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ARCTIC ICE COVER STATE MONITORING BASED ON SATELLITE DATA

Albedo of the Snow–Glasier Surface of Svalbard

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Abstract—This paper discusses the results of measurements of the albedo of the snow–glacier surface of Svalbard using the example of an Aldegonda glacier (the Green Fjord area) and surrounding area of the Russian settlement of Barentsburg that have been carried out in last years, including the third field phase of the International Polar Year, 2007–2008. The temporal and spatial variability of the albedo and its relationship to the natural and anthropogenic contamination of the surface are analyzed.

Keywords: Arctic, Svalbard, albedo, surface contamination

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Methods of satellite remote sensing of the Earth's surface (ERS) are based on analyzing electromagnetic radiation, which in the case of passive sensing is either radiated by the object of research itself or is the reflection of solar radiation (Smirnov, 2011). The electromagnetic self-radiation in the atmosphere is partially absorbed and scattered by water vapor, carbon dioxide, and others. Part of it is absorbed by the surface or lost in the reflection from it. In the case of remote sensing of albedo (from Latin *albus* means white), ultraviolet (UV), visible, and near infrared (IR) ranges of the electromagnetic spectrum are usually used. In the UV region the range of 320–400 nm is the most important one. The solar radiation is not absorbed in it by oxygen and ozone. The visible range (400–800 nm) is most commonly used in the ERS. At the same time, in the polar regions the use of sensing results in the visible range for the study of the underlying surface (sea ice and snow–glacier covers of the Arctic islands and archipelagos) is limited to daylight hours (polar day) and relatively clear (low cloudiness) weather.

In climate research and thermal balance calculations, integral (300–3000 nm) and spectral albedos obtained for a specific wavelength are used. The latter circumstance is extremely important, since the contaminants of the snow–glacier surface of anthropogenic (black carbon–carbon dioxide) and natural origin (particles of mineral and biological origin) have a selective absorption nature and can successfully be determined by ERS methods. The more so since the influence of snow surface contamination near major industrial objects in the Arctic (harbor, power plants, settlements, objects of oil and gas industry, etc.) extends for tens of kilometers (Demin et al., 2011).

The reflectance of the snow–glacier surfaces has a fundamental spectral dependence (Winther et al., 2003). The same surface type (for example, fresh snow) will have different albedos in different parts of the spectrum (Smirnov, 2011). It is maximum in the short-wavelength part of the visible spectrum and minimum in the near infrared part. One of the main reasons for the seasonal changes in the albedo in the Arctic are the variability of the metamorphic structure of the snow–glacier surface (Aleksandrov et al., 1996).

Correct estimations of albedo in the polar regions of the Earth, first and foremost, sea ice and ice sheets, are extremely important for assessing possible climate changes. According to a number of domestic and foreign researchers, positive feedbacks, such as the albedo–surface air temperature, generate and maintain the so-called Arctic amplification mechanism. Thus, the monitoring of reflectance characteristics of snow–glacier surfaces at different spatial scales is extremely important and is impossible without the use of means and methods of the ERS. Similar observations are primarily necessary for verification small and medium resolution images of artificial Earth satellites (AESs). These include Terra and Aqua satellites with a MODIS spectroradiometer and AES Meteor-M № 1, Landsat-5,7, Resurs-DK, and a number of others (Smirnov et al., 2011). These AESs make it possible to obtain information about reflective characteristics of the surface in different ranges of visible and infrared infrared part of spectrum with a spatial resolution from 1 to 1000 m. Qualitative ERS data verification requires detailed and regular ground true measurements in different spectral ranges (Winther et al., 1999, 2001).

The ice cover area of the Arctic islands and the area of their snow cover and its duration in total are significant indicators of climate change. In this case, glaciers and snow cover of Svalbard are by far the most studied when compared with other Arctic islands

(Winther et al., 2003). One of the most important results of these studies is the conclusion of the sustainable reduction of the glacier area of the archipelago since the 1930s. The main causes of this process are related to the influence of both advective and radiative factors of climate change. Apparently, the causes of the current state of ice and snow cover of the archipelago and tendencies of its future development should be sought in the interaction of these mechanisms. An important role is played by the reflectance of mentioned surfaces itself.

As is known, the radiation balance of the ice surface is determined not only by the quantity of incoming shortwave solar radiation, which is defined not only by astronomical factors, the moisture content of the atmosphere, the presence of different gas components, and the influence of cloudiness, but also by the reflective of the underlying surface. Moreover, the albedo is an important characteristic for determining the absorbed short-wave radiation by the radiation-active layer of the glacier; i.e., it determines the amount of ablation caused by radiation.

It is known that the brightest in form and most significant with respect to content processes of transformation of snow–glacier covers in the Arctic region occur in spring and in summer. At this time a sharp decrease in the surface albedo is observed due to maximum insolation and contact heat transfer, while ablation processes become most intense. The decrease in albedo is caused not only by processes that occur directly on the surface, but also by complex processes of thermal metamorphism that take place in the active layer of snow or ice and are caused by the penetration of solar radiation (Timirev and Nazarov, 1988). The amount of albedo of such a surface is sharply reduced for a very short period of time after being quasi-constant and maximum for many months (Winther et al., 2003). During this period the maximum speed of ablation is observed. The contribution of radiation and advection factors does not remain constant. In addition, in the Arctic, the consequences of natural or anthropogenic contamination of the surface are particularly large and unpredictable during the melting of snow and ice. However, the contamination can both strengthen and weaken the ablation process. The ablation intensity reduces at the surface contamination level, which exceeds a certain critical value (of the surface concentration). In this case, the polluted layer at the surface plays the role of a shield (protector) that delays melting significantly (Peschanskii, 1969; Ivanov et al., 2003).

As is known (Aleksandrov et al., 1996), the underlying surface albedo depends on its structure, time of day, and a number of meteorological factors. Long term observations of the land surface (tundra) albedo on Svalbard are carried out at the research station of the Norwegian Polar Institute in the settlement of Ny-Alesun (Winther et al., 2003). However, observations made at meteorological stations give an idea of albedo amounts typical for limited (constant) surface areas in different seasons. Route (profile or areal) observations make it possible to obtain mean albedos that characterize the reflectance of large areas.

Spatial albedo measurements (the so-called areal survey) on Svalbard have not been carried out until recently. It was possible to carry them out for the first time on the small Aldegonda glacier located on the west coast of the Green Fjord (the West Spitsbergen Island) in April 2005.

In domestic practice, a field albedometer constructed based on the M-115M thermoelectric pyranometer (Yanishevskii, 1957) was used for measurements of the albedo of natural surfaces. It measures the solar-radiation intensity in a wavelength range of approximately 300–3000 nm. In measurements on slopes (of glaciers, hillsides, mountains, etc.), the methodology proposed at the Arctic and Antarctic Research Institute (AARI) was used (Ivanov and Polyakov, 2013). In the study of the relationship between albedo and artificially contaminated surface areas, we used the practical and methodological recommendations set out in (Peschanskii, 1967).

Areal measurements of albedo carried out for the first time on the Aldegonda glacier showed significant spatial and temporal variability of this characteristic. In April, the surface albedo varied from 58 to 84% (Fig. 1). The glacier at this time of year is completely covered with snow, and there are usually no signs of melting snow. In this case, the spatial distribution of the albedo is determined by the topography of the glacier surface (slope azimuth), the height of mountain ranges surrounding the glacier (as a consequence, permanent or temporary shading of some parts of the glacier), and the nature of the solar radiation arrival (the change in solar elevation during the day).

In July–August spatial changes in surface albedo of the glacier were more significant and amounted to about 5–65%. The reason is the almost widespread melting of snow, up to its complete disappearance in the lower part of the glacier.

As is shown in Fig. 2, albedo minimum values (5%) are observed at the bottom of the glacier, which is adjacent to the lateral moraine, where there is the greatest contamination of its surface with detritus rocks. The albedo value is affected by lateral moraines on the northern periphery of the glacier. Not only does the presence of a significant amount of detrital material on the ice surface influence the situation, but so does the additional reflection of the solar radiation from moraine side surfaces. The surface albedo depends on the time of day (the solar elevation and shading of individual parts of the surface). For example, at noontime, albedo of open areas of the glacier surface is 20–40% less than that of shaded areas. In these areas the snow cover is less prone to destructive thermal metamorphism caused by melting (*Handbook of Snow*..., 1986). Here, the albedo can reach 65%.

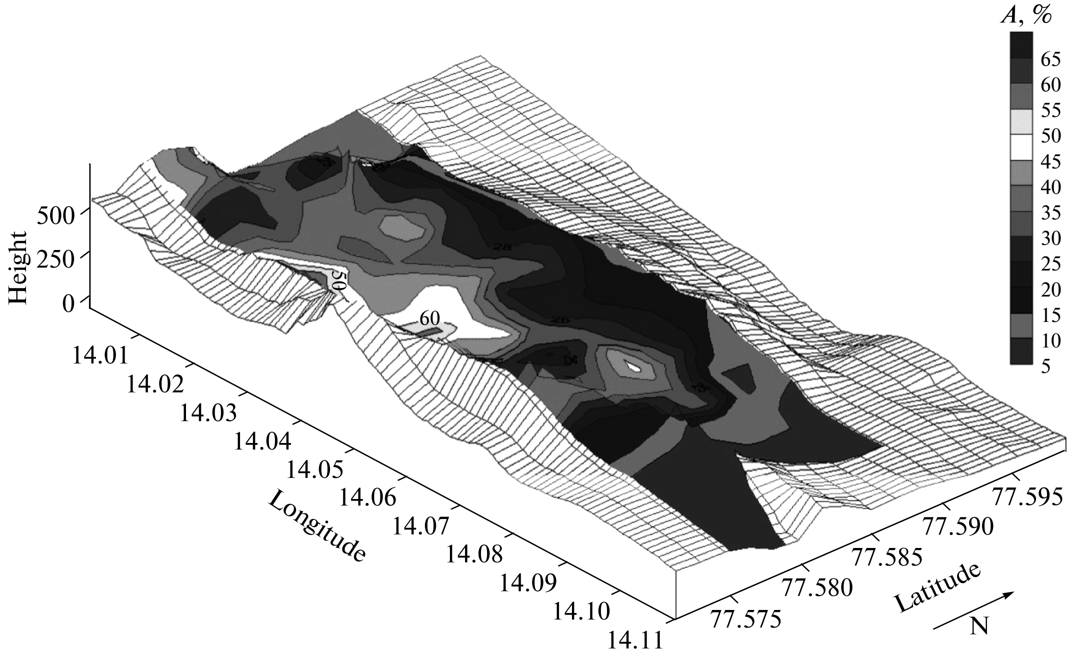

Fig. 1. Albedo of the snow surface of the Aldegonda glacier in April 16–21, 2005.

Thus, the surface albedo of the glacier experiences significant spatial and temporal variability in spring and in summer. This fact is important for the correct calculation of the surface radiation balance, the share of solar energy expended on heating and melting on the surface, as well as on the interlayer melting that should be taken into account in the modern mathematical models of different resolution levels.

As was mentioned above, the contamination of snow–glacier surfaces has a significant effect on the albedo value. In Arctic conditions, the anthropogenic (manmade) contamination of surface areas, particularly in the vicinity of settlements where different economic (mining, construction, etc.) and other activities (tourism) take place, is of great importance. Let us consider these facts using the example of the Russian settlement of Barentsburg miners located on the eastern shore of the Green Fjord (West Spitsbergen island). It is known (Peschanskii, 1967; Ivanov, 2003; Ivanov et al., 2003) that the melting rate in contaminated surface areas is complex and depends in a complex way both on the type of the contaminant material and on its surface concentration. We tried to repeat the famous experiment (Peschanskii, 1967) using coal crumb as a pollutant, which is a key element of the anthropogenic contamination in the vicinity of the mining settlement of Barentsburg. Sites with different concentrations of surface coatings were prepared outside the settlement that made it possible to compare the results with the albedo of the background (clean) surface (see Fig. 3a).

In the case of an increase in the surface contamination concentration, the albedo accordingly decreases. In the case of the repeated (in 24 h) measurement of the albedo of the background part of the surface, a significant decrease of its reflectance was recorded, which indicates a certain change in its structure. The latter circumstance is caused by the known processes of destructive (thermal) metamorphism of snow crystals as a result of melting by the heat of solar radiation and contact heat exchange with the atmosphere (*Handbook of Snow*..., 1986). Under these conditions the right geometrical shape of snow crystals is violated. They become round and increase in size. Water layers appear between them. The reflectance of such a surface decreases. The main contribution in the reduction of the albedo is made by a decrease in the so-called thickness albedo (Timirev and Nazarov, 1988). The latter is defined as the ratio of the reverse flow of the solar radiation scattered by the snow layer (backscattering) to the total solar radiation incoming to the surface. As in the case of similar experiments on the fast ice in the Beaufort Sea (Ivanov et al., 2003) and on the Himalayan glaciers (Singh et al., 2010), the absolute change (decrease) of albedo is the most significant in the case of an increase in the concentration of surface contamination from 0 to 500 g/m^2. A further increase in the concentration does not lead to a significant reduction in the albedo. In our experiment, the maximum change in the surface albedo was recorded at an intermediate but not maximum concentration of coal crumb. This critical concentration was 250 g/m^2. For comparison, for the conditions of the surface con-

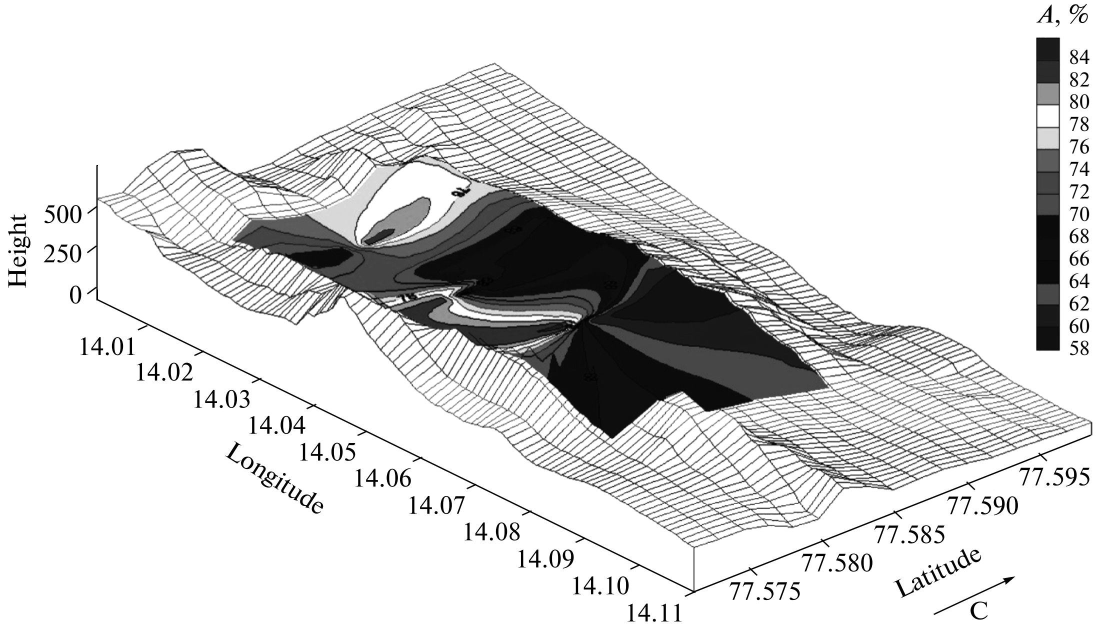

Fig. 2. Albedo of the Aldegonda glacier surface in July 26–August 15, 2005.

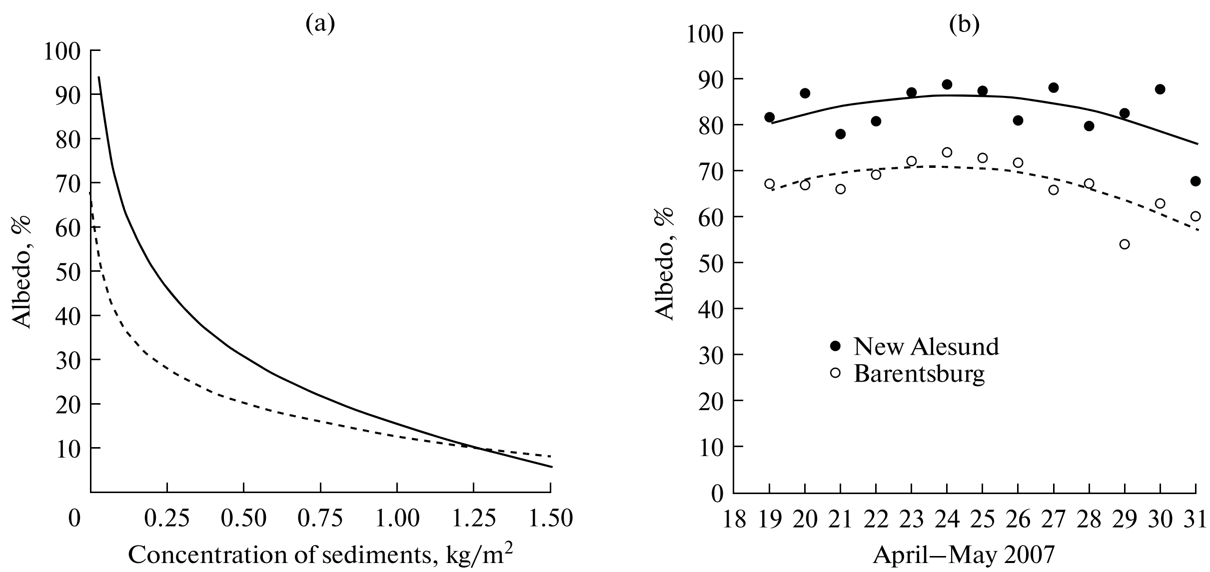

Fig. 3. Contaminated snow-surface albedo: changes in the snow-surface albedo depending on the surface contamination concentration (the solid line is the initial state; the dotted line refers to the state 24 h later) (a) and the albedo of snow in settlements of Barentsburg and New Alesund (b).

tamination of the fast ice in the Beaufort Sea (beach pebbles no larger than 5 mm were used as the experimental material), it was 1000 g/m^2. A further increase in the surface concentration of contaminants led to the reduction of the melting rate of the fast ice on the surface by about 20% (Ivanov et al., 2003). Qualitatively similar results were obtained in (Peschanskii, 1967). The difference in absolute values of the critical concentration of the surface contamination is caused primarily by the use of particles with different compositions, colors, and sizes.

As was noted above, the snow-surface contamination in the Arctic can be caused not only by industrial activities, but also by other types of anthropogenic impact. For example, in a number of Norwegian settlements of the archipelago, tourism actively develops in spring. In this case vehicles (snowmobiles) become the main source of contamination. Thus, the nature of the surface contamination (its chemical composition) changes qualitatively. Figure 3b shows data on the snow-surface albedo in Barentsburg (industrial contamination) and New Alesund (tourism) obtained in joint measurements made during the International Polar Year 2007–2008 (Ivanov et al., 2013). The comparison of the snow cover albedo in Barentsburg, where coal mining is conducted, with values that are characteristic for the Norwegian settlement of New Alesund, where research activities and tourism prevail, has shown that on average the albedo of snow in the range 300–3000 nm in Barentsburg is 15–20% less than that in New Alesund.

CONCLUSIONS

According to experimental studies, the snow–glacier surface albedo undergoes significant spatial and temporal variations both during the day and during the season. Significant influence is caused by the natural contamination of the surface by sedimentary materials, which, together with the daily variations (different zenith angles of the Sun) and uneven shading of individual parts of the glacier, forms a complex spatial and temporal pattern of the albedo distribution. These circumstances should be taken into account in verification images of high and medium resolution obtained using AES.

AES data obtained in different spectral ranges make it possible to determine the area of distribution, nature, and intensity of contamination of snow–glacier surfaces in the vicinity of major industrial and tourist sites of the archipelago in more detail, taking into account different chemical compositions of carbon compounds (soot aerosol, coal particles from enrichment facilities, coal dumps, fuel of different types, etc.). This makes it possible to monitor these objects in detail.

The Aldegonda glacier can be considered a basic (test) site taking into account the data obtained on it for a number of years by experts of the AARI and St. Petersburg State University. It is obvious that the further observation program should be expanded, focused on individual and specific glacier areas (zone of the firn formation, maximum ablation, various shading conditions, natural contamination, etc.), and supplemented by the synchronization of ground-based observations with orbits, survey rate, and swath (survey) width of corresponding AES.

It is necessary to continue field experiments aimed at the quantitative and qualitative assessment of the impact of anthropogenic contamination on the snow–glacier cover of the Svalbard in view of opportunities of AES of medium and high resolution. This is extremely relevant given the well-known dramatic consequences of anthropogenic impacts on the fragile nature of Arctic regions (Contamination of the Arctic..., 1998), as well as the observed current climate warming of the archipelago (Nordli et al., 2014).

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