CHAPTER 4

# Cryosphere

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## Introduction

The cryosphere refers to the Earth's frozen realm. As such, it includes the 10 percent of the terrestrial surface covered by ice sheets and glaciers, an additional 14 percent characterized by permafrost and/or periglacial processes, and those regions affected by ephemeral and permanent snow cover and sea ice. Although glaciers and permafrost are confined to high latitudes or altitudes, areas seasonally affected by snow cover and sea ice occupy a large portion of Earth's surface area and have strong spatiotemporal characteristics.

Considerable scientific attention has focused on the cryosphere in the past decade. Results from 2 × $CO_2$ General Circulation Models (GCMs) consistently predict enhanced warming at high latitudes, especially over land (Fitzharris 1996). Since a large volume of ground and surface ice is currently within several degrees of its melting temperature, the cryospheric system is particularly vulnerable to the effects of regional warming. The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) states that there is strong evidence of Arctic air temperature warming over land by as much as 5 °C during the past century (Anisimov *et al.* 2001). Further, sea-ice extent and thickness has recently decreased, permafrost has generally warmed, spring snow extent over Eurasia has been reduced, and there has been a general warming trend in the Antarctic (e.g. Serreze *et al.* 2000).

Most climate models project a sustained warming and increase in precipitation in these regions over the twenty-first century. Projected impacts include melting of ice sheets and glaciers with consequent increase in sea level, possible collapse of the Antarctic ice shelves, substantial loss of Arctic Ocean sea ice, and thawing of permafrost terrain. Such rapid responses would likely have a substantial impact on marine and terrestrial biota, with attendant disruption of indigenous human communities and infrastructure. Further, such changes can trigger positive feedback effects that influence global climate. For example, melting of organic-rich permafrost and widespread decomposition of peatlands might enhance $CO_2$ and $CH_4$ efflux to the atmosphere.

Cryospheric researchers are therefore involved in monitoring and documenting changes in an effort to separate the natural variability from that induced or enhanced by human activity. This entails, by extension, understanding how cryogenic processes may be affected under a warming scenario; e.g. enhanced coastal thermoerosion, changes in precipitation patterns, surface run-off and glacier mass balance, assessment of avalanche risk, and understanding the increased potential for detachment slides or thermokarst.

Cryosphere specialists in the field of geography generally integrate elements of climatology, geomorphology, and hydrology. Although differentiated by the specific subfield, methods of data collection and analysis, and diverse backgrounds and training, they are united in several respects: (1) a shared interest in near-surface water at and below the freezing point; (2) a reliance on primary data sources derived from field sampling or remotely-sensed imagery; (3) an interest in extrapolating results spatially and/or temporally; and (4) a desire to understand the synergistic dynamics between the Earth's cryosphere and current, past, and future climate.

## Snow Cover and Sea Ice

The spatial and temporal interrelationships among Earth's troposphere, snow cover, and sea ice have been the subject of much research among geographers over the past several decades. At winter peaks in spatial extent, snow covers approximately 46 million km$^2$ of the Northern Hemisphere landmass, while sea ice covers 14–16 million km$^2$ of the Arctic Ocean and 17–20 km$^2$ of Antarctica's Southern Ocean. Recent interest in snow cover and sea ice has stemmed from the realization of their significance in climate diagnostics and as potential monitors and instruments of global climate change. While studies of large-scale snow cover and sea ice dominate research activities, traditional small-scale studies of snow as a freshwater source, flood threat, and avalanche danger has also been maintained within geography. Sea-ice cover is a critical component of the climate system as it reduces solar radiation receipt at the Earth's surface by increasing the albedo. Equally important, it reduces the flux of heat, moisture, and momentum between the atmosphere and ocean. There is significant concern regarding the effect that potential future warming may have upon the extent and thickness of polar sea ice (Shapiro-Ledley 1993).

Quality snow-cover and sea-ice data have become increasingly valuable to the geographer. Traditional ground-based observations of snow depth provide for very long data records, although the data often require intensive quality control. The Historical Daily Climate Dataset (HDCD; Robinson 1993) includes rigorously quality-controlled daily snow-depth data for approximately 1,000 stations within the United States. The advancement of remote sensing technology, and its application to the spatial problems facing a geographer, have promoted the use of visible satellite imagery in the monitoring of snow-cover extent on regional-to-global scales. Taken together, ground-based and remotely sensed snow-cover products have been at the center of numerous geographic studies of snow-cover extent variability, reflecting climate variations on various temporal and spatial scales (e.g. Barry *et al.* 1995; Hall *et al.* 2000; Robinson *et al.* 1995; Walsh 1995). During the past decade, the evolution of microwave remote sensing systems has allowed for improved estimation of the physical properties of snow cover, including snow-water equivalence, snow-cover extent, snow depth, and the onset of snow melt (e.g. Hall *et al.* 1996; Sturm *et al.* 1993; Tait *et al.* 1999). When combined with the technology of geographic information systems (GIS), passive microwave data are beginning to be used for climate-change studies within which the amount of available water, the date of peak accumulation, and the associated spatial distribution can be monitored (Goodison and Walker 1993). Frequent cloud cover and long periods of wintertime darkness have made passive microwave instruments essential in monitoring sea ice to produce databases that extend back through the late 1970s. This has yielded numerous studies of interannual variation and trends in sea-ice coverage, thickness, and concentration (e.g. Cavalieri *et al.* 1997; Maslanik *et al.* 1996; Vinnikov *et al.* 1999).

In the area of process-based snow-cover research within geography, the most basic principle continually studied is the radiational effect of snow cover (e.g. Baker *et al.* 1991; Ellis and Leathers 1998). Over the past decade, snow-cover researchers in geography have come fully to appreciate the significant effects of snow cover on large-scale atmospheric temperature patterns. Much climatological research has focused on the synergistic relationship between lower-atmospheric temperature patterns and snow cover on regional to continental scales (e.g. Baker *et al.* 1992; Leathers and Robinson 1993; Leathers *et al.* 1995). As a result, climatologists have become increasingly concerned with the role of snow cover in climate diagnostics and climate change. Research in this area has included study of the influence of snow cover and sea ice on mid-latitude cyclone intensities and trajectories, and the co-variability between snow cover and geopotential height fields and atmospheric teleconnections (e.g. Changnon *et al.* 1993; Clark *et al.* 1999; Robinson and Dewey 1990).

Over the past decade, much of the geographic research associated with the hydrological and mechanical characteristics of snow cover has centered on improving simulation of the operative physical processes. Recent geographic research in the area of snow melt has been dominated by studies designed to improve the quantitative methods behind water-yield forecasting on temporal scales of days to months (e.g. Davis *et al.* 1995; Grundstein and Leathers 1998; Rowe *et al.* 1995). In working toward the goal of improved forecasts, a strong emphasis has been placed on accurately representing and modeling snow-water equivalence (e.g. Marshall *et al.* 1994; Mote and Rowe 1996; Schmidlin *et al.* 1995). Geographic research associated with the mechanics of snow cover has focused on increasing the base of knowledge surrounding the snow avalanche phenomena. Over the past decade, geographers have researched the climatology of avalanches (e.g. Mock and Kay 1992), the characteristics and geological controls of avalanche paths (e.g. Butler and Walsh 1990), the variability of snow and snowpack strength in relation to terrain (e.g. Birkeland *et al.* 1995; Elder 1995), and avalanche forecasting (e.g. McClung and Tweedy 1994).

Clearly, the nature of snow-cover research conducted by geographers across North America is very diverse. Many of the significant relations between snow cover and Earth's climate have been identified in recent years. The association between snow cover and glacier growth and decay is dictated by the mass balance equation, as discussed in the next section.

## Glaciers

The term "glacier" refers to perennial alpine glaciers, ice caps, the major ice sheets of Greenland and Antarctica, and the extensive continental glaciers that repeatedly expanded over the northern parts of North America, Scandinavia, and Europe during recurrent glacial stages. Glaciers respond to regional and global changes in both ambient temperature and the balance between the mass received by snow accumulation and that lost by ablation processes. The observed twentieth-century warming, and the anticipated future warming, raise concerns about future mass balance changes to the Antarctic and Greenland ice sheets that collectively contain about 70 meters of equivalent sea-level rise. Due to their size and slow response times, it is difficult to quantify their current mass balances, although Antarctica's balance is thought to be near zero or slightly positive while Greenland's net balance may be slightly negative (IPCC 2001: ch. 11). Current estimates suggest that Greenland is close to balance at elevations above 2,000m, but ice in many coastal areas has thinned in the last decade, particularly in the southeast (Thomas and PARCA Investigators 2001). Smaller ice caps, glaciers, and rock glaciers may serve as critical harbingers of current climatic change because they respond more quickly to environmental changes (Dyurgerov and Meier 1999). Recent observations indicate that most, if not all, ice fields in the tropics and subtropics are currently experiencing rapid retreat (Hastenrath and Greischer 1997; Thompson *et al.* 2000, and references therein).

The Antarctic and Greenland ice sheets, as well as carefully selected tropical and subtropical ice caps, continuously preserve the annual snowfall and its chemical constituents over many millennia. These frozen archives provide critical information about the Earth's past climatic conditions from areas where few paleoclimatic or meteorological records exist. Ice-core paleoclimate histories fill a critical temporal gap between the shorter, high-resolution records available from corals, tree-rings and lake sediments and the longer, lower-temporal resolution histories from deep ocean cores. Ice-core histories also fill spatial gaps by providing climatic information from the polar regions and from high elevation, remote sites in the tropics and the mid-latitudes. Ice cores from the central part of the Greenland ice sheet reveal large and rapid changes in the North Atlantic climate regime during the Late Glacial Stage (Dansgaard *et al.* 1989; Taylor *et al.* 1993). Ice cores from the Guliya ice cap on the Tibetan Plateau (Thompson *et al.* 1997) confirm that these rapid changes occurred well beyond the confines of the North Atlantic. The recognition that the Earth's climate system is capable of large and abrupt changes is relatively new. The more parochial view tends to consider climate change as a gradual process, proceeding slowly due to the large inertia in the climate system. Ice cores from the South American Andes (Thompson *et al.* 1995, 1998) confirm that the Late Glacial Stage cooling in the tropics was concomitant and comparable in magnitude to that in the mid- and higher latitudes. Additionally, these ice-core histories reveal that the Younger Dryas cold event, centered at 12,600 yr BP, lasting roughly one millennium and first recognized in the North Atlantic region, was also characteristic of the South American climate regime. The Younger Dryas ended concurrently over both South America and the North Atlantic sector.

Delmas *et al.* (1992) provides a comprehensive overview of the spectrum of paleoclimatic information available from ice cores. Due to the low concentrations of many atmospheric constituents in the polar atmosphere, polar ice cores provide information unavailable elsewhere. For example, the dustiness of the global atmosphere during the Late Glacial Stage is revealed by comparison of dust histories from Antarctica and Greenland (Mosley-Thompson and Thompson 1994). Similarly, bipolar comparisons of the excess sulfate histories

(Mosley-Thompson *et al.* 1993) reveal volcanic eruptions capable of perturbing the stratosphere and thereby temporarily reducing global surface temperatures. Finally, the gases trapped within the bubbles of polar ice cores reveal the pre-anthropogenic concentrations of greenhouse gases such as carbon dioxide and methane, and conclusively demonstrate human modification of atmosphere chemistry by the burning of fossil fuels (Barnola *et al.* 1991).

## Permafrost and Periglacial Geomorphology

Several significant events have occurred in the past decade in the field of geocryology. First, two topic-specific books were published that supplement Washburn's (1980) classic *Geocryology: A Survey of Periglacial Processes and Environments*. In 1989, Peter Williams and Michael Smith of Carleton University published *The Frozen Earth: Fundamentals of Geocryology*. The productive partnership between soil physics (Williams) and geography (Smith) is reflected in their approach, which is soundly based on thermodynamic principles and supported by extensive field and laboratory research. French's (1996) second edition of *The Periglacial Environment* is a survey text covering modern and past (Pleistocene) processes and landforms.

A second significant event took place in summer 1998 when Canada was host to the Seventh International Conference on Permafrost. Sponsored by the International Permafrost Association, the conference proceedings have historically provided an important outlet for geocryological research. North American geographers were well represented, and the plenary talk was given by Chris Burn, professor of geography at Carleton University.

A third event of note was the publication in 1992 of the Proceedings of the 22nd Annual Binghamton Symposium in Geomorphology. Edited by geographers John Dixon (Arkansas) and Athol Abrahams (SUNY-Buffalo), *Periglacial Geomorphology* contains fourteen chapters, of which the senior author of eleven is a geographer. Indeed, fifteen of the twenty-three contributors are geographers and two-thirds of these are from American universities.

A final significant event relates to the establishment of a quarterly journal devoted to geocryology, *Permafrost and Periglacial Processes*. Although it is specialized and has a worldwide subscription of only 200, it constitutes the single most concentrated outlet for geocryological research in North America and Eurasia. An occasional special issue covers such topics as cryosols and, most recently, periglacial cryostratigraphy, paleoenvironments, and processes.

Process-based geomorphological and surficial studies constitute an important research component in the community (Thorn 1992). The purpose is to understand and quantify fundamental physical and chemical processes in the periglacial environment. As such, these include evaluating the impact of aeolian sediment transport (Lewkowicz 1998), coastal and deltaic processes (Walker 1991, 1998), and the potential impact of rising sea levels on coastal zones (Walker 1992). Hydrologic studies address sediment transport (Lewkowicz and Wolfe 1994), discharge (Caine 1996), nivation and snowbank hydrology (Lewkowicz and Harry 1991) and solute transport in alpine streams (Caine and Thurman 1990). Although most of the field sites are from higher latitudes including the Antarctic (Hall 1993), other studies have been conducted in alpine regions of Canada (Harris 1994) and the Tibetan Plateau (Wang and French 1994). Clark and Schmidlin (1992) and Marsh (1998) provide reviews of relic periglacial landforms in the eastern United States.

A major emphasis in process-based geomorphology is associated with mass movement in periglacial regions. This includes creep (Harris *et al.* 1993), solifluction (Smith 1992), active-layer detachment slides and rapid mass movement (Lewkowicz and Hartshorn 1998).

The unique set of landforms characteristic of periglacial environments has been the focus of a number of process-based field studies. Perhaps the best known are the publications of J. R. Mackay addressing the formation and characteristics of pingos in the Tuktoyaktuk region of northwestern Canada. These studies cover a period of nearly forty years, and recent summaries of unique long-term observations and field experiments are now available (Mackay 1998). The growth mechanisms, internal structure, and chemical properties of palsas and related frost mounds have been reviewed by Nelson *et al.* (1992). Pediments (French and Harry 1992) and cryoplanation terraces (Nelson 1998) have been analyzed for formative process and climatic significance, as have thaw lakes (Burn 1992).

A large number of studies have focused on processes in the permafrost and active layer. Mackay (1992) evaluated the frequency and patterns of ground cracking and the development of ice-wedge polygons in tundra (Mackay 1997). Burn (1997) has examined the near-surface cryostratigraphy for paleoenvironmental reconstruction in the western Arctic coastal region of

Canada. The importance of cryostructures in evaluating the regional history and cryoprocesses has been demonstrated by Murton and French (1994) in the same region.

Considerable effort has been devoted to the study of heat-transfer processes in the active layer and upper permafrost (Nelson *et al.* 1993). The primary goal is to identify the factors that determine active layer thaw and permafrost stability, so as to make more realistic predictions given a regional warming scenario. These include site-specific studies to model conductive and nonconductive heat-transfer processes (Hinkel *et al.* 1997; Outcalt *et al.* 1990) and to estimate soil thermal properties (Allard and Fortier 1990). Field studies have quantified the impact of surface disruption by fire (Burn 1998) and forest clearing (Nicholas and Hinkel 1996) on permafrost degradation.

Studies of the seasonal development of the active layer at the scale of regional watersheds (Nelson *et al.* 1997) and estimates of scale-dependent thaw depth variability (Nelson *et al.* 1998) reflect an effort to extrapolate plot results to the regional scale. At a more extensive areal and longer temporal scale, a concerted effort has been made to understand the impact of global climatic change in periglacial environments (Smith and Riseborough 1996; Woo *et al.* 1992) and to model the potential impact of climatic warming on permafrost stability (Anisimov *et al.* 1997).

## Toward the New Millenium

The Cryosphere Specialty Group (CSG) was formally organized at the 1997 meeting of the AAG in Fort Worth, Texas. The initiative was largely the result of efforts by H. Jesse Walker to "foster communication between practitioners dealing with the various elements of the cryosphere, to establish linkages with related organizations, and to enhance research on and teaching of cryospheric topics" (Bylaws of the CSG of the AAG 1998). As such, it is a topical and regional specialty group that includes those geographers who might otherwise refer to themselves as climatologists, hydrologists, or geomorphologists.

Researchers focusing on Earth's cryosphere have a promising future within geography. The field is still relatively young and practitioners are favorably positioned to provide needed information on the unique processes that characterize this large and varied portion of the earth. These insights are also essential to improve understanding of the global climate system, its past variations, and potential future changes. Therefore, as a subdiscipline, cryospheric research will continue to be of increasing importance to its parent disciplines of hydrology, climatology, and geomorphology.

For snow-cover researchers in geography, the beginning of the twenty-first century will likely see a continuation of the increasing demand for knowledge of the synergistic relationship between snow cover and Earth's atmosphere on the larger spatial scales. The use of satellite-derived snow-cover products is expected to increase during the next several decades as data records lengthen and additional sensing platforms are launched. Improvements in satellite technology should promote regular monitoring of the physical properties of snow cover, particularly the water content, and representation of snow cover via quantitative modeling. From one-dimensional snow-melt models to three-dimensional GCMs, the recognition of snow cover as a significant global climate component, water source, flood threat, and avalanche danger should be enhanced through geographic research in the early years of the twenty-first century.

In the field of glacier research, the future will likely continue to focus on obtaining and interpreting high-resolution ice core records. The results from the Greenland Ice Sheet Projects (GISP) indicate that significant temperature oscillations occur at decadal to sub-decadal scales, although no forcing mechanism has been unambiguously identified. Future projects will likely include further sampling of high-latitude ice sheets and glaciers, and temperate glaciers in both hemispheres to determine interhemispheric synchronicity. Since high-quality ice-core records serve as repositories of atmospheric gases and particulates, they can be used to model the evolution of atmospheric chemistry and atmosphere–ocean dynamics, and to validate GCM models.

Research in periglacial geomorphology will continue to emphasize field-based projects to quantify mass and energy fluxes. Given that many periglacial processes operate at relatively slow rates or, in some cases, at high rates over very short time-periods, long-term efforts to monitor and model these processes in remote areas are required. In addition to collecting baseline data, much of the effort will concentrate on understanding the impact of climate change and human activity on process rates. Further research will be directed toward extrapolating site-specific results to larger regions and across longer time-frames. In this effort, digital databases including digital elevation models (DEMs), vegetation atlases, and ground ice maps will ultimately prove invaluable to developing and validating coupled terrestrial-atmospheric-hydrologic-vegetation models.

Several unifying trends in cryogenic research can be identified. First, a concerted effort is underway to develop cryospheric databases. The intent is to collect and organize relevant historical data, and to provide a repository for the wealth of digital data currently being collected by automated sensors. This information is then organized and made available to the community through a website. To a large degree, this effort has been spearheaded at the national and international levels by Roger Barry, Director of the World Data Center-A for Glaciology/National Snow and Ice Data Center (NSIDC), the archive for cryospheric data (Clark and Barry 1998).

Second, there is an increased emphasis on numerical modeling of temporal and spatial patterns. These models are often run on a GIS platform and utilize remotely sensed imagery or algorithms to spatially extrapolate site-specific measurements. For this reason, the issues of scaling and scale-dependant variability are likely to have high research priority in the near future. Data collections such as those discussed above will be instrumental in these efforts.

Finally, following the general trend in science, geocryologists are becoming more interdisciplinary in their outlook. This creates an opportunity for practitioners to promote and demonstrate the utility of cryospheric research as it relates to regional and global issues. Although the importance of glaciers as recorders and harbingers of climate change is well known to the international community of earth scientists, the role of permafrost has been notably neglected. This oversight also extends to the GCM modeling efforts, which often lack a realistic permafrost component. The situation can only be rectified by participating in national and international workshops and organizations (e.g. IPCC and the WMO), and by targeting prominent journals for dissemination of important findings. Similarly, cryosphere geographers must advocate and promote the importance and utility of discipline-specific perspectives in addressing the issues as we enter the twenty-first century.

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