1 Snow Cover and the Climate System

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1.1 Introduction

At the end of each winter, large areas in high latitudes and altitudes of both hemispheres are covered by snow. In a few months most of it disappears, only to start building up again in the late autumn (Gutzler and Rosen, 1992; Robinson, Dewey, and Heim, 1993; Groisman et al., 1994a). In many regions, particularly in the Southern Hemisphere, this seasonal expansion of snow cover is restricted by the limits of land masses. In the polar regions, however, the seasonal expansion of sea ice over the ocean allows snow cover to expand, significantly changing the properties of the sea ice (Ledley, 1991). The depth of snow cover varies widely, and in some mountainous regions (e.g., Alps, Rocky Mountains) it can exceed 3 m. The first snow is light and white with a density of around 100 kg m^{-3}. At the end of winter, most of the snow on the ground is much denser (up to 500 kg m^{-3}) and dirtier, and so it loses its whiteness (see Pomeroy and Brun, Chapter 2). The first autumn snowfall, when the daytime temperature remains below freezing, can start the formation of seasonal snow cover, but later advection of warm air and/or solar radiation may melt it. A single weather event can extend continental snowlines equatorward by up to 1,000 km (Lamb, 1955; Cohen and Rind, 1991), although it usually takes a few weeks between the first snowfall and formation of the stable snow cover in high latitudes (e.g., Russia). In lower latitudes (e.g., China, United States) snow cover is more ephemeral and can melt and regrow several times during the winter. After being established, however, feedback processes tend to support the existence of the snow cover, mostly because of the high reflectivity (albedo) that reduces the surface radiation balance and thus the energy available for snowmelt.

Because it covers more than half the Northern Hemispheric land area each year, and it has such varying properties, seasonal snow cover is an important ecological factor in many extratropical regions. Snow cover is a radiative sink. The high shortwave albedo (reflectivity), which, combined with its high thermal emissivity, increases the amount of infrared radiation lost near the earth's surface (Male and Gray, 1981).

The radiative losses are not quickly replaced by heat fluxes from below because of the insulating properties of the snow. These insulating properties are particularly effective at night. For example, the temperature of the upper surface of a 10-cm snow cover may drop by more than 10°C overnight but the temperature of the underlying soil surface may drop by less than 1°C. Snow on the ground, therefore, keeps the near-surface soil relatively warm, preventing it from deep freezing and protecting the root systems of plants from damage. The presence of a sufficiently deep snow cover is vital in many areas to maintain sufficiently warm subnivean temperatures for the winter grain crop. In a similar fashion, snow cover provides a relatively favorable winter habitat for small mammals (e.g., field mice) that are unable to migrate far from their summer homes.

For some species, snowmelt represents the most important environmental perturbation, or stimulus, in the whole year (Hoham and Duval, Chapter 4). Changes in the timing and character of snowmelt (Davies and Vavrus, 1991) will therefore affect biospheric systems within the sphere of influence of the snowmelt regime.

Seasonal snow cover has important effects on ecosystems that are remote from the snow cover itself. For example, the Indian summer monsoon is influenced by the previous season's snow cover in western Eurasia and the Tibetan Plateau (Hahn and Shukla, 1976; Verma, Subramaniam, and Dugam, 1985; Barnett et al., 1989). Indeed, seasonal snow cover is such an important part of the global climate system that it can be argued that *all* ecosystems – around the globe – are indirectly affected by snow cover because of its role as a component of the climate system.

Whether the focus of ecological interest is directed toward populations that are intimately associated with snow cover – as is the case with this volume – or is widened to those ecosystems with a more remote dependence, an understanding of snow cover climatology and its links with the atmosphere are important foundations. This importance is heightened by the prospect of a large-scale climate change. Satellite observations of Northern Hemisphere snow cover are available from 1966 to present (Dewey and Heim, 1981, 1982; Robinson et al., 1993). These records show a strong inverse link between Northern Hemisphere snow cover and temperature (Figure 1.1). The same conclusions can be drawn from the analysis of paleoclimatic data and sensitivity experiments with global climate models (Budyko and Izrael, 1991; Mokhov, 1984; Cohen, 1994). The prospect of a continuing enhanced greenhouse gas effect (Intergovernmental Panel on Climate Change [IPCC], 1996) has clear implications for snow cover ecosystems. The timing, depth, internal structure, and extent of seasonal snow cover will change, affecting these ecosystems. Because of the spatial scale of the two-way interactions between snow cover and the atmosphere, a changing climate, coupled with a

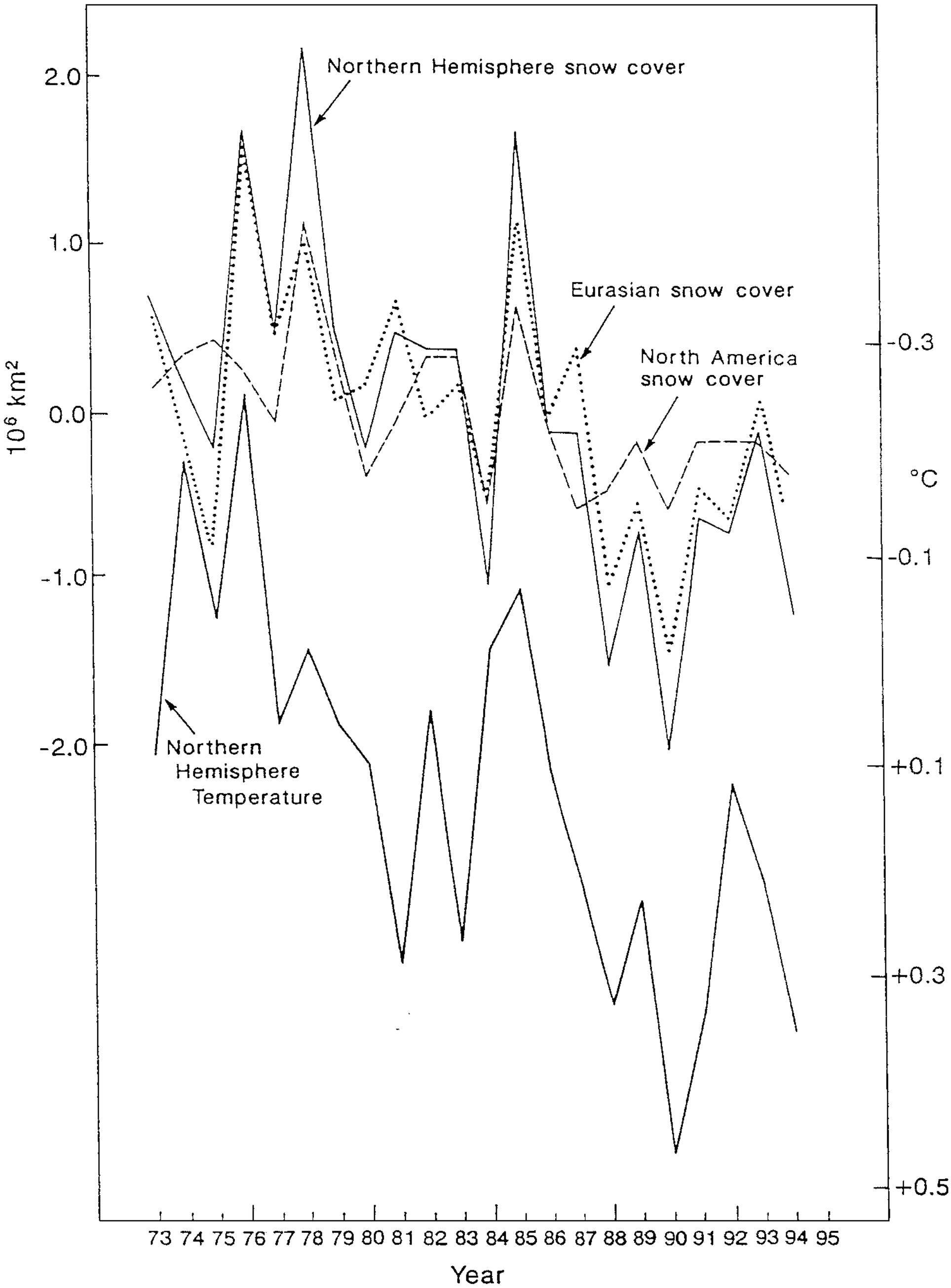


Figure 1.1. Annual snow cover variations derived from satellite shortwave observations (anomalies from the 1973–1994 means) for Northern Hemisphere, North America, Eurasia (left-hand scale), together with Northern Hemisphere combined land and sea temperature (anomalies from 1951–1981 mean) (right-hand scale; inverted). (Matson, 1986; Ropelewski, 1993, updated; courtesy of D. Garrett, National Oceanic and Atmospheric Administration, National Weather Service, Washington, DC; Jones, 1994.)

changing snow cover, has ecological implications beyond the geographical confines of snow cover.

In addition to being an important forcing factor in atmospheric change, the two-way interaction means that snow cover is a useful detector and monitor of this change (Barry, 1985; Schlesinger, 1986). Changes in snow cover extent, amount, and density, when reliably detected, will also indicate a change in the global hydrological cycle and ecosystems over the entire extratropical land area (Watson, Zinyowera, and Moss, 1996). Consequently, in this chapter, in addition to considering the nature of snow cover–atmosphere interactions, we also describe snow cover observations.

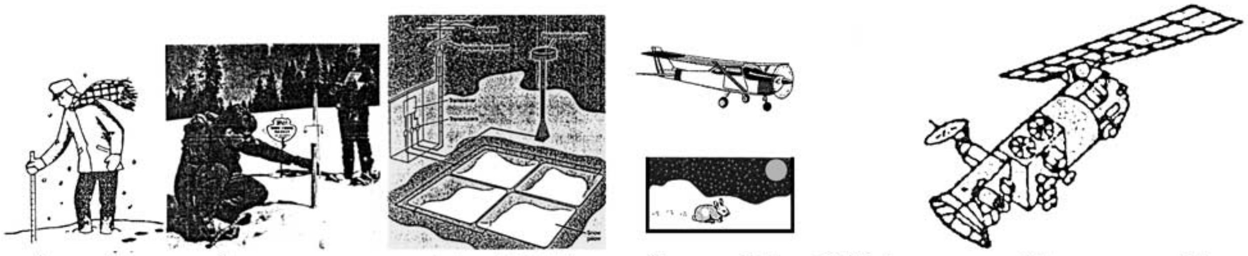
1.2 Snow Cover Observations and Data Sources

The importance of snow cover information for various human activities was a reason for early establishment of snow observation systems. In the first millennium, snow cages installed upstream in the mountains were used for flood forecasting in China (Biswas, 1970). Currently, several northern countries have accumulated a century-long time series of in situ snow cover observations (Jackson, 1978; Pfister, 1985; Mestcherskaya, Belyankina, and Golod, 1995; Brown and Goodison, 1996; Hughes and Robinson, 1996; Easterling et al., 1997). Initially, in the first generation of observations, snow on the ground was characterised only by snow depth measurements. These measurements were made by snow sticks. In some countries (e.g., Russia) snow depth measurements were made separately at field and forest locations to account for significant differences in snow accumulation. The need to know the water equivalent of snowpack, and a requirement for a better spatial representativeness of snow monitoring, led to the establishment of snow course observations. This is when an observer surveys a transect, collecting many samples of snowpack and recording its amount and microphysical properties (type, density, presence of crust, etc.). This arduous procedure proved to be reliable for many practical reasons in agro-meteorology and hydrology and stays mostly intact in many countries. The first digital data sets of snow courses recently became available from the World Data Center for Glaciology (National Snow and Ice Data Center [NSIDC], 1996). Nineteen years ago, in the western United States and Alaska, snow courses were gradually replaced by an automated system (SNOTEL) (Rallison, 1981) that currently delivers the point snowpack water equivalent information from more than 600 remote sites in the Rockies and Cordilleras (Aguado et al., 1992; Cayan, 1996; Redmond and Schaefer, 1997).

The major uncertainties relating to ground-based (in situ) observations concern the initial accuracy of point or snow-course measurements and the consequent up-scaling to area averages (Sevruk, 1992). A recent discussion of the requirements for and techniques of ground-based snow observations is provided by Pomeroy and Gray (1995). In windblown areas, snow tends to accumulate in forested areas and ravines, leaving open plain areas with less snow than in the forest. Snow melts on exposed sites more quickly than in protected locations and can be blown away or sublimate during snow flurries (Vershinina and Volchenko, 1974; Pomeroy and Jones, 1996; Mestcherskaya et al., 1995). In mountainous regions, snow accumulation is extremely heterogeneous because of variable wind exposure, orographic effects, and adiabatic effects, which influence snowmelt (Pomeroy and Brun, Chapter 2). This makes the spatial generalization of snow cover information a difficult task. Moreover, it is impossible to derive regional information in relatively remote areas (e.g., northern Canada, Siberia), where in situ measurements are rare. Consequently, remote techniques provide the only feasible method of acquiring regional snow cover distributions (Karl et al., 1989). Remote techniques can be divided into airborne and satellite-borne methods. Advantages and disadvantages of the different techniques are shown in Figure 1.2.

Airborne passive observations are based on the fact that soundings of natural γ-radiation from the land surface are decreased by water (liquid or frozen) overlying the land and in the upper 20 cm of the soil. Hence, comparative soundings made before snowfall and before snowmelt will give estimates of the total amount of water equivalent of snow (SWE) on the ground, combined with upper soil water, along a flight route (Kogan, Nazarov, and Fridman, 1969; Peck, Carrol, and Vandmark, 1980). A limitation is the separation of the above- and below-ground water proportions. In spite of this and other shortcomings (cf. Jones and Carroll, 1983; Glynn et al., 1988; Carroll and Carroll, 1989), the method has proved useful for a wide range of users. Estimates of snow cover extent and SWE with a mean areal accuracy of approximately 10 mm are routinely provided in parts of North America (Carroll, 1995).

Satellite-borne observations of snow cover are made in the shortwave (visible and near-infrared) and microwave bands. The data in Figure 1.1 were derived from satellite shortwave measurements. The original data consist of digitised maps of weekly snow cover extent prepared from National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellites, supplemented by GOES and METEOSAT observations (Matson and Wiesnet, 1981; Wiesnet et al., 1987; Dewey and Heim, 1981, 1982; Matson, 1986; Ropelewski, 1993; Robinson, Keimig, and Dewey, 1991; Robinson et al., 1993). Although the observations started in 1966, the series is not regarded as being



	IN SITU MEASUREMENTS			AIRBORNE	SATELLITE-BORNE MEASUREMENTS		
	Snow rulers	**Snow courses**	**Automated stations**	**Gamma-radiation sounding**	**Visible imagery**	**Microwave passive sounding**	**Microwave active sounding**
Measured snow characte-ristic	Snow depth at a given point	Snow depth and snow water equivalent; SWE for each landscape and average over the region	SWE at a given point	SWE along the flight track	Snow cover extent over the grid cell	Snow cover extent and SWE over the grid cell	SWE over the grid cell
Advan-tages	Long time series (up to 100 years)	Most reliable source of the regional SWE; relatively long time series	Can be installed in remote areas; "labor-free"	Provides reliable regional estimates of SWE	Global coverage; relatively long time series (since 1966)	Global coverage; superior spatial (25 km x 25 km) and temporal (daily) resolution	Superior spatial resolution (up to tens of meters)
Disadvan-tages	Often are not representative of the surrounding terrain; do not provide SWE estimates	Extremely laborious technique	Problems with spatial representativeness of the site can be developed with time; short time series	Application of the technique requires high investments; short time series	Time increment (week) does not satisfy most of the users; does not provide SWE estimates	Absence of reliable universal algorithm of the SWE evaluation; short time series (since 1987)	Absence of reliable universal algorithm of the SWE evaluation; there are no products with global coverage
Key reference	Gray & Male (1981)	Gray & Male (1981)	Rallison (1981)	Carroll (1995)	Robinson et al. (1993)	Armstrong (1993)	Matzler and Schanda (1984)

Figure 1.2. Advantages and disadvantages of different observation techniques (SWE = snow water equivalent).

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homogeneous until the end of 1972 (Robinson et al., 1993). The spatial resolution of the data varies by latitude, ranging from a grid cell resolution of 20,643 km^2 at high latitudes to 42,394 km^2 at lower latitudes. The proportion of the Northern Hemisphere land area that has experienced snow cover during at least one week in the last 20 Januarys amounts to 55 percent (54.2×10^6 km^2). On average, 23 percent of the entire global surface (50 percent of the land) is permanently or temporarily covered by snow during the year (Sevruk, 1992).

Microwave measurements of snow cover extent and water equivalent have been made by sensors aboard geostationary satellites since 1987 (Weaver, Morris, and Barry, 1987; Barry, 1991). The scattering of microwave energy emitted by the ground is related to the amount of dry snow (number of grains). Although melting snow is indistinguishable from wet bare soil in these observations, passive microwave remote sensing does have a considerable advantage of being operable in nearly all weather conditions and in darkness. Active microwave remote sensing has the potential for very high resolution (tens of meters) snow cover observation, but the delivery of acceptable SWE observations is problematic (Matzler and Schanda, 1984; Leconte, 1993). Although snow cover extent observations are now regarded as reliable (Ferraro et al., 1994; Basist and Grody, 1994), sadly, there are continuing problems with reliable indications of SWE with these measurements.

The old "surface-based" observational network remains a viable and important component of the snow observing system that should not be replaced by the satellite network. They are, in fact, complementary. Notwithstanding current problems, satellite-based snow cover/depth observations probably will cover the future needs of many users of snow data (Armstrong, 1993; Ferraro et al., 1994). Economics and scientific objectives now require a merging of all available snow information in one superior enhanced data set. It is necessary to ensure homogeneity in the transfer from the old surface-based network to the new observational network during this merging. This transfer has not gone smoothly (Robinson et al., 1991; Armstrong, 1993; Barry et al., 1994), but the effort is still under way.

The situation with snow data availability is changing quickly and, no doubt, after this book is published new sources will have emerged. At the moment, processing of some very large data sets (e.g., raw satellite images) requires too many computer resources for many users. Nevertheless, current snow data availability is itemised as follows:

- A large global archive (more than 8,000 stations worldwide) of mean monthly precipitation (including frozen precipitation) has been accumulated in

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the Global Historical Climatology Network data set (Vose et al., 1992, Peterson and Vose, 1997). This is available free of charge via the Carbon Dioxide Information Analysis Center, Oak Ridge, Tennessee, USA. In the former Soviet Union (FSU), each station (10,000 of them) has an adjustment set to produce unbiased long-term values of precipitation. Data from 622 Soviet stations (adjustments and monthly values) through 1999 are now available through World Data Center-A, Asheville, North Carolina, USA.

- Recently (1991–1992) a data set containing daily snow data for a selected set of first-order stations, together with specially selected snow data for the heavily wooded areas totally 284 stations of the FSU, has been received by the U.S. National Climatic Data Center (NCDC) from Russia in the framework of the USA-FSU bilateral exchange of data and was quality controlled at the NSIDC in Boulder, Colorado. These data are currently available on CD-ROM (NSIDC, 2000). A large data set of snow depth and SWE has been collected over the entire FSU at the State Hydrological Institute (St. Petersburg, Russia), Institute of Geography of the Russian Academy of Science (Moscow), and World Data Center-B (Obninsk, Russia). More than half these data (more than 1,300 stations) are currently available from NSIDC.
- A data set of daily snow depth measurements from 195 stations in the United States is available free of charge from the U.S. Carbon Dioxide Information Data Center (Easterling et al., 1997).
- A database comprising parallel observations of snowfall, its water equivalent, and snow on the ground for 335 Canadian stations has been collected at World Data Center-A (up to 1992) and is available from the Meteorological Service of Canada, Downsview, Ontario.
- A snow course data set for the western United States for the past 50 years is currently computerised (Shafer and Huddleston, 1986).
- The Historical Daily Climatic Data Set for the United States, for more than 1,000 stations with snowdepth and snowfall data before 1988, has been assembled and quality controlled (Robinson, 1988, 1993). These data are available at the NCDC and may be augmented for the last years from the "Summary of the Day," the U.S. national archive that is currently being updated and quality controlled at the Data Operations Branch of the NCDC (Groisman, Sun, and Heim, 2000).

- Alaska is virtually a snow laboratory because it contains maritime, continental, and Arctic climates in close proximity. The data from intensive snow-related studies (snow courses, passive microwave sounding, studies of microphysics of snow on the ground) performed during the past 30 years by the Geophysical Institute of the University of Alaska at Fairbanks (Benson, 1992; Friedman, Benson, and Gleason, 1991) are now in computer form and available to the scientific community.
- European and Asian countries maintain their snow-related data separately. An exception is the North Atlantic Climatological Data Set Project (Frich, Brodsgaard, and Cappelen, 1991; Frich, 1994), an international venture between the meteorological services of eleven countries with a goal of compiling a joint representative archive of reference meteorological data. This project has been completed in 1996.

Each summer the U.S. National Operational Hydrologic Remote Sensing Center/NOAA compiles and distributes a CD-ROM that contains the previous season's airborne and satellite snow data and products for most of North America (Carroll, 1995).

Global snow cover data (visible imagery) are available from NOAA/National Environmental Satellite and Data Service and from the World Data Center for Glaciology. This center provides a wide range of snow-related products from conventional observations and remote sensing, including the unique Global Climatology of Mean Monthly Snow Depth (Schutz and Bregman, 1988).

Special Sersor Microwave/Image products are being prepared for distribution at the World Data Center for Glaciology on CD-ROM.

The U.S. NOAA-NASA Pathfinder Program (NOAA-NASA, 1994) was established to play an integral role in the development of Earth-related data and information systems of these two agencies. All initial projects of this program involve remotely sensed, space-based observations. Two types of these observations (advanced very high-resolution radiometer, and SSM/I) provide snow cover information in visible and near infrared and in the microwave wavelengths, respectively. The progress of this program is associated with the creation of several data services (NASA Distributive Active Archive Centers and NOAA Data Centers) that can be conveniently accessed on the Internet and the World Wide Web. Currently, a significant part of snow cover information is available from these centers. It is expected that, after 1997, most of this information will be readily available to users worldwide.

1.3 Snow Cover Climatology

As indicated previously, relatively reliable global-scale observations have been available only since the early 1970s. From a climatological point of view, the period since then has not been stable. Besides the warming (possibly induced partly by greenhouse gas increases), there have been other climate forcings. The eruptions of El Chichón and Pinatubo injected large amounts of aerosol into the stratosphere (Minnis et al., 1993), and some pronounced El Niño and La Niña events affected the global heat balance (Quinn and Neil, 1992). Some of the warmest years of the century (and possibly for several centuries) have occurred in the period (Bradley and Jones, 1993). This instability needs to be borne in mind when considering global snow cover climatology. It prevents us from using satellite data for precise evaluation of an average climatic state of seasonal snow cover extent. But it helps us use these data for studying the snow cover sensitivity to various external factors as well as for evaluation of internal relationships between snow cover and the other climate variables.

1.3.1 Spatial and Temporal Distributions of Snow Cover Extent

Figure 1.3 (see plate section) shows the seasonal distributions of snow cover extent in the Northern Hemisphere (Groisman et al., 1994a). The snow cover seasons are different from the usual climatological seasons because of the extensive snow cover in March and the relative paucity of snow cover in September. Some regions experience large interannual variability in seasonal snow cover, reflecting large fluctuations and/or systematic changes during the past 20 years (Barnett et al., 1989; Gutzler and Rosen, 1992; Karl et al., 1993; Barry et al., 1994; Groisman et al., 1994a; Groisman, Karl, and Knight, 1994b; Brown, Hughes, and Robinson, 1995). The regions of high variability (Figure 1.4 [see plate section]) were termed snow transient regions by Groisman et al. (1994a). Climatic changes most probably will occur in the snow transient regions and/or in their vicinity; thus, these regions are of special interest because of the strong potential for climate-induced ecosystem impact.

Caution must be exercised when referring to trends over relatively short periods, but the negative trends in Northern Hemispheric, North American, and Eurasian snow cover shown in Figure 1.1 for the period 1973–1994 are all statistically significant at the 0.05 level (Groisman et al., 1994a). Overall, the extent of annual Northern Hemisphere snow cover has declined by around 7 percent over the past 26 years (1973–1998). The correlations with Northern Hemispheric temperatures are –0.67 (Northern Hemisphere), –0.57 (North America), and –0.59 (Eurasia) (all significant at the 0.01 level). The decrease in snow cover has been most pronounced in the April–September