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

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 45º 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

43 physicists, chemists, biologists and, prospectively, astrophysicists to topical problems related to ice, snow and cold

44 in a wider interdisciplinary context, beyond the present conventional understanding (see above).

2. Cryosphere and cryogenic anomalies

46 Cold regions and natural phenomena related to cold are often described with terms enclosing the prefix *cryo* that

47 means *cold*. The totality of phenomena on the Earth related to or linked with snow, ice or ice-like products (such

48 as gas hydrates) comprises the Earth's cryosphere – a complex synergic system with self-organized constituents

49 which maintains the heat and mass exchange with the environment and spreads over the atmosphere, the

50 hydrosphere, the lithosphere and the biosphere (Melnikov and Gennadinik, 2011).

51 The large extent of cryogenic objects, their variability in space and time, as well as the discontinuity of the

52 cryosphere, have inspired development of special management technologies. Such technologies, taking into

53 account the stabilizing and bio-protective effects of ice, rooted in specific properties of ice, have become applicable

54 to the areas outside the high-latitude and low temperature regions (Melnikov et al., 2010).

55 Recent investigations of the cryosphere have yielded discovery and scientific description of a number of unique

56 natural objects and phenomena called "cryogenic anomalies". Below we consider examples of recently investigated

57 cryogenic anomalies, tentatively divided into six groups: ice structure, glaciation, ocean, atmospheric ice and water,

58 biota and cold, and rates of processes.

3. Ice structure

60 Being a compositionally simple material, ice possesses diverse anomalous properties. It can exist in seventeen

61 phase states, out of which eleven states are clearly expressed. This diversity shows up in physicochemical and

62 biological processes, and in the types of precipitation: one type for rain, eight types for snow, and two mixed water-

63 ice types (Eisenberg and Kauzman, 1975). There are paradoxically different properties brought together in ice: it

64   is at the same time elastic and plastic, crystalline and amorphous, semiconducting and dielectric, lighter than water

65   but harder than steel (Maeno, 1988). With its crystals built uniquely by hydrogen bonds, ice provides a standard

66   for estimating these bonds. The complexity of the ice structure and its non-equilibrium phase transitions are

67   sufficient for self-organizing synergetic behavior and formation of stable macroscopic objects, like the classical

68   snowflakes or drop clusters in atmospheric clouds (Shavlov et al., 2011).

69   **4. Glaciation**

70   Glaciation is the most impressive cryogenic phenomenon on the Earth. Currently ice covers more than 10% of the

71   Earth's surface, but the area of glaciation was much larger in some periods of the Earth's history. Traces of early

72   Proterozoic glaciations (Huron, about 2300 myr ago) are found on all modern continents, which is evidence of

73   global glaciation, even taking into account the drift of continents. About 300 myr ago a large part of Gondwana

74   was covered by ice (The Winters, 1979).

75   The exact cause of glaciations remains debatable but their cyclic nature is beyond doubt. The complex pattern of

76   glacial cycles cannot be explained uniquely by orbital forcing of eccentricity, obliquity, and precession that change

77   in Milakovitch cycles (Milanković, M., 1939), but correlates also with global geological events.

78   Glaciation obviously reduces the area of rocks exposed to wind erosion and causes progressive CO_2 increase by

79   more active respiration of bacteria, which recycle dead organics at less active photosynthesis. This, in turn,

80   enhances the greenhouse effect of the atmosphere and thus increases the temperature. Due to this negative feedback,

81   oscillations in the cryosphere correlate with phases of global greenhouse-gas and temperature cycles. There is also

82   a positive feedback that controls ice waxing and waning (Le Hir et al., 2008). In particular, the increasing albedo

83   may have been responsible for the strongest glaciation about 800 myr ago, the so called Snowball Earth (Kirschvink

84   et al., 1997). The observed recent shrinking of areas covered by glaciers is often attributed to anthropogenic impacts

85 which became a real geological force in the 20th century (Vernadsky V.I., 1965). The true extent of this effect will

86 be clear in the near future.

87 The very existence of ice sheets changes the composition and physical properties of the lithosphere, the

88 hydrosphere, and the atmosphere. Moving ice transports great amounts of material and, at the same time, preserves

89 the entrained objects. During glaciations, crust becomes denser; volcanism increases; ice sheets extended to the

90 troposphere change the atmospheric composition and circulation; sea level falls and climate changes. After the ice

91 retreat the formerly frozen territories experience isostaic rebound and terrain smoothing, changes in landscapes,

92 such as formation of rivers and lakes, and changes in biota, such as species composition.

93 **5. Permafrost**

94 Formation of permafrost is the principal consequence of glaciation. Remnants of permafrost that formed during the

95 last glacial event currently cover large territories. The stability of permafrost is one of the greatest challenges, first

96 of all for Russia, where it occupies 65% of the territory, but also for the global climate-biosphere system, because

97 of strong links between the permafrost and boreal forests, tundra, peatlands, rivers and other water reservoirs.

98 Objects and phenomena associated with permafrost to a large extent determine the sustainability of the Siberian

99 climate-biosphere system (taiga) and the conditions of land use and life of the population. The ice barriers

100 dramatically change natural flows of water and material in mid latitudes, change hydrological regimes and create

101 traps for gases. The methane traps cause jet degassing of hydrocarbons (Melnikov et al., 1997) which, in turn, can

102 lead to cooling of rocks, formation of gas hydrates, accumulation of large amounts of methane, and to the methane

103 explosions. The latter cause significant changes in both underwater and land topography (see Figure 2).

104 On the land, such explosions may produce giant craters which subsequently transform into lakes (see Figure 3).

105 Tracking such processes over large areas in real time with proper resolution in space, as well as the early warning

106 of expected gas explosions, are important tasks envisaged in the PEEX Science Plan (Lappalainen et al., 2016).

107 Permafrost leaves imprints in the gravity field, as in the case of the Hudson Bay, where the gravity field is lower

108 than elsewhere at this latitude (Tamisiea et al., 2007), possibly, as a consequence of the North American glaciation.

109 About 75,000 years ago the ice (3.7 km thick in the Hudson Bay area) covered most of the present northern US and

110 Canada, which has left a large depression. On the contrary, the gravity field over the 1 km thick permafrost (such

111 as in East Siberia) can reach 50 mGal. On the geological time scale, this field can influence the homeostasis of

112 living organisms and their speciation.

113 **6. Ocean**

114 Oceanic ice is a major control of the global climate as it screens heat and mass transfer in both vertical (across the

115 air-water interface) and horizontal directions. Warm currents, such as that of North Atlantic, move mainly along

116 the ocean surface due to thermal expansion of warm water. Glaciers on the way of warm currents can melt rapidly

117 because the ice not necessarily should reach the seafloor to stop them but can be only commensurate with the

118 surface water layer.

119 Another great challenge addressed in the PEEX Science Plan is the ongoing change in the Arctic Ocean ice cover,

120 showing increasingly larger and longer-exposed ice-free areas (Hayes et al., 2014; Schaefer et al., 2014; Döscher

121 et al., 2014). This tendency is favorable for exploring and transportation of the Northern Siberian oil and gas

122 comprising about 25% of their total world resources (Yenikeyeff and Krysiek, 2007).

123 **7. Atmospheric ice and water**

124 Ice has very high heat capacity, specific heat of melting, and dielectric constant. The phase transition forms shields

125 of different types and scales from the gas hydrates stored in permafrost to the ice sheets that cover the entire

126 Antarctic continent and affect the global climate and evolution of life. In the global Earth system, the cryosphere

127 acts as the temperature stabilizer due to exceptional thermal inertia of ice and water occupying a great part of the

128 Earth's surface.

129 The Earth's atmosphere contains a large amount of water in the form of vapor, liquid and ice which influences the

130 planetary heat budget. Moreover, the atmosphere acts as a "thermal shield" aggregating the water molecules into

131 ice particles and thus holding back on the Earth the water, vital for the maintenance of life. The phase transitions

132 of atmospheric ice produce diverse sudden effects and various precipitation types: rain, ice, drizzle, moist snow,

133 snow, sleet, or hail. In the dry troposphere, the air cools down adiabatically at 0.98º C per 100 m. Hence,

134 condensation of originally nearly saturated water vapor starts already at a few hundred meters above the surface.

135 Along with sublimation, this leads to the heat release, which affects temperature profiles and other properties of

136 the atmosphere. Generally, condensation of pure water vapor starts at 400 - 00% supersaturation (e.g. Pruppacher

137 and Klett, 1997). However, condensation in the real atmosphere starts shortly after relative humidity exceeds 100%

138 due to the presence of solid or liquid aerosol particles acting as condensation nuclei, or even below 100% in some

139 cases (Kulmala et al., 1997). Similarly, ice nucleation is initiated upon nuclei like dust particles, biological particles

140 etc., including anthropogenic aerosol particles (e.g. Hoose and Möhler, 2010, Atkinson et al. 2013). Thus, the air

141 pollution facilitates formation of ice crystals and cloud droplets, and therefore affects the air temperature and

142 precipitation processes and its spatiotemporal variability (Rosenfeld et al. 2014). The aerosol-cloud-climate

143 interactions (see e.g. Kulmala et al., 2011), as well as air pollution-weather-climate interactions (Ding et al. 2016,

144 Petäjä et al., 2016) have been and are under rigorous investigations.

145 **8. Biota and cold**

146 A number of facts in the evolution biology would be unexplainable without cryosphere. Contrary to the common

147 thinking, the existence of life is consistent with negative temperatures. For example, photosynthesis is quite

148 possible at temperatures below 0oC (Kramer P.J., Kozlowski T.T., 1960). For billions of years, the cryosphere

149 assured the stability of environment required for development of life. The mean annual air temperatures on the

150 Earth were naturally maintained near the ice-water transition point. Ice, like water, possesses exceptional

151 thermostatic properties, and is thus a very strong stabilizer of the temperature regime, along with wide spread of

152 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,

153 and its volumetric heat capacity is 3300 times that of air. The high heat capacity of ice (2.06 kJ/kg·K) is comparable

154 with that of water, which makes the ice-snow-water system the Earth's largest storage of solar energy. The very

155 phase change point has additional (likewise abnormal) thermal stability: the specific heat of ice melting is five

156 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

157 Gennadinik, 2011).

158 Permafrost contains organic matter in the form of biogenic gases, products of biodegradation, or as ancient viable

159 bacteria. In Russia, the evidence of bacteria in permafrost was obtained in the latest 19th century, together with

160 finding of mammoths in Northern Siberia and during studies of soils in the Russian Far East. Novel information

161 about bacterial communities has been obtained from studies of Antarctic permafrost. Cyanobacteria, with their age

162 about 500 kyr, were discovered in the station "Vostok" ice cores at 3600 m depth (Water sampling, 2003).

163 Many microorganisms are stable against freezing and not only survive but even grow at negative temperatures.

164 More than 10% of water in organic tissues remains unfrozen at temperatures below -20°C. Many basic processes

165 in microbial, soil, geophysical, and cosmological systems are associated with cooling and ice-water phase changes.

166 Ribosome activity is often more successful at low temperatures, which may be the evidence that life could have

167 originated in cold conditions (Vlassov et al., 2005).

168 Life processes can remain active at below 0 ° C in capillaries and on ice surface in permafrost. Micro-organisms

169 can exist in media with low dimensionality (2 or less), such as liquid films and capillaries filled with super-cooled

170 water. The porous structure of the environment ensures the transport of nutrients and life wastes (Möhlmann,

171 D.T.F., 2009).

172 Even comparatively minor heating to 50-60°C leads to denaturation of proteins and can stop operation of a living

173 system, while freezing even to the near-absolute zero temperatures does not change the configuration of

174 biomolecules, so that the life functions can resume after thawing. Enzymes that regulate metabolism in organisms

175 show similar behavior (Dethier and Villee, 2005).

176 It is still unclear how and why the metazoans originated about a billion years ago. The obviously required sufficient

177 amount of oxygen has been commonly explained by its gradual photosynthetic accumulation in the atmosphere.

178 However, origination of metazoans may have been due to the higher concentration of oxygen in cold water. The

179 origin of the skeletal organisms at the Proterozoic/Phanerozoic boundary was possibly favored by the calcium

180 carbonate release by organisms at the high oxygen availability. The oxygen enrichment in oceans at the

181 Vendian/Cambrian boundary may have resulted from glaciation, water cooling, hence, increasing gas solubility

182 and favorable water circulation patterns. Note that the first giant organisms have appeared precisely during this

183 cooling event. Furthermore, gigantism, associated with specific heat exchange, is known to be typical of polar

184 biota. Biotic and cooling events have been closely related all over the Phanerozoic. The major Jurassic and latest

185 Cretaceous extinctions occurred during the stages of cold climate (The Winters, 1979).

186 **9. Typical rates of processes**

187 Natural objects are characterized by their typical scales in time and space. The common sense suggests that

188 temporal and spatial scales change more or less similarly, which implies that typical change rates are not too

189 variable. However, this rule does not work for the cryosphere, which can be either accelerator or decelerator of

190 various processes (Melnikov et al., 2013). For instance, paleo-bacteria preserved under ice shields remain viable

191 for millions of years. Ice slow down biotic processes due to the following properties:

192 • low dielectric and magnetic susceptibility, which reduces electromagnetic fields;

193 • high stiffness, which resists mechanic impacts;

194   • low permeability, which decelerates mass transport;

195   • high heat capacity and anomalous specific heat of melting, which damp temperature variations.

196   Hence, interaction between an object and its environment in cryosphere is basically restricted to weak gravity

197   effects and very slow diffusion. The capability of ice to decelerate biological processes has practical uses: freezing

198   of organs or storage of seeds, not to mention the household refrigerators. Similar mechanisms protect the biota of

199   Antarctic paleo-lakes, such as Lake Vostok, hidden under kilometers-thick ice maintaining its sustainable thermal

200   regime (Thoma et al., 2008).

201   On the contrary, processes on the surface of ice or ice-bearing systems are often faster than usual due to formation

202   of electrolytes, chemical reactions, and accelerated transport. "Ice fingers of death" is an example of a very rapid

203   process with extremely high gradients of physical parameters in the vicinity of cryogenic objects. This phenomenon

204   (also known as brinicles, brine icicles or ice stalactites) develops in shallow water beneath the sea ice, mainly in

205   the southern high latitudes, in the form of slowly rotating jets of extremely cold and saline (and therefore heavy)

206   surface water sinking down to the ocean bottom (Martin, 1974). The point is that the formation of sea ice at very

207   low air temperatures is associated with the decomposition of calcium bicarbonate into CO2 and $CaCO_3$. Then CO_2

208   releases into the air, whereas slowly rotating jets of the cold dense surface water sinks down to the seafloor and

209   propagates downslope leaving frozen footprints with entrapped bottom-dwelling sea animals.

210   Cryogenic phenomena developing at various rates are presented in the log-log space/time coordinates in Fig. 4

211   showing extremely wide range of scales. Some objects, such as paleo-bacteria survived in ice over half a million

212   years or "ice fingers of death", fall beyond the scope of any particular science. To emphasize their multidisciplinary

213   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, 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.

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

236 to the process-based approach unifying investigation of the totality of cryogenic phenomena from molecular to

237 planetary scales (see Figure 4) in an interdisciplinary science, *cryology*, armed with all necessary methods of

238 geosciences, physics, chemistry and biology.

239 **12. Concluding remarks**

240 Ice has very high heat capacity, specific heat of melting, and dielectric constant. The phase transition forms shields

241 of different types and scales from the gas hydrates stored in permafrost to the ice sheets that cover the entire

242 Antarctic continent and affect the global climate and evolution of life. In the global Earth system, the cryosphere

243 acts as the temperature stabilizer due to exceptional thermal inertia of ice and water occupying a great part of the

244 Earth's surface.

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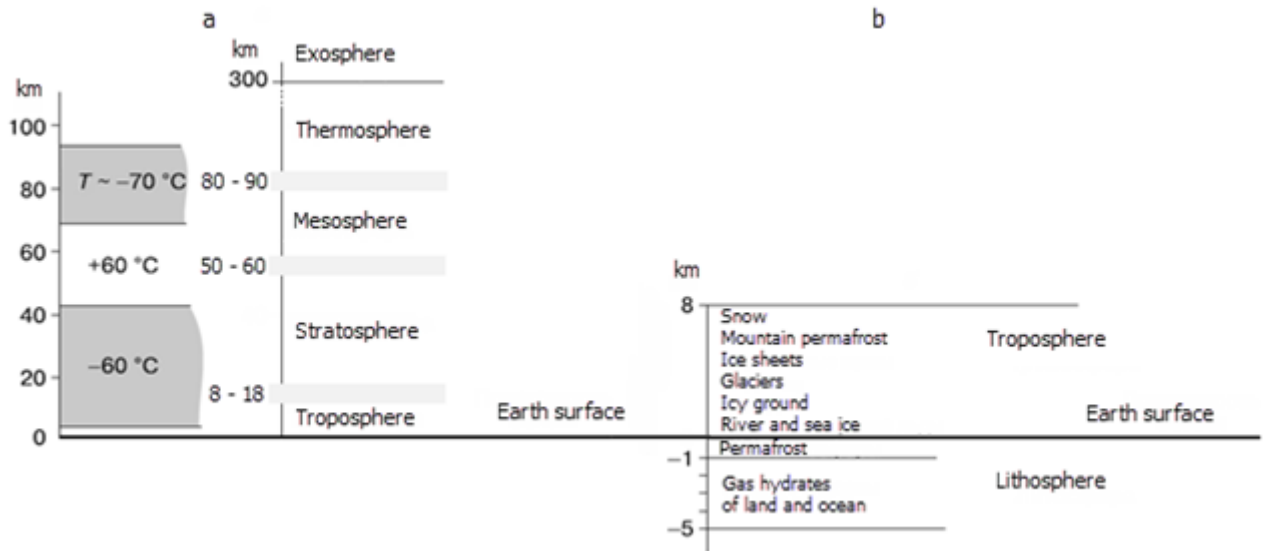
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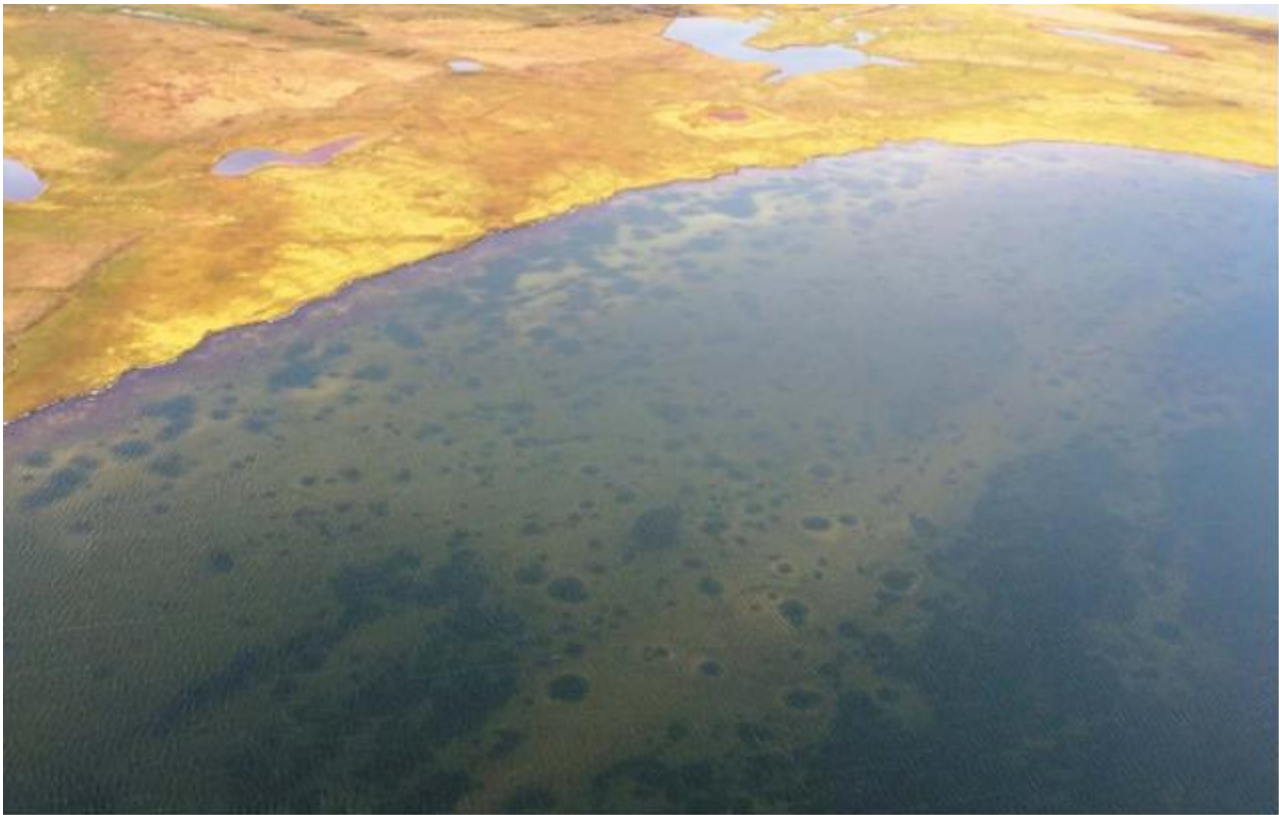
426   Figure 1: The Earth's cryosphere: from (a) the uppermost atmosphere, to (b) 5 km below Earth's surface, where

427   ice exists as hydrates at positive temperatures.

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429   Figure 2: Photo of a lake on the Yamal Peninsula showing numerous craters from gas explosions on the lake bottom

430   (Bogoyavlensky, 2015).

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Figure 3: New crater produced by gas explosion on the Yamal Peninsula in 2014 (Leybman et al., 2015; photograph

by Vladimir Pushkarev borrowed from "Siberian Times").

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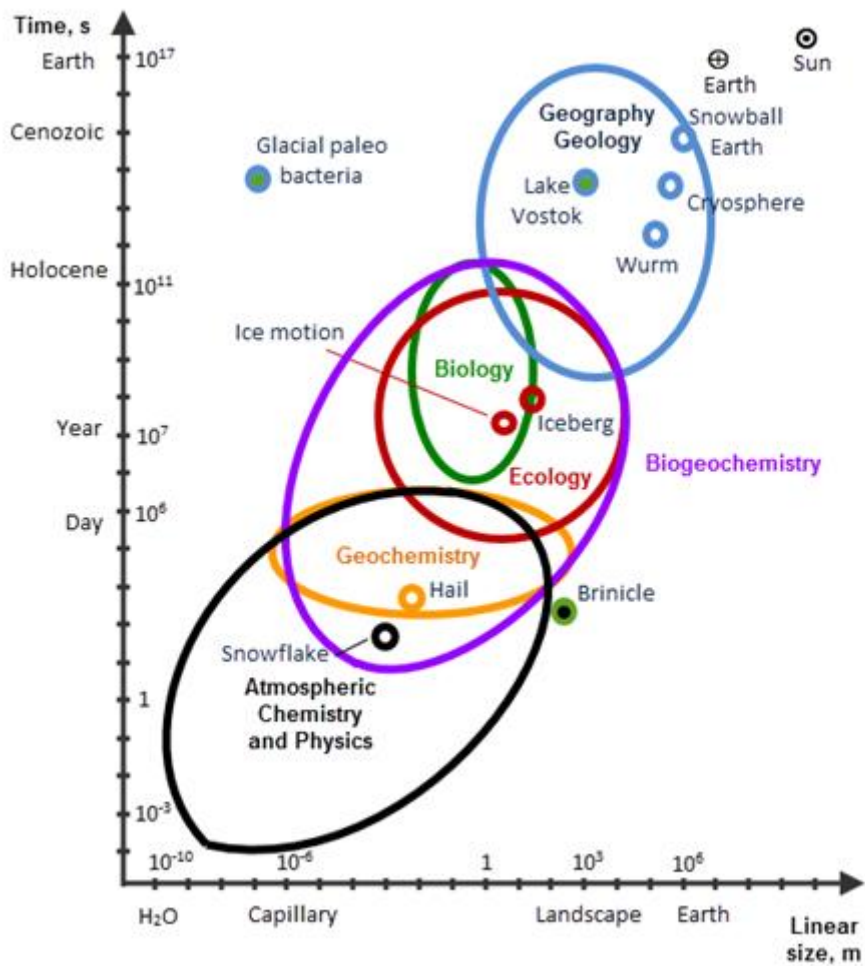
Figure 4: Log-log space-time diagram of cryogenic phenomena of different nature. Large ellipses or circles with

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.