GLACIERS AND THEIR SIGNIFICANCE FOR THE EARTH NATURE

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Summary

Past, present and future of glaciation are a major focus of interest for glaciology, i.e. the science of the natural systems, whose properties and dynamics are determined by glacial ice. Glaciology is the science at the interfaces between geography, hydrology, geology, and geophysics. Not only glaciers and ice sheets are its subjects, but also are atmospheric ice, snow cover, ice of water basins and streams, underground ice and aufeises (naleds). Ice is a mono-mineral rock. Ten crystal ice variants and one amorphous variety of the ice are known. Only the ice-1 variant has been revealed in the Nature. A cryosphere is formed in the region of interaction between the atmosphere, hydrosphere and lithosphere, and it is characterized by negative or zero temperature. Glaciology itself studies the glaciosphere that is a totality of snow-ice formations on the Earth's surface. Its typical properties are water presence in solid phase, slow mass exchange, high reflectivity, great heat expenditures for the phase transitions, and a specific mechanism that affects the land and the Earth's crust. The glaciosphere mainly determines the contemporary latitudinal zonality, enhances an inter-latitude air mass exchange, and influences the World ocean level. Existence of perennial snow patches and glaciers is possible within the limits of the chionosphere. A level of the Earth's surface above which accumulation of the atmosphere precipitation dominates over its melting and evaporation forms a snow line. The main elements of the glacio-nival belt (or a zone) are snow patches and glaciers. Glaciers are

ice masses mainly of atmosphere origin which undergo viscous-plastic flow due to the action of gravity and take the form of a flow, a dome (a sheet) or a floating plate. Land glaciers which overlie a stone bed, located above the ocean level, and also “marine” glaciers, consisting of their internal parts, i.e. “marine” sheets with outlet glaciers, overlying a stone bed, and located significantly below the ocean level, and their peripheral parts, i.e. floating ice shelves are recognized. Glaciers are formed as a result of accumulation and transformation of solid atmosphere precipitation under long-term positive ice balance. They consist of accumulation area and ablation area which are separated by an equilibrium line, i.e. by the line on a glacier where the ice increment during the whole year is equal to its expenditure. A glacier runoff is presented by melting waters from a seasonal snow, firn and ice, together with liquid precipitation, coming into a river from the whole surface of the glacier. It is equal to the difference between the melting (plus liquid precipitation) and secondary water freezing inside a glacier thickness. Glaciers are good natural regulators of the runoff since they transform it into a direction useful for people. Additional water from glaciers can be obtained by means of blackening of their surfaces that increases absorption of the solar energy and thus causes enhanced melting. The idea is proposed to transport icebergs from Antarctica to shores of South America, Australia, the Near East countries for the purpose of obtaining large volumes of fresh water. Climate changes and fluctuations result in permanent variations of the glacier masses and sizes. In the geological past, the most significant glacier fluctuations resulted in alternation of glacier and inter-glacier epochs. The last great degradation of glaciers related to decreasing the Late Pleistocene glaciation took place during the period between 17 and 10 thousand years ago.

1. Introduction

The main storage of fresh water is concentrated in glaciers. More than one tenth of the land is covered with “eternal” ice, and one fifth of the whole surface of our planet is annually coated with snow. Still larger area in Eurasia and America was covered with snow and ice during so called glacier epochs. But, in response to the following climate warming, ice sheets had melted, having made many marks: glacial deposits, hills and lakes, large boulders, formerly brought by glaciers, etc. At present, in the inter-glacial epoch, the snow cover and ice are still widespread. Their future state highly depends on the anthropogenic impact on Nature, and under considerable warming they can completely disappear.

2. Development of Glaciology

The past, present, and future of glaciation are a major focus of interest in glaciology, i.e. science of natural systems whose properties and dynamics are determined by glacial ice. In its historical development, glaciology developed from hydrology and geology, and for a long time it was traditionally considered as a part of hydrology. However, in the middle of the 20th century it became clear that problems and methods for studying of solid and liquid water are quite different. Nowadays, glaciology became an individual branch of knowledge assuming a place at the interfaces between geography, hydrology, geology, and geophysics.

Natural ice attracted a great interest very long time ago. Atmospheric ice, snow avalanches, and glaciers were already mentioned in manuscripts of Aristotle, Pheocrite, Poliby, Strabone, and many other geographers and historians. Glaciers of Iceland and their catastrophic melting under volcanic eruptions were described in Scandinavian sagas of the 13th century. Information about the alpine glaciers is presented in the "Kosmographie" by S. Münster in1544, and a mention of the Caucasus glaciers can be found in the "Life of Georgia" by Bagrationi Vakhushty (1745). The first scientific work on glaciology became a book by O. Saussure "Voyages dans les Alpes" (1779-96) where the ice flow and avalanching were already analyzed.

After his expedition to Peru (1735-43) P. Buger described a boundary of eternal snow. However the climatic concept of this phenomenon was first introduced by Alexander von Humbolt only in 100 years. At the end of the 1750s, M.V. Lomonosov introduced the notion of a "frosty layer of the atmosphere" and made some notes on icing of highlands and polar regions of the Earth.

In the middle of the 19th century, the first glaciological investigations were carried out in the Alps using physical methods. Developments of the first schemes of glacier structure (L. Agassiz, D. Tyndall), and creation of a kinematic theory of permanent glacier flow (H. Reid, S. Finsterwalder), establishing the qualitative regularities of glacier oscillations (F. Forel) are referred to the middle and the second half of the 19th century.

As early as in the middle of the 19th century, the first investigators of the Alps estimated sizes of many glaciers, determined temperature in their thickness, dependence of the glacier forms on topography, had proved reality of the glacier motions, and drawn their first schemes. Such notions as viscosity, plasticity, sliding, fluidity were the basis for the first hypotheses on glacier movement.

Any glacier always corresponds to a local relief as it is a common product of two main factors which are climate and topography. Already O. Saussure acknowledged, in addition to the sliding, also the glacier adaptation to a valley form, i.e. a glacier deformation under certain topographic conditions. But, the concept of the glacier adaptation to the housing relief was absolutely elaborated by Randue, who identified glaciers with a liquid in his hydrodynamic theory.

The close connection of glaciers with a relief, found out in the Alps, promoted creation of a number of morphological classifications of glaciers. The glacier motion became the most important criterion distinguishing them from dead ice and immovable snow (snow patches). In the second half of the 19th century, the alpine school of the glacier investigation was finally established; study of interactions between glaciers and a relief, measurements of their sizes and determination of forms as well as time variations was predominant in this school.

At the end of the 19th century, studies of polar glaciers began, and at the beginning, approach to the glacier phenomena, for example in Greenland, was the same as in mountains. But, soon, E. Drigalsky introduced the notions "continental glacier" and "inland ice sheets". The main result of the polar researches of that time are presented in the monograph by C.S. Wright and R.E. Priestley "Glaciology" where genetic approach to the phenomena was used for the first time, and influence upon regime of those factors as the air temperature, atmospheric precipitation, surface inclination, denudation was analyzed. These authors have created a genetic classification, i.e. a classification with respect to a process of ice formation: congelation, recrystallization, infiltration, etc.

In the period between1930 and1950, great attention was drawn to the climatic and meteorological factors of accumulation and ablation on glaciers that was related to names of Scandinavian scientists H. Ahlmann and H. Sverdrup. Ahlmann had proved the direct relationship of the glacier regime and the climate, and based on that he developed a geophysical classification of glaciers separating notions “polar” and “temperate” glacier. These ideas became the basis for the Scandinavian school of glaciology.

Comprehensive studies of glacier interaction with the environment were started in these years. They included studies on glacier existence conditions at entrance and influence of glaciers on river runoff (conditions at exit). These works established new directions in glaciology, i.e. the glacial hydrology and hydraulics.

The first scientist to look at the ice as a subject for petrographic investigations was Antonine Dobrowolsky. He had created the petrographic classification of ice which included not only types of igneous and sedimentary rocks, but also processes forming the ice objects in the atmosphere, hydrosphere and lithosphere. The next step had been achieved by P.A. Shumsky whose ideas were based on both petrographic and genetic ice rock classifications along with zonality of the ice formation processes. Considering the natural ice forms in the light of the processes forming them, Shumsky distinguished three main groups of the ice rocks, which were congelative, sedimentary and metamorphic, and revealed regularities of their formation. It was proved that not only glaciers as a whole, but also the ice formation zones, changing along altitude, contain important climatic information.

Investigations on glacier mass balance were for the first time widely organized during the International Geophysical Year (1957-58), and then they were further developed during the International Hydrological Decade (1965-74) when a special program for studying the balance of heat, ice and water was carried out at the selected mountain-glacier basins.

Using of physical methods in glaciology, having been started in still the 19th century, is nowadays supplemented and improved by mathematical methods. Dynamic glaciology, initiated by J. Nye has been further developed too. P.A. Shumsky formulated a closed system of equations and additional conditions determining the state and processes in glaciers.

Dynamic glaciology is the science of glaciers as the macroscopic systems. A glacier is considered here as a totality (population) of fields characterized in each point by averaged values of their parameters. A notion of tensor quantities, among those was such ice property as its deformation rate, had been introduced into general glaciology. Having characterized a glacier as a system where fields of density, tension, velocity and temperature are inter-related, dynamic glaciology has introduced into glaciology also a category of field which is now widely used in the science of glaciers.

The objects of modern glaciology are not only glaciers and ice sheets, but also the atmospheric ice, snow cover, ice of water reservoirs and streams, underground ice and aufeises (naleds). Widening of the glaciology scope is motivated by that all main problems of glaciology as well as practical use and transformation of ice on the Earth concern all kinds of natural ice formations, though the main attention is focused on glaciers.

The glaciology family tree is presented in Figure 1. Its main trunks are geology and physics, and derivatives from them are climatology, geomorphology and hydrology. Interlacing of different “branches” form the present complicated structure of the science of natural ices, i.e. combination of its individual branches and basic directions of investigations.

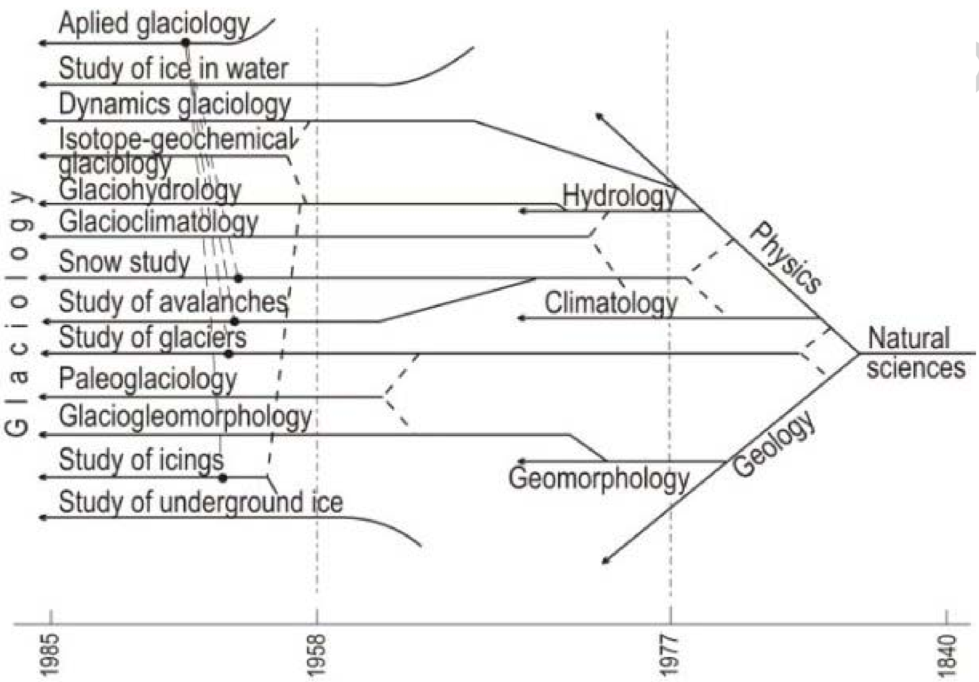

Figure 1. The glaciology tree

Glaciology was developed especially quickly in the 20th century. In parallel with the existing problems each decade brings new tasks, and the methods are introduced to promote formation of new branches and directions of investigations. Owing to the efforts of German and Swiss scientists, in the 1920s, glacio-geodesy appeared. In the 1930s, the field of glacio-meteorology was originated in the Scandinavian countries. In the 1940s, an impetus had been given to the development of glacio-hydrology in some of the European countries. The 1950s became an epoch when structural glaciology was given a rise, the main contribution to which was made by Soviet and American scientists. In the 1960s, the efforts of mainly Soviet and English researchers resulted in the appearance of dynamic glaciology, and the works of American, and then Soviet engineers brought the first successes in the deep drilling of ice. At last, the 1970s were marked by great advances in isotope-geochemical glaciology, and we should note here the pioneering investigations of the Danish and French scientists. The 1980s and the 1990s were the periods of the space glaciology development which brought new possibilities in most of the branches of glaciology.

3. Ice as a Natural Substance

Ice is a mono-mineral rock as it is the solid phase of water and does not contain any other minerals. Ten crystal ice variants and its amorphous variety are known. Figure 2 presents the phase diagram of water, demonstrating under what temperatures and pressures one or another variant is stable.

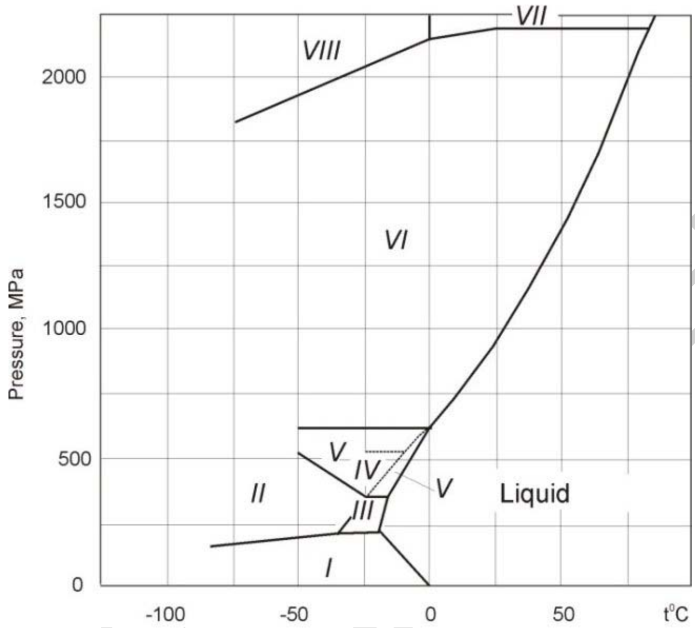

Figure 2. The water phase diagram

Only one variant, i.e. the ice-I, is revealed in the Nature. The variants ice-II, ice-III, and ice-V are kept for a long time under the pressure, if the temperature does not rise above -170°C. Under a heating up to approximately -150°C, they are transformed into the cubic ice-Ic, which is not shown in the diagram since nothing is known about its stability. The other way to obtain ice-Ic is by condensation of water vapor onto a base cooled down to -120°C. Due to vapor condensation on the cold base, amorphous ice is formed. Both these ice forms can spontaneously transform into usual ice-I, and this process is accelerated by rising temperature. Ice-IV is a meta-stable phase in the zone of ice-V instability. Ice-VI is formed more easily, and possibly, it is more stable, if the heavy water is subjected to pressure. The curve of ice-VII melting is studied up to a pressure of 20 hPa, and in this case it melts at a temperature of 400°C. Ice-VIII is a low-temperature ordered form of ice-VII. Ice-IX is a meta-stable phase appearing under super-cooling of ice-III, and it actually represents its low-temperature form.

Usually, the natural ice of the variant ice-I is significantly purer than water since the substances are poorly soluble in the ice. Ice can contain mechanical impurities which are solid particles, droplets of concentrated solutions, and gas bubbles. Under long static loads and under the action of its own mass, ice becomes a fluid. The dependence between the steady-state velocity of its flow and tension of the poly-crystal ice is hyperbolic, i.e. exponent in the equation increases with growth of the tension. The velocity of the ice flow is directly proportional to the energy of activation and inversely proportional to absolute temperature, so that with drop of the temperature ice tends to attain the properties of a perfect black body. On average, at a temperature close to the melting point, the ice fluidity is 10^6 times greater than that of rocks, and this encourages glacier motion and a number of other natural phenomena. Under the influence of a crystal surface energy and that of viscosity-tension relationships of the crystal lattice, arising at a deformation, ice undergoes re-crystallization in its solid phase, and sometimes transfers into the liquid phase (regelation) or vapor sate (sublimation).

Crystals of all the ice variants are built from water molecules united into a three-dimensional skeleton (Figure 3). The nodes of the lattice, formed by blocks of the oxygen atoms, are placed at the corners of tetrahedrons; such that each cell is connected with the other four. The hydrogen atoms (protons) participate in the formation of the connections, and their positions are not fixed, so that the hydrogen link between the molecules is weak, and it is set completely at only a very low temperature.

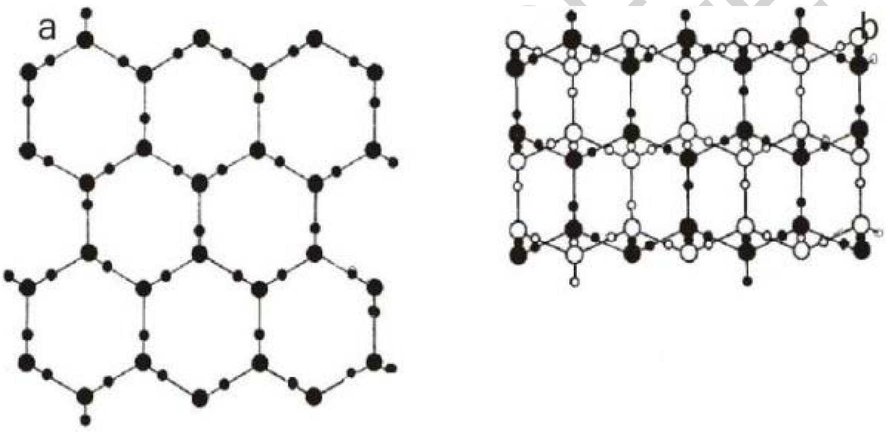

Figure 3. Atomic structure of the ice: a is a view, parallel to hexagonal axes; b is the same, but perpendicular; large circles are the oxygen atoms, small ones are those of hydrogen; long lines are hydrogen links, short ones are co-valent

The physical properties of ice are mostly anisotropic, i.e. they are different under measurements in different crystallographic directions. These differences are related to the features of fine structure of the ice crystals, in the spatial lattice of which the base planes play the main parts, having particularly high density of their molecules, but relatively apart.

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Biographical Sketch

Vladimir Mikhailovich Kotlyakov (born in 1931) is a member of the Russian Academy of Sciences (elected in 1991). He is Director of the Institute of Geography, Russian Academy of Sciences. With particular interest in glaciology and physical geography in polar and mountain regions, he directed the twenty-year project resulting in the World Atlas of Snow and Ice Resources (published in 1997).

V.M. Kotlyakov has participated in many expeditions. He worked and wintered in the Arctic, the Antarctic, and at the slope of the highest summit in Europe, the Elbrus, and he headed the high mountain glaciological expeditions to the Pamirs.

The main theoretical results of V.M. Kotlyakov`s works consist in elucidation of laws of snow and ice accumulation of the Antarctic ice sheet as well as ice sheets in general (1961), the snow cover of the Earth and its fluctuations within time and space (1968), the tasks and abilities of space glaciology (1973), the application of isotope and geochemical methods to the study of the environment and its evolution (1982), the study of the past for four glacial-interglacial cycles (1985 and further on). During the last years, V.M. Kotlyakov dealt with the global changes of the environment, geographical aspects of global and regional ecological problems, the problems of interaction between nature and society.

V.M. Kotlyakov is the honorary president of the Russian Geographical Society and President of the Glaciological Association. In 1987-91, V.M. Kotlyakov was elected the President of the International Commission of Snow and Ice, and in 1987–93, he was the member of the Special, and later Scientific, ICSU Committee of the International Geosphere-Biosphere Program, in 1988–96, the vice-president of the International Geographical Union. Now he is a member of the Earth Council.

V.M. Kotlyakov is elected a member of the Academia Europaea and the Academies of Sciences of France and Georgia, a honorary member of the American, Mexican, Italian, Georgian, and Estonian Geographical Societies.