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Introduction

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Snow cover is a part of the "cryosphere," which traces its origins to the Greek word *kryos* for frost. The cryosphere collectively includes those portions of the earth system where water is in a solid form and includes sea ice, river and lake ice, glaciers, ice caps and ice sheets, frozen ground (including permafrost), and snow cover. The cryosphere is an integral part of the global climate system with important linkages and feedbacks generated through its influence on surface energy and moisture fluxes, precipitation, hydrology, and atmospheric and oceanic circulation (Fig. 1.1). In terms of spatial extent, snow cover is the second largest component of the cryosphere after seasonally frozen ground (~65 million km^2) with a mean maximum areal extent of 47 million km^2, about 98% of which is located in the Northern Hemisphere where temporal variability is dominated by the seasonal cycle (Fig. 1.2).

1.1 Basic properties of snow

The following discussion of basic snow properties is presented to provide the uninitiated reader with the background to understand the discussion of snow physics and modeling in Chapters 2–4.

Snow originates in clouds at temperatures below the freezing point. As moist air rises, expands and cools, water vapor condenses on minute nuclei to form cloud droplets on the order of 10 microns in radius. When cooled below 0 °C such small droplets do not necessarily freeze and may "super cool" down to −20 °C and occasionally down to −40 °C. Once a droplet has frozen it grows quickly at the expense of the remaining water droplets because of the difference in saturation vapor pressure between ice and water. The form of the initial ice crystal, columnar, platelike, dendritic, etc. (see Fig. 1.3) depends on the temperature at formation, but subsequent

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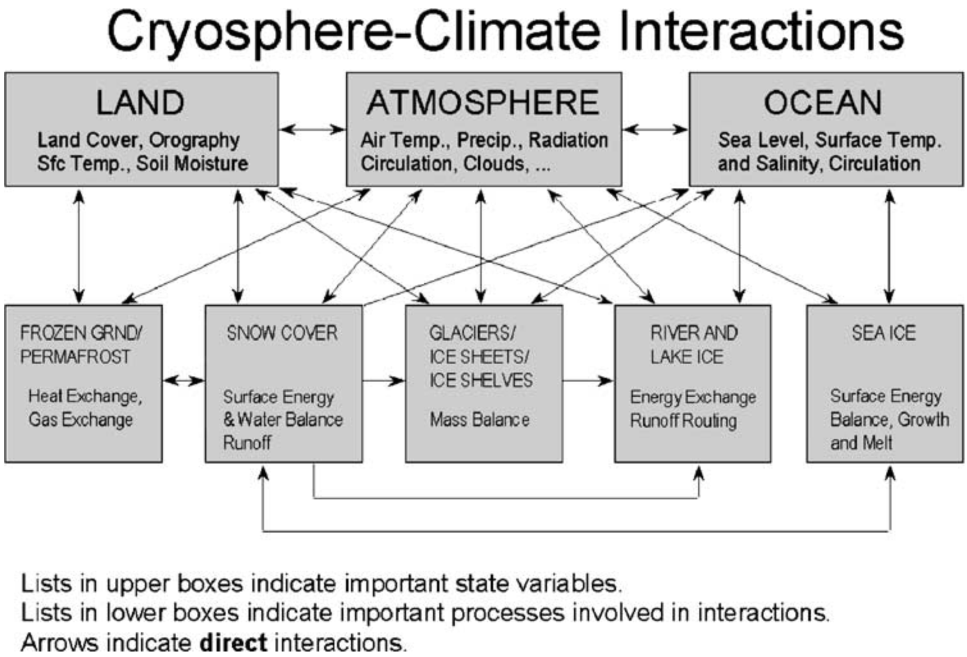

Figure 1.1. Schematic diagram outlining a number of the important interactions between the cryosphere and other major components of the climate system. *Source*: G. Flato, CliC Science and Coordination Plan, 2001.

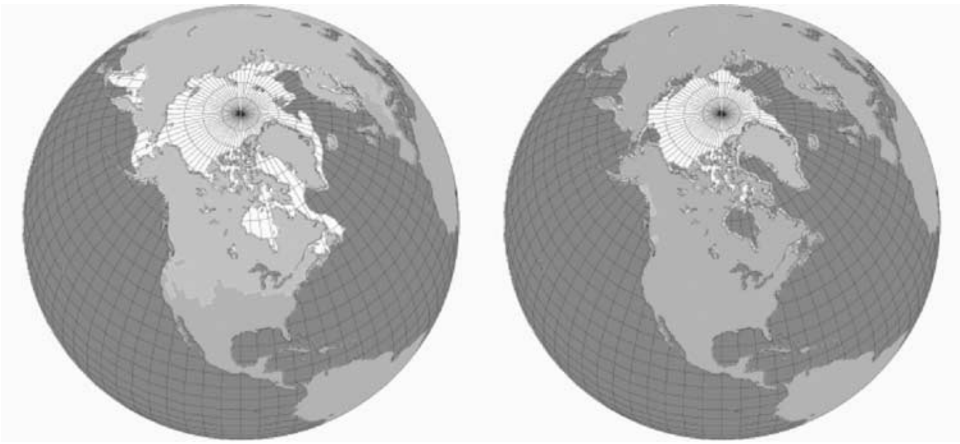

Figure 1.2. Mean seasonal variation in snow (gray) and sea-ice cover (white) between February (left) and August (right) as derived from satellite data. Data from NSIDC "Weekly Snow Cover and Sea Ice Extent," CD-ROM, NSIDC, 1996. (Plate 1.2.)

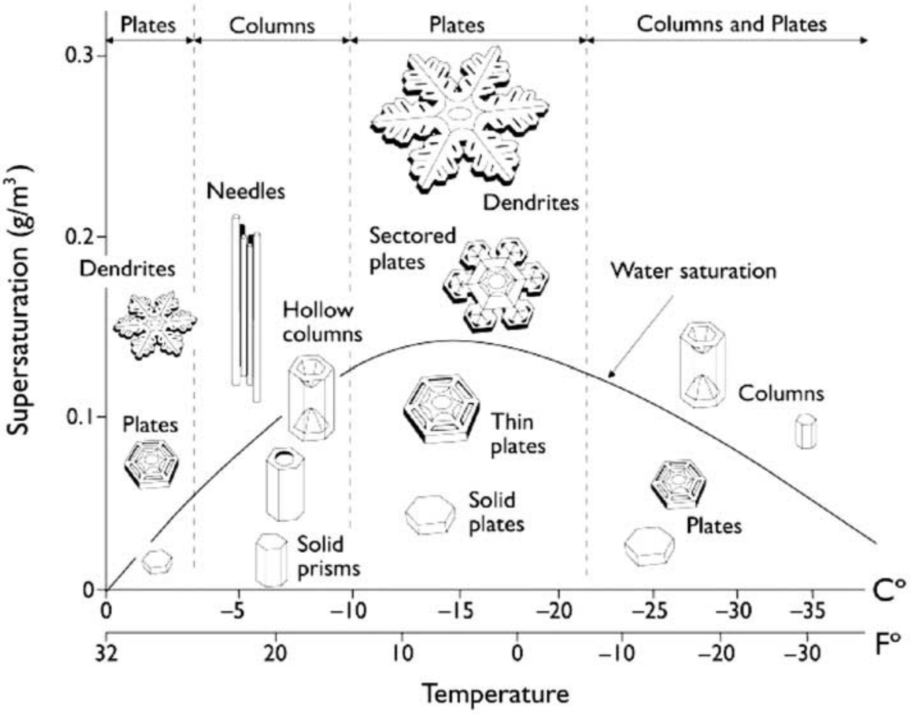

Figure 1.3. Snow crystal morphology diagram showing types of snow crystals that grow at different temperatures and humidity levels, *Source*: Libbrecht, 2003, with permission. Diagram is based on original work by Nakaya (1954).

growth and structural detail also depend on the degree of supersaturation (Hobbs, 1974 and Chapter 2 of this book). During its fall to earth a snow crystal may undergo considerable change due to variations in temperature and humidity with altitude. The character of a surface layer after a snowfall depends on the original form of the crystals and on the weather conditions during deposition. For example, when a snowfall is accompanied by strong winds, crystals are broken into smaller fragments favorable for close packing. After deposition snow may dissipate rapidly by melting or sublimation or it may persist for long periods. If it persists it will undergo metamorphism, changing its grain texture, size, and shape, primarily as a result of the effects of temperature and overburden pressure as it becomes buried by subsequent snowfalls. Snow metamorphism can occur rapidly because the crystals are thermodynamically active due to their large surface area to volume ratio (complex shape) and because their temperature is at, or proportionally close to, the melting temperature. Over the winter the typical snow cover accumulates and develops as a complex layered structure made up of a variety of snow grains, reflecting both the weather and climate conditions prevailing at the time of deposition as well as the persisting influence of metamorphism within the snow cover over time (Armstrong, 1977; Colbeck, 1986; Colbeck *et al.*, 1990 and Chapter 2, Fig. 2.7).

The three basic properties used to describe snow cover are the related parameters of depth, density, and snow water equivalent (SWE). "Snow depth" refers to the thickness or height of snow, typically expressed in centimeters. Maximum snow depths range from a few centimeters in regions with ephemeral snow cover, to several meters in moist cold mountain regions. "Snow density," as with any material, is simply the ratio of mass to volume for a given sample. The standard unit of measurement is kilograms per cubic meter (kg m^{-3}) with typical values for newly fallen snow of 30–150 kg m^{-3} increasing to a maximum seasonal snowpack density of approximately 400–500 kg m^{-3}. However, wind-deposited snow may rapidly achieve densities of 300–400 kg m^{-3} and crusts that form following the refreezing of melting snow may have densities of about 700–800 kg m^{-3}. For reference, the density of pure ice (bubble free) is 917 kg m^{-3} and the density of water is 1000 kg m^{-3}. Thus the bulk of the seasonal snow cover is typically composed of 50 percent or more of air by volume throughout the winter. This simple fact has great significance with respect to the processes of metamorphism that depend directly on the amount of water vapor contained in the air spaces surrounding the snow grains (Armstrong *et al.*, 1993). SWE is the thickness of the layer of water resulting from the melting of the initial volume or thickness of snow and is typically expressed in kg m^{-2} or mm. Further details on these basic snow properties and the instrumentation used to measure them are provided in Chapter 5.

1.2 Importance of snow in the climate system

Several fundamental physical properties of snow modulate energy exchanges between the surface and the atmosphere. The most important properties are the surface reflectance (albedo), the thermal insulating properties of snow, and the ability to change state (latent heat). Physical properties of a snowpack such as crystal structure, density, and liquid water content are also important for transfers of heat and water. These basic properties also determine the mechanical state of the snow cover, which is important for over-snow transportation and avalanche potential. The following paragraphs adapted from the *EOS Science Plan* (Goodison *et al.*, 1999) outline the importance of these properties for the climate system:

The *surface reflectance* of incoming solar radiation is important for the surface energy balance (Wiscombe and Warren, 1981). Typical albedo values for non-melting snow-covered surfaces are high (~80–90%) except in the case of forests (see Table 1.1). The higher albedo for snow causes rapid shifts in surface reflectivity in autumn and spring in high latitudes. However, the overall climatic

Table 1.1 *Typical ranges for surface albedo.*

Fresh, dry snow	0.80–0.95
Old, dry snow	0.70–0.80
Wet snow	0.50–0.70
Melting ice/snow	0.25–0.80
Snow-covered forest	0.25–0.40
Snow-free vegetation/soil	0.10–0.30
Water (high solar elevation)	0.05–0.10

significance is spatially and temporally modulated by cloud cover (planetary albedo is determined principally by cloud cover), and by the small amount of total solar radiation received in high latitudes during winter months. The high reflectivity of snow generates positive feedbacks to surface air temperature through the so-called "snow–albedo feedback," e.g. an initial warming results in a retreat in snow cover, lower albedo, higher absorbed solar energy, and warmer air temperatures. Groisman *et al*. (1994a,b) observed that snow cover exhibited the greatest influence on the earth radiative balance in the spring (April to May) period when incoming solar radiation was greatest over snow-covered areas.

The *thermal properties* of snow also have important climatic consequences. Snow on the ground typically has a density in the range of 100–500 kg m^{-3} and the significant air fraction means snow is very effective at cutting off (or de-coupling) heat and moisture transfers from the ground surface to the overlying atmosphere. The thermal conductivity (a measure of the ability to conduct heat) of fresh snow is $\sim$0.1 W m^{-1} K^{-1} which is 10–20 times lower than values for ice or wet soil. Snow also has important influences on heat flow through ice (e.g. river, lake, or sea ice). The flux of heat through thin ice continues to be substantial until it attains a thickness in excess of 30–40 cm. However, even a small amount of snow on top of the ice will dramatically reduce the heat flux and slow down the rate of ice growth. The insulating effect of snow also has major implications for the hydrological cycle. In non-permafrost regions, the insulating effect of snow is such that only near-surface ground freezes and deep water drainage is uninterrupted (Lynch-Stieglitz, 1994).

The large amount of energy required to melt ice (*the latent heat of fusion*, 3.34×10^5 J kg^{-1} at 0 °C) means that snow retards warming during the melt period. However, the strong static stability of the atmosphere over areas of extensive snow tends to confine the immediate cooling effect to a relatively shallow layer, so that associated atmospheric anomalies are usually short-lived and local to regional in scale (Cohen and Rind, 1991; Cohen, 1994). In some areas of the world such as Eurasia, the cooling associated with a heavy snowpack and moist spring soils is known to play a role in modulating the summer monsoon circulation (e.g.

Vernekar *et al*., 1995). Gutzler and Preston (1997) presented evidence for a similar snow–summer circulation feedback over the southwestern United States.

Snow–climate feedbacks such as the snow–albedo feedback operate over a wide range of spatial and temporal scales and the feedback mechanisms involved are often complex and incompletely understood. A major thrust of recent snow modeling work (see Chapter 4) is the correct representation of important snow processes in climate models in order to properly simulate the response of the climate system to external forcing such as increased greenhouse gases. A review of earlier efforts to model snow–climate interactions and feedbacks was provided by Groisman (in Jones *et al*., 2001).

1.3 Importance of snow in natural and human systems

In addition to their impacts on the climate system, snow-cover variability and change have important consequences for a wide range of natural and human systems. In many semi-arid regions of the world such as central Asia and western North America, runoff from mountain snowpacks represents the major source of water for stream flow and groundwater recharge. For example, over 85% of the annual runoff from the Colorado River basin in the southwestern United States originates as snowmelt. In these areas, snow accumulation is a critical resource for drinking water, irrigation, hydro-electrical generation as well as natural river ecosystems. A series of low snow accumulation years in these areas is typically associated with increased risk of forest fires, widespread crop failure, and difficulties meeting local demand for electricity. Worldwide, it is estimated that over one billion people depend on snow accumulation for water resources.

Jones *et al*. (2001) provided a major review of the role of snow in ecological systems. A primary influence of snow is in moderating winter meteorological conditions within and beneath the snow cover. Soil temperature and soil freezing/thawing processes have a great impact on ecosystem diversity and productivity. Beneath even 30 cm of snow the organisms and soil are well protected from the extreme diurnal temperature fluctuations occurring at the snow surface. Exchanges of carbon, methane, and other gases between the land surface and the atmosphere can also continue during the winter period because of the insulating effect of the snow cover (Sommerfeld *et al*., 1993). Gaseous emissions under the snow may represent a significant part of the annual flux of carbon fixed by photosynthesis. Snow influences on soil temperature are also important for hydrology. When soil moisture freezes, the hydraulic conductivity is reduced leading to either more runoff due to decreased infiltration or higher soil moisture content due to restricted drainage. Knowing whether the soil is frozen is important in predicting surface runoff and spring soil moisture reserves (Zhang and Armstrong, 2001).

Snow cover is also an important recreation and tourism resource in mid-latitudinal mountain regions of the world (e.g. the Rocky Mountains, the Appalachians, and the European Alps). In general, winter tourism in the Rocky Mountains and New England is estimated to provide an economic benefit that exceeds $8 billion (Adams *et al.*, 2004). In contrast, snow can also be a major hazard, causing delays in ground and air transportation, damage to crops and livestock, and accidents, injuries and loss of life during extreme storms. It is estimated that even 5 cm of snowfall in urban areas can increase fuel consumption by 50 percent. In the United States alone the annual cost for snow removal from highways and airport runways exceeds $2 billion with the economic impact of flight delays and airport closures adding another $3.2 billion annually (Adams *et al.*, 2004). McKelvey (1995) provides a history of snow removal and its costs in United States cities. Mergen (1997) and Kirk (1998) provide fascinating coverage of the highly varied and often historically important influences of snow on human activities. In mountainous areas of the world, snow avalanches are an ever-present hazard with the potential for loss of life, property damage, and disruption of transportation. During the period 1985–2005, avalanche fatalities have averaged about 20–30 per year in North America but have averaged approximately 120 per year in the European Alps (McClung and Schaerer, 2006). A National Academy of Sciences/National Research Council report summarized snow avalanche hazards and approaches to mitigation in the United States (Voight *et al.*, 1990).

1.4 Climate change implications

As noted above (Section 1.2) snow-cover extent and temperature are negatively correlated through the snow–albedo feedback mechanism, with the strongest feedbacks operating during the spring period. Chapin *et al.* (2005) showed that pronounced summer warming in Alaska was associated with a lengthening of the snow free season caused by earlier snowmelt. Satellite data suggest that Northern Hemisphere snow-cover extent has decreased by about 5% over the 1966–2004 period (IPCC, 2007), and climate model simulations for the next 100 years suggest an extensive northward retreat of NH snow cover, particularly over Eurasia (Fig. 1.4).

Climate warming impacts on snow cover (e.g. earlier spring melt, shorter snow-cover season, lower peak accumulations, and higher potential for rain-on-snow and thaw events) will have far-reaching effects on the natural and human systems described above. Shallow snow cover at lower elevations in temperate regions is the most sensitive to temperature fluctuations and hence the most likely to experience increased melt (Scherrer *et al.*, 2004; IPCC, 2007). Changes to the snow cover and snow melt regime will have major implications for water resources (e.g. reduced

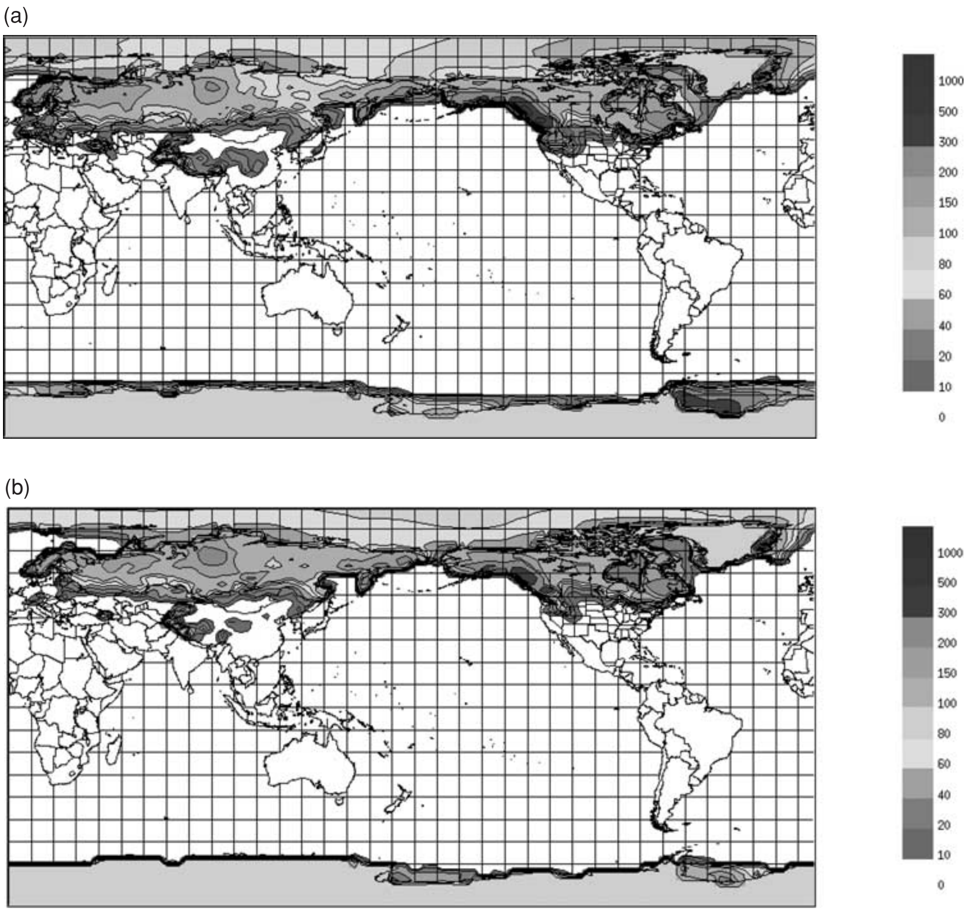

Figure 1.4. Comparison of mean March winter SWE (mm) simulated by the Canadian coupled global climate model (CGCM3) for the 1981–2000 "current climate" period (a) with simulated mean SWE for the 2081–2100 period (b) based on the SRES A2 emission scenario. Data courtesy of the Canadian centre for climate modeling and analysis. (Plate 1.4.)

spring runoff, increased potential for evaporation) and water resource-sensitive industries such as hydro-electric power and agriculture (Barnett *et al.*, 2005). IPCC (1998) provide an assessment of the impacts and vulnerabilities to changes in hydrology and water resources. In mountainous areas, for example, the snow line is likely to rise, but this may be partially compensated by higher precipitation above the freezing level. Ski resorts located in temperate mountain ranges (e.g. western North America, New Zealand, and the European Alps) already experience mean monthly winter temperatures that are only slightly below freezing, and any significant increase in air temperature will adversely impact the length of the ski season. In Austria, for example, it is estimated that an increase in temperature of

1.5 °C will shorten the ski season by about 15 days (Breiling, 1998). Scott *et al.* (2003) showed that improvements in snowmaking capacity reduced the vulnerability of the ski industry in southern Ontario (Canada) to the impact of warmer temperatures.

In summary, snow has substantial impacts, both positive and negative, on the natural environment and human activities. Documenting and understanding these impacts represents an important challenge, and one that is essential for adapting to a changing snow-cover climate.

1.5 Layout of book

It is against this backdrop of impending large-scale changes to snow cover on the surface of the earth that scientists are working to provide new and improved information for decision makers. The essence of this process is captured in this book with a review of the latest understandings of *Physical processes within the snow cover and their parameterization* in Chapter 2, a review of *Snow–atmosphere energy and mass balance* in Chapter 3, a history of snow model development in *Snow-cover parameterizations and modeling* in Chapter 4, and a look at *Snow-cover data: measurement*, *products, and sources* in Chapter 5.

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