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DEPENDENCE OF SNOW COVER DENSITY UPON ITS STRUCTURE AND TEXTURE

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The results of measuring the snow cover density for the period from 2005 to 2017 are presented. The data on snow density have been obtained during regular observations carried out on stationary horizontal sites located in Yuzhno-Sakhalinsk and during field work. 227 snow pits have been sampled, and more than 2,000 values of snow density for different snow layers have been analyzed. Data on distribution of snow density in different landscapes have been compiled and structured. The maximum density of snow has been found to be typical of treeless regions with dominating strong winds. Typical densities characteristic of the specific types of the snow structure have been revealed. The density of snow layers has been found to vary depending on the type of snow in the range from 40 kg/m^3 (newly fallen snow) to 790 kg/m^3 (ice crust).

Metamorphism of snow, snow density, Sakhalin, snow, snow cover

INTRODUCTION

The variation range of snow density is broad, depending on many factors: air temperature and moisture, wind velocity, the type of falling snowflakes, densification of snow due to its own weight and due to the weight of the above layers of snow, the changes in the structure and texture of the snow mass in the process of metamorphism, snow melting during thaws, etc. [*Voitkovsky, 1999*].

Currently, a sufficient number of studies have been carried out in Russia and abroad, which are devoted to snow density in different parts of the world [*Veinberg, 1936; Shepelevsky, 1939; Evfimov, 1941; Rikhter, 1945; Lurye and Savelyev, 1959; Kuzmin, 1966; Savelyev et al., 1967; Gray and Male, 1981; Geldsetzer and Jamieson, 2000; Rybalchenko, 2011; Kazakov et al., 2013*]. It is to be noted, however, that most studies conducted by the Soviet (Russian) scientists were published more than half a century ago.

To goal of this study was to analyze the actual data of the layer-by-layer measurements of snow density made in different landscape zones.

In the paper, the results of measurements of snow cover density are summarized, made in the period of 2005–2017 by the workers of the laboratory of avalanche and mudslide processes of the Sakhalin branch of the Far East Geological Institute (FEGI), FEB RAS, on Sakhalin Island (2005–2017) and on the Kola Peninsula (2016–2017).

The data presented will be of interest for permafrost scientists and specialists of applied research institutes using the values of snow density for calculating the parameters of snow avalanches, the volumes of snow drift, the carrying capacity of the snow cover, the water equivalent of the snow cover, etc. Because of unavailability of actual data, specialists have to use values averaged by the materials obtained from meteorological stations, resulting in calculation errors.

METHODOLOGY

The data on snow cover density were obtained both during regular observations made on stationary horizontal sites located in the vicinity of Yuzhno-Sakhalinsk and during field expeditions in the territory of Sakhalin Island (2005–2017) and of the Kola Peninsula (2016 and 2017) (Fig. 1).

The main location used for regular observations of the snow cover of Sakhalin Island was the piedmont part of the western spur of the Mount of Bolshevik (Susunay Ridge), where four observation sites were established.

Site 1 (66 pits): the absolute height is 80 m, the sloping degree is 3°, the vegetation is composed of young birch and alder wood, the substrate surface is represented by sedge, bluegrass, clover, etc.; the facies type is moderately hydromorphic.

Site 2 (23 pits): the absolute height is 110 m, the sloping degree is 4°, the vegetation is composed of buckwheat, dropwort, Pale Indian Plaintain, etc., the substrate surface is represented by sedge; the facies type is heavily hydromorphic.

Site 3 (28 pits): the absolute height was 70 m, the sloping degree is 2°, the vegetation is composed of Angelica ursina, the substrate surface is represented by sedge and by gramineous grasses; the facies type is slightly hydromorphic.

Site 4 (22 pits): the absolute height is 64 m, the sloping degree is 2°, the vegetation is composed of

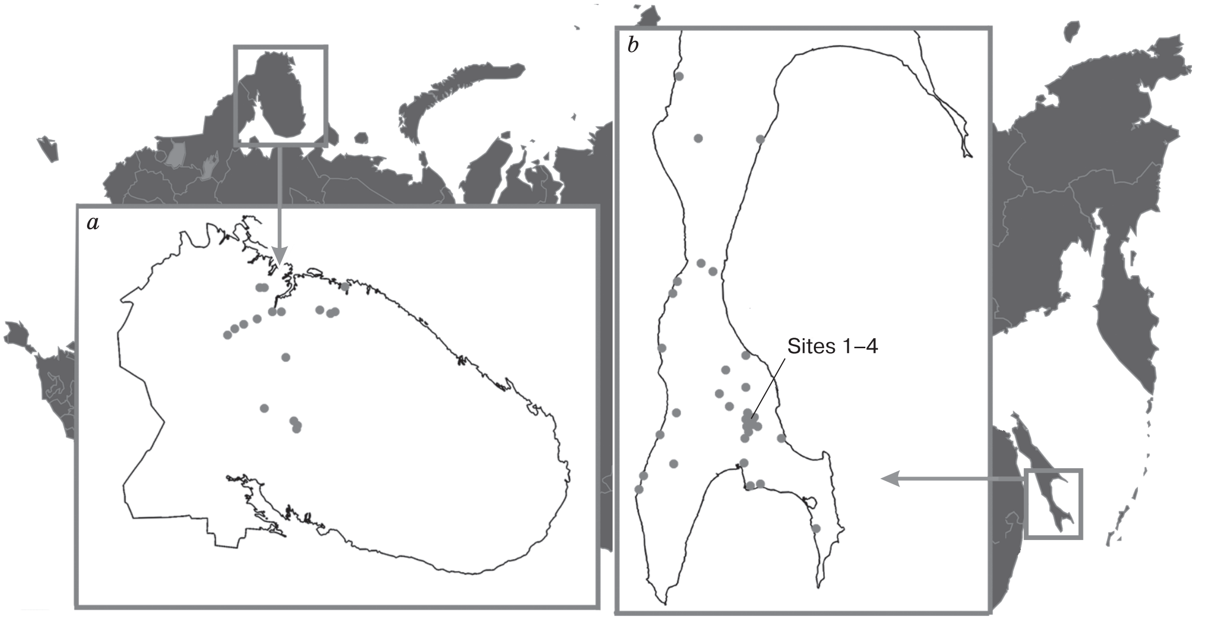

Fig. 1. Location of the monitoring sites in the territory of the Kola Peninsula (*a*) and of Sakhalin Island (*b*).

buckwheat, Angelica ursina, coltsfoot, the substrate surface is represented by sedge; the facies type is slightly hydromorphic.

The measurements were made on those sites with different regularity (from daily observations to once every 15 days) from the snow onset date to the snow offset date from 2005 to 2017 (139 pits were drilled, 1084 snow cover layers were analyzed).

Periodic irregular measurements of the snow cover density were conducted in different regions of Sakhalin: on the eastern and western coasts of the central and southern parts of the island, Susunay Ridge and Mitsulsky Ridge, etc. (58 pits were drilled, 572 snow cover layers were analyzed).

In March 2016 and in March 2017, measurements were made in the territory of the Kola Peninsula: in the area of Murmansk, along the Murmansk–Teriberka, Kola–Verkhnetulomsky, Murmansk–Kirovsk highways and in the area of Kirovsk (30 pits were drilled, 329 snow cover layers were analyzed). The study was conducted in different landscape zones (tundra, forest tundra, taiga, and mixed forest).

The vertical snow profile was divided into layers different for their genesis and morphology. For each layer, the class of the shapes of ice crystals was determined (the layer structure), using the method proposed by E.G. Kolomyts, taking into account the studies of the workers of the laboratory of avalanche and mudslide processes of the Sakhalin branch of the FEGI, FEB RAS [*Kononov and Kazakov, 2011; Kazakov et al., 2012; Kolomyts, 2013*]. In the course of evolution, an ice crystal undergoes a single chain of structural transformations, beginning with the faceted shape up to the skeletal, sectorial, and laminar shapes. For each layer, the sizes of the crystals and the layer texture were determined, snow density, the temperature on the snow layer contacts were measured, and meteorological observations were made.

Density of the snow layers was measured using a single method and standard equipment. From each layer, 3 samples of snow were taken using a 100 cm^3 cylindrical cup and weighed; the measurement results were averaged. An electronic balance with the weighing accuracy up to 0.01 g was used.

The prevailing structure of the ice crystals was determined for the snow cover layers, using the previously taken photographs of the ice crystals. A sample consisted of at least 20 ice crystals. The percentage of the errors relating to determining the class of the ice crystal shape exceeded the error of measuring the snow cover density and the ice crystal diameter, as the snow density was measured using one calibrated set of instruments, the ice crystals' diameter was found using a millimeter grid, and the structure of snow fully depended on the operator's skills before the winter season of 2013/14. Beginning with 2013, the process of selecting snow crystals was automated, which allowed more precise and complete data on the types and sizes of crystals in a snow layer to be obtained [*Kononov and Kazakov, 2011*].

In total, more than 2000 values of the snow cover density were analyzed. We chose homogeneity of a snow cover layer to be the general parameter for analyzing the snow density values. Considering the operator's error and the statistical error, we selected the layers, in which the percentage of the snow crystals of

Table 1. **Density of different types of snow according to the authors and from literature**

Type of snow [*Kolomyts, 2013*]	International classification code [*Fierz et al., 2012*]	Snow density according to monitoring data*, kg/m^3			Number of values	Standard deviation	Standard error	Density of different types of snow, kg/m^3				
								[*Veinberg, 1936*]	[*Evfimov, 1941*]			[*Kotlyakov, 1984*]
		Mean density	Min. density	Max. density				Mean density	Min. density	Mean density	Max. density	
Newly fallen	–	10	77	150	39	34.5	5.5	50–65	–	–	–	200
Fragmental	DFdc	50	125	240	55	46.3	6.2	70–190	105	146	191	200–300
Sublimational-polyhedral	RGsr, RGlr	80	171	260	45	39.1	5.8	200–500	–	–	–	200–500
Faceted	RGxf, FCxr, FCso	120	243	390	112	64.1	6.1		201	227	276	
Semi-skeletal	FCso, FCxr	150	262	360	61	47.9	6.1		194	221	235	
Skeletal	DHla, DHcp, DHpr, DHch, DHxr	160	284	380	75	49.8	5.8					
Sectorial	–	240	303	370	11	41.0	12.4					
Regelatic-polyhedral	MFcl, MFpc	60	310	500	50	96.4	13.6		272	316	406	–

* Monitoring data for 2005–2017 from sites 1–4.

one class was more than 75 %. Such layers constituted about 20 % of the original sample (more than 400 values). In the other cases, the layers constituted a mixture of 3–5 types of snow in different proportions.

THE RESULTS

Measurements made from stationary horizontal sites

To determine the dependence of the snow density on its structure and texture, we considered only those data which were obtained from the stationary horizontal sites established in the vicinity of Yuzhno-Sakhalinsk, sites 1–4), i.e., we excluded the results of the observations made in the near-crest zones of the mountain ridges and in the near-edge parts of the seashore terraces, as in these zones the wind regime is the main characteristic determining the snow density. The snow layers in which the number of crystals belonging to one class of shapes was more than 75 % were considered to be homogeneous.

Table 1 contains minimum, mean, and maximum values of the densities of different types of snow, based on the data obtained from the horizontal sites of Sakhalin Island. The lowest densities are characteristic of the newly fallen snow, and the highest density values relate to the regelatic type of snow with polyhedral crystals.

We compared the data obtained on the density of different types of snow (Table 1) with the results provided by other researchers [*Veinberg, 1936; Evfimov, 1941; Kotlyakov, 1984*], in accordance with the types of snow they identified and the classification we used, proposed by *E.G. Kolomyts* [*2013*]. The comparison showed the mean values of snow density to be generally similar, whereas the maximum and minimum values varied significantly (Table 1).

Taken from the stationary horizontal sites of Sakhalin Island, about 80 % samples of newly fallen snow had the density less than 100 kg/m^3, and only 20 % samples had the density of 100–150 kg/m^3 (Fig. 2). Already at the stage of the faceted type of snow, the snow layers with the density less than 100 kg/m^3 disappeared, and the samples of snow having the density of 100–150 kg/m^3 constituted only 8 %. The largest fraction of the samples (34 %) of the faceted type of snow was related to the range of 200–250 kg/m^3. As the snow structure changed to the semi-skeletal type, the fraction of the samples with the snow density of 200–250 kg/m^3 decreased to 28 %, while the highest share of the samples (48 %) related to the snow density of 250–300 kg/m^3. Further, in the transition to the skeletal stage, the proportion of the samples with this density (250–300 kg/m^3) remained to be practically at the same level, constituting 44 %. The proportion of the layers with the snow density exceeding 300 kg/m^3 increased to 26 %, whereas in the layers of the semi-skeletal type of snow the share of samples of this density constituted only 13 %. In the layers composed of crystals of the sectorial class of shapes, the largest proportion of the samples, like in the semi-skeletal and skeletal layers, was 45 %. The fraction of the snow samples having high density (more than 300 kg/m^3) increased to 45 %. Thus, as snow evolved from the newly fallen type to the sectorial class of shapes, the fraction of the samples of snow having higher density grew (Fig. 2).

No clear dependence between the density values of different types of the secondary idiomorphic snow (faceted, semi-skeletal, skeletal, sectorial, and laminar types) has been revealed; however, the densities of the layers composed primarily of crystals of the faceted class of shapes are generally somewhat lower than the densities of the semi-skeletal, skeletal, and sectorial classes (Fig. 2).

It has been noted that in the layers the density of which is more than 30 % higher than the density of the adjacent layers, the growth rate of ice crystals slows down. At the same time, in the layers below the solidified layers the growth rate of the mean diameter of the ice crystals and decrease of the snow density are observed [*Lobkina, 2012*].

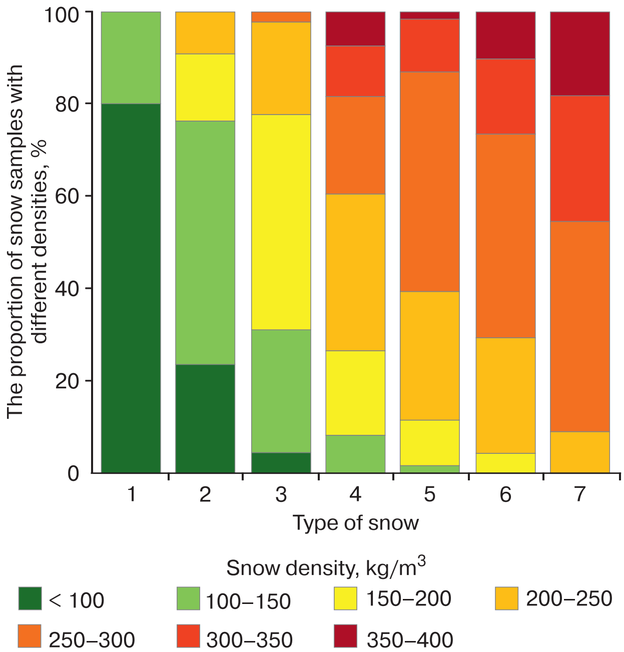

Fig. 2. Breakdown of the number of samples of different types of snow with different densities as percentage of the total number of samples (sites 1–4, 2005–2017).

Type of snow (according to E.G. Kolomyts): 1 – newly fallen snow, 2 – fragmental snow, 3 – sublimational-polyhedral, 4 – faceted snow, 5 – semi-skeletal snow, 6 – skeletal snow, 7 – sectorial snow.

The mean densities of the layers having the solid structure were found to be lower than those of the layers having the columnar or fibrous texture; they are primarily found within the range of 200–250 kg/m^3, whereas the density values of the layers having the columnar and fibrous texture are 250–300 kg/m^3 (Table 2). This agrees with the above noted difference between the densities of the layers of the faceted type and the layers of the semi-skeletal, skeletal, and sectorial classes of shapes, as the solid texture is more characteristic of the layers of the faceted type of snow.

No significant relation between snow density and the snow crystal's diameter was revealed without considering the structure of the snow mass, for the layers of the faceted and skeletal types, with the number of crystals of a certain type in the layer exceeding 90 %, certain direct dependence has been observed, noted for the diameter of the faceted crystals constituting 0.2–0.7 mm (61 layers were analyzed), for skeletal crystals – 1.0–1.5 mm (37 layers were analyzed).

About two-thirds of the samples consisted of a mixture of several types of snow in different proportions. The densities of such layers varied in a broad range (100–480 kg/m^3), depending on the proportion of the number of crystals belong to different classes of shapes.

The density of the snowpack was found to be much higher in the areas exposed to wind (the near-edge parts of seashore terraces, the upper parts of the mountain ridges). To take an example, the mean densities of the layers consisting of crystals of secondary idiomorphic snow (of the faceted, semi-skeletal, and skeletal types), in the near-edge parts of the seashore terraces of the western coast of Southern Sakhalin were 300–400 kg/m^3, while the mean densities of such layers on the horizontal sites located in the vicinity of Yuzhno-Sakhalinsk varied within 200–300 kg/m^3.

Analysis of the long-term data on measuring snow density on sites 1–4 established in the vicinity of Yuzhno-Sakhalinsk (Fig. 3) demonstrates that at the beginning of winter layers having snow density below 150 kg/m^3 prevail. This is related to intense snow accumulation, causing an increase in the height of the snowpack due to snowfalls. Then, in the process of metamorphism, snow begins to solidify, result-

Table 2. **Density of snow having different structure (sites 1–4, 2005–2017)**

Texture of snow	Snow density, kg/m^3			Number of values	Standard deviation	Standard error
	Minimum	Mean	Maximum			
Solid	90	257	530	224	69	5
Columnar	110	274	500	435	62	3
Fibrous	130	277	480	271	56	3

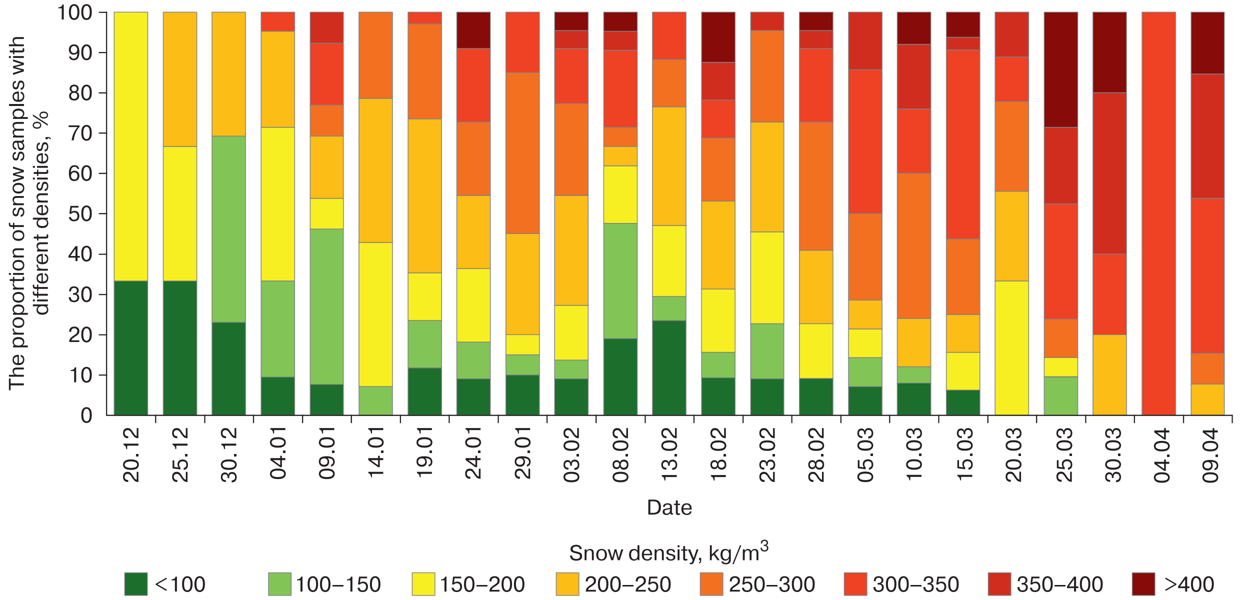

Fig. 3. Breakdown of the snow densities throughout the winter season according to long-term monitoring data as percentage of the total number of samples (sites 1–4, 2005–2017).

ing in the increase of the total density of the snowpack from the first third of January. However, snow layers having density less than 100 kg/m^3 are found throughout the winter, which is related to precipitation; their fraction varies depending on the amount of snow falling during winter. Beginning with the second ten days' period of January, the fraction of the snow layers with density exceeding 200 kg/m^3 increases. By the first ten days of March, there are layers in the snowpack having density of 300 kg/m^3 and higher, which is caused by the increase in the air temperature and mixed precipitation resulting in formation of regelatic layers. The presence of snow layers having high density throughout the winter is related to the processes of the rise of water vapor, which increase the growth rate of the snow crystals in the near-ground part of the snowpack, contribute to formation of the snow crust and cause regelation of individual crystals in the snow layers. Snow layers having density of over 400 kg/m^3 are observed not every year; over the period in question, such density was found in regelatic crust (60 % samples), layers composed of regelatic snow (25 %), and ice crust (15 %).

The highest values of the measured densities were found to be characteristic of regelatic and ice crusts and are equal to 600–790 kg/m^3.

During winter, density of 200–250 kg/m^3 prevails in the layers composed of faceted snow (40 % samples), with the largest number of the faceted snow layers recorded in January and in February; semi-skeletal layers have the density of 250–300 kg/m^3 (40 %), they occur most often in February; skeletal layers having the density of 250–300 и 300–350 kg/m^3 have an equal number of layers, which in total make up 66 %, they occur most often in February, too. For snow layers in the phase of regressive metamorphism, the density of 300–350 kg/m^3 prevails; such layers most often occur in the first third of March.

Initial density is one of the major characteristics of the snow cover, which influences the rate of its re-crystallization, and hence, the time of origination of the avalanche-hazardous layers. It has been established that, the higher the density of the snow layers is, the slower the processes of sublimation metamorphism proceed in them [*Lobkina, 2012; Kazakov, 2015*]. Sublimational re-crystallization under conditions of Sakhalin Island is the main genetic mechanism of forming avalanches more than 5000 m^3. According to the observation data, avalanches of the genetic class of snow cover re-crystallization in the south of the island account for 31 % of the total number of avalanches [*Kazakov, 2009*].

Observations in different landscape zones of Sakhalin Island and of the Kola Peninsula

Snow density depends on many factors and differs much in different landscapes. Observations made in mixed and dark coniferous forests, on the seashore terraces of Sakhalin Island and in mixed forests, taiga, tundra, forest tundra, alpine tundra, and on the marshes of the Kola Peninsula showed that the density of snow with the same structure and texture could essentially differ depending on the landscape zone. The density of crystals packing in a layer is the decisive factor. It is evident that the highest snow density is characteristic of forest-free areas exposed to strong winds. For Sakhalin Island, these are seashore terraces, and for the Kola Peninsula, they are tundra and alpine tundra.

For example, the density of the layers having the solid texture of snow and composed of faceted crystals (>70 %), with the diameter 0.2–0.5 mm on horizontal sites (sites 1–4) varies from 130 to 360 kg/m^3 (the mean density is 233 kg/m^3), on the seashore terraces of the western coast of southern Sakhalin, it varies from 290 to 410 kg/m^3 (the mean density is 357 kg/m^3).

Regarding the density of the layers of secondary idiomorphic snow (from faceted to laminar snow) in different landscapes of the Kola Peninsula, the following conclusions can be made: in general, the highest snow density is characteristic of the tundra (from 200 to 450 kg/m^3, the mean density is 325 kg/m^3), and the lowest density refers to the forest tundra (from 120 to 400 kg/m^3, the mean density is 258 kg/m^3). The forest tundra has the largest variance of the density values – from 80 to 500 kg/m^3, the mean density is 313 kg/m^3. For example, the density of one of the layers in a pit drilled on 03.03.2017 in the forest tundra (the area of Kilpvyavr Lake) reached 500 kg/m^3 (80 % snow crystals belonged to the faceted class of shapes, and 20 % referred to the semi-skeletal class, they had solid texture, and the mean size of a snow crystal was 0.7 mm).

DISCUSSION OF RESULTS

In studying snow density, an observer's error was inevitable, as the observations were made during a lengthy time period by different operators, and the equipment they used had different degrees of precision.

We observed dependence of the snow density on the diameter of snow crystals in layers in which there were 90 % crystals of the same class; however, in two-thirds of the cases, the layers had a mixed structure, which, firstly, made it difficult to reveal the relations and, secondly, decreased the possibility of their use for practical purposes.

As can be seen from Fig. 2, in the course of evolution from freshly fallen snow to sectorial snow (according to [*Kononov and Kazakov, 2011*]), for each subsequent type of snow, the fraction of the samples having higher density increases. In general, newly fallen snow has the lowest density, while sectorial snow is characterized by the highest density. The layers of the faceted type of snow are characterized by lower density values than the layers of the semi-skeletal, skeletal and sectorial types of snow.

The measurements demonstrate that the total density of the snowpack increases by the end of the winter season to constitute about 300 kg/m^3 by the time of maximum water content, whereas the mean density of the snowpack at the beginning of the winter season varies from 80 to 220 kg/m^3 and depends on the general weather conditions, the characteristics of snowfalls, the moisture content of the underlying ground, etc.

In carrying out different research and applied works, it is necessary to remember that the density of different layers of snow may differ several times at the same time and place. For example, in the pit drilled on 25.02.2016, there were snow layers having density from 120 kg/m^3 for fragmental snow up to 330 kg/m^3 for the skeletal types and 760 kg/m^3 for regelatic crust (Yuzhno-Sakhalinsk, site 4).

In order to obtain the dependence of snow density on its structure, texture, diameter of crystals and other parameters, it is necessary to increase the amount of data.

CONCLUSIONS

1. The density of the snow layers varied considerably from 10 kg/m^3 (newly fallen snow) to 790 kg/m^3 (ice crust). The density values of the largest number of snow samples (more than 50 %) from the layers in which fragmental crystals prevail are in the range of 100–140 kg/m^3, sublimational-polyhedral crystals – 140–180 kg/m^3, regelatic-polyhedral crystals – 300–400 kg/m^3, faceted – 220–260 kg/m^3, skeletal – 260–320 kg/m^3. The highest density values are characteristic of regelatic crystals and ice crust (600–790 kg/m^3).

2. In the evolution of snow from newly fallen snow to the sectorial class of shapes, the fraction of the samples with higher density gradually grows. The fraction of the snow samples with the density of 250–300 kg/m^3 for the layers of the semi-skeletal, skeletal, and sectorial types remains to be at the level of 44–48 %.

3. During the winter season, for the layers consisting of different types of snow, the following densities were determined (on the horizontal sites located in the vicinity of Yuzhno-Sakhalinsk): a) the faceted type of snow – 200–250 kg/m^3 (40 % samples), with the largest number of the layers of this snow observed in January and in February; b) the semi-skeletal types of snow – 250–300 kg/m^3 (40 % samples), more often found in February; c) the skeletal type of snow – 250–300 and 300–350 kg/m^3 (66 %), mostly found in February; d) snow in the phase of regressive metamorphism with the density of 300–350 kg/m^3; such layers are most commonly found in the first third of March.

Thus, snow density varies in a wide range, with different layers of the snow cover; the density of different layers of snow may differ several times at the same time and place, which has to be taken into consideration in conducting studies and in carrying out applied research.

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