

Cryodiversity: the World of Cold on the Earth and in the Solar System

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Effects and objects associated with the cryosphere, the world of cold, are extremely diverse due to anomalous thermodynamic and electromagnetic properties of ice, intermediate strength of hydrogen bonds, broad occurrence of cryogenic systems, and combinations of these causes.

Unlike many other processes, those in the cryosphere have variable rates. They can speed up or slow down under the effect of physicochemical properties of ice. Cryospheric time is a missing link between geological and biological time scales: humans feel the planetary dynamics via dynamics of the cryosphere.

The world of cold has been an important agent in evolution, as it created conditions for the life origin and existence and has controlled the rates and mechanisms of biological processes.

Modern technologies for data acquisition and sharing change both the form and methods of research. Discovering and exploring fast processes becomes possible due to advanced videorecording tools while progressively increasing remote sensing potentialities allow high-resolution imaging of objects in the Solar System. Real-time big data acquired by modern measurement systems bridge the gap between the conventional approaches to modeling of elementary processes and assessment of environment parameters.

Keywords: cryodiversity, cryosphere, rates of processes, hydrogen bond, evolution factor, geophysical monitoring, big data.

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Introduction

Evidence of objects and effects associated with the cold and H₂O phase transitions makes a large part of the current data boom. Cryospheric effects are diverse and often unusual. Occurring at the biotic-abiotic borderline, they are easily observable and vital for human practices as they draw forth the resources and factors that maintain sustainable existence of the humanity, but remain overlooked. We suggest the term cryodiversity for the assemblage of processes and objects related to the cryosphere and H₂O phase change [Melnikov et al., 2013]. By this paper, we want to draw attention of the scientific community to the importance of the world of cold and cryodiversity in terms of data and methods.

Features of ice

It is reasonable to begin our discussion with causes of cryodiversity. What unites all diverse cryospheric effects? A simplistic answer would be that ice is a specific material and a key element in the world of cold on the Earth (the cryosphere). The diversity of its effects is due to three basic features crucial for the cryosphere as a whole: anomalous thermodynamic and electromagnetic properties of ice, intermediate strength of hydrogen bonds, and broad occurrence of cryogenic systems and conditions.

Anomalous thermodynamic and electromagnetic properties of ice

Ice has abnormal heat capacity, specific heat of melting, and dielectric permittivity. The phase transition forms shields of different types and scales from gas hydrates stored in permafrost to ice sheets that cover the entire Antarctic continent and affect the global climate and life evolution.

Intermediate strength of hydrogen bonds

With its crystals built uniquely by hydrogen bonds, ice provides a standard for estimating these bonds. The hydrogen bonds provide both stability and mobility of cryogenic systems being stable but about ten times weaker than the covalent bonds. They are essential in proteins, nucleic acids, and biopolymers [Pauling, 1948]. Their breakup and formation stand behind biological processes and the very life origin. Thus, cryogenic systems have controlled the rates of processes commensurate with those in living organisms for the whole history of life.

Broad occurrence of cryogenic systems

One of most widespread substances, H₂O, exists in three phase states on the Earth's surface and in the upper lithosphere due to thermodynamic conditions formed in the course of the geological history and chemical reactions after the Earth accretion from the protoplanetary disk.

The cryosphere, which is persistent on the global scene of biotic-abiotic interactions controls features of both. As a consequence, the living matter has affinity to the cold and can adapt to cryotic conditions (e.g., cryophilic organisms). On the other hand, the cryosphere has been studied better than the other Earth's spheres, which brings geocryological research to the leading edge of science.

The combination of these features leads to cryodiversity (Fig. 1).

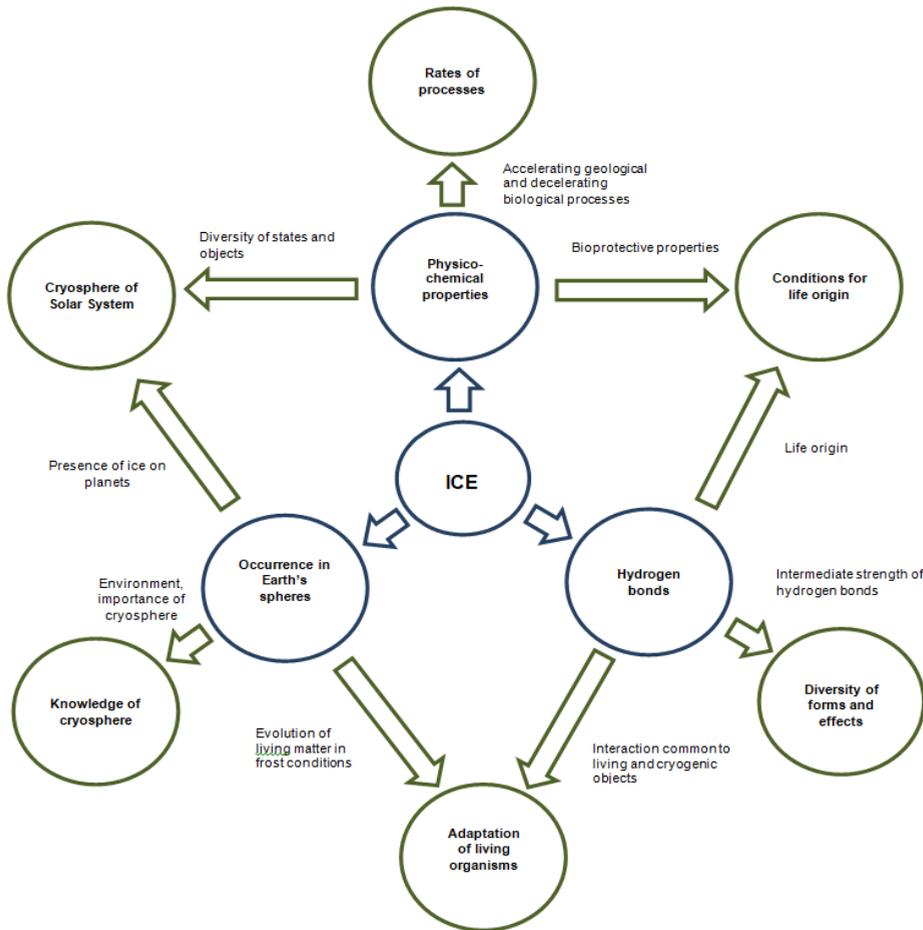


Fig. 1. Features of ice and their manifestation in cryosphere.

Conditions for life origin

The atmosphere acts as a “thermal shield” aggregating water molecules into ice particles and thus holding water back on the Earth. They are water and ice that gave birth to life and have extrapolated their structure of hydrogen bonding onto the first life elements.

The fact that mean annual air temperature on the Earth long remained within the ice-water phase transition appears quite natural. Both ice and water are widespread on the Earth and have exceptional thermal inertia, i.e., the cryosphere is actually a thermostat. Note for comparison that the heat capacity of water (4.183 kJ/(kg•K)) is five times that of soil, and its volumetric heat capacity is 3300 times as high as that of air. Therefore, 3300 times more heat is required for 1°C heating of one liter of water than for air. With their high heat capacity, water and ice (2.060 kJ/(kg•K)) store most of terrestrial heat.

Furthermore, the phase change point has additional thermal stability, also anomalous. Specific heat of ice melting (332 kJ/kg) is higher than, for instance, in gold and mercury, by factors of 5 and 28 (66.2 and 12, respectively). Temperature stability maintains favorable conditions for the origin and growth of biota. Ice acts as a bioprotector and stabilizes environmental parameters.

It is not fortuitous that the temperature of the ice-water transition has been taken for zero in the temperature scales of Celsius and Reaumur.

The anomalous physicochemical properties of ice are responsible for slowing down the rates of biological processes. This is the case of paleobacteria that keep viable below ice shields. In cryotic conditions, all processes are very slow due to the absence of many effects common to the normal environment: high dielectric permittivity and magnetic permeability of ice abate electromagnetic fields, its high stiffness confronts mechanic impacts, low permeability impedes transport of material through ice, high heat capacity and abnormal melting heat damp temperature variations, etc. Thus, all interactions between an object and its environment in the cryosphere is basically restricted to weak gravity effects. Such almost constant conditions maintained a comfortable “greenhouse” environment for the earliest life.

According to the hypothesis of Arrhenius-Goldansky [Goldansky et al., 1986], life originated in cold clouds at cryotic temperatures as a result of shock polymerization during water crystallization and other processes. Ribosome activity is often more successful at low temperatures, which may be additional evidence that life could have originated in cold conditions [Vlassov et al., 2005]. Biota found in sub-ice lakes in Antarctica has been among most exciting recent discoveries in this respect [Zotikov, 2010].

If life came from outside the Earth, the cold may have been crucial to preserve it (note the tenacity of bacteria and seeds for an infinitely long time at low temperatures). Investigation into extraterrestrial life focuses on its search in cold regions of Mars and on moons of Jupiter and other planets.

Many studies of earliest life follow the ideas of Haldane [1929] and Oparin [1968] on the chemical origin and evolution of life, and formation of complex proteins out of simpler compounds. Another similar hypothesis suggests hydrocarbon crystallization of life [Yushkin, 2004] meaning that minerals may have catalyzed the origin of more complex hydrocarbons and transferred a part of their structure (in terms of information) to the first biological molecules. The model of Yushkin [2004] shows that many biological processes were guided by crystallization and ordering common to the whole nature and that the formation of biological structures was a transition to a higher ordering level.

According to Vernadsky [2001], the living matter is a key agent in the formation and regulation of rock compositions, as well as physical properties of the biosphere, atmosphere, and hydrosphere. The cryosphere is apparently a link between the biotic and abiotic components of the planet: it first cherished the life and then allowed creating comfortable conditions for its existence.

Adaptation of living organisms. Cryophilic biota

As we noted, the hydrogen bonds are stable, and thus ensure tenacity of the living matter and, on the other hand, are highly mobile and diverse being weaker than the covalent bonds.

The water-ice phase change, the most widespread and largest-scale on the Earth, strongly changes the properties of systems and affects their behavior. Biological activity is possible in the presence of water, or the liquid phase of ice, which creates the environment for material and information exchange. Crystallized water either kills or preserves the living. Life continues due to active impact it causes on itself and on its ambience. Biological systems become smart and capable of responding to changing conditions, including by changing their own properties and the properties of the environment.

Water in certain conditions can be presented as a mixture of liquid crystal structures, which has important implications for understanding the vital activity of organisms. It is structured

The phase diagram of ice (Fig. 2) shows a range of life conditions and the points of standard ambient temperature and pressure (750 mm of mercury and 25°C) and standard temperature and pressure (760 mercury mm and 0°C). Note that the latter are in the center of life conditions. The diversity of ice states shows up in physicochemical and biological processes, and in multitude of precipitation types: one type of rain, eight types of 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].

Knowledge of cryosphere

The cryosphere is the best documented Earth's sphere because it is quite easily accessible and because people have been living in cold climates for millennia. However, we currently witness a breakthrough in technologies, which changes dramatically the form and content of research.

Progressively improving resolution of observation systems brings about quite different ways of experimenting and monitoring in geosciences, including geocryology. In classical approaches, experiment was the most effective research tool and implied reproducing the target effect or object and, on this basis, predicting the respective conditions and properties to the least possible error using various noise reduction techniques. However, experiments of this kind are superceded by modern monitoring systems supplying big data from real objects in natural conditions. Hypotheses and models based on big data analysis can be updated as more data is acquired, while noise can be picked out and investigated separately.

The conventionally monitored parameters in geosciences belong to domains of physics and chemistry or geography and geology and are estimated using the respective modeling formalism. The two classical groups of methods have almost no overlap in the phase space of characteristic observation scales. In fact, there are no efficient averaging techniques that would make physical and chemical models applicable to geographic and geological descriptions. Current monitoring projects, such as the Pan-Eurasian Experiment (PEEX), a multidisciplinary research for Arctic-boreal areas [Lappalainen et al., 2015], change the scale of the conventional observations: various precise measurements are performed *in situ*, in real time, and at exceptionally high spatial and temporal resolutions.

Thus, the advanced geophysical observation systems bridge up the conventional approaches: simple physical-chemical models of elementary processes and assessment of climate and environment (Fig. 3). Big data acquired by modern monitoring projects can furnish explicit rather than implicit evidence for checking the existing and new models of complex targets.

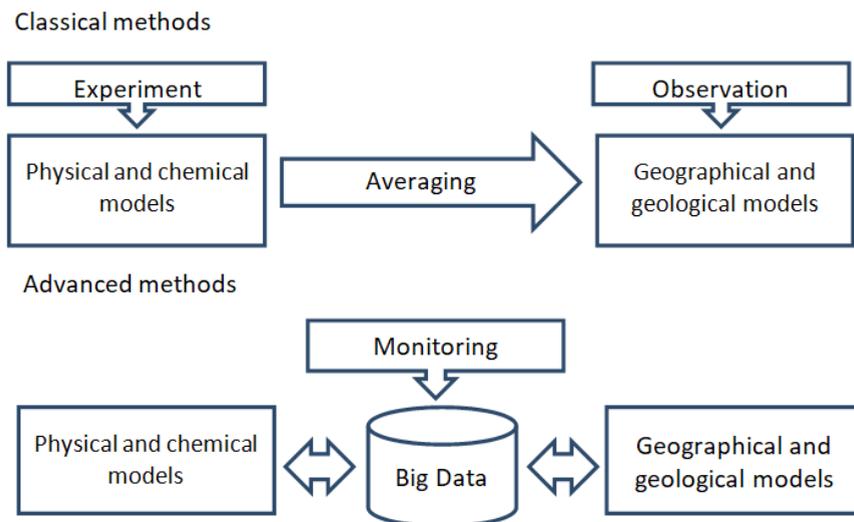


Fig. 3. Classical and advanced methods in geosciences

Cryosphere of the Solar system

The Earth stores the least amount of water ice among ten planets (and their moons) in the Solar System (Fig. 4) [Komarov & Isaev, 2010], and this is one of reasons why the evolution has been associated with variability of biotic and abiotic objects in response to glaciation cyclicality. The typical rates and gradients of cryospheric physical processes on the Earth differ strongly from those in rocks.

Conditions on some icy moons of other planets in the Solar System are, in brief, as follows [Komarov & Isaev, 2010].

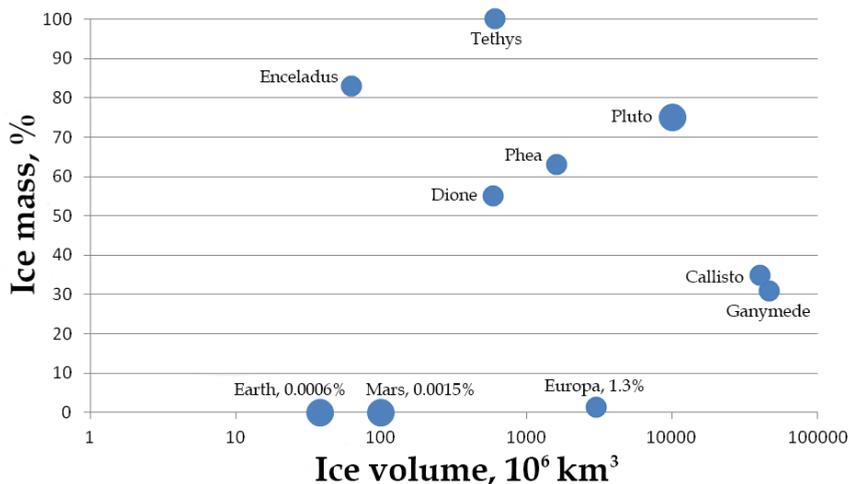


Fig. 4. H₂O ice in the Solar System planets and their satellites.

Ganymede is a satellite of Jupiter, the largest satellite in the Solar System, bigger than Mercury, consisting of approximately equal amounts of silicate rocks and H₂O ice, which makes up to 90 wt.% of the satellite surface. Similar conditions exist on *Callisto*, another Jupiter's moon. The known features of its surface suggest the existence of periglacial processes similar to those on the Earth.

Europa is one more moon of Jupiter which has the smoothest surface in the Solar System consisting mainly of ice, with few craters but numerous fractures. This made thinking of a sub-ice water ocean, where life might exist [Jewitt et al., 2006].

Enceladus is a geologically active moon of Saturn, with geysers-like jets including ice particles, reaching a height of 250 km, shot from a subsurface ocean of liquid water around the south pole. The icy geysers caused by tidal heating, offer the brightest example of cryovolcanism which has been discovered also on Triton and Ceres. NASA experts infer that Enceladus may possess potentially habitable environments for microbial extraterrestrial life.

Trans-Neptunian objects of icy planetoids in the Kuiper Belt, mainly composed of various ice types (H₂O, CO₂, N₂O₃, CH₄, NH₃, CH₃OH, etc.), are of special interest [Jewitt & Luu, 2004]. Pluto, which is no longer classified as a planet, is the best known among them. Future studies of these objects will have important implications for the origin of planets in the Solar System.

Enhancing analytical, multimedia, and communication opportunities ensures gaining rapidly growing amounts of exceptionally valuable data on remote extraterrestrial objects, though with an inevitable time lag proportional to their distance from the Earth.

Typical rates of processes

Any natural object or process has its typical scale in time and space. According to the classical paradigm, the temporal scale correlates with the spatial one, i.e., there must exist an interval of typical rates for the evolution of conventionally studied objects.

A log-log diagram of characteristic linear sizes and times presents an elongate zone of classical studies (Fig. 5). The Earth and the Sun are shown to illustrate the range of scales. In geosciences and biology, there are two additional well documented domains of annual and circadian cycles.

A more complicated diagram (Fig. 6), with domains studied by classical sciences (physical chemistry, geography, geology, and biology), provides a more detailed picture, where Vernadsky's synthetic biogeochemistry stands out in largest ranges of rates and times. Note that phenomena studied by geocryology (circles of different colors) are extremely diverse and fall within a broad interval of scales.

The diagram also includes some recently discovered phenomena associated directly with the cryosphere. Some of them are far beyond the limits of space-time scales of the classical sciences, due to high thermal inertia of ice that changes the characteristic rates of processes. They are, namely, paleobacteria, volcanoes and related stratospheric processes, and ice fingers of death (Fig. 6).

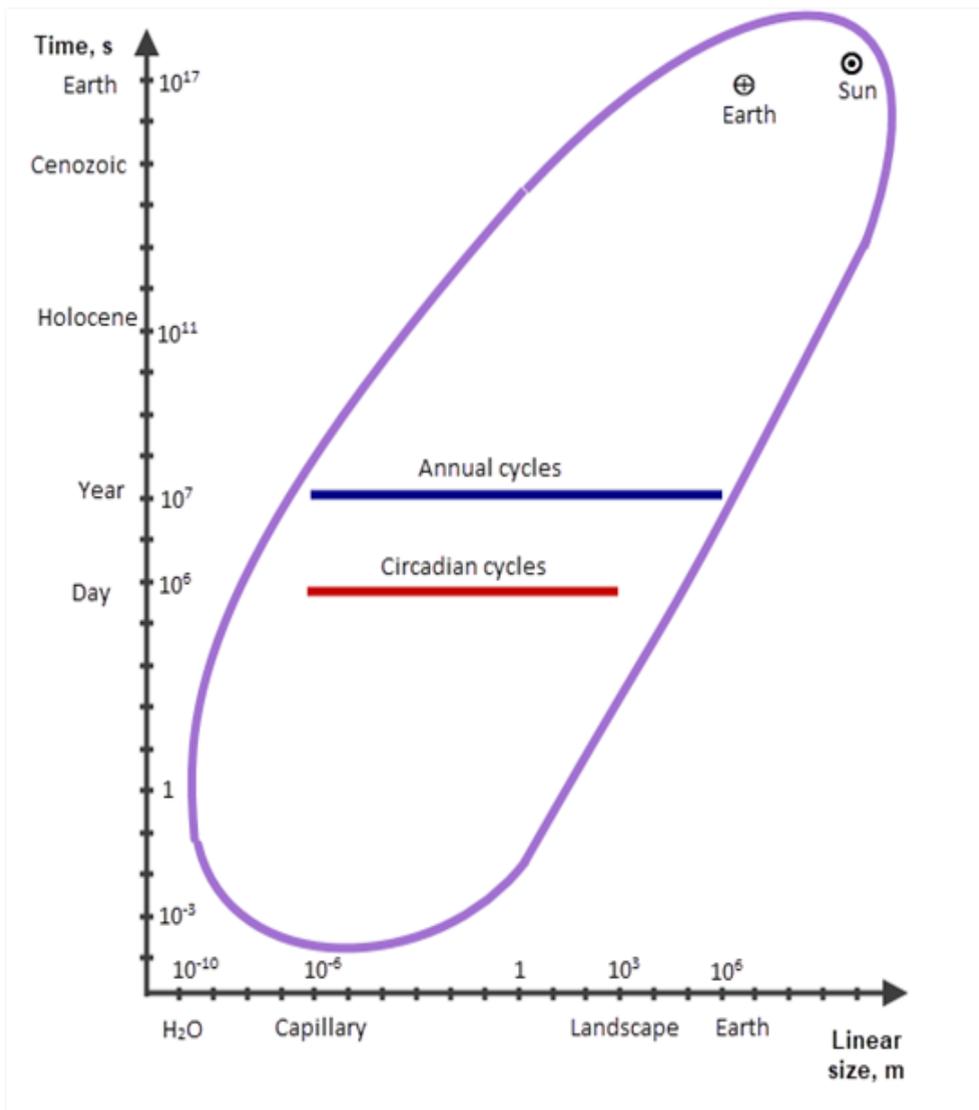


Fig. 5. Subjects of classical studies.

“Ice fingers of death” is an example of a very rapid process with extremely high gradients. This phenomenon (also known as brinicles, brine icicles or ice stalactites) develops in marine shelf areas beneath the sea ice, in the form of slowly rotating jets of extremely cold and saline (and therefore heavy) surface water sinking down to the ocean bottom, freezing and killing all living organisms on its way [Cartwright, 2013]. The brinicles were discovered due to new multimedia and data sharing tools which allow insights into rare and unique processes. The rarity often results from very high rates associated with essentially nonlinear positive (when the process goes up) and negative (when it goes down) feedbacks. Without advanced technologies, such effects would be just observed but now they are subjects of comprehensive investigation, thus extending the classical limits of research fields.

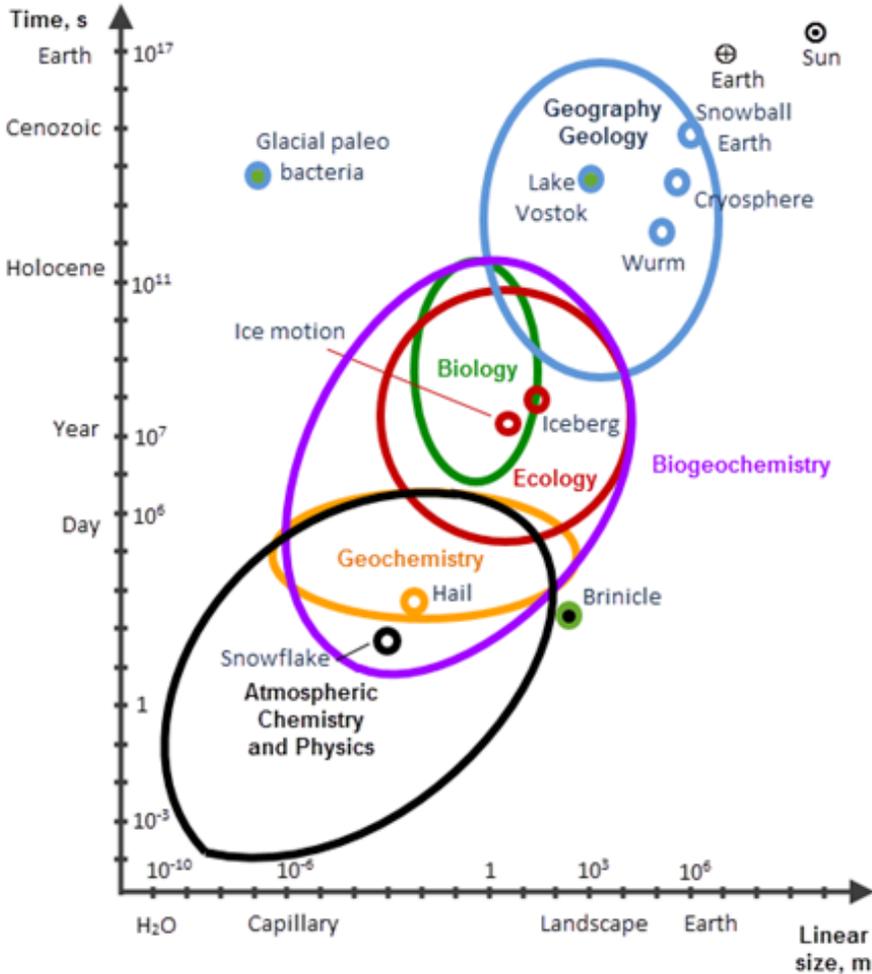


Fig. 6. Subjects of advanced studies

Several recent decades of studies addressing bacteria in ice and in permafrost have actually implemented the philosophical ideas of Vernadsky [1991] and other scientists on the living planet. The existence of bacteria that can remain viable for millions of years and resume reproduction upon minor temperature changes of a few degrees gives rise to research for making true the old dream of people to reach high longevity and life quality. It also has implications for the linkage between the origin of ice and microbial life on the Earth (and other celestial bodies) and the comet material in the Universe.

Geocryology deals with both very slow and very fast processes: a glacier can persist for 500,000 years while a snowflake can melt in 2 seconds. On the other hand, a snowflake that falls on the surface of an Arctic glacier at 1 m/s moves on into its interior at 1 mm/yr, which is slower than the plate motion. Alfred Wegener created his theory of continental drift [Wegener, 1922] when observing the Greenland ice sheet, and it took 30 years for his theory to become universally accepted.

Perceiving geological time is problematic for the human conscience synchronized with the biological time [Vernadsky, 1975], whereas the annual and circadian cycles in cryospheric objects fit the intuitive perception and state of humans, being the background of their life. Climate trends shape up the historic memory of people and their idea of the “time arrow”.

People feel the dynamics of their home planet via the dynamics of the cryosphere: It acts as a regulator accelerating the natural rates of geological processes to the rates perceptible for humans. Therefore, it is not surprising that the geological processes related to and induced by the cryosphere (primarily, global warming) are at the focus of public attention. In this respect, a broad perspective proceeding from long-period cyclicity and climate trends appears reasonable, which suggests that we are currently approaching a climate optimum, probably, preceding another cooling.

Cryosphere as a factor of evolution

The cryosphere has influenced the life cycles of extraterrestrial and terrestrial geological and biological evolution.

All existing models explaining the formation of planets in the Solar System, beginning with Kant’s nebular hypothesis, include, as a key element, the distribution of H₂O molecules in both protostellar nebula and inside protoplanetary disks, where relatively light H₂O molecules occur on the periphery of agglomerated material in both cases. As we noted, H₂O has been held back on the Earth’s surface and in the atmosphere due to the shield where water is crystallized. Large amounts of ice and water on the planet’s surface had created stable thermodynamic conditions for the origin of life and its maintenance while the H₂O molecules themselves are building blocks for living matter and define the rates of biological processes controlled by hydrogen bonds.

On the other hand, ice-rich environments slow down the characteristic rates of biological activity, while processes in the cryosphere, which are the fastest geological processes, facilitate our perception of the planetary dynamics as an alive ever changing system.

The mechanisms responsible for the influence of the cryosphere on different systems are summarized in Table.

System	Influence mechanism	Evolution factor
Solar System	Separation of protoplanetary material and accretion of planets	Kuiper Belt, icy moons of gas giants, presence of H ₂ O on planets’ surface
Earth’s surface	Preservation of water	Necessary conditions for biological activity
Biosphere	Thermal regulation of Earth surface near 0°C	Stable conditions required for life origin and evolution
Biosphere	Intermediate strength of hydrogen bonds	Control of evolution rates
Biosphere	Thermal inertia	Deceleration of biological processes
Lithosphere, hydrosphere	Dependence on annual and circade cycles	Acceleration of geological processes

Thus, the cryosphere was crucial for the formation and evolution of the Solar System, as well as the terrestrial environments and biota, and affects many current processes.

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