Cryosols as a test of our knowledge of Earth as a system: Review

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Abstract

Cryosols are a key component of the cryosphere and, therefore, play a major role in the earth's energy, water, and geochemical cycles. Several examples are given to demonstrate how Cryosols have contributed to our increased understanding of earth's dynamic systems. Cryosols may account for up to 50% of the global soil organic carbon pool. Atmospheric temperatures have increased by ±3ºC over the past decades in arctic and Antarctic regions. Based on studies of active-layer dynamics and carbon budgets, continued warming may initiate a positive feedback mechanism whereby carbon stored in the near-surface permafrost may be released to the atmosphere as CO_2. Polar soils and the underlying permafrost are a major source of other biospheric greenhouse gases, including CH_4, and N_2O. Radioactive fallout, toxic metals, and other anthropogenic pollutants have accumulated in polar soils and have impacted terrestrial, aquatic, and marine ecosystems. Polar soils are important for studying extremophiles such as endolithic lichens in Antarctica and microorganisms in 2-8 million-year-old permafrost in Siberia and Antarctica. Antarctic soils have been used for interpreting features and processes on Mars, including patterned ground, thermokarst, and rock glaciers. Finally, polar soils are an important component of environmental observatories and provide a data repository for studying environmental change.

Key Words

Polar soils, Gelisols, cryosphere, earth-system science

Introduction

Polar soils comprise 18 x 10^6 km^2 or about 13% of earth's land surface (Bockheim and Tarnocai, in press). The main feature of polar soils is the presence of permafrost within 1 to 2 m of the surface that leads to the formation of patterned ground on the surface and frost mixing (cryoturbation) in the soil. Approximately 80% of the soils in the polar regions are identified as Cryosols or Gelisols in modern global soil-taxonomic schemes. In the recent past, the study of polar soils was considered to be a purely academic exercise. However, in the past 15 years, cryopedology has emerged as a powerful sub-discipline of soil science that has contributed greatly to our understanding of earth systems. The primary aim of this review paper is to illustrate the interactions of Cryosols with earth's dynamic systems.

Cryosols, the cryosphere, and earth-system science

One of the great scientific challenges of the 21st century is to forecast the future of planet Earth. Writing of this challenge relative to global warming, John Lawton (2001) states: "we find ourselves, literally, in uncharted territory, performing an uncontrolled experiment with planet Earth that is terrifying in its scale and complexity" (p. 1965). From these challenges has emerged the discipline of Earth System Science (ESS), which includes the main components of planet Earth—the atmosphere, the hydrosphere, the cryosphere, the geosphere, the biosphere, and the pedosphere (Figure 1).

The cryosphere covers a substantial amount of Earth's surface and includes water in solid form, including sea ice, lake ice, river ice, snow cover, glaciers, ice caps and ice sheets, and permafrost. The cryosphere and its extensive cover of Cryosols is an integral part of the global climate system with important linkages and feedbacks generated through its influence on surface energy and moisture fluxes, clouds, precipitation, hydrology, and atmospheric and oceanic circulation. Through these feedback processes, Cryosols play a significant role in global climate and in climate model response to global change.

Cryosols and the global carbon cycle

Cryosols contain approximately over 1700 Gt of soil organic carbon (SOC) in the upper 3 m, which accounts for about 50% of the world's SOC (Tarnocai *et al.* 2009). In arctic tundra soils, a large portion (approximately 81%) of SOC is stored below the seasonal thaw layer (active layer) in the near-surface permafrost (transition layer) to depths in excess of 300 cm (Bockheim and Hinkel 2007; Tarnocai *et al.* 2009). Atmospheric temperatures have increased by ±3ºC over the past three decades in arctic and Antarctic regions. Studies of active-layer dynamics and carbon budgets suggest that continued warming may initiate a positive feedback mechanism whereby carbon stored in the near-surface permafrost may be released to the atmosphere as CO_2. (Schuur *et al.* 2008). At the present time, our knowledge is insufficient to describe the interactions between the components of the Earth system and the relation between the carbon cycle and other biogeochemical and climatological processes (Falkowski *et al.* 2000). However, the arctic may be viewed as a bellwether for the global implications of climate change (Corell 2006).

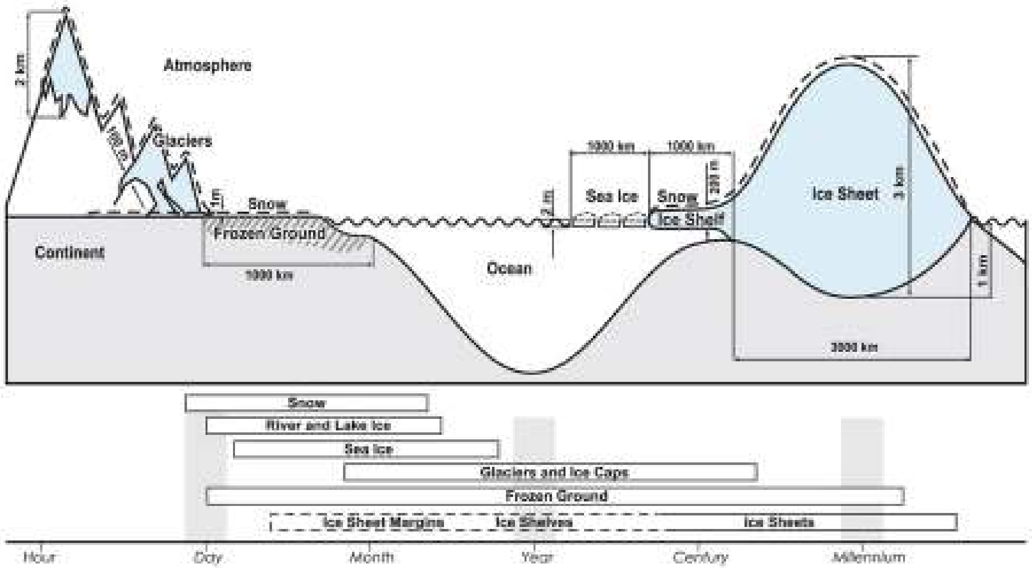

Figure 1. Components of the cryosphere and their typical time scales (IPCC 2007).

Examples of Cryosols and our knowledge of Earth as a system

Six examples are given to illustrate the role that the study of Cryosols has played in the emerging discipline of ESS.

Cryosols and biospheric gases

Trace gas fluxes in polar regions have attracted substantial attention in recent years, because of the large quantites of carbon and nitrogen stored there and the associated feedbacks to climate change. The primary trace gases of concern are carbon dioxide, methane, and N_2O. Whereas arctic Cryosols currently are considered to be in balance relative to CO_2 inputs and outputs, they are a source for CH_4 (Christensen *et al.* 2008). Large methane and nitrous oxide “bursts” have been observed from Cryosols during the onset of freezing (Li *et al.* 2007; Mastepanov *et al.* 2008). Experimental studies suggest that warming of shallow arctic seas may activate archaeal microbial communities and generate large amounts of CH_4 from submarine permafrost (Koch *et al.* 2008). There are approximately 10 Tg of methane C as gas hydrates (clathrates) in the world’s oceans and submarine permafrost (Kvenvolden and Lorenson 2001).

Cryosols and anthropogenic pollutants

During the winter the circumarctic air mass becomes polluted by anthropogenic pollutants from fossil fuel combustion, smelting and industrial processes from regions to the south. Polar regions have accumulated, via long-range transport, toxic constituents such as mercury and other heavy metals, radioactive fallout and other pollutants. These pollutants have not only caused an “arctic haze,” which threatens the world energy balance, but also they have impacted terrestrial, aquatic, and marine ecosystems (Barrie *et al.* 1992; Aarkrog 1994). Many of the world’s largest petroleum reserves exist in permafrost regions such as Alaska and northern Russia. As these reserves are exploited for fossil fuels, spills and leaks can be expected. Unfortunately, there is insufficient information regarding the bioremediation of Cryosols contaminated by petroleum hydrocarbons (Van Stempvoort and Biggar 2008).

Cryosols and extremophiles

An extremophile is an organism that thrives in and even may require physically or geochemically extreme conditions that are detrimental to the majority of life on Earth. Cryosols and the underlying permafrost are important for studying extremophiles. Friedmann (1982) discovered “cryptoendolithic” microorganisms, primarily lichens, in Antarctic Cryosols and rocks. These microorganisms survive not only by adaption to low temperatures, but also by changing their mode of growth, being able to grow between the crystals of porous rocks. The yearly gross productivity of the cryptoendolithic microbial community may contribute substantially to the SOC levels founds in Antarctic Cryosols (Friedmann *et al.* 1993). Significant numbers of microorganisms of various ecological and morphological groups have been preserved in ancient permafrost at temperatures ranging from -9 to -13°C and depths of up to 100 m (Gilichinsky *et al.* 1992). This preservation has been observed both in the arctic and the Antarctic (Gilichinsky *et al.* 2007) and in sediments ranging between 2 and 8 million years in age (Figure 2).

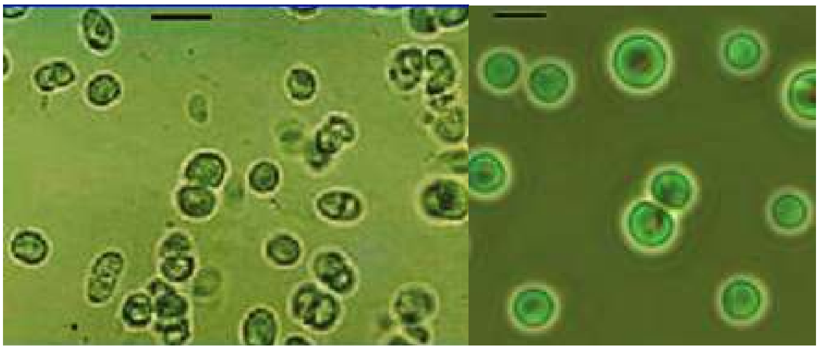

Figure 2. Cyanobacteria from the contemporary surface layer (left) and ancient permafrost (right) from Beacon Valley, Antarctica (Gilichinsky *et al.* 2007).

Cryosols and extraterrestrial systems
Cryosols have been used as both Martian and lunar analogues. For example, the Antarctic Dry Valleys have been considered an analog of the environment at the surface of Mars because of the hyper-acid, cold-desert conditions (Wentworth *et al.* 2005; Marchant and Head 2007). Moreover, geomorphic features in the region have been useful in interpreting features on Mars, including patterned ground, thermokarst and rock glaciers suggesting ice-rich permafrost, drop moraines, and gelifluction lobes (Figure 3).

Figure 3. Patterned ground in Antarctica (left; photo by J. Bockheim) and on Mars (right; photo by M. Mellon).

Cryosols and environmental observatories
Environmental observatories are established to provide long-term, multi-faceted research observations to detect how the environment is changing. The Barrow (Alaska) Environmental Observatory, a 3,000-ha research reserve, was established in 1992 to encourage long-term research on permafrost, including Cryosols. The observatory is one of 23 terrestrial field bases established across the circumarctic to improve comparative observations and access information on environmental change in the North (http://www.scannet.nu/content/view/136/166/). Antarctic Specially Protected Areas (ASPAs) were established as part of the Antarctic Treaty to protect outstanding environmental, scientific, historic, aesthetic or wilderness values, or a combination of these values. At the present time, 67 sites have been established throughout the Antarctic region (≥60ºS). A permit is required to enter an ASPA.

Cryosol databases for earth systems modeling
There are several Cryosol databases that are useful for modeling earth sciences. These include databases stored at the National Snow & Ice Data Center (NSIDC; http://www.nsidc.org), the *Atlas of Northern Circumpolar Soils* (http://eusoils.jrc.ec.europa.eu/library/Maps/Circumpolar/Index.html); the Northern & Mid Latitudes Soil

Database (NMLSD; http://daac.ornl.gov/SOILS/guides/mid_latitude_soils.html); the U.S. Department of Agriculture, National Resources Conservation Service soil data mart (http://soildatamart.nrcs.usda.gov/) and Landcare Research New Zealand's Antarctic soils database (http://soils.landcareresearch.co.nz/contents/SoilData_About.aspx?currentPage=SoilData_About&menuItem=SoilData).

Conclusions

Cryosols are a key component of the cryosphere and play an important role in earth's systems, including the global C cycle, the transfer and accumulation of anthropogenic pollutants, the evolution of ancient microorganisms in permafrost, the study of extraterrestrial systems, and monitoring environmental change. Cryosol databases will continue to serve in modeling earth systems.

References

Aarkrog A (1994) Radioactivity in polar regions – main sources. *J. Envir. Radioact.* **25**, 21-35.

Barrie LA, Gregor D, Hargrave B, Lake R, Muir D, Shearer R, Tracey B, Bidleman T (1992) Arctic contaminants: sources, occurrence and pathways. *Sci. Total Envir.* **122**, 1-74.

Bockheim JG, Hinkel KM (2007) The importance of "deep" organic carbon in permafrost-affected soils of arctic Alaska. *Soil Sci. Soc. Am. J.* **71**, 1889-1892.

Bockheim JG, Tarnocai C. *In press*. Gelisols. In 'Encyclopedia of Soil Science (2nd edit.)' (Ed. Huang PW). Taylor and Francis, London, UK.

Christensen TR, Friborg T, Johansson M (2008) Trace gas budgets of high arctic permafrost regions In 'Ninth International Conference on Permafrost' (Eds. Kane DL, Hinkel KM). Institute of Northern Engineering, University of Alaska. **1**, 251-256.

Corell RW (2006) Challenges of climate change: An arctic perspective. *Ambio* **35**, 148-152.

Falkowski P *et al.* (16 co-authors) (2000) The global carbon cycle: A test of our knowledge of Earth as a system. Science 290:291-296.

Friedmann EI (1982) Endolithic microorganisms in the Antarctic cold desert. *Science* **215**, 1045-1053.

Friedmann EI, Kappen L, Meyer MA, Niewow JA (1993) Long-term productivity in the cryptoendolithic microbial community of the Ross Desert, Antarctica. *Microb. Ecol.* **25**, 51-69.

Gilichinsky DA, Vorobyova EA, Erokhina LG, Fyordorov-Dayvdov DG, Chaikovskaya NR (1992) Long-term preservation of microbial ecosystems in permafrost. *Adv. Space Res.* **12**(4), 255-263.

Gilichinsky DA (22 co-authors) (2007) Microbial populations in Antarctic permafrost: biodiversity, state, age, and implication for astrobiology. *Astrobiology* **7**, 275-311.

International Panel on Climate Change (2007) Climate change 2007: the physical science basis. IPCC 4th Assessment Rep. AR4 (http:/./www.ipcc.ch).

Koch K, Knoblauch C, Wagner D (2008) Methanogenic community composition and anaerobic carbon turnover in submarine permafrost sediments of the Siberian Laptev Sea. *Environ. Microbiol.* **11**, 657-668.

Kvenvolden KA, Lorenson LD (2001) The global occurrence of natural gas hydrate. *Geophys. Monog.* **124**, 3-18.

Lawton J (2001) Earth system science. *Science* **292**, 1965.

Marchant DR, Head JW III (2007) Antarctic dry valleys: microclimate zonation, variable geomorphic processes, and implications for assessing climate change on Mars. *Icarus* **192**, 187-222.

Mastepanov M, Sigsgaard C, Dlugokencky EJ, Houweling S, Ström L, Tarnstorf MP, Christensen TR (2008) Large methane burst during onset of freezing. Nature 456:628-631, doi:10.1038/nature07464.

Schuur EAG (18 co-authors) (2008) Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle. *BioScience* **58**, 701-714.

Tarnocai C, Canadell JG, Schuur EAG, Kuhry P, Mazhitova G, Zimov S (2009) Soil organic carbon pools in the northern circumpolar permafrost region. Global Biogeochem. Cycles 23:GB2023, doi:10.1029/2008GB003327.

Yu J, Sun W, Liu J, Wang J, Wang J Meixner FX (2007) Enhanced net formations of nitrous oxides and methane underneath the frozen soil in Sanjiang wetland, northeastern China. J. Geophys. Res.—Atmos. 112, D07111, doi:10.1029/2006JD008025.

Van Stempvoort D, Biggar K (2008) Potential for bioremediation of petroleum hydrocarbons in groundwater under cold climate conditions: A review. *Cold Regions Sci. & Tech.* **53**, 16-41.

Wentworth SJ, Gibson EK, Velbel MA, McKay DS (2005) Antarctic dry valleys and indigenous weathering in Mars meteorites; Implications for water and life on Mars. *Icarus* **174**, 383-395.