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978-0-521-76981-5 - The Global Cryosphere: Past, Present and Future
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Excerpt
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1 Introduction

1.1 Definition and extent

The *cryosphere* is the term which collectively describes the portions of the Earth's surface where water is in its frozen state – snow cover, glaciers, ice sheets and shelves, freshwater ice, sea ice, icebergs, permafrost, and ground ice. The word *kryos* is Greek meaning icy cold. Dobrowolski (1923, p.2; Barry *et al*. (2011)) introduced the term cryosphere and this usage was elaborated by Shumskii (1964, pp. 445–55) and by Reinwarth and Stäblein (1972). Dobrowolski and Shumskii included atmospheric ice, but this has generally been excluded. The cryosphere is an integral part of the global climate system. It has important linkages and feedbacks with the atmosphere and hydrosphere that are generated through its effects on surface energy and on moisture fluxes, by releasing large amounts of freshwater when snow or ice melts (which affects thermohaline oceanic circulations), and by locking up freshwater when they freeze. In other words, the cryosphere affects atmospheric processes such as clouds and precipitation, and surface hydrology through changes in the amount of fresh water on lands and oceans. Slaymaker and Kelly (2006) published a study of the cryosphere in the context of global change, while Bamber and Payne (2004) detailed the mass balance of glaciers, ice sheets, and sea ice. The discipline of *glaciology* encompasses the scientific study of snow, floating ice, and glaciers, while the study of permafrost (*cryopedology*) has largely developed independently.

In a report on the International Polar Year, March 2007–March 2009, the World Meteorological Organization (2009) identified the following important foci of cryospheric research: rapid climate change in the Arctic and in parts of the Antarctic; diminishing snow and ice worldwide (sea ice, glaciers, ice sheets, snow cover, permafrost); the contribution of the great ice sheets to sea-level rise and the role of subglacial environments in controlling ice-sheet dynamics; and methane release to the atmosphere from melting permafrost. These topics will be discussed, but in each case we first survey the basic characteristics and processes at work for each cryospheric element. We also consider the past cryosphere throughout geological time and model simulations of future cryospheric states and their significance. In the concluding chapter, practical applications of snow and ice research are presented. We begin by considering the dimensions of the cryosphere.

Dimensions of the cryosphere

Table 1.1 shows the major characteristics of the components of the cryosphere.

Figure 1.1 illustrates the global distribution of these components.

Table 1.1 Areal and volumetric extent of major components of the cryosphere (updated after Goodison *et al.*, 1999).

Component	Area (10^6 km^2)	Ice volume (10^6 km^3)	Sea level equivalent (m)[a]
LAND SNOW COVER[b]			
Northern Hemisphere			
Late January	46.5	0.002	
Late August	3.9		
Southern Hemisphere			
Late July	0.85		
Early May	0.07		
SEA ICE			
Northern Hemisphere			
Late March	14.0 [c]	0.05	
Early September	6.0 [c]	0.02	
Southern Hemisphere			
Late September	15.0 [d]	0.02	
Late February	2.0 [d]	0.002	
PERMAFROST (underlying the exposed land surface, excluding Antarctica and S. Hemisphere high mountains)			
Continuous [e]	10.69	0.0097–0.0250	0.024–0.063
Discontinuous and sporadic	12.10	0.0017–0.0115	0.004–0.028
CONTINENTAL ICE AND ICE SHELVES			
East Antarctica[f]	10.1	21.7	52
West Antarctica[f] and Antarctic Peninsula	2.3	3.0	5
Greenland[g]	1.7	2.85	7.3
Small ice caps and[h] mountain glaciers	0.74	0.24	0.6
Ice shelves[f]	1.5	0.66	

a) Sea level equivalent does not equate directly with potential sea-level rise, as a correction is required for the volume of the Antarctic and Greenland Ice Sheets that are presently below sea level. 400,000 km^3 of ice is equivalent to 1 m of global sea level.
b) Snow cover includes that on land ice, but excludes snow-covered sea ice (Robinson *et al.*, 1995).
c) Actual ice areas, excluding open water. Ice extent ranges between approximately 7.0 and 15.4 × 10^6 km^2 for 1979–2004 (Parkinson *et al.*, 1999a).
d) Actual ice area excluding open water (Gloersen *et al.*, 1993). Ice extent ranges between approximately 3.8 and 18.8 × 10^6 km^2. Southern Hemisphere sea ice is mostly seasonal and generally much thinner than Arctic sea ice.
e) Data calculated using the Digital Circum-Arctic Map of Permafrost and Ground-Ice Conditions (Brown *et al.*, 1998) and the GLOBE-1 km Elevation Data Set (Zhang *et al.*, 1999).
f) Ice-sheet data include only grounded ice. Floating ice shelves, which do not affect sea level, are considered separately (Huybrechts *et al.*, 2000; Drewry *et al.*, 1982; Lythe *et al.*, 2001).
g) Dahl-Jensen *et al.* (2009).
h) Radić and Hock (2010).

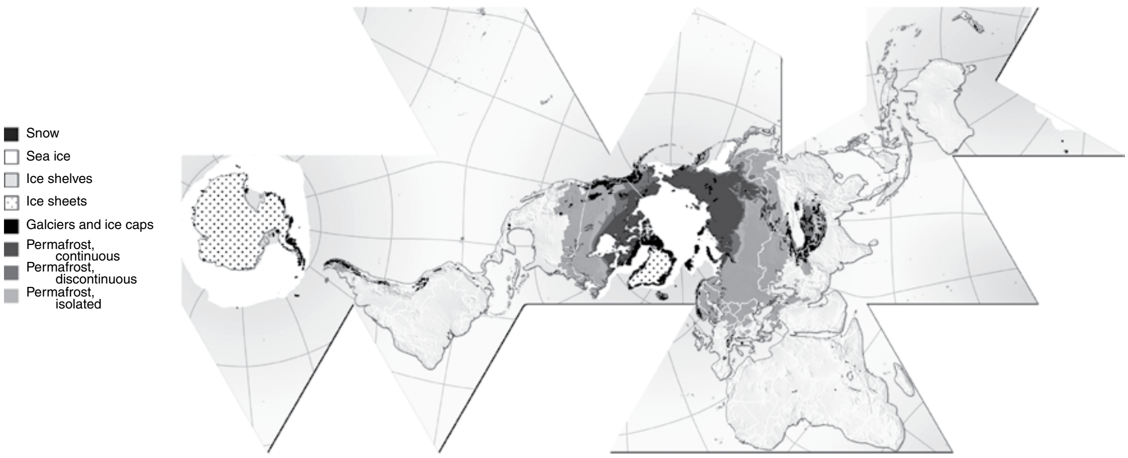

Figure 1.1 The global distribution of the components of the cryosphere (from Hugo Ahlenius, courtesy UNEP/GRID-Arendal, Norway). http://upload.wikimedia.org/wikipedia/commons/b/ba/Cryosphere_Fuller_Projection.png. See color version in plates section.

The cryosphere has seasonally varying components and more permanent features. Snow cover has the second largest extent of any component of the cryosphere, with a mean annual area of approximately 26 million km^2 (Table 1.1). Almost all of the Earth's snow-covered land area is located in the Northern Hemisphere, and temporal variability is dominated by the seasonal cycle. The Northern Hemisphere mean snow-cover extent ranges from ~ 46 million km^2 in January to 3.8 million km^2 in August. Sea ice extent in the Southern Hemisphere varies seasonally by a factor of five, from a minimum of 3–4 million km^2 in February to a maximum of 17–20 million km^2 in September (Gloersen *et al.*, 1993). The seasonal variation is much less in the Northern Hemisphere where the confined nature and high latitudes of the Arctic Ocean result in a much larger perennial ice cover, and the surrounding land limits the equator-ward extent of wintertime ice. The Northern Hemisphere ice extent varies by only a factor of two, from a minimum of 7–9 million km^2 in September to a maximum of 14–16 million km^2 in March during 1979–2004. Subsequent years have seen much smaller areas in late summer.

Ice sheets are the greatest potential source of freshwater, holding approximately 77 percent of the global total. Freshwater in ice bodies corresponds to 65 m of world sea level equivalent, with Antarctica accounting for 90 percent of this and Greenland almost 10 percent. Other ice caps and glaciers account for about 0.5 percent (Table 1.1).

The *World Atlas of Snow and Ice Resources* (Kotlyakov, 1997) provides maps of climatic factors (air temperature, solid precipitation), snow water equivalent, runoff, glacier morphology, mass balance and glacier fluctuations, river freeze-up/break-up, avalanche occurrence, and many other variables. The maps range from global, at a scale 1:60 million, to regional maps at 1:5 million to 1:10 million and local maps of individual glaciers at 1: 25,000 to 1:100,000.

Permafrost (perennially frozen ground) may occur where the mean annual air temperature (MAAT) is less than –1°C and is generally continuous where MAAT is less than –7 °C. It is estimated that permafrost underlies about 22 million km^2 of exposed Northern Hemisphere land areas (Table 1.1), with maximum areal extent between about 60º and 68º N. Its thickness exceeds 600 m along the Arctic coast of northeastern Siberia and Alaska, but permafrost thins and becomes horizontally discontinuous towards the margins. Only about 2 million km^2 consists of actual ground ice ("ice-rich"). The remainder (dry permafrost) is simply soil or rock at subfreezing temperatures. A map of Northern Hemisphere permafrost and ground ice (1:10 million) was published by Brown *et al*. (2001) and is available electronically at: http://nsidc.org/data/ggd318.html

Seasonally frozen ground, not included in Table 1.1, covers a larger expanse of the globe than snow cover. Its depth and distribution varies as a function of air temperature, snow depth and vegetation cover, ground moisture, and aspect. Hence it can exhibit high temporal and spatial variability. The area of seasonally frozen ground in the Northern Hemisphere is approximately 55 million km^2 or 58 percent of the land area in the hemisphere (Zhang *et al*., 2003b).

Ice (see **Note 1.1**) also forms on rivers and lakes in response to seasonal cooling. The freeze-up/break-up processes respond to large-scale and local weather factors, producing considerable inter-annual variability in the dates of appearance and disappearance of the ice. Long series of lake-ice observations can serve as a climatic indicator; and freeze-up and break-up trends may provide a convenient integrated and seasonally specific index of climatic perturbations. The total area of ice-covered lakes and rivers is not accurately known and hence this element has not been included in Table 1.1.

1.2 The role of the cryosphere in the climate system

The elements of the cryosphere play several critical roles in the climate system (Barry, 1987; 2002b). The primary one operates through the ice–albedo feedback mechanism. This concerns the expansion of snow and ice cover increasing the albedo, thereby increasing the reflected solar radiation and lowering the temperature, thus enabling the ice and snow cover to expand further. At the present day this effect is working in the opposite direction with the shrinkage of snow and ice cover lowering the albedo and increasing the absorption of solar radiation, thereby raising the temperature and further reducing the snow and ice cover. On a global scale the ice–albedo effect amplifies climate sensitivity by about 25–40 percent (depending on cloudiness changes).

A second major influence is the insulation of the land surface by snow cover and of the ocean (as well as lakes and rivers) by floating ice. This insulation greatly modifies the temperature regime in the underlying land or water. The difference in the temperature of air overlying bare ground versus snow-covered ground is of the order of 10 °C based on winter measurements in the Great Plains of North America. The absence of snow cover could mean higher mean-annual surface air temperature, but severe wintertime cooling, and a substantial increase in permafrost areas over high latitude regions of the Northern Hemisphere such as Siberia (Vavrus, 2007).

A third effect is on the hydrological cycle due to the storage of water in snow cover, glaciers, ice caps, and ice sheets and associated delays in freshwater runoff. The time scales involved range from weeks to months in the case of snow cover, decades to centuries for glaciers and ice caps, to 10^5–10^6 years in the case of ice sheets and permafrost. The more permanent features of the cryosphere have accordingly a great influence on eustatic changes in global sea level (see Table 1.1). A 1 mm rise in eustatic sea level requires the melting of 360 Gt of ice.

A fourth effect is related to the latent heat involved in phase changes of ice/water. This applies to all elements of the cryosphere. It is estimated, for example, that a 10 cm snow cover over England has a latent heat of fusion of 10^{15} kJ; melting the Greenland Ice Sheet would require ~10^{21} kJ. Ohmura (1987) calculated that the melting of ice since the Last Glacial Maximum about 20 ka accounted for 26–39 × 10^3 MJ m^{-2}, of similar magnitude to the total energy stored in the climate system (30–60 × 10^3 MJ m^{-2}).

A fifth effect is caused by seasonally frozen ground and permafrost modulating water and energy fluxes, and the exchange of carbon (especially methane), between the land and the atmosphere.

1.3 The organization of cryospheric observations and research

The organization of cryospheric data began during the International Geophysical Year (IGY), 1957–1958, with the establishment of the World Data Center (WDC) system.

World Data Centers for Glaciology were designated in the United States, the Soviet Union, and the United Kingdom. In 1976, World Data Center-A for Glaciology was transferred from the US Geological Survey in Tacoma, WA to the National Oceanic and Atmospheric Administration (NOAA) in Boulder, CO, where it has subsequently been operated by the University of Colorado (Barry, 2002a). The scope of its operations expanded to address data on all forms of snow and ice and in 1981 the National Environmental Satellite Data and Information Service (NESDIS) of NOAA designated a National Snow and Ice Data Center (NSIDC). Its financial support was greatly augmented by contracts and grants from the National Aeronautics and Space Agency (NASA) and the National Science Foundation. Roger G. Barry served as Director from 1976 until 2008 and was succeeded by Mark Serreze. Details on its data holdings and research activities may be found at: http://nsidc.org. World Data Centre-C for Glaciology addresses bibliographic data and is operated by the Scott Polar Research Institute at Cambridge, UK. World Data Center-D for Glaciology was established at the Laboratory for Glaciology and Geocryology, Lanzhou, China in 1986. The letter designations were dropped in 1999 and in 2009 the International Council of Science (ICSU) decided to convert the WDC system into a World Data System. This is not yet operational but in the interim the WDCs continue to function as before.

Over the last few years, major advances have occurred in the organization of snow and ice observations and research. Initially, the organization took place within the various cryospheric subfields (snow, avalanches, glaciers and ice sheets, freshwater ice, sea ice, and permafrost). Then, beginning in the 1990s, the Global Climate Observing System (GCOS), and its partners the Global Ocean Observing System (GOOS) and Global Terrestrial Observing System (GTOS), defined Essential Climate Variables (ECVs) (Barry, 1995; GCOS, 2004). For the cryosphere, these include snow cover, glaciers, permafrost, and sea ice. Global Terrestrial Networks (GTN) were specified for glaciers (GTN-G) and permafrost (GTN-P) (http://gosic.org/ios/GTOS_observing_system.asp).

At a higher level, the Integrated Global Observing System (IGOS) initiated the preparation of a report on a cryosphere theme (Key *et al.*, 2007) which documented the available and needed cryospheric data sets. In May 2007, the 15th Congress of the World Meteorological Organization (WMO) received a proposal from Canada to create a Global Cryosphere Watch (GCW), analogous to the Global Atmosphere Watch (GAW). The GCW is now in a planning stage seeking to identify the necessary steps to implement it (http://igos-cryosphere.org/documents.html).

In July 2007, at the XXIVth General Assembly of the International Union of Geophysics and Geodetics (IUGG) in Perugia, Italy, the IUGG Council launched the International Association of Cryospheric Sciences (IACS) as the eighth IUGG Association. This superseded the International Commission for Snow and Ice (ICSI) (Radok, 1997, Jones, 2008). The IACS has the following five divisions: snow and avalanches; glaciers and ice sheets; marine and freshwater ice; cryosphere, atmosphere and climate; and planetary and other ices of the solar system (http://www.iugg.org/associations/iacs.php).

The International Glaciological Society (IGS) – successor to the British Glaciological Society originally founded in 1936 – is based in Cambridge, England. It organizes international conferences on all topics addressed by glaciology and publishes the *Journal of Glaciology* and the *Annals of Glaciology*; the latter contains papers presented at IGS-sponsored conferences. Other journals include the online-only journal of the European Geophysical Society, *The Cryosphere*, *Cold Regions Science and Technology, Zeitschrif für Gletscherkunde und Glaziologie, Seppyo* published by the Japanese Society of Snow and Ice, *Sneg i Lyod* (snow and ice), a successor to *Materialy Glatsiologicheskhikh Issledovanni* (in Russian), published by the Russian Academy of Sciences, Institute of Geography, and the *Journal of Glaciology and Cryopedology* (in Chinese), published by the Lanzhou Institute of Glaciology. Snow and ice research is, however, published in a wide variety of disciplinary and interdisciplinary journals, as shown by the references (pp. 358–459).

On the research side, the World Climate Research Programme (WCRP) established a Climate and Cryosphere (CliC) Project in 2000 (Allison *et al.*, 2001; Barry, 2003) that has four thematic areas – interactions between the atmosphere, snow and land, interactions between land ice and sea level, interactions between sea ice, oceans, and the atmosphere, and cryosphere–ocean/cryosphere–atmosphere interactions on a global scale (http://clic.npolar.no). The CliC project is directed by a Science Steering Group and regularly organizes workshops and conferences.

Grassl (1999) presented an overview of international research programs and groups that have contributed observations or modeling studies of the cryosphere and its elements.

1.4 Remote sensing of the cryosphere

Cryospheric science has benefitted enormously from the ready availability of satellite data since the mid 1960s. We will summarize briefly the main instruments that have operated and some of their applications. Further details are provided in the relevant chapters.

The hemispheric analysis of snow cover extent began in October 1966 from NOAA's polar orbiting Very High Resolution Radiometer (VHRR) and continued with the use of the Advanced VHRR (AVHRR) and other visible-band satellite data. Global snow cover maps are now available from the Moderate Resolution Imaging Spectroradiometer (MODIS) on Terra (February 2000–present) and Aqua (July 2002–present). In December 1972, NASA launched the Electrically Scanning Microwave Radiometer (ESMR) on Nimbus 5 enabling all-weather mapping of sea ice extent. In October 1978, the Scanning Multichannel Microwave Radiometer (SMMR) launched on Nimbus 7 allowed sea ice concentrations and snow water equivalent to be delimited. The SMMR operated until August 1987 and records have continued to the present with the Special Sensor Microwave Imager (SSM/I) on Defense Meteorological Satellite Program (DMSP) satellites. The Advanced Microwave Scanning Radiometer – Earth observing system (AMSR-E) on board the Aqua satellite provides higher spatial resolution (http://weather.msfc.nasa.gov/AMSR/).

The Landsat series began in 1972 and in April 1999 Landsat 7 was launched. The Multispectral Scanner (MSS) with 80 m resolution operated through the mid 1990s, but with Landsat 4 (1982), and Landsat 5 (1984), the Thematic Mapper (TM) with 30 m resolution came into use. With Landsat 7 launched in April 1999, the Enhanced TM (ETM) could provide data at 15 to 30 m resolution. Landsat data have been widely used for mapping mountain glaciers. Together with 15 m resolution data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument (http://asterweb.jpl.nasa.gov/asterhome/) aboard the Terra satellite, outlines for over 93,000 glaciers have been compiled into the database of the Global Land Ice Measurement from Space (GLIMS) project at the NSIDC.

Extensive synthetic aperture radar (SAR) data have been obtained since the 1990s. The European Space Agency's (ESA) Earth Remote Sensing (ERS)-1 active microwave instrument operated between 1992–1996 and ERS-2 has been operating since 1996. The available time series has been used to determine ice sheet mass balances. The Canadian RADARSAT-1 sensor has been providing SAR coverage of Arctic sea ice since 1995. In 1997 RADARSAT was rotated so that the first high-resolution mapping of the entire Antarctic continent could be performed. The RADARSAT-II mission launched in late 2007, which carries a C-band SAR offering multiple modes of operation including quad-polarization, ensures the continuity and improvement of SAR coverage of Arctic sea ice. The NASA scatterometer on QuikSCAT has operated since 1999 providing another view of sea ice extent.

ERS radar altimetry has been used to estimate ice thickness in both polar regions. In 1997 interferometry with SAR was used to obtain ice velocity vectors over the East Antarctic ice streams. NASA's Geoscience Laser Altimeter System (GLAS) on the Ice, Cloud, and land Elevation Satellite (ICESat) was used to measure ice sheet elevations and changes in elevation, as well as sea ice freeboard from February 2003 through November 2009. Changes in mass balance of the two major ice sheets have been derived directly from the Gravity Recovery and Climate Experiment (GRACE) of NASA launched in March 2002. In February 2010 the European Space Agency (ESA) launched the Earth Explorer CryoSat mission, carrying a SAR Interferometric Radar Altimeter (SIRAL). The radar altimeter is dedicated to precise monitoring of changes in the thickness of sea ice in the polar oceans and variations in the thickness of the Greenland and Antarctic Ice Sheets.

NOTE 1.1

Ice: ice is the solid phase, usually crystalline, of water. The word derives from Old English *is*, which has Germanic roots. There are other ices – carbon dioxide ice (dry ice), ammonia ice, and methane ice – but these will not concern us here. Ice is transparent or an opaque bluish-white color depending on the presence of impurities or air inclusions. Light reflecting from ice often appears blue, because ice absorbs more of the red frequencies than the blue ones. Ice at atmospheric pressure is approximately nine percent less dense than liquid water. Water is the only known non-metallic substance to expand when it freezes.

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PART I

THE TERRESTRIAL CRYOSPHERE

The terrestrial cryosphere forms the largest element of the overall cryosphere of the Earth (Table 1.1). It embraces seasonal snow cover (including avalanches), glaciers and ice caps, and the two large ice sheets of Greenland and Antarctica. It also includes perennially and seasonally frozen ground and freshwater ice in lakes and rivers. Each of these major components is treated in separate chapters.