# TRENDS IN THE FORMATION OF SNOW COVER AGAINST THE BACKGROUND OF GLOBAL CLIMATE CHANGES (ACCORDING TO OBSERVATIONS AT THE UKRAINIAN ANTARCTIC STATION "ACADEMIC VERNADSKY")

**Dr. Serhii Klok**[1]

**Assoc. Prof. Dr. Anatolii Kornus**[2, 3]

**Assoc. Prof. Dr. Olesia Kornus**[2]

**Dr. Olena Danylchenko**[2]

[1] Ukrainian Hydrometeorological Institute, **Ukraine**, sklok_8@ukr.net
[2] Sumy A.S. Makarenko State Pedagogical University, **Ukraine**, a_kornus@ukr.net
[3] Sumy State University

**ABSTRACT**

In order to obtain the characteristics of the snow cover, and to identify its changes and their main trends, in this work, using mathematical and statistical methods, we analyzed snow observation data at the meteorological site of the Ukrainian Antarctic station "Academic Vernadsky" for the period 1997-2020. The obtained results indicate a significant shift in the time boundaries of the period of occurrence of the snow cover, as well as the structure of its deposition, which may be evidence of changes in the nature of atmospheric processes. Attention should be paid to the fact that after 2005 there have been changes in the structure of formation of the snow cover at the area of Academic Vernadsky polar research base: this process has become slower, especially in the first half of winter. At the same time, the total amount of precipitation to the end of the snow accumulation season remains relatively stable. As a result of the study, it was possible to identify the long-term component of the snow cover height, the period of which is 11.03 years with overtones of 5 and 2.5 years, the analysis of which indicates a possible effect on formation of the snow mass in the studied area of the El Niño phenomenon. The results should be used in developing weather forecast models.

**Keywords:** snow cover height, snow mass growth, harmonics, amplitudes, phases.

## INTRODUCTION

Snow is a product of atmospheric processes, therefore, the characteristics of the snow cover have a significant amount of information about the processes themselves: their power, nature, spatial and temporal scales, etc. Unlike other weather parameters, which are instantaneous or discrete, the snow cover remains for a certain time on the underlying surface, thereby opening up wider prospects to its researchers. Based on regional characteristics, as well as modern climate changes, it can be assumed that its characteristics undergo changes and require constant updating, especially in the Polar Regions.

Snow cover in the area of the Ukrainian Antarctic Station (UAS) "Academic Vernadsky" persists for most part of the year, and in some cases − the whole year. Therefore, its influence on the weather conditions of the region and their formation is extremely significant, which, accordingly, increases interest in the study of snow cover [4, 7-9, 11, 13]. Being a product of atmospheric precipitation, snow cover, in turn, significantly affects them, primarily as a component of the water and radiation balance of certain territories [1, 2, 17, 18].

Snow is the main component the glacial mass gains. According to the estimates by many scientists (Velicogna 2009; Mouginot et al. 2019; Rignot et al. 2019) [19, 20, 22] the ice sheets today are significantly reduced due to thawing. Thus, the study of snow is important for explaining the mass balance of glaciers.

Quantifying snow precipitation in Antarctica faces many unique challenges such as wind and other technical difficulties due to the harsh environment. In view of the logistic difficulty in obtaining reliable snow measurements, researchers have resorted to using other means, like satellite observations, reanalysis data sets and climate models [15]. But direct measurement of snow precipitation in Antarctic using ground-based instruments is important to validate the results from climate models, reanalyses and satellite observations. This study analysed snow measurements and these data of measurement can be used as a standard for validating snow observations from satellites and the long-term results obtained from climate models and reanalysis data sets.

## METHODS AND EXPERIMENTAL PROCEDURES

The study of the characteristics and conditions of formation of the snow cover in the above-mentioned area was began from the beginning of the operation of British station Faraday − from the middle of the twentieth century [3, 21]. In the work, using by physical and statistical methods, analyzed the data of daily observations of the snow cover height obtained at the meteorological playground of the Ukrainian "Academic Vernadsky" polar research base (65°14′44″S, 64°15′28″W) from 1997 to 2020, which made with 2 stationary snow depth gauges.

The available series of instrumental observation data for precipitation at Antarctica are extremely limited, which is associated, first of all, with the late discovery of the continent, as well as with the limited logistics operations in the region even today. In the course of the work, well-known methods of mathematical and statistical analysis were used, implemented through the built-in functions of the software Microsoft Excel, Statistica from StatSoft Inc., Surfer from Golden Software LLC.

To analyze the observational data in order to identify the components of the precipitation variability, a harmonic analysis technique was used, i.e. there were obtained trigonometric functions (harmonics) that were multiples of the series length. In this case, the harmonic equation has the following form:

$$G_k = A_k \cdot \cos(\omega_k \cdot t - \varphi_k), \qquad \omega_k = 2 \cdot \pi / T_k \qquad (1),$$

where $k$ is the harmonic number, $A_k$ – $k^{th}$ harmonic amplitude, $\omega_k$ – $k^{th}$ harmonic frequency, $T_k$ – $k^{th}$ harmonic period, $\varphi_k$ – $k^{th}$ harmonic phase, $t$ – time (Brooks 1953).

Full expansion in a Fourier series involves the determination of harmonics, in the amount of *N/2*, where *N* is the series length. Harmonic characteristics are determined by finding the Fourier coefficients $a_k$ and $b_k$ are given as:

$$a_k = 2 \div N * \sum_{i=1}^{N}\left[x_i * \sin(\omega_k * t_i)\right],\ b_k = 2 \div N * \sum_{i=1}^{N}\left[x_i * \cos(\omega_k * t_i)\right] \quad (2)$$

With the aim of the Fourier coefficients calculation by the linear regression method in Microsoft Excel, the sines and cosines of harmonics for a certain date were calculated as used by (Blattner et al.1999):

$\sin_i = \sin(i \cdot \Omega \cdot date)$, $\cos_i = \cos(i \cdot \Omega \cdot date)$ (3),

where $\Omega = \frac{2\ \pi}{T}$; *date* – date corresponding to the source series value.

The linear regression equations were estimated using the coefficient of determination (Kd) $R^2$, which is the proportion of the variance in the dependent variable that is predictable from the independent variable(s). The significance of the coefficients was checked by using t-Student's criterion. The F-statistic was used to determine whether the observed relationship between the dependent and independent variables was random.

**THE RESEARCH RESULTS AND DISCUSSIONS**

Snow cover is one of important elements of the environment. The research area is characterized by unstable weather conditions, which are formed under the influence of marine air mass (Averyanov 1990; Sedunov 1991; Bogdanova et al. 2007; Klok 2010, 2013). With unstable weather, often in winter there is precipitation both in the liquid and in the solid phase, which affects the quality of precipitation measurement. In this work, we analyzed the data of daily snow precipitation amounts as well as about daily snow depth.

It has been established that the formation of a snow mass of 2-3 m high in the region occurs under relatively warm conditions (average January temperature of 0.7 °C, the sum of the temperatures of the winter months is -23.7 °C) and during long (6-7 months) winter. Therefore the snow cover has distinctive features. In particular, snow falls wet, its temperature is close to 0 °C, the dynamic factor increases its density to 0.5 g/cm$^3$ and higher. It is formed by the compaction type, which indicates the predominance of the destructive metamorphism processes − especially at the initial stage. In the subsequently, there is an intensification of the constructive metamorphism processes, although, due to an increase in wind load during snowfalls and a fairly loyal temperature regime, they are somewhat limited.

The greatest practical interest, taking into account the planning of economic activities, is the analysis of main dates of the snow mass formation during the year: the dates of the beginning and the end of period of the snow deposition, the dates of the snow cover maximum thickness, the dates of the period of maximum increments of the snow mass, as well as the dates of formation of its main layers [1-2]. At the UAS "Academic Vernadsky" meteorological site, daily observations of the snow height have been constantly recorded since 1997 [7-15]. The accumulated material makes it possible to analyze the dynamics of dates of the beginning and the end of existence of the snow cover and make conclusions about the duration of the existence of the snow cover (Fig. 1).

As can be seen from fig. 1, during the 24-year (1997-2020) observation period, there is a clear tendency to shift the timing of beginning of the permanent snow cover formation to later, and its complete destruction − to earlier dates. If at the beginning of the studied period the formation of snow cover was observed in March, today it is stable in April.

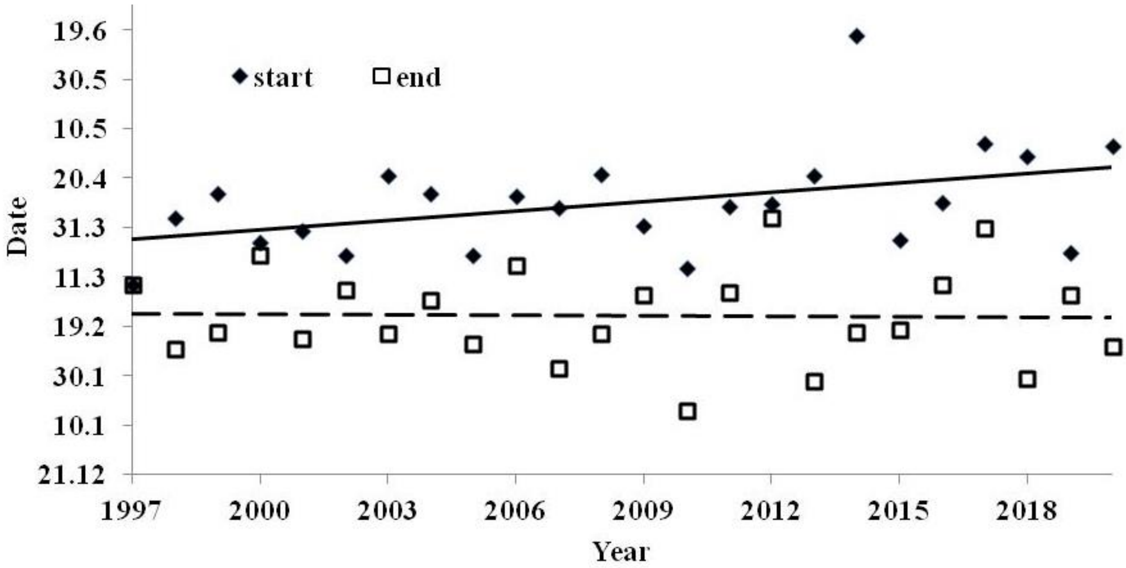


**Fig. 1.** Dynamics of dates of the beginning and the end of snow cover period at the meteorological site of the UAS "Academic Vernadsky"

The average dates for the destruction of snow cover also shifted, although somewhat less − from the third decade of February to mid-February. As a result, we have a stable tendency to decrease of snow cover occurrence period in the study area. More details of formation of the snow cover and its statistical characteristics are reflected in Table 1. It should be noted that the coefficient of determination ($R^2$) is the most effective estimate of the regression model and shows how the obtained result describes the observational data. At the same time, the F-statistic (Fisher's criterion) demonstrates how much the result obtained can be trusted − a confidence interval of 95% corresponds to a value of F-statistic more than 2.0 [5].

**Table 1.** Characteristics of stages of the snow cover formation at the meteorological site of the UAS "Academic Vernadsky" for 1997-2020

| Phases' characteristics | Period, days | Average date | | Trend, days per 10 years | Coefficient of determination | F-statistic | Uncertainty, days |
|---|---|---|---|---|---|---|---|
| | | 1997 | 2020 | | | | |
| the beginning of snow cover period | 366.52 | 25.III | 25.IV | 12.70 | 18.10 | 4.860 | 0.6 |
| the end of snow cover period | 356.16 | 24.02 | 21.II | -0.80 | 0.09 | 0.019 | 0.6 |
| the maximum of snow cover depth | 365.55 | 24.X | 1.XI | 0.46 | 0.46 | 0.100 | 0.9 |

As already noted, the dates of the beginning of formation of the snow cover shifted most significantly. With a linear trend of 12.7 days over 10 years, a shift of 1 month occurred over a 24-year observation period (Fig. 2). An analysis of dates of the maximum snow cover for the period under study also showed their shift to later dates. However, the dates of maximum snow depth as well as the dates snow thawing have shifted less significantly.

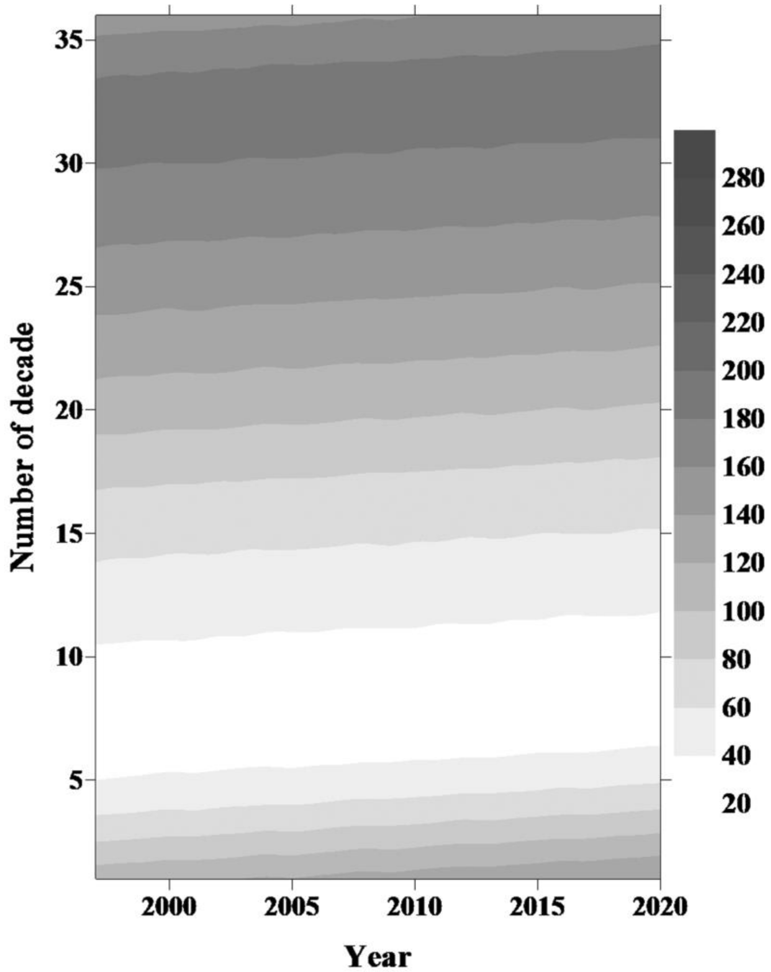


**Fig. 2.** Diagram of dates of the establishment of the maximum height of snow cover at the meteorological site of the UAS "Academic Vernadsky" for the period 1997-2020

Some statistical characteristics of dynamics of the shift in the date of the maximum height of snow cover, which were calculated in the course of this work, are reflected graphically in Table 2.

**Table 2.** Characteristics of dynamics of the intra-annual component of snow cover depth according to the observations at UAS "Academic Vernadsky" (1997-2020)

| Duration of observation | Period, days | Uncertainty, days | Trend, cm per 10 years | $R^2$ | F |
|---|---|---|---|---|---|
| 1997-2020 | 365.8 | 0.6 | 2.7 | 0.66 | 1693.5 |

With the help of mathematical and statistical methods, we obtained the amplitudes and phases of harmonics of the intra-annual component of the snow depth, among which the next three were statistically significant − 57, 103 and 240 days (Fig. 3). The first two harmonics are characterize the initial period of formation of the snow cover, and the third − the period of maximum increments of the snow mass (late July − early August), which will be discussed below.

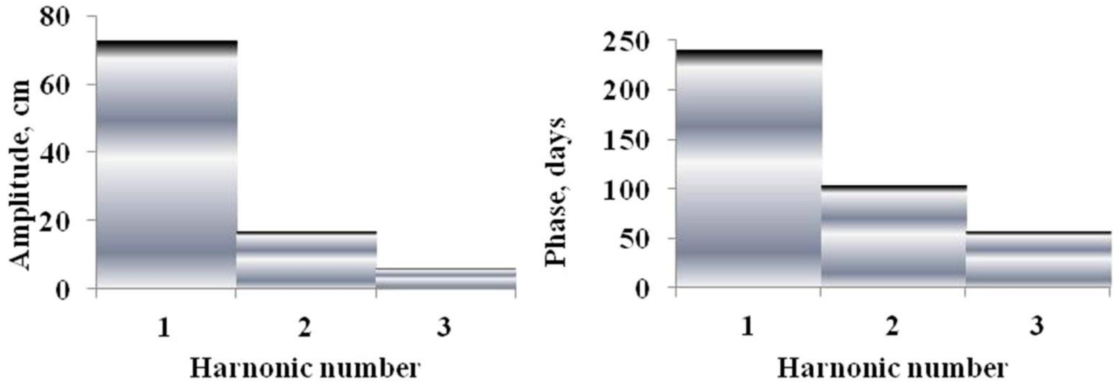


Fig. 3. Amplitudes and phases of seasonal component of the snow cover height according to the data of observations at UAS "Academic Vernadsky" for the period of observations 1997-2020

Accordingly, during 1997-2020 at area of UAS "Academician Vernadsky" there is a Fig. 4. Today, the maximum depth of the snow cover at UAS is fixed in early November.

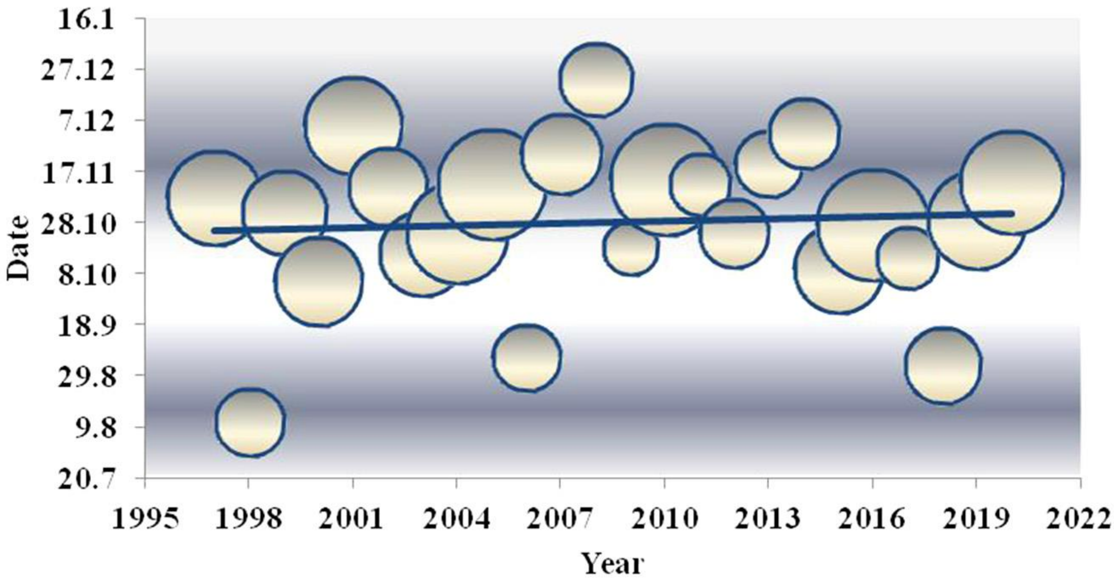


**Fig. 4.** Dates of maximum of the snow cover depth at the meteorological site of UAS "Academic Vernadsky" for the period 1997-2020

The long-term intra-annual distribution of the snow cover height and its increments is shown in Fig. 5.

It should be noted that the statistical analysis of increments of the snow cover height (in this case, the daily increments) makes it possible to identify the main periods of snow accumulation, during which the formation of various snow layers are occurs. Since snow is a type of atmospheric processes, these periods are especially clearly visible when comparing data on the amount of snowfall with the snow pits (vertical sections) of snow mass, the analysis of which is extremely informative [11, 12].

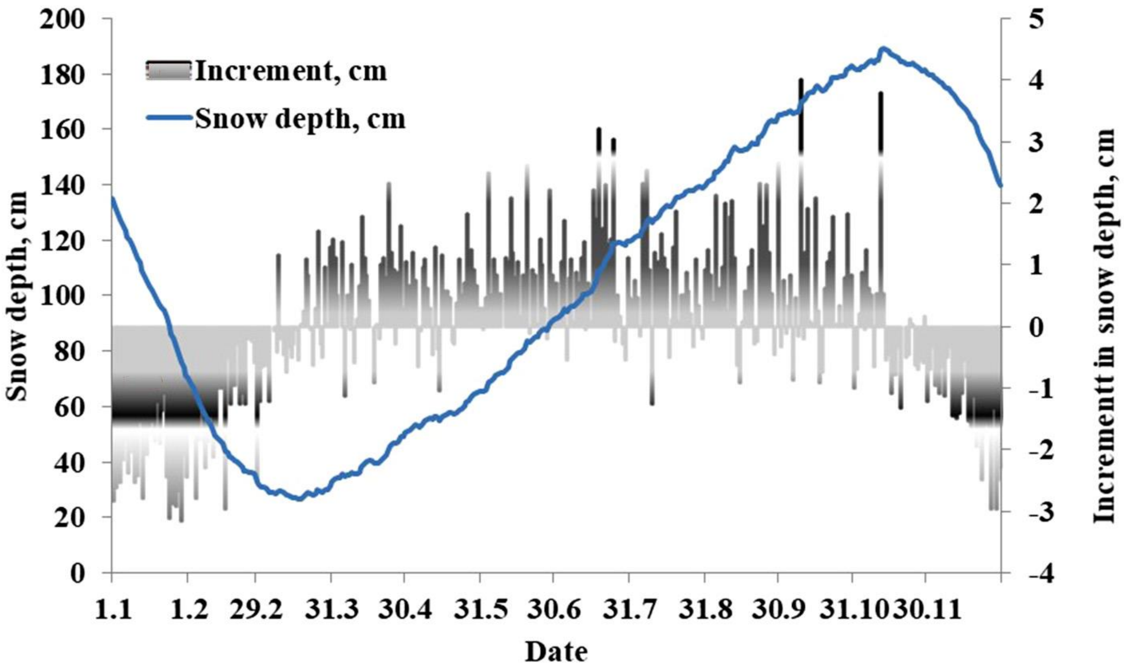


**Fig. 5.** Long-term seasonal distributions of the snow cover height and its daily increments at the UAS "Academic Vernadsky" meteorological site for the period 1997-2020

Analysis of the snow accumulation curve showed, that during the period from April to August are formed 6-8 stable layers (although in some unstable winters their number may be greater), the total height of which is about 250-260 cm. Because the layers are built by certain atmospheric processes, the dates of their formation from year to year are quite close. During the period of maximum snow growth (July-August) an avalanche-hazardous layer of insignificant vertical thickness is formed. The snow thawing time is characterized by 3-4 stable periods.

All of the above mentioned us to make an assumption about the presence of significant changes in the very process of formation of the snow mass at area of "Academic Vernadsky" polar research base, which is manifested in changes in the height of the snow cover at the UAS during 1997-2020, the dynamics of which is shown in Fig. 6.

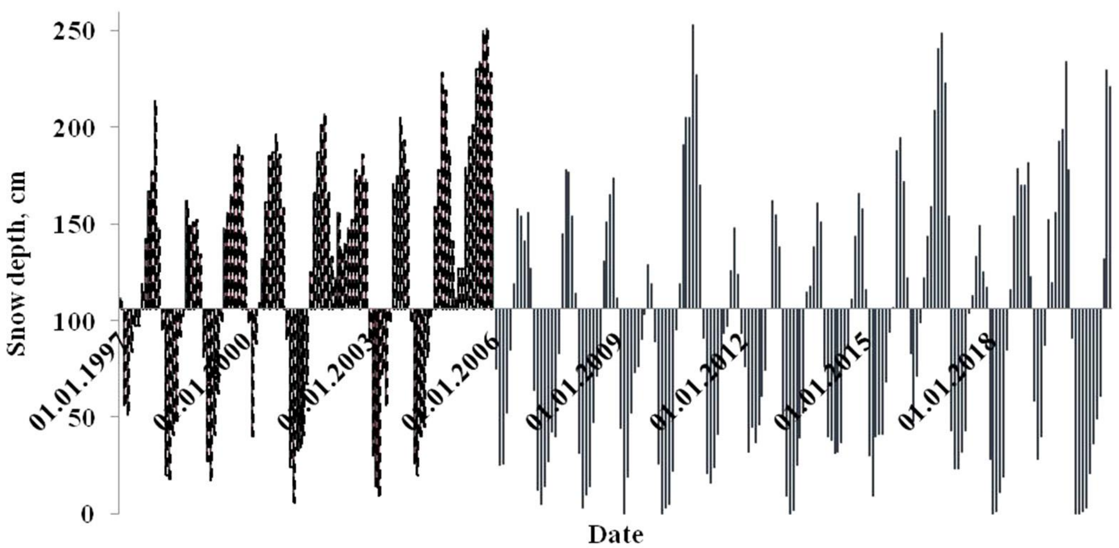


**Fig. 6.** Dynamics of height of the snow cover at the meteorological site of the UAS "Academician Vernadsky" for the observation period 1997-2020

On the background of variability of the intra-annual component of height of the snow cover, of interest is, first of all, the abrupt decrease in the values of this indicator and the duration of the period with snow after 2005; secondly, the presence of quasiperiodic components, which are clearly seen on given earlier Fig. 4.

The process of snow cover formation at the UAS "Academician Vernadsky" is shown in more detail in the following diagram (Fig. 7), which reflects the full distribution of the snow cover depth by months during all observation years. Changes in the structure of snow deposition since 2006 are obvious. The snow cover formation process in the first half of the winter season became slower and its height was less, although the amount of precipitation during the winter season remained practically unchanged. In this case, it may be logical to assume certain changes in the general atmospheric circulation system, in particular, the trajectories and power of cyclones that form the snow cover of the region. Also important are the role of other factors that cause snow compaction and a change of aggregate state of the precipitation.

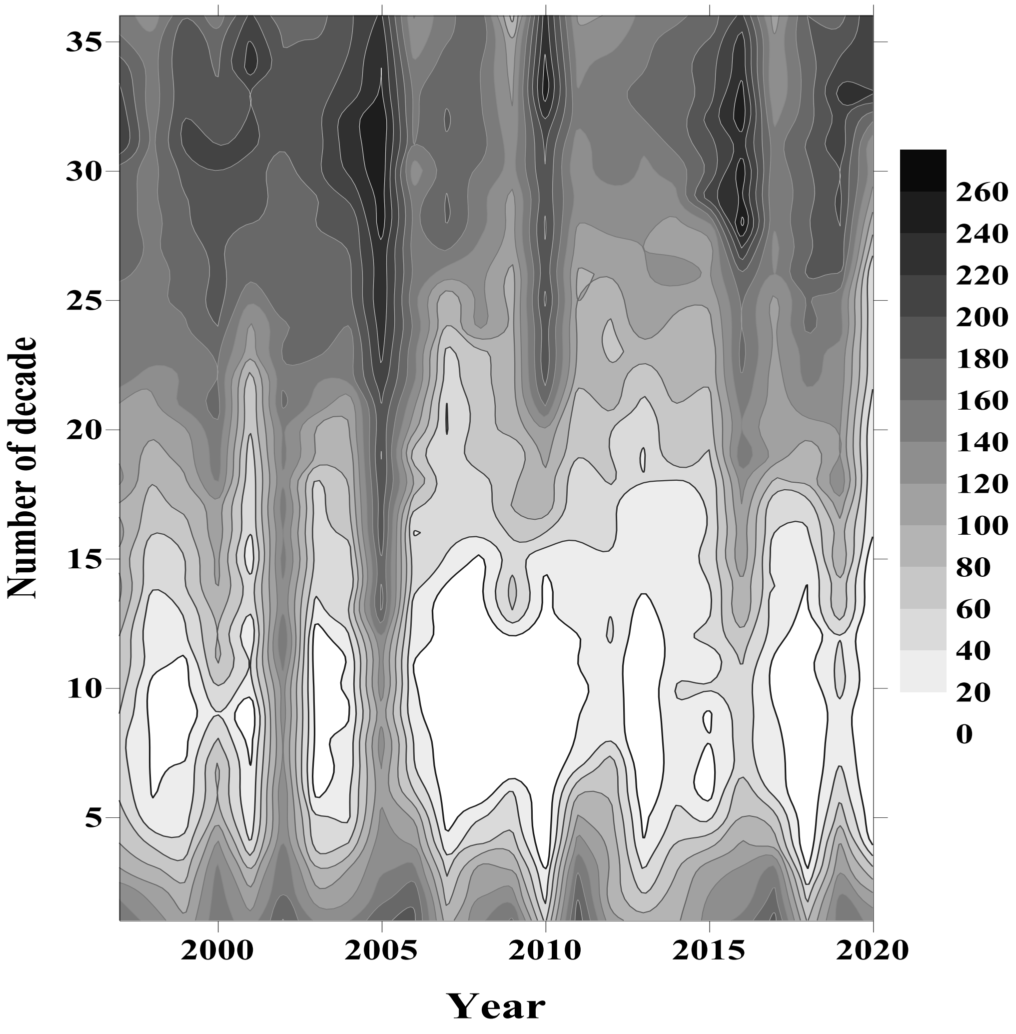


**Fig. 7.** Full distribution of the snow cover depth at the area of UAS "Academic Vernadsky" for the observation period 1997-2020

In addition to the intra-annual component, during the study the long-period component of dynamics of the snow cover height was identified (Fig. 8), the period of which is 11.03 years. More detailed information about the obtained component of slow fluctuations of the snow cover height is shown on Fig. 8, in particular, here can be seen the limits of the main periods in 2005 and 2015.

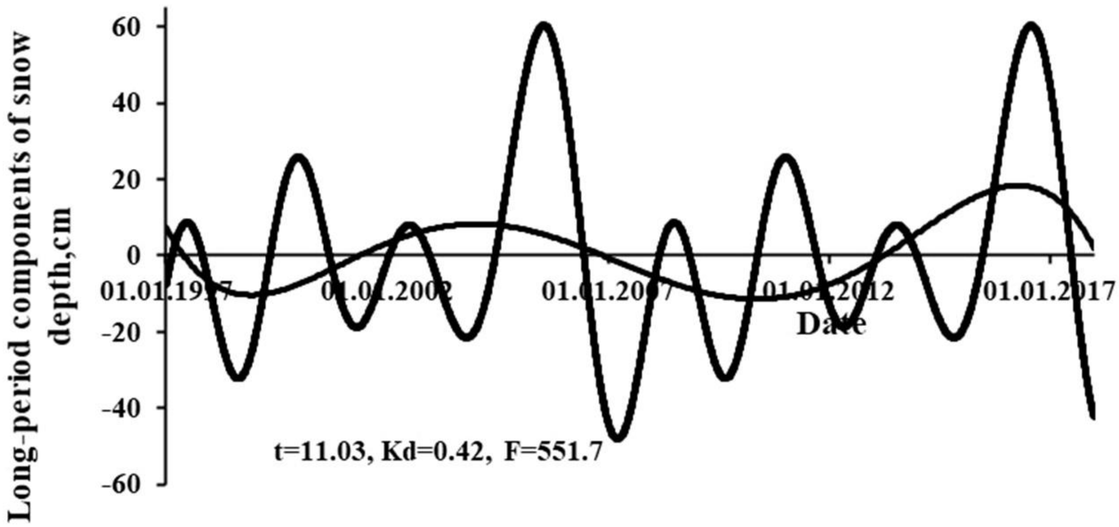


**Fig. 8.** Long-period component of the snow cover height with a period of 11.03 years according to observations at the UAS "Academic Vernadsky" for the period 1997-2020

The overtones of the fundamental harmonic, at the level of periods of 5 and 2.5 years, are of particular interest, since they are identical to the El Niño harmonics, which may indicate the influence of this phenomenon on the formation of the snow mass on the UAS "Academic Vernadsky" (Fig. 9).

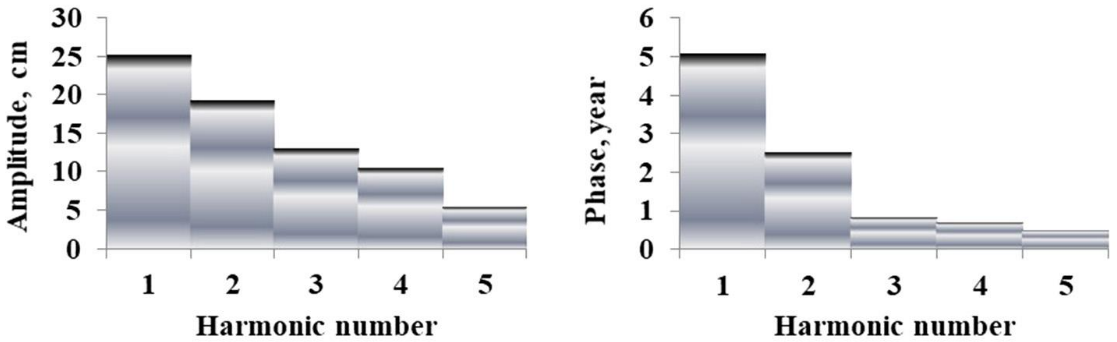


**Fig. 9.** Amplitudes and phases of harmonics of the snow cover height according to observations at the UAS "Academic Vernadsky" for the period 1997-2020

Obviously, the spectrum of harmonics of the snow cover depth is so much wider, but today its more detailed studies are limited by the duration of a number of instrumental measurements.

**CONCLUSION**

During the study period, significant changes in the process of snow cover formation in the area of the UAS "Academic Vernadsky" have been observed. First of all, there is a shift in the main dates characterizing the snow cover: the dates of the beginning and the end of the snow cover period, as well as the maximum of snow accumulation, to later dates.

The formation of layers of the snow cover, differing in the type of compaction (the number of which ranges from 6 to 8), occurs at the same time from year to year. Obviously, this indicates that the stratification of the snow mass arises under the influence of the same synoptic processes. The maximum increase of the snow mass is observed in July, as a result of which the most unstable layers of snow are formed at this time, which can be potentially avalanche-prone layers.

Attention should be paid to the fact that after 2005 there have been changes in the structure of formation of the snow cover at the area of UAS "Academic Vernadsky": this process has become slower, especially in the first half of winter. At the same time, the total amount of precipitation to the end of the snow accumulation season remains relatively stable. As a result of the study, it was possible to identify the long-term component of the snow cover height, the period of which is 11.03 years with overtones of 5 and 2.5 years, the analysis of which indicates a possible effect on formation of the snow mass in the studied area of the El Niño phenomenon. The seasonal component (annual cycle) with a period of 366.04 days (which explains the shift of main data of the snow cover) describes 58% of the total variability, and the long-period (period of 11.03 years) − 17.6%.

The obtained results give a broad understanding of the properties of snow and the very process of snow accumulation in the study area. It should be noted the importance, relevance and prospects of conducting glaciological studies in the future, since the amount of snowfall to a large extent forms the water balance of the territory, and the conditions and duration of its occurrence − the radiation balance of the Polar regions. The stratigraphy of the snow mass reflects its seasonal dynamics, the processes occurring within it under the influence of various factors. It also makes it possible to assess the real amount of precipitation. The results should be used in developing weather forecast models.

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