GENESIS AND GEOGRAPHICAL ASPECTS OF GLACIERS

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Summary

There exist ten crystal variants of ice and one amorphous form in Nature, however only one form ice-1 is distributed on the Earth. Ten other ice variants steadily exist only under a certain combinations of pressure, specific volume and temperature of medium, and those are not typical for our planet. The ice density is less than that of water by 9%, and owing to this water reservoirs are never totally frozen., Thus life is sustained in them during the winter time. As a rule, ice is much cleaner than water, and specific gas-ice compounds called as crystalline hydrates are found in ice. Among the different spheres surrounding our globe there are cryosphere (sphere of the cold), glaciosphere (sphere of snow and ice) and chionosphere (that part of the troposphere where the annual amount of solid precipitation exceeds their losses). The chionosphere envelopes the Earth with a shell 3 to 5 km in thickness. In the present epoch, snow and ice cover 14.2% of the planet's surface and more than half of the land surface. About 99% of the whole ice mass is concentrated in glaciers and their mass is are 32 times as large as the mass of surface waters of the land. A glacier is a mass of ice of predominantly atmospheric origin, which undergoes viscous-plastic flow under the action of gravity and takes the form of a stream, system of streams, dome, or a floating plate. A regime of snow-ice formations is characterized by five boundary levels which are snow and firn lines, equilibrium line, boundary of snow patches, and a seasonal snow line. The following glacier formations are recognized : ice sheets, i.e. a complex of ice domes, outlet and ice shelves; reticular glaciers, i.e. a combination of local glaciers, ice domes with large valley and piedmont glaciers; mountain glacierization, i.e. a combination of different glacier types in mountains, first and foremost of valley and corrie glaciers. Glaciers are indicators of regions with maximal water resources for a given territory. Since the 1960s, glacier inventories are made up and published in many countries, they contain main

characteristics of the glaciers: sizes, forms, positions and regimes. Now, glaciers occupy on the Earth an area of 16.25 million km^2 that is only 1.5-2 times as small as the glaciation area in the Late Pleistocene.

1. Introduction

Ice is the most widespread form of matter in the Universe. Planets Mars, Jupiter, Saturn, Uranus contain enormous masses of ice. Some satellites of the planets, like, Jupiter's satellite Europa, are almost completely formed by ice. Our planet Earth is not an exeption; more than one tenth of the land is taken up by "eternal" ices, and every year, $1/5^{th}$ of it is covered with snow.

The geological history of the Earth evidenced that, despite the climate continuous variations and progressive development of the biosphere, the mean temperature near the Earth's surface changed in the limits of only 5 and 40 °C. It is much less than recent temperature range in different regions of the globe, i.e. from 40°C and even 50°C heat in tropical deserts to -70°C frosts in North-East of the Euroasia and -80°C in the Antarctica. Similar conditions are essential for the existence of ice which is perennial in polar regions and seasonal over great expanses in middle latitudes. Regular temperature transfer through 0 °C or closeness of the temperature conditions to this critical point over many territories cause great variability of the snow-ice conditions on the Earth and a variety of the ice forms which are observed in Nature.

2. Properties of Natural Ice

From time immemorial, ice interested people, but serious scientific investigations of ice were started only in the second half of the 19th century. Studying ice turned out to be very difficult. When the same parameters were measured under laboratory conditions, the results differed by tens and sometimes hundreds of times. Field observations were also inconsistent. The ice properties surprisingly depended on many conditions, and first and foremost, on external pressure and temperature.

Modification	Crystal system	Quantity Number of the oxygen atoms in a cell	Temperature, °C	Pressure, *MPa*	Density, *kg m*$^{-3}$	Dielectric constant (static)
I	Hexagonal	4	0	0,.1	931	94
Ic	Cubic	8	–130	0,.1	930	–
II	Rhombohedronic	12	–35	210	1180	37
III	Tetragonal	12	–22	200	1160	117
V	Monoclinic	28	–5	530	1230	144
VI	Orthorhombic, tetragonal	10	15	800	1310	193
VII	Cubic	2	25	2500	1490	~ 150
VIII	Tetragonal	8	–50	2500	1490	~ 3
IX	Tetragonal	12	–110	230	1160	~ 4

Table 1. Structures and properties of the ice variants

As instrumentation improved, and conditions of the ice experiments became more sophisticated, scientists could create ice which was not similar to that in Nature. At the beginning of the 20th century, the German scientist G. Tamman discovered, and American physicist P. Bridgeman investigated the phenomenon of polymorphism of ice, i.e. its capability to have different crystal structure that results in significant change of all the physical properties of ice. It turned out that 10 crystalline variants of ice and one amorphous form can exist in Nature, and what is found on the Earth’s surface is only one of the variants which is called by physicists as ice-1.

Ten other ice variants exist stably only under certain combinations of pressure, specific volume and temperature (see Table 1), which are graphically shown on the diagram (Figure 1). The ice variants II, III and V may for a long time remain at the atmosphere pressure, if the air temperature does not rise above -170 °C. When water vapor condenses on a surface cooled down to -160 °C and below, an amorphous ice is formed which transforms itself into an ordinary one at temperature rising up to -129 °C, and, in this case, the latent heat is released.

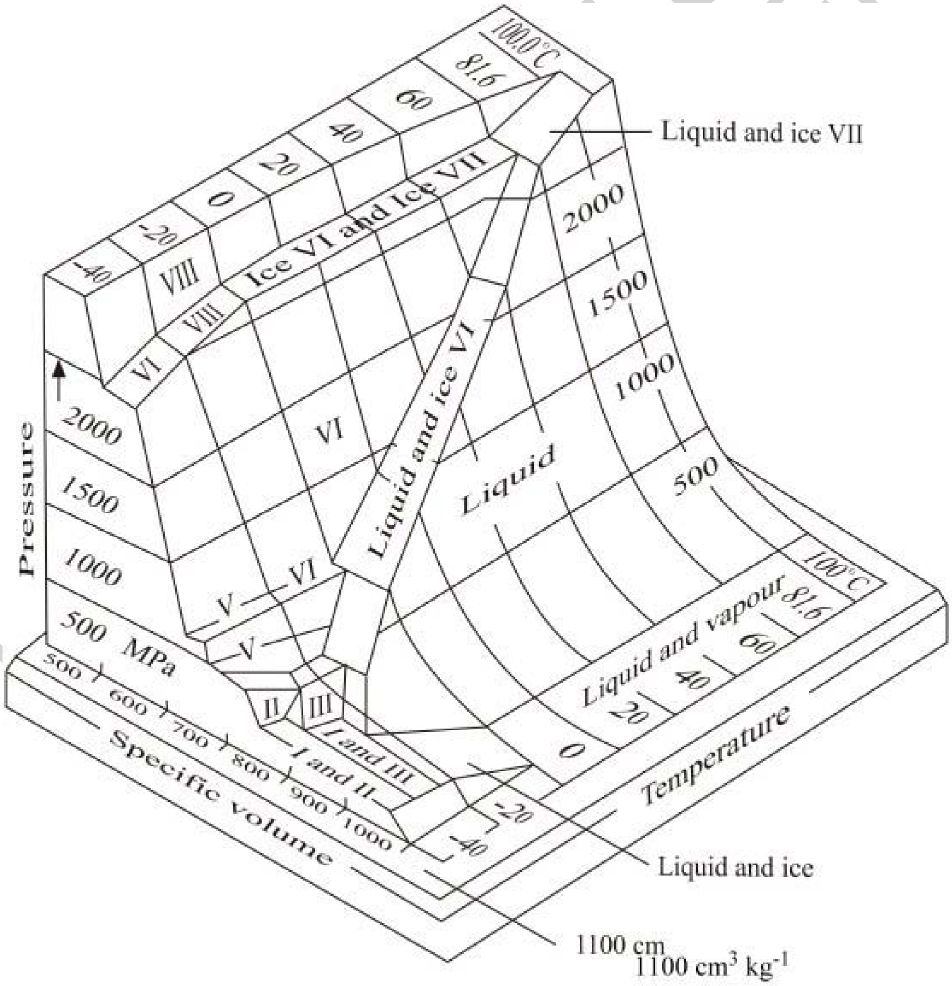

Figure 1. Surface “pressure - specific volume - temperature” for different ice variants and water

Ice-IV is an unstable phase in the zone where ice-V stably exists. It is slightly easier to obtain ice-VI which turns out to be stable if heavy water is frozen under pressure. Under a great pressure of 20 GPa ice-VII melts. Ice-VIII is actually an ordered form of ice-VII appearing under a low temperature. Finally, ice-IX is an unstable phase appearing when ice-III is super-cooled. So, ice may exist within a wide range of the temperatures and pressures which never occur on the Earth's surface.

Polymorphism typical to ice is difficult to be found in Nature. Meanwhile, some ice varieties differ in their properties from ordinary ice as much as different rocks may be distinguished. Under conditions of deep vacuum and very low temperatures, ice which was 2-2.5 times as compact as all other varieties had been obtained. It has no crystal lattice, and it is an amorphous form of ice unique to a certain extent and its properties are still unknown.

What is the great mystery of Nature when under decreased the temperature liquid water or water vapor suddenly transform into a solid crystal substance? The water molecule is known to consist of one oxygen and two hydrogen atoms. The oxygen atom occupies in this molecule a strictly fixed position, while the hydrogen atoms probably move between the oxygen atoms. When water is freezing, the irregular arrangement of its molecules is changed into a regular structure. Crystallization of water is a complex physical process which starts not inside its whole mass, but only in places where conditions are already "ready" for the emergence of a crystal. First, small groups of the water molecules with their thickness equal to an elementary cell of the crystal lattice transform into the solid state. As the temperature decreases, the critical size of the ice nuclei providing its further growth increases too. Thus, water crystallization becomes more probable and runs quicker.

The most surprising thing distinguishing ice among other solid bodies is the decrease of its density by 9% relative to liquid water density. While pieces of a solid substance usually sink in their melt, as freezing take place, but ice does not sink in the water. This property often causes breakdowns in heat-engineering and water-supplying systems, but it is benevolence of Nature as it does not allow water bodies to be frozen through, and, thus, saves life inside them during the cold seasons.

As a rule, to initiate ice crystal formation in water alien particles are needed to induce formation of the crystal nucleus, and thereby accelerate crystallization. If water or air does not contain crystals or the crystal nucleus, then liquid water may for a long time be in a super-cooled state. Experimentally, in the absence of any crystal nucleus, we can cool water down to -50 °C, and sometimes still lower. In Nature, at a reservoir surface water can be super-cooled down only to -1 °C. In clouds, the temperature can drop down to -12 °C, sometimes to -30 °C and a bit lower, but there is still no ice. However, when crystal nucleus appears under such conditions, rapid ice formation starts immediately.

As a rule, ordinary ice (ice-I) is much cleaner than water, because solubility of many substances in ice very poor. The density of clean ice is 916.7 kg m^{-3} at 0 °C and atmospheric pressure. However, under a greater pressure, ice can be compressed, and such conditions persist on the Earth. For example, in the Antarctic ice sheet whose thickness in some places exceeds 4000 m, and where temperature changes from -60 °C at the surface to -3 °C at the glacier bed, in its deep layers the ice density reaches 921 kg m^{-3}. In theory, under low temperatures it can be still greater, but ice always contains trapped air bubbles, so its real density changes from 815-820 to 905-914 kg/m^3.

Water as a rule is present in ice. It is formed when ice melts as a result of a heat income, as pressure increases, and as salt content increases resulting in temperature decrease by which ice transforms into liquid state. Water exists in the form of thin films between the ice crystals. As the heat income and the consequent ice melting increase, water horizons and lenses appear in the ice.

Experiments had shown that, as a consequence of melting under the Sun's rays penetrating the ice, the water thin film blankets air bubbles inside the ice crystals. The so-called "water bags" appear then, and from them the water can enter into the inter-crystal space. Therefore, dense apparently water prrof glacier ice, turns out, in fact, to be penetrable to water.

Even when the temperature is considerably lower than the freezing point of water, a fluidic layer with a width of 10^{-5} -10^{-6} cm, which corresponds to 35-340 water molecules, exists at the ice crystal surfaces. This thin layer of liquid at the crystal surfaces has a pronounced effect on the metamorphism of snow, and, obviously, explains the phenomenon of regelation inherent to ice.

Regelation is refreezing of water into ice due to recrystallization which takes place at the contact points between ice crystals when the pressure increase induces a process of fusion. The phenomenon of regelation was discovered in 1850 by M. Faraday. He made an experiment pressing two ice pieces with wetted surfaces against each other and obtained their fast congelation. D. Tyndal gave a term to this phenomenon: he had sawed by tightened metal wire through a piece of ice, but the latter remained unbroken. Obviously, behind the wire ice was freezing owing to a heat loss expended for the melting in front of the wire. Regelation is sometimes bad for house-keeping and economy, but it is widely used when one needs to freeze metal and other surfaces to ice.

It has been clarified recently, that some gas-ice combinations, termed as crystalline hydrates, occur in ice. These are substances in which the water crystal lattice contains cavities, capable of adopting alien molecules. If there is a great quantity of water molecules, then the whole gas may transfer into the hydrate form, and, in this case, molecules of methane, propane and other hydrocarbons appear to be between the water molecules. No chemical bond between water and gases exists, and, under the normal conditions, they are able to burn. Deposits of crystalline hydrates are found in Siberia which is occupied by permafrost rocks. Such ice, being deposited not very deeply, is a promising fuel for future. Volume of 1 m^3 of such ice contains up to 200 m^3 of natural gas.

It may be supposed that, at great depths in glaciers, air exists inside the ice not as bubbles, but in the form of similar hydrate combinations. At least, inside the ice core from deep Antarctic holes the air bubbles ceased to appear in the ice at depths of 940-1100 m. Clearly, the air dissolved in the ice exists there in the form of crystalline hydrates.

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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 resulted in the World Atlas of Snow and Ice Resources (published in 1997). He participated in many expeditions. He worked and wintered in the Arctic, the Antarctica, at the slope of the highest summit of Europe, the Elbrus, headed the high mountain glaciological expeditions to the Pamirs. The main theoretical results of his 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 snowiness of the Earth and its fluctuations within time and space (1968), the tasks and abilities of the 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, he dealt with the global changes of the environment, geographical aspects of global and regional ecological problems, the problems of interaction between the Nature and society. He is the vice-president of the Russian Geographical Society and the President of the Glaciological Association. In 1983–87, was elected the President of the International Commission of Snow and Ice, in 1987–93, he was the member of the Special, and later Scientific, ICSU Committee of the International Geosphere-Biosphere Programme, in 1988–96, the vice-president of the International Geographical Union. Now he is a member of the Earth Council. He is elected a member of the Academia Europaea and the Academy of Sciences of Georgia, a honorary member of the American, Mexican, Italian, Georgian, and Estonian Geographical Societies.