		
150	▬ ///	0.35	17.5	0.5	1.1
145	▬ ///	0.37	25.9	0.7	1.0
138	▬ ◪ ///	0.37	7.4	1.0	1.5
136	▬ ///	0.50	5.0	1.0	1.5
135	▬ ◪ ∫	0.35	7.0	1.0	1.7
133	▬ ▮ ///	0.50	5.0	1.0	1.2
132	▬ ◪ ///	0.35	73.5	1.0	1.7
111	▬ ◪ ///	0.40	24.0	0.7	1.2
105	▬ ◪ ///	0.36	14.4	0.9	1.7
101	▬ ◪ ///	0.38	26.6	1.0	1.5
94	▬ ◩ ∫	0.35	7.0	1.0	2.0
92	▬ ◪ ///	0.39	62.4	0.8	1.5
76	◩ ∫	0.50	10.0	1.0	1.8
74	▬ ◪ ///	0.40	72.0	0.5	1.3
56	▬ ◪ ///	0.43	34.4	0.5	1.2
48	▬ ◪ ///	0.53	254.4	0.4	0.8
0	Total water content, mm		914.0		

CONCLUSIONS

1. Snow lithostratigraphic complex is a snowpack that occurs in a landscape of certain type, undergoes deposition and metamorphism in similar conditions and has same patterns of snow stratification, microstructure, and physical properties. Therefore, similar snow lithostratigraphic complexes form in similar landscapes. It is suggested to describe snow complexes quantitatively via degrees of changes in snowpack structure and snow microstructure using coefficients of recrystallization, secondary stratification, and structuring.

2. The lithostratigraphic division of snow makes basis for estimation of snow properties in unexplored areas with reference to those in studied lithostratigraphic complexes.

3. Classification of snow complexes allows their mapping (including in unexplored areas) for assessment of territory accessibility in winter time, avalanche and flooding risks, and warming effect of snow on vegetation.

4. Snow evolution is deterministic, and its physical parameters are controlled by landscape properties (moisture regime, winter weather, etc.).

5. Snow evolution in most of Russian regions (from plainlands to highlands, from Europe to Far East, and from the Caucasus to the Arctic) leads to the formation of skeletal ice crystals in 20 to 60 days after deposition, depending on landscape properties.

6. The approach based on snow evolution as a series of successive microstructure changes allows estimating the rates of these changes, as well as physical properties (including bearing capacity) of snow controlled by sizes and shapes of ice crystals. Thus it becomes possible to predict the time of avalanching and choose the prevention strategy.

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References

Bartlett, S.J., Rüedi, J.-D., Craig, A., Fierz, C., 2008. Assessment of techniques for analyzing snow crystals in two dimensions. Ann. Glaciol. 48, 103–112.

Bolov, V.R., 1981. Avalanches Produced by Snowfall, Snow Blowing, and Sublimation Snow Recrystallization: Formation, Prediction, and Man-Induced Triggering. Author's Abstract. Candidate Thesis (Geography). Nalchik, 28 pp. (in Russian)

Bolov, V.R. (Ed.), 1984. Guide to Preventive Avalanche Triggering Using KS-19 Artillery Systems. Gidrometeoizdat, Moscow, 108 pp. (in Russian)

Bozhinskiy, A.N., Losev, K.C., 1987. Fundamentals of Avalanche Studies. Gidrometeoizdat, Leningrad, 280 pp. (in Russian)

Chereshkin, D.S., Kononov, A.A., Tishchenko, D.V., 1999. Safety risks for information systems: Classification principles. Vestnik RFFI 62 (17), 68–72.

Drevilo, M.S., 1981. Classification of New Precipitation Snow. UGMS, Yuzhno-Sakhalinsk, 24 pp. (in Russian)

Drevilo, M.S., 2001. Geoenvironmental Research of Snow: Landscape Approach (Case Study of Sakhalin Island). Author's Abstract. Candidate Thesis (Geography). Barnaul, 27 pp. (in Russian)

Drevilo, M.S., Zhiruev, S.P., Okopnyi, V.I., Gensiorovskiy, Yu.V., Kazakov, N.A., 2000. Snow monitoring in Sakhalin Island. Materialy Glaciol. Issled. 89, 89–94.

Durov, A.G. (Ed.), 1971. The Murmansk Region. An Atlas. GUGK, Moscow, 44 pp. (in Russian)

Gensiorovskiy, Yu.V., 2007. Estimating maximum storage of snow from its landscape properties. Materialy Glaciol. Issled. 102, 73–79.

Gensiorovskiy, Yu.V., Kazakov, N.A., Lobkina, V.A., Kononov, I.A., 2011. Microtopography control of snow structure and microstructure in different types of stratigraphic complexes, in: Snow Physics, Chemistry, and Mechanics. Proc. Intern. Conf. KANO, Yuzhno-Sakhalinsk, pp. 134–135. (in Russian)

Gray, D.M., Male, D.H. (Eds.), 1981. Handbook of Snow: Principles, Processes, Management and Use. Pergamon Press, Toronto, 776 pp.

Kazakov, N.A., 2000. Geological and Landscape Criteria for Avalanche and Debris Flow Hazard Prediction in Road Construction (Case Study of Sakhalin Island). Author's Abstract. Candidate Thesis (Geology & Mineralogy). Moscow, 36 pp. (in Russian)

Kazakov, N.A., 2009a. Constructive metamorphism of snow and avalanche formation features in Sakhalin Island and in the Kuriles, in: Glaciology in Early 21st Century. Proc. Intern. Conf. Univ. Kn., Moscow, pp. 70–77. (in Russian)

Kazakov, N.A., 2009b. A natural avalanche complex as a trigger system. Ibid., pp. 110–115. (in Russian)

Kazakov, N.A., Gensiorovskiy, J.V., Zhiruev, S.P., Drevilo, M.S., 2012. Stratigraphic complexes of a snow cover. Ann. Glaciol. 58 (61), 39–44.

Kolomyts, E.G., 1976. Snow Structure and Landscape Indication. Nauka, Moscow, 206 pp. (in Russian)

Kolomyts, E.G., 1977. Methods for Crystal Morphology Analysis of Snow Structure. Nauka, Moscow, 200 pp. (in Russian)

Kolomyts, E.G., 2013. Evolution Theory in Structural Snow Studies. GEOS, Moscow, 435 pp. (in Russian)

Komsomolskiy, G.V., Siryk, I.M. (Eds.), 1967. The Sakhalin Region. An Atlas. GUGK, Moscow, 135 pp. (in Russian)

Kononov, I.A., 2012. Software design for automated studies of snow stratigraphy in pits, in: Modern Problems of Geology, Geochemistry, and Geoenvironment in the Russian Far East. Proc. 4th All-Russian Conf. of Early-Carrier Scientists, Dalnauka, Vladivostok, pp. 264–265. (in Russian)

Kononov, I.A., 2014. Software for detection and size measurements of ice crystals in photographs of crystal samples from different snow layers, in: Annales of Integrate Pool of Web Resources for Science and Education, 61 (6), 2–3.

Kononov, I.A., Kazakov, N.A., 2011. Size and shape of ice crystals in snow: Problem formalization for machine-aided identification. Ice and Snow (Led i Sneg) 51 (3), 85–90.

Kotlyakov, V.M., 2002. Selected Works. Book 5. In the World of Snow and Ice. Nauka, Moscow, 383 pp. (in Russian)

Kotlyakov, V.M., 2004. Selected Works. Book 2. Earth's Snow and Glaciers. Nauka, Moscow, 447 pp. (in Russian)

Kotlyakov, V.M., Grosswald, M.G., Krenke, A.N. (Eds.), 1984. Glossary of Glaciology. Gidrometeoizdat, Leningrad, 528 pp. (in Russian)

Litenko, N.L., 1992. Facies, hydromorphic properties, and functioning of landscapes in Sakhalin Island, in: Problems of Geography and Geomorphology of the Soviet Far East, DVGU, Vladivostok, pp. 17–26. (in Russian)

Lobkina, V.A., 2012. Recrystallization of snowpack at sites with different degrees of humidity. Ann. Glaciol. 53 (61), 27–30.

Lobkina, V.A., 2013. Snow recrystallization in landscape facies of different moisture conditions (South Sakhalin). Kriosfera Zemli XVII (3), 89–93.

Lobkina, V.A., Mikhalev, M.V., 2011. Formation of snow layer structure depending on the original microstructure of precipitation snow. Ice and Snow (Led i Sneg) 51 (2), 53–56.

Moskalev, Yu.D. (Ed.), 1965. Tentative Guide to Snow Avalanche Mitigation. Gidrometeoizdat, Leningrad, 397 pp. (in Russian)

Paffengolts, K.N. (Ed.), 1978. Glossary of Geology. Nedra, Moscow, 970 pp. (in Russian)

Rikhter, G.D., 1955. Use of snow in national economy, in: Problems of Snow Research and Economic Uses. Izd. AN SSSR, Moscow, pp. 5–22. (in Russian)

Saveliev, B.A., 1980. Structure and Composition of Natural Ice. Moscow University Press, Moscow, 280 pp. (in Russian)

Shchukin, I.S., 1980. Quadrilingual Glossary of Physiography. Sov. Encycl., 703 pp. (in Russian)

Sochava, B.V., 1978. Fundamentals of the Theory of Geosystems. Nauka, Novosibirsk, 319 pp. (in Russian)

Sokratov, S., Kazakov, N., 2012. Dry snow metamorphism expressed by crystal shape. Ann. Glaciol. 58 (61), 51–56.

The International Classification for Seasonal Snow on the Ground, 2009. IHP–VII Technical Documents in Hydrology No. 83, IACS Contribution No. 1, UNESCO, Paris, 80 pp.

The International Classification for Seasonal Snow on the Ground, 2012. Guidelines for Snow Description. Russian Version. Materialy Glaciol. Issled. 2, 80 pp. (in Russian)

Tushinskiy, G.K., 1949. Avalanches: Origin and Mitigation. Geografgiz, Moscow, 214 pp. (in Russian)

Tushinskiy, G.K., 1950. Snowpack evolution. Voprosy Geografii 27, 350–355.

Voitkovskiy, K.F., 1977. Mechanic Properties of Snow. Nauka, Moscow, 126 pp. (in Russian)

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