

# 1 INTRODUCTION TO THE CRYOSPHERE

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In this place, nostalgia  
roams, patient as slow  
hands on skin, transparent  
as melt-water. Nights are light  
and long. Shadows settle  
on the shoulders of air.  
Time steps out of line  
here, stops to thaw  
the frozen hearts of icebergs.  
Sleep isn't always easy in this place  
where the sun stays up all night  
and silence has a voice.  
—Claire Beynon, “At Home in Antarctica”

EARTH SURFACE TEMPERATURES ARE CLOSE TO THE triple point of water, 273.16 K, the temperature at which water vapor, liquid water, and ice coexist in thermodynamic equilibrium. Indeed, water is the only substance on Earth that is found naturally in all three of its phases. Approximately 35% of the world experiences temperatures below the triple point at some time in the year, including about half of Earth's land mass, promoting frozen water at Earth's surface. The global

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cryosphere encompasses all aspects of this frozen realm, including glaciers and ice sheets, sea ice, lake and river ice, permafrost, seasonal snow, and ice crystals in the atmosphere.

Because temperatures oscillate about the freezing point over much of the Earth, the cryosphere is particularly sensitive to changes in global mean temperature. In a tight coupling that represents one of the strongest feedback systems on the planet, global climate is also directly affected by the state of the cryosphere. Earth temperatures are primarily governed by the net radiation that is available from the Sun. Because solar variability is modest on annual to million-year timescales (less than 1% of the solar constant), the single most dynamic control of net radiation is the global albedo—the planetary reflectivity—which is heavily influenced by the areal extent of snow and ice covering the Earth. The simple but illuminating global climate models of Mikhail Budyko and William Sellers explored this feedback in the late 1960s, demonstrating the delicate balance between Earth's climate and cryosphere.

## GEOGRAPHY OF EARTH'S SNOW AND ICE

Perennial ice covers 10.8% of Earth's land surface (table 1.1 and figure 1.1), with most of this ice stored in the great polar ice sheets in Greenland and Antarctica. Smaller glaciers and icefields are numerous—the global population is estimated at more than 200,000—but these ice masses cover a relatively small area of the landscape. An additional 15.4% of Earth's land surface is covered by

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**Table 1.1**  
Area and Volume of the Global Cryosphere

<i>Perennial Ice</i>						
<i>Location</i>	<i>Area</i> ( $10^6 \text{ km}^2$ )		<i>Volume</i> ( $10^6 \text{ km}^3$ )	<i>Sea Level Equivalent</i> (m) <sup>a</sup>		
Greenland ice sheet	1.7		2.9	7.1		
Antarctic ice sheet <sup>b</sup>	13.3		25.4	56.2		
Mountain glaciers <sup>c</sup>	1.1		0.22–0.38	0.56–0.97		
Permafrost	22.8		0.01–0.04	0.03–0.10		
<i>Snow and Sea Ice</i>						
<i>Type and Hemisphere</i>	<i>Area</i> ( $10^6 \text{ km}^2$ )			<i>Extent</i> <sup>d</sup> ( $10^6 \text{ km}^2$ )		
	<i>Minimum</i>	<i>Maximum</i>	<i>Mean</i>	<i>Minimum</i>	<i>Maximum</i>	<i>Mean</i>
<i>Sea ice</i>						
Northern	4.8	13.6	9.8	6.6	15.5	11.8
Southern	1.9	14.5	8.7	3.0	18.8	12.0
<i>Snow</i>						
Northern				3.1	46.7	24.9
Southern				13.9	15.1	14.3

*Note:* Sea ice data is from January 1979 to March 2011, and Northern Hemisphere snow data is from November 1966 to March 2011.

<sup>a</sup>Sea level equivalent is the increase in global average eustatic sea level that would occur if all of this ice was transferred to the oceans.

<sup>b</sup>Includes marine-based (floating) ice shelves, but excludes peripheral icefields.

<sup>c</sup>Mountain glaciers and polar ice caps, excluding the Greenland and Antarctic ice sheets but including dynamically independent icefields peripheral to each ice sheet (see chapter 6).

<sup>d</sup>*Extent* is the total area of the region experiencing snow or ice cover. For sea ice, this includes all satellite pixels (with a resolution of ca.  $625 \text{ km}^2$ ) with an ice concentration of at least 15%; the remainder of the area in a pixel can be land or open water. Snow extent is defined by the edge of the region with near-continuous snow cover; there can be snow-free patches within this region.

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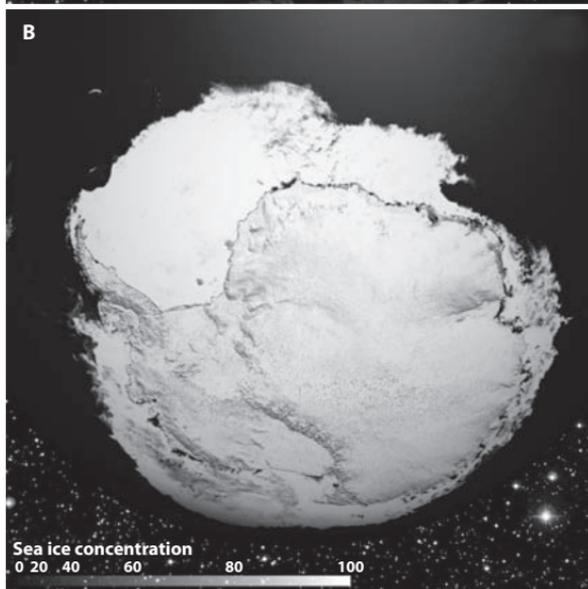
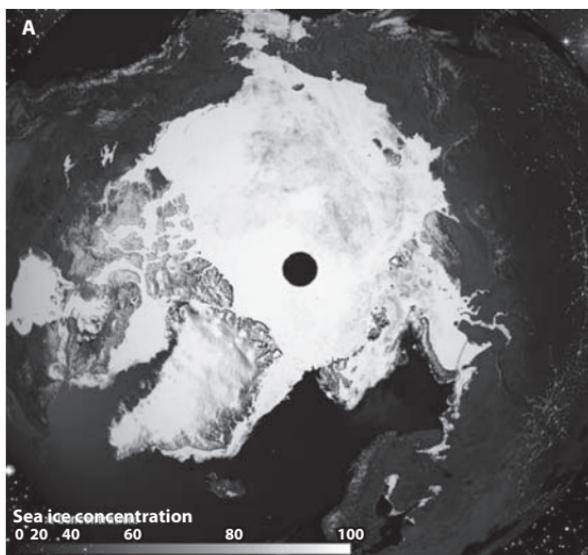
permafrost: frozen ground that ranges from a few meters to hundreds of meters deep.

In contrast to this permanent ice, seasonal snow and ice fluctuate dramatically. Snow cover is the most variable element of the cryosphere. From 1966 to 2011, the Northern Hemisphere winter snow cover reached an average maximum extent of  $46.7 \times 10^6$  km<sup>2</sup>: almost half of the Northern Hemisphere land mass (figure 1.3). There is almost complete loss of this snow each summer, with permanent snow cover limited to the interior of Greenland and the accumulation areas of other high-altitude and polar ice caps.

Because the Southern Hemisphere continents are situated at lower latitudes (excepting Antarctica), southern snow cover is less extensive. It is also less studied, with satellite composite images of total snow-covered area available only since 2000. The South American Andes, high elevations of southeastern Australia, much of New Zealand, and the islands off of Antarctica all experience seasonal snow, as do the high peaks in tropical East Africa. Based on the July 0°C isotherm, the total area of this maximum snow cover is estimated to be  $1.2 \times 10^6$  km<sup>2</sup>, with most of this snow residing in the Patagonian icefields

Figure 1.1. Global (a) Arctic and (b) Antarctic sea ice cover, February 1, 2011. Also shown are the Greenland and Antarctic Ice Sheets. Data provided by the National Center for Environmental Prediction/NOAA and the U.S. National Snow and Ice Data Center. Images from *The Cryosphere Today*, University of Illinois at Urbana-Champaign (<http://arctic.atmos.uiuc.edu/cryosphere/>).

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of South America. Combined with the permanent blanket of snow over Antarctica, this gives a peak Southern Hemisphere terrestrial snow cover of  $15.1 \times 10^6$  km<sup>2</sup>, approximately one-third that of the Northern Hemisphere.

There is less of a seasonal cycle for the Southern Hemisphere snowpack, as most of Antarctica is too cold to experience summer melting. Snows are perennial across the frozen continent, with melting confined to the coastal periphery. As a tangential but delightful consequence of this, earthshine is exceptionally bright in December and January, when the Sun is sojourning in the Southern Hemisphere and reflected sunlight from Antarctica adds to the solar illumination of the Moon. In a sense, everyone in the world can see the Antarctic snows in the lunar orb.

The white blanket that spreads over the land surface each winter has a direct parallel in the high-latitude oceans, where sea ice forms a thin veneer that effectively transforms water to land for much of the year. Figure 1.2 illustrates a “field” of snow-covered ice floes aligned by the wind during sea-ice breakup in early summer (June 2005). Sea ice is made up of a combination of first-year and multiyear ice. First-year ice forms anew from in situ freezing of seawater each year. Multiyear ice has survived at least one summer melt season, persevering through two main mechanisms: (i) some ice remains at high latitudes as a result of being landfast, stuck within a channel or bay, or cycled within ocean gyres that trap rather than export the ice; (ii) ice floes ridge or pile up in areas of convergence, producing thick, resilient ice.

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Figure 1.2. Snow-covered sea ice floes and melt ponds during spring breakup, Button Bay (Hudson Bay), Manitoba, Canada. The ice floes are aligned by the wind. Scientific instrumentation (a ground-based microwave scatterometer) is visible in the center of the picture. (Photograph by John Yackel.)

These mechanisms often operate in concert and are more prevalent in the Arctic than the Antarctic, resulting in a thicker ice cover and more multiyear ice in the north.

Relative to the continents, seasonal cycles of ice in the oceans are more hemispherically symmetric (table 1.1), although there are interesting north–south contrasts. Passive microwave remote sensing for the period 1979–2011 indicates an average minimum Northern Hemisphere ice area of  $4.8 \times 10^6 \text{ km}^2$ , typically reached in September. Maximum ice cover is usually attained in late winter, with an average March ice-covered area of  $13.6 \times 10^6 \text{ km}^2$ . Sea

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ice in the Southern Ocean has a larger seasonal cycle, with relatively little multiyear ice. Annual mean sea-ice cover in the south is  $8.7 \times 10^6 \text{ km}^2$ , varying from  $1.9 \times 10^6 \text{ km}^2$  (February) to  $14.5 \times 10^6 \text{ km}^2$  (September).

Combining the hemispheres, global sea-ice area is relatively constant, varying from  $15.4 \times 10^6$  to  $20.8 \times 10^6 \text{ km}^2$ , with a minimum in February and a peak in November. Global ice extent—the area of the oceans containing sea ice, as demarcated by the ice edge—varies from  $18.4 \times 10^6$  to  $27.3 \times 10^6 \text{ km}^2$ . Mean annual global ice area and extent are  $18.5 \times 10^6$  and  $23.9 \times 10^6 \text{ km}^2$ .

Combining the snow and sea-ice cover, the seasonal cryosphere blankets  $59 \times 10^6$  and  $30 \times 10^6 \text{ km}^2$  in the Northern Hemisphere and Southern Hemisphere, respectively. Figure 1.3 illustrates the geographic distribution. Additional elements of the cryosphere include seasonally frozen ground and freshwater (river and lake) ice.

This snow and ice cover influences the surface albedo and energy budget of the planet fluxes of heat and moisture between the atmosphere and surface and the patterns of circulation in the ocean and atmosphere. Each element of the global cryosphere interacts with and affects weather, climate, and society, and each is highly sensitive to global climate change.

This book explores the physics and characteristics of the global cryosphere, with an emphasis on cryosphere–climate interactions. Chapter 2 presents an overview of the structure of snow and ice in its various manifestations on Earth, including the material properties that

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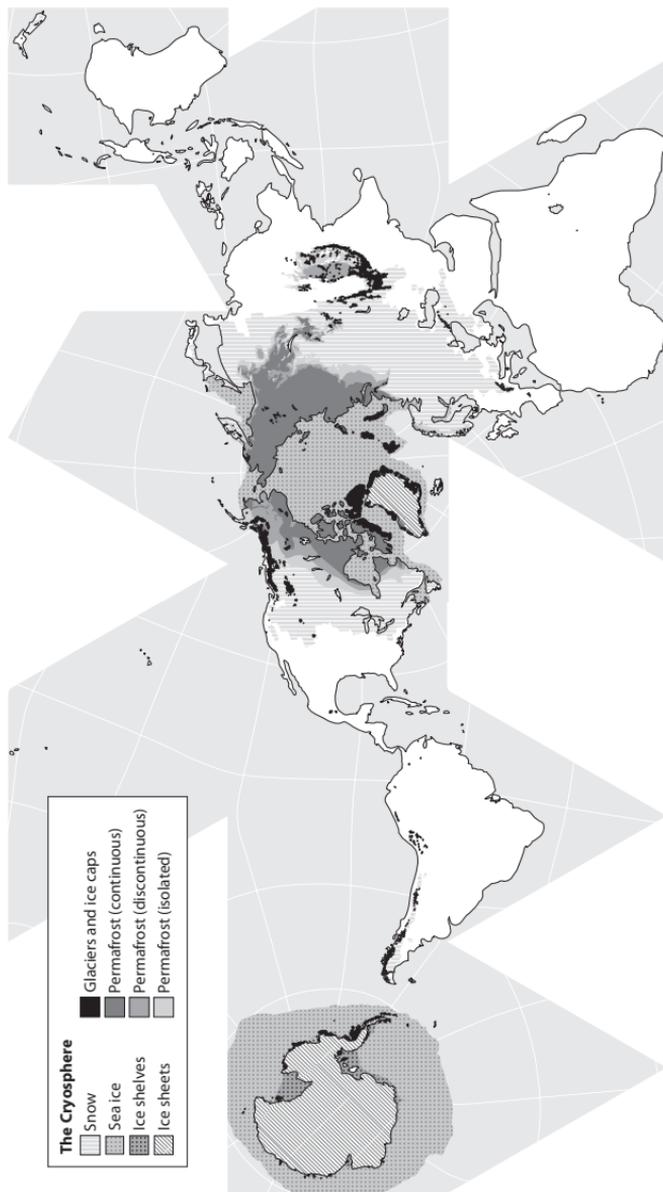


Figure 1.3. Areal coverage of global glaciers, permafrost, and winter snow and sea ice cover. (Image adapted from the UNEP/GRID-Arendal Global Outlook for Ice and Snow (2007). Original map design and cartography by Hugo Ahlenius; <http://maps.grida.no/go/graphic/the-cryosphere-world-map>.)

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make it such a peculiar and intriguing substance. The thermodynamics of snow and ice are examined in chapter 3. Chapters 4–7 provide an overview of Earth’s different cryospheric realms: seasonal snow, freshwater ice, sea ice, glaciers, ice sheets, and permafrost. I discuss cryosphere–climate processes and the role of the cryosphere in the global climate system in chapter 8. Chapter 9 concludes with a perspective of cryospheric changes throughout Earth history, including a brief overview of cryospheric vulnerability to recent and future climate warming.

This offers an entry to some of the important aspects of snow and ice in the global climate system. It is not possible to provide a comprehensive overview within the pages of this volume, so I confine the focus to a basic physical introduction to the cryosphere and cryosphere–climate interactions. Many fascinating aspects of the cryosphere, such as avalanche science, snow and ice microphysics, ice cores, and cold regions geomorphology, are overlooked. Interested readers will find many excellent texts that delve deeper into snow and ice science, and suggestions for further reading for each chapter are provided in the Annotated Bibliography.