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Discussions

Cryosphere: a kingdom of anomalies and diversity

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Abstract. The cryosphere of the Earth overlaps with the atmosphere, hydrosphere and lithosphere over vast areas with temperatures below zero C and pronounced H_2O phase changes. In spite of its strong variability in space and time, the cryosphere plays the role of a global thermostat keeping the thermal regime on the Earth within rather narrow limits affording continuation of the conditions needed for the maintenance of life. Objects and processes related to cryosphere are very diverse due to the following basic reasons: anomalous thermodynamic and electromagnetic properties of H_2O, intermediate intensity of hydrogen bonds, and very wide spread of cryogenic systems all over the Earth. These features yet attract insufficient attention of research communities. Cryology is usually understood as a descriptive discipline within physical geography basically limited to glaciology and permafrost research. We emphasize its broad interdisciplinary landscape involving physical, chemical and biological phenomena related to the H_2O phase transitions and various forms of ice. This paper aims to attract

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attention of readers to crucial importance of cryogenic anomalies which make the Earth atmosphere and the entire Earth system very specific, if not unique, objects in the universe.

1. Introduction

Nowadays the Earth system is facing the so-called "Grand Challenges". The rapidly growing population needs fresh air and water, more food and more energy. Herewith, the humankind suffers from the climate change, deterioration of the air, water and soils, deforestation, acidification of ocean waters and the biodiversity losses. The Grand Challenges are threatening the security of the upcoming societies. As stated in the Earth System Manifesto, the humankind has only a 40-year window to avoid the Earth system collapse (https://www.atm.helsinki.fi/peex/images/manifesti_peex_ru_hub2.pdf).

Especially strong environmental changes are observed and, moreover, are expected to go on during the next decades in the North Eurasia and Arctic Ocean (IPCC, 2014). The rate of the changes in the Arctic Region is higher than elsewhere in the world (Smith et al., 2015; IPCC, 2013). Furthermore, the threats from climate change and deterioration of the environment are redoubled by the restricted natural resources, unrestrained migration tendencies, and uncertainties in political and socio-economic developments (Smith, 2010).

The totality of environmental problems in their relation to human activities in North Eurasia (the area extended north of 45° N, including the Arctic Ocean and between the Atlantic and Pacific Oceans in latitude) is addressed in the recently launched international program "Pan-Eurasian Experiment" (PEEX) aimed at responding to the Grand Challenges faced by the European countries, Russia and China (Lappalainen et al., 2014; Kulmala et al., 2015). The PEEX Science Plan (Lappalainen et al., 2016) focuses on the Polar and Arctic regions and, specifically, on the cryosphere in the context of modern challenges of the North-Eurasian environment.

Historically, the cryosphere research has been developing in frames of physical geography, with the major focus on glaciology and permafrost research. The present paper attracts attention of the broad geoscience community of physicists, chemists, biologists and, prospectively, astrophysicists to topical problems related to ice, snow and cold in a wider interdisciplinary context, beyond the present conventional understanding (see above).

2. Cryosphere and cryogenic anomalies

Cold regions and natural phenomena related to cold are often described with terms enclosing the prefix *cryo* that means *cold*. The totality of phenomena on the Earth related to or linked with snow, ice or ice-like products (such as gas hydrates) comprises the Earth's cryosphere – a complex synergic system with self-organized constituents which maintains the heat and mass exchange with the environment and spreads over the atmosphere, the hydrosphere, the lithosphere and the biosphere (Melnikov and Gennadinik, 2011).

The large extent of cryogenic objects, their variability in space and time, as well as the discontinuity of the cryosphere, have inspired development of special management technologies. Such technologies, taking into account the stabilizing and bio-protective effects of ice, rooted in specific properties of ice, have become applicable to the areas outside the high-latitude and low temperature regions (Melnikov et al., 2010).

Recent investigations of the cryosphere have yielded discovery and scientific description of a number of unique natural objects and phenomena called "cryogenic anomalies". Below we consider examples of recently investigated cryogenic anomalies, tentatively divided into six groups: ice structure, glaciation, ocean, atmospheric ice and water, biota and cold, and rates of processes.

3. Ice structure

Being a compositionally simple material, ice possesses diverse anomalous properties. It can exist in seventeen phase states, out of which eleven states are clearly expressed. This diversity shows up in physicochemical and biological processes, and in the types of precipitation: one type for rain, eight types for snow, and two mixed water-ice types (Eisenberg and Kauzman, 1975). There are paradoxically different properties brought together in ice: it is at the same time elastic and plastic, crystalline and amorphous, semiconducting and dielectric, lighter than water but harder than steel (Maeno, 1988). With its crystals built uniquely by hydrogen bonds, ice provides a standard for estimating these bonds. The complexity of the ice structure and its non-equilibrium phase transitions are sufficient for self-organizing synergetic behavior and formation of stable macroscopic objects, like the classical snowflakes or drop clusters in atmospheric clouds (Shavlov et al., 2011).

4. Glaciation

Glaciation is the most impressive cryogenic phenomenon on the Earth. Currently ice covers more than 10% of the Earth's surface, but the area of glaciation was much larger in some periods of the Earth's history. Traces of early Proterozoic glaciations (Huron, about 2300 myr ago) are found on all modern continents, which is evidence of global glaciation, even taking into account the drift of continents. About 300 myr ago a large part of Gondwana was covered by ice (The Winters, 1979).

The exact cause of glaciations remains debatable but their cyclic nature is beyond doubt. The complex pattern of glacial cycles cannot be explained uniquely by orbital forcing of eccentricity, obliquity, and precession that change in Milakovitch cycles (Milanković, M., 1939), but correlates also with global geological events.

Glaciation obviously reduces the area of rocks exposed to wind erosion and causes progressive CO2 increase by more active respiration of bacteria, which recycle dead organics at less active photosynthesis. This, in turn, enhances the greenhouse effect of the atmosphere and thus increases the temperature. Due to this negative feedback, oscillations in the cryosphere correlate with phases of global greenhouse-gas and temperature cycles. There is also a positive feedback that controls ice waxing and waning (Le Hir et al., 2008). In particular, the increasing albedo may have been responsible for the strongest glaciation about 800 myr ago, the so called Snowball Earth (Kirschvink et al., 1997). The observed recent shrinking of areas covered by glaciers is often attributed to anthropogenic impacts which became a real geological force in the 20th century (Vernadsky V.I., 1965). The true extent of this effect will be clear in the near future.

The very existence of ice sheets changes the composition and physical properties of the lithosphere, the hydrosphere, and the atmosphere. Moving ice transports great amounts of material and, at the same time, preserves the entrained objects. During glaciations, crust becomes denser; volcanism increases; ice sheets extended to the troposphere change the atmospheric composition and circulation; sea level falls and climate changes. After the ice retreat the formerly frozen territories experience isostaic rebound and terrain smoothing, changes in landscapes, such as formation of rivers and lakes, and changes in biota, such as species composition.

5. Permafrost

Formation of permafrost is the principal consequence of glaciation. Remnants of permafrost that formed during the last glacial event currently cover large territories. The stability of permafrost is one of the greatest challenges, first of all for Russia, where it occupies 65% of the territory, but also for the global climate-biosphere system, because of strong links between the permafrost and boreal forests, tundra, peatlands, rivers and other water reservoirs. Objects and phenomena associated with permafrost to a large extent determine the sustainability of the Siberian climate-biosphere system (taiga) and the conditions of land use and life of the population. The ice barriers dramatically change natural flows of water and material in mid latitudes, change hydrological regimes and create traps for gases. The methane traps cause jet degassing of hydrocarbons (Melnikov et al., 1997) which, in turn, can lead to cooling of rocks, formation of gas hydrates, accumulation of large amounts of methane, and to the methane explosions. The latter cause significant changes in both underwater and land topography (see Figure 2).

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On the land, such explosions may produce giant craters which subsequently transform into lakes (see Figure 3). Tracking such processes over large areas in real time with proper resolution in space, as well as the early warning of expected gas explosions, are important tasks envisaged in the PEEX Science Plan (Lappalainen et al., 2016). Permafrost leaves imprints in the gravity field, as in the case of the Hudson Bay, where the gravity field is lower than elsewhere at this latitude (Tamisiea et al., 2007), possibly, as a consequence of the North American glaciation. About 75,000 years ago the ice (3.7 km thick in the Hudson Bay area) covered most of the present northern US and Canada, which has left a large depression. On the contrary, the gravity field over the 1 km thick permafrost (such as in East Siberia) can reach 50 mGal. On the geological time scale, this field can influence the homeostasis of living organisms and their speciation.

6. Ocean

Oceanic ice is a major control of the global climate as it screens heat and mass transfer in both vertical (across the air-water interface) and horizontal directions. Warm currents, such as that of North Atlantic, move mainly along the ocean surface due to thermal expansion of warm water. Glaciers on the way of warm currents can melt rapidly because the ice not necessarily should reach the seafloor to stop them but can be only commensurate with the surface water layer.

Another great challenge addressed in the PEEX Science Plan is the ongoing change in the Arctic Ocean ice cover, showing increasingly larger and longer-exposed ice-free areas (Hayes et al., 2014; Schaefer et al., 2014; Döscher et al., 2014). This tendency is favorable for exploring and transportation of the Northern Siberian oil and gas comprising about 25% of their total world resources (Yenikeyeff and Krysiek, 2007).

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7. Atmospheric ice and water

Ice has very high heat capacity, specific heat of melting, and dielectric constant. The phase transition forms shields of different types and scales from the gas hydrates stored in permafrost to the ice sheets that cover the entire Antarctic continent and affect the global climate and evolution of life. In the global Earth system, the cryosphere acts as the temperature stabilizer due to exceptional thermal inertia of ice and water occupying a great part of the Earth's surface.

The Earth's atmosphere contains a large amount of water in the form of vapor, liquid and ice which influences the planetary heat budget. Moreover, the atmosphere acts as a "thermal shield" aggregating the water molecules into ice particles and thus holding back on the Earth the water, vital for the maintenance of life. The phase transitions of atmospheric ice produce diverse sudden effects and various precipitation types: rain, ice, drizzle, moist snow, snow, sleet, or hail. In the dry troposphere, the air cools down adiabatically at 0.98° C per 100 m. Hence, condensation of originally nearly saturated water vapor starts already at a few hundred meters above the surface. Along with sublimation, this leads to the heat release, which affects temperature profiles and other properties of the atmosphere. Generally, condensation of pure water vapor starts at 400 - 00% supersaturation (e.g. Pruppacher and Klett, 1997). However, condensation in the real atmosphere starts shortly after relative humidity exceeds 100% due to the presence of solid or liquid aerosol particles acting as condensation nuclei, or even below 100% in some cases (Kulmala et al., 1997). Similarly, ice nucleation is initiated upon nuclei like dust particles, biological particles etc., including anthropogenic aerosol particles (e.g. Hoose and Möhler, 2010, Atkinson et al. 2013). Thus, the air pollution facilitates formation of ice crystals and cloud droplets, and therefore affects the air temperature and precipitation processes and its spatiotemporal variability (Rosenfeld et al. 2014). The aerosol-cloud-climate interactions (see e.g. Kulmala et al., 2011), as well as air pollution-weather-climate interactions (Ding et al. 2016, Petäjä et al., 2016) have been and are under rigorous investigations.

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8. Biota and cold

A number of facts in the evolution biology would be unexplainable without cryosphere. Contrary to the common thinking, the existence of life is consistent with negative temperatures. For example, photosynthesis is quite possible at temperatures below 0oC (Kramer P.J., Kozlowski T.T., 1960). For billions of years, the cryosphere assured the stability of environment required for development of life. The mean annual air temperatures on the Earth were naturally maintained near the ice-water transition point. Ice, like water, possesses exceptional thermostatic properties, and is thus a very strong stabilizer of the temperature regime, along with wide spread of ice over the Earth's surface. The heat capacity of water (4.183 kJ/kg·K) is five times the mean heat capacity of soil, and its volumetric heat capacity is 3300 times that of air. The high heat capacity of ice (2.06 kJ/kg·K) is comparable with that of water, which makes the ice-snow-water system the Earth's largest storage of solar energy. The very phase change point has additional (likewise abnormal) thermal stability: the specific heat of ice melting is five times as high as in gold (332 against 66.2 kJ/kg) and is higher than, say, in mercury by a factor 28 (Melnikov and Gennadinik, 2011).

Permafrost contains organic matter in the form of biogenic gases, products of biodegradation, or as ancient viable bacteria. In Russia, the evidence of bacteria in permafrost was obtained in the latest 19th century, together with finding of mammoths in Northern Siberia and during studies of soils in the Russian Far East. Novel information about bacterial communities has been obtained from studies of Antarctic permafrost. Cyanobacteria, with their age about 500 kyr, were discovered in the station "Vostok" ice cores at 3600 m depth (Water sampling, 2003).

Many microorganisms are stable against freezing and not only survive but even grow at negative temperatures. More than 10% of water in organic tissues remains unfrozen at temperatures below -20°C. Many basic processes in microbial, soil, geophysical, and cosmological systems are associated with cooling and ice-water phase changes. Ribosome activity is often more successful at low temperatures, which may be the evidence that life could have originated in cold conditions (Vlassov et al., 2005).

Life processes can remain active at below 0 ° C in capillaries and on ice surface in permafrost. Micro-organisms can exist in media with low dimensionality (2 or less), such as liquid films and capillaries filled with super-cooled water. The porous structure of the environment ensures the transport of nutrients and life wastes (Möhlmann, D.T.F., 2009).

Even comparatively minor heating to 50-60°C leads to denaturation of proteins and can stop operation of a living system, while freezing even to the near-absolute zero temperatures does not change the configuration of biomolecules, so that the life functions can resume after thawing. Enzymes that regulate metabolism in organisms show similar behavior (Dethier and Villee, 2005).

It is still unclear how and why the metazoans originated about a billion years ago. The obviously required sufficient amount of oxygen has been commonly explained by its gradual photosynthetic accumulation in the atmosphere. However, origination of metazoans may have been due to the higher concentration of oxygen in cold water. The origin of the skeletal organisms at the Proterozoic/Phanerozoic boundary was possibly favored by the calcium carbonate release by organisms at the high oxygen availability. The oxygen enrichment in oceans at the Vendian/Cambrian boundary may have resulted from glaciation, water cooling, hence, increasing gas solubility and favorable water circulation patterns. Note that the first giant organisms have appeared precisely during this cooling event. Furthermore, gigantism, associated with specific heat exchange, is known to be typical of polar biota. Biotic and cooling events have been closely related all over the Phanerozoic. The major Jurassic and latest Cretaceous extinctions occurred during the stages of cold climate (The Winters, 1979).

9. Typical rates of processes

Natural objects are characterized by their typical scales in time and space. The common sense suggests that temporal and spatial scales change more or less similarly, which implies that typical change rates are not too variable. However, this rule does not work for the cryosphere, which can be either accelerator or decelerator of various processes (Melnikov et al., 2013). For instance, paleo-bacteria preserved under ice shields remain viable for millions of years. Ice slow down biotic processes due to the following properties:

- low dielectric and magnetic susceptibility, which reduces electromagnetic fields;
- high stiffness, which resists mechanic impacts;
- low permeability, which decelerates mass transport;
- high heat capacity and anomalous specific heat of melting, which damp temperature variations.

Hence, interaction between an object and its environment in cryosphere is basically restricted to weak gravity effects and very slow diffusion. The capability of ice to decelerate biological processes has practical uses: freezing of organs or storage of seeds, not to mention the household refrigerators. Similar mechanisms protect the biota of Antarctic paleo-lakes, such as Lake Vostok, hidden under kilometers-thick ice maintaining its sustainable thermal regime (Thoma et al., 2008).

On the contrary, processes on the surface of ice or ice-bearing systems are often faster than usual due to formation of electrolytes, chemical reactions, and accelerated transport. “Ice fingers of death” is an example of a very rapid process with extremely high gradients of physical parameters in the vicinity of cryogenic objects. This phenomenon (also known as brinicles, brine icicles or ice stalactites) develops in shallow water beneath the sea ice, mainly in the southern high latitudes, in the form of slowly rotating jets of extremely cold and saline (and therefore heavy) surface water sinking down to the ocean bottom (Martin, 1974). The point is that the formation of sea ice at very low air temperatures is associated with the decomposition of calcium bicarbonate into CO2 and CaCO3. Then CO2 releases into the air, whereas slowly rotating jets of the cold dense surface water sinks down to the seafloor and propagates downslope leaving frozen footprints with entrapped bottom-dwelling sea animals.

Cryogenic phenomena developing at various rates are presented in the log-log space/time coordinates in Fig. 4 showing extremely wide range of scales. Some objects, such as paleo-bacteria survived in ice over half a million years or "ice fingers of death", fall beyond the scope of any particular science. To emphasize their multidisciplinary nature, these objects are marked by two colors indicating the relevant pairs of disciplines.

10. Cryodiversity and its role in the Earth system

The Earth's cryosphere spreads from the oceanic depths reaching ~5 km to the boundary between the atmosphere and outer space (called Karman line) at ~100 kilometers above the sea level. The cryospheres of the Earth and other planets with their satellites actually comprise the cryosphere of the Sun System with its radius ~100 au, where the density of solar wind (radiated plasma) is high. Thus, the terrestrial cryosphere is an object among a diversity of planets and other large objects in the Solar System, which differ in their distances to the Sun; rotation rates and orbiting paths with the respective diurnal and annual cycles; chemical compositions; and presence or absence of the atmospheres. Some planets of the Solar System and their satellites store great amounts of ice, much more than the Earth (Fig. 5), both in absolute values and relative to the mass of the respective celestial bodies. Recent extraterrestrial missions have demonstrated impressive cryogenic processes and phenomena on various planets and satellites (Komarov and Isaev, 2010).

11. Cryogenic objects in the Solar system

Historically, the Earth's cryosphere was investigated in the scope of exploration of the high-latitude or mountain regions characterized by cold climate, large stocks of ice and snow, and strong thermal effects of the H_2O phase transitions. Those investigations were basically performed in the conceptual framework of geographical disciplines, such as glaciology or permafrost science. The first priority belonged to description, quantification and inventory of phenomena, with comparatively little attention to concrete features of the background physical, chemical and biological processes. Such approach, although motivated by immediate practical purposes, limits our knowledge of the cryosphere basically to its present state and geological past.

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In view of the ongoing climate change and massive anthropogenic deterioration of the environment, it becomes critical to be able to predict the near future of the Earth's cryosphere in its capacity as the major stabilizer of the Earth climate and environment. To this end, a leap is needed from the currently dominating descriptive approach to the process-based approach unifying investigation of the totality of cryogenic phenomena from molecular to planetary scales (see Figure 4) in an interdisciplinary science, *cryology*, armed with all necessary methods of geosciences, physics, chemistry and biology.

12. Concluding remarks

Ice has very high heat capacity, specific heat of melting, and dielectric constant. The phase transition forms shields of different types and scales from the gas hydrates stored in permafrost to the ice sheets that cover the entire Antarctic continent and affect the global climate and evolution of life. In the global Earth system, the cryosphere acts as the temperature stabilizer due to exceptional thermal inertia of ice and water occupying a great part of the Earth's surface.

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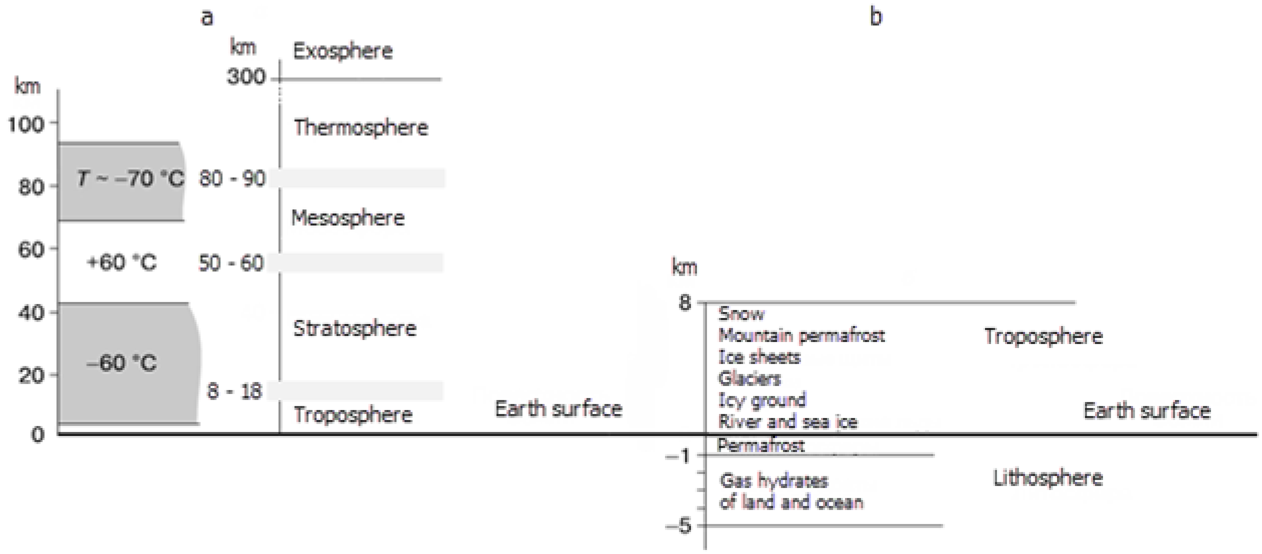

Figure 1: The Earth's cryosphere: from (a) the uppermost atmosphere, to (b) 5 km below Earth's surface, where ice exists as hydrates at positive temperatures.

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Figure 2: Photo of a lake on the Yamal Peninsula showing numerous craters from gas explosions on the lake bottom (Bogoyavlensky, 2015).

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434 Figure 3: New crater produced by gas explosion on the Yamal Peninsula in 2014 (Leybman et al., 2015;
435 photograph by Vladimir Pushkarev borrowed from "Siberian Times").

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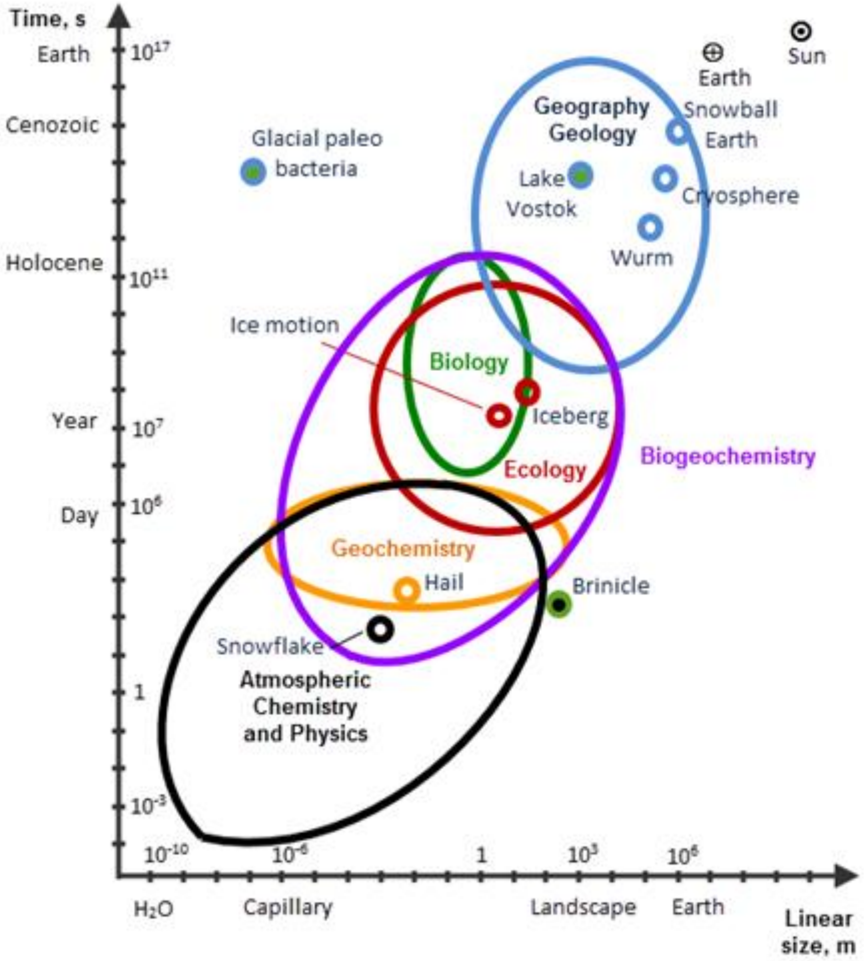

Figure 4: Log-log space-time diagram of cryogenic phenomena of different nature. Large ellipses or circles with different colors identify various sciences. Small circles show various objects of the cryosphere. The Earth and the Sun are shown to illustrate the range of scales.