Snow

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The impact of snow on humans and the environment is considerable. Snow covers approximately 30% of the Earth's land surface on a seasonal basis, with additional coverage at high elevations, over polar ice sheets and sea ice. Snow lying on the ground, or on ice influences hydrologic, biologic, chemical, and geologic processes. Snow exerts an impact on activities as diverse as engineering, agriculture, travel, recreation, commerce and safety. In turn, the presence and state of snow are influenced by weather, climate, topography, proximity to water bodies and humankind.

INTRODUCTION

The low heat conductivity, high thermal emissivity, low vapor pressure and high reflectance of snow differ greatly from snow-free land. The accurate forecasting of local daily temperatures, regional climatic anomalies and the location and strength of cyclonic systems relies, in part, on knowledge of the distribution and state of regional snow cover (Walsh and Ross, 1988; Groisman *et al.*, 1994; Clark *et al.*, 1999). Model simulations of climate change show that spatial decreases in snow extent amplify global warming (Meehl and Washington, 1990).

Recent years have seen the availability of more accurate and complete information on the spatial extent and physical state of snow. This is leading to a better understanding of the variability of snowfall and snow cover on annual to decadal scales, of cryosphere–climate interactions, and of the role snow may play in regional and global climate change.

OBSERVING SNOW

Station observations are the primary means of monitoring snowfall, despite the spatial limitations of the global observing network. Data-scarce areas include high latitudes and mountainous regions. Where station density is high, these point measurements provide data of sufficient accuracy for baseline climatologic applications. There is no hemispheric snowfall product derived from station data for either daily or monthly totals.

Ground-based data on snow cover depth are also relatively sparse outside of the lower elevations of the middle latitudes. Included, are station observations made at a single point, and along less abundant, several kilometer long snow courses. Data on the amount of water in a snow pack (water equivalent) are gathered at a very few of the point sites, along snow courses, and by snow pillows that measure snow mass in some mountainous regions.

Visible and passive microwave sensors, on geostationary and polar orbiting satellites, record information used to monitor snow cover on regional to hemispheric scales. Snow cover extent is best identified on visible imagery by recognizing characteristic textured surface features and brightness. Shortcomings include the inability to detect snow cover when solar illumination is low or when skies are cloudy, and the lack of all but the most general information, on pack depth.

The recognition of snow using microwave techniques results from differences in the emissivity of snow-covered and snow-free surfaces across several different frequency ranges. Information on water equivalent can be obtained, although not of the accuracy necessary for climatologic studies. Clouds and low solar illumination are not problems when using microwave data to chart snow cover; however there are difficulties in identifying shallow or wet snow.

SNOW VARIABILITY

The considerable interannual variability of snow makes long-term data sets a necessity when investigating means, trends, low frequency events or interactions of snow with other climatic elements. The standard 30-year climatic normal used for variables such as temperature and precipitation may not be of a sufficient length for realistic cryospheric means. Unfortunately, consistent decades-long data are scarce. Satellite-derived snow maps have been available since the late 1960s. Station data exist for approximately the past century, though of decreasing abundance early on. In all cases, limitations in the collection, quality control, archiving and synthesis of snow data must be considered before applying the data in long-term climatologic investigations.

For the past several decades, weekly maps of Northern Hemisphere snow extent have been produced by US National Oceanic and Atmospheric Administration (NOAA) analysts (Robinson *et al.*, 1993). This constitutes the longest satellite-derived data set of any environmental variable. While produced in a relatively consistent manner since late 1966, original observer inexperience and lower image resolution necessitated a reanalysis of the interval prior to 1972. The earlier period is currently being reanalyzed, but until it is completed, only the time series from 1972 to the present is available for analysis. Microwave records go back to the late 1970s, but studies of time series over this period are just beginning.

According to the NOAA maps, the mean annual Northern Hemisphere snow cover extent is 25.3 million km^2, with 14.7 million km^2 over Eurasia and 10.6 million km^2 over North America (including Greenland). Snow cover was

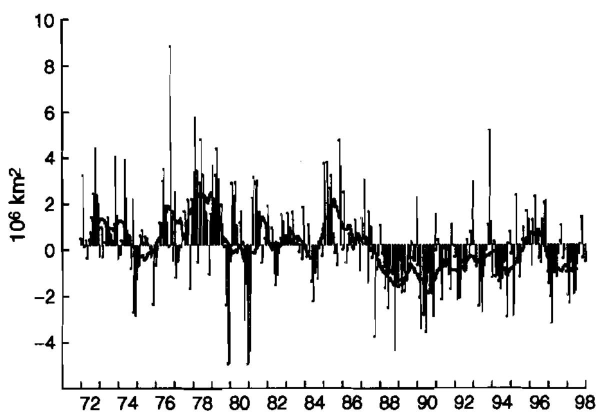

Figure 1 Anomalies of monthly snow cover extent over Northern Hemisphere lands (including Greenland) between January 1972 and December 1998. Also shown are 12-month running anomalies of hemispheric snow extent, plotted on the seventh month of a given interval. Anomalies are calculated from NOAA snow maps. Mean hemispheric snow extent is 25.3 million km^2 for the full period of record. Updates to the time series may be viewed at http://climate.rutgers.edu/snowcover

more extensive in the first half of the satellite record than in the past decade (Figure 1). Between 1972 and 1985, annual means of snow extent fluctuated around a mean of 25.9 million km^2. An abrupt transition occurred in 1986 and 1987, and since then the mean annual extent has been 24.2 million km^2. Monthly anomalies from the long-term mean are most often less than 3 million km^2, however on occasion they are 4 and 5 million km^2, with October 1976 having a positive anomaly of over 8 million km^2.

Recent decreases in snow extent are large during the spring and summer, while winter and fall extents show no statistically significant change. The tendency toward less late-season cover in recent years begins in February. During seven of the first 15 years of record, February snow extent exceeded the January value. This has occurred only once in the past 12 years.

Station records for portions of the Northern Hemisphere continents suggest that spring and early summer snow extents in the past decade may be at their lowest values of the century. Otherwise, seasonal extents in the latter portion of this century exceed those of earlier years. Annual and decadal fluctuations are embedded in this upward trend, and at least over portions of central North America, the variability of snow cover duration has also increased throughout the century (Frei *et al.*, 1999). The increase in snow cover duration in this region is accompanied by statistically significant increases in seasonal snowfall. In recent decades, snowfall has also been heavier to the lee of the North American Great Lakes than earlier in the century (Leathers and Ellis, 1996). These findings are in line with observations from Canada and the former Soviet Union, with all areas appearing to be part of a trend towards increased precipitation over the middle latitudes lands in the Northern Hemisphere (Brown, 2000).

CONCLUSIONS

An increasing body of evidence suggests that snow plays a critical role in the climate system and will continue to be an important climate variable to monitor when assessing climate change. However, there remain many unanswered questions regarding the variability of snow and the long-term representativeness of recent empirical studies of cryosphere–climate interactions, such as links between snow extent and monsoon strength. Additional information is needed over space and time, including better information over sea ice and ice sheets in both hemispheres. Historic station data sets of snowfall and snow cover remain to be collected and analyzed. Recent efforts to integrate visible and microwave satellite and station data must continue for past intervals and future years. Studies need to examine variations in snow water equivalent, and work begun recently to improve model simulations of snow must continue.

Should increasing levels of greenhouse gases result in warmer conditions over the coming decades, it can be expected that the coverage of snow across continental landmasses will decrease, which in turn should enhance the warming. Snow cover is likely to become established later in the fall, and melt sooner in the spring. Areas where snow cover is ephemeral throughout the winter season will see the ground covered less often. Likewise, it is possible that warming will be accompanied by an increased flux of moisture into the high latitudes, resulting in a deeper winter snow pack in some regions, though probably in a shortened snow season.

See also: **Climate Feedbacks**, Volume 1; **Permafrost**, Volume 1; **Sea Ice**, Volume 1.

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