The North American Snowline

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Careening down a mountainous slope, loathing a long, if not impossible, commute home, worrying about the availability of moisture for the germination of crops, remembering a time when "it was up to my knees from December to March." These are just a few of the diverse thoughts, opinions, and memories people have of snow. Falling snow or snow lying on the ground exert an impact on human activities as diverse as engineering, agriculture, travel, recreation, commerce, and safety (Rooney 1967; Snyder *et al.* 1980). Snow influences hydrologic, biologic, chemical, and geologic processes at and near the surface of the earth (Jones and Orville-Thomas 1987). Empirical and modeling studies also show snow cover to have an influential role within the climate system (Barnett *et al.* 1989; Walsh *et al.* 1985). Global models of anthropogenically induced climate change suggest enhanced warming in regions where snow cover is currently ephemeral (Dickinson *et al.* 1987). For this reason, it has been suggested that snow cover might be a useful index for monitoring global climate change (Barry 1985).

Just where and when does snow lie on the ground over the North American continent? I explore this by examining the boundary separating snow-covered from snow-free land. I document the annual march of this snowline equatorward and back to the Arctic using satellite-derived data from the past two decades and station observations to examine the variability of the midwinter snowline over the central United States since the turn of this century.

Delineating the Snowline

The location of the snowline may be determined by observing surface conditions from the ground or from an elevated platform. Most commonly, the former includes integrating observations from a network of official climatologic stations, and the latter involves interpretation of one or a suite of satellite images.

Ground observations of snow cover are commonly made daily, although in some regions (particularly mountainous areas) measurements are made only once or twice a month. While practices vary, if the standard open, level observing site is greater than 50 percent snow covered, snow depth is measured and recorded. With daily observations and a network of stations to draw from, the location of the snowline may be quite accurately determined. However, a series of caveats must be ascribed to the preceding statement. Problems with the delineation of the snowline from surface observations arise: when observers fail to make measurements or do not maintain standard observation practices (Robinson 1989); when drifting makes an accurate assessment of cover difficult; where a sufficiently dense network of stations is absent (for example, mountainous terrain and arctic lands); where significant topographic diversity makes interpolation of snow conditions between stations virtually impossible; and where snow cover is exceedingly patchy. Station observations of snow cover are available over the United States and Canada for the past century, although the number and coverage of these sites increased significantly towards the middle of this century and has remained relatively stable for the past 50 or 60 years.

The delineation of the snowline from aircraft and satellites is achieved by several means. Local snowlines are examined from aircraft photographically as well as by instruments that measure surface-emitted gamma radiation. Regional and continental snowlines are gleaned from visible satellite observations of solar radiation reflected off of the earth's surface and from microwave radiation emitted by the surface. The visible approach has the benefits of being directly interpretable by the human eye and by having imagery with a resolution of 1 kilometer available daily over the entire North American continent. Disadvantages of a visible approach include the inability to monitor surface conditions where clouds are present and where dense vegetation precludes reliable observations of the underlying surface. Low solar illumination is not a significant liability, since most high-latitude regions are snow covered before the diminution of light and remain covered until spring. Charts of snow cover from visible imagery have been available continuously since the late 1960s.

Microwave radiation penetrates winter clouds, permitting an unobstructed signal from the earth's surface to reach a satellite. The discrimination of snow cover is possible mainly because of differences in emissivity between snow-covered and snow-free surfaces. Spatial resolution is on the order of several tens of kilometers, making a detailed delineation of the snowline difficult, particularly where snow is patchy. It is also difficult to identify shallow or wet snow using microwaves, and recognition of snow is a problem where vegetation masks the surface. Microwave-derived snow products have been available since the late 1970s.

The accuracy of delineating the snowline over North America also depends upon the condition of the snow pack. The situation is simplest when snow cover is fresh, as the transition between full cover and snow-free ground commonly occurs over only several kilometers. Charting the snowline where the snow pack has not been replenished for days to weeks is more difficult. With time, the coverage of snow becomes patchy, as a result of drifting and preferential melting on open fields and south-facing slopes. Thus, the width of the transition zone between full cover and snow-free ground may be several tens of kilometers.

In summary, the snowline produced from satellite or station observations will at best be accurate to within a few kilometers (for instance, fresh snow and visible satellite charting), and may be difficult to discern within a range of 50 or perhaps even 100 kilometers (for instance, old snow and a network of stations located tens of kilometers apart). However, such limitations are not of great concern when analyzing the snowline over large regions, particularly when averaging on monthly or longer time scales.

North American Snowline: 1971-1990

The snowline over the North American continent is in a constant state of flux. Its movement may be tracked using data from U.S. National Oceanographic and Atmospheric Administration hemispheric snow charts. The National Oceanographic and Atmospheric Administration weekly charts depict the snowline based on a visual interpretation of photographic copies of visible satellite imagery by trained meteorologists. Charting began in 1966, but only since the early 1970s has the accuracy been such that charts are considered suitable for continental-scale studies (Wiesnet *et al.* 1987).

The snow season begins in North America in September, when snow cover becomes established over the high Arctic and on lofty mountain peaks. By October, the mean snowline (defined here as the isoline denoting a 50 percent frequency of snow cover) at lower elevations has advanced beyond the Arctic Circle and encircles the Canadian Rockies (Figure 1). The snowline continues its equatorward trek throughout the fall and early winter, reaching its southernmost position in January or occasionally in February (Figure 1). At this time, the mean snowline lies close to the 40th parallel across the United States, taking a dip towards 35° in the southern Rockies. All of Canada and Alaska, except for maritime regions and the western Canadian prairie, are virtually assured a continuous mid-winter snow cover, while snow may cover the ground as much as 10 percent of the time as far south as 35°.

In April, the mean snowline in the center of the continent retreats across the United States-Canada border and is located near the prairie-boreal forest

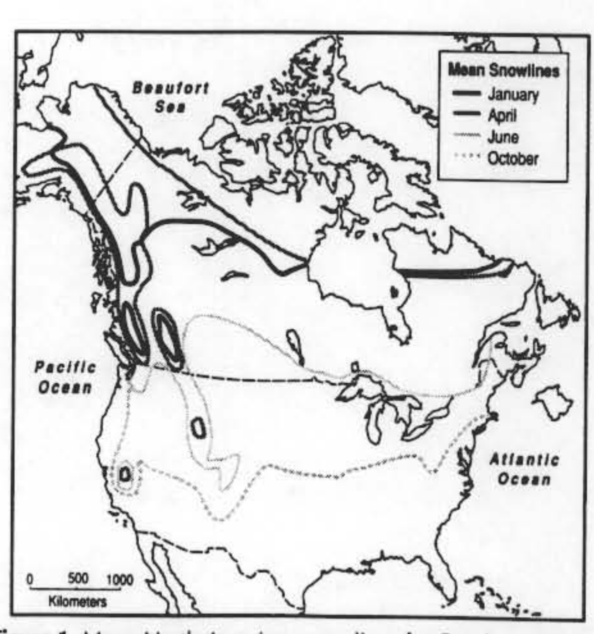

Figure 1. Mean North American snowlines for October, January, April, and June, derived from National Oceanographic and Atmospheric Administration weekly snow charts for January 1971 to June 1990. The mean snowline is defined as the isoline denoting a 50 percent frequency of snow cover.

boundary in central Canada (Figure 1). Toward the east, the snowline lies between 45° and 48°. The Rockies, Cascades, and Sierras normally remain snow covered in mid spring. The mean snowline in June lies near the taiga-tundra boundary in Alaska, the Keewatin and northern Mackenzie Districts of the Northwest Territories, and in northern Québec and Newfoundland (Figure 1). The Canadian Rockies also remain snow covered. By the end of June, the North American snow season has almost run its course. Melt has progressed well into the islands of the Canadian archipelago, and by mid July all lands are snow free.

The seasonal position of the snowline has varied considerably from year to year over the past two decades. This is well expressed by the area of North America covered with snow in each season (Figure 2). Snow areas have varied from year to year by 2 to 3 million square kilometers in each season, the extreme maximum varying from 1.2 times the minimum in winter to 1.8 times the minimum in summer. No trends in fall, winter, or spring snow cover are discernible over the period, although the springs of 1987 through 1990 exceeded or were close to previous minima. Summer cover was appreciably lower in the early and late 1980s than at other times in the past two decades.

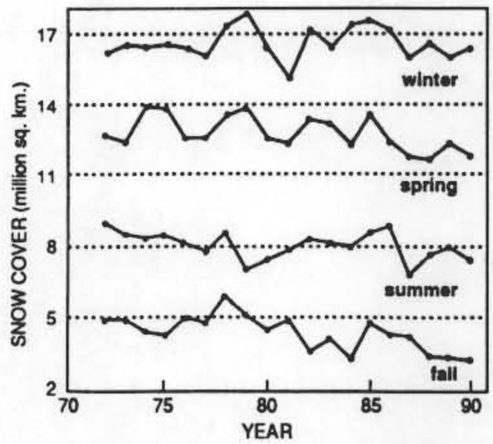

Figure 2. Seasonal snow cover (million square kilometers) over North America (including Greenland) from winter 1971 to 1972 to fall 1990. Data from National Oceanographic and Atmospheric Administration weekly snow charts.

Central United States Snowline: 1900-1989

A network of 143 stations with daily snow data since the turn of the century is available over eleven central U.S. states, enabling an investigation of snowline dynamics over this period (Robinson 1988). The inhomogeneous spacing of the stations and occasional data gaps in the network requires grouping of station reports into 1° latitude by 4° longitude divisions. Division values are an average of all available reports, which range from one to eight depending on day and region. Of the past nine decades, the January snowline was at its southernmost in the 1970s and was at its northernmost, roughly 3° or 4° poleward of the 1970s line, in the 1900s (Figure 3). A division is considered to be snow covered in a given decade when more than half of the days have a cover more than or equal to 2.5 centimeters for at least five Januaries. A decade-by-decade count of the number of divisions meeting this criterion shows the first five decades of this century to have less January snow cover than the most recent

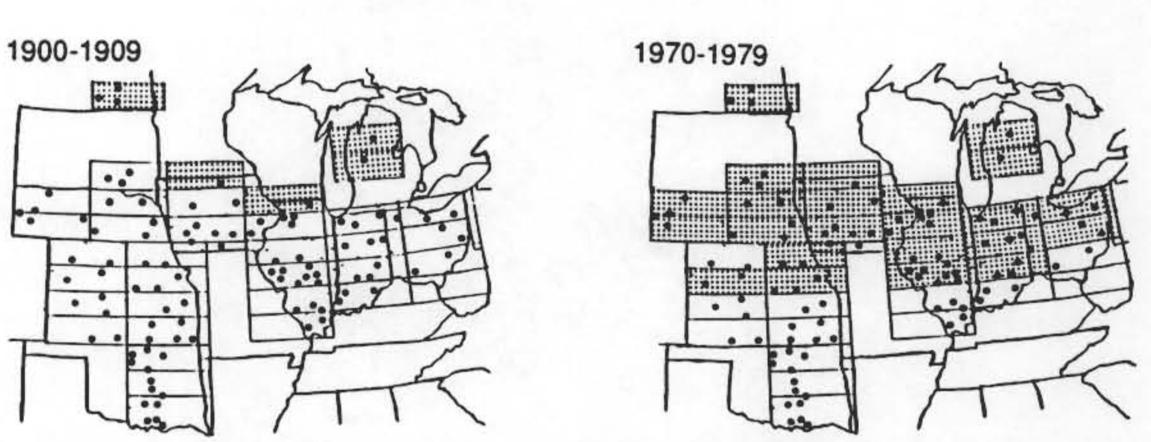

Figure 3. January snow cover over the central United States from 1900 to 1909 and 1970 to 1979. Study divisions with five or more years with more than half of the days in the month with a snow cover greater than or equal to 2.5 centimeters. Dots = study stations.

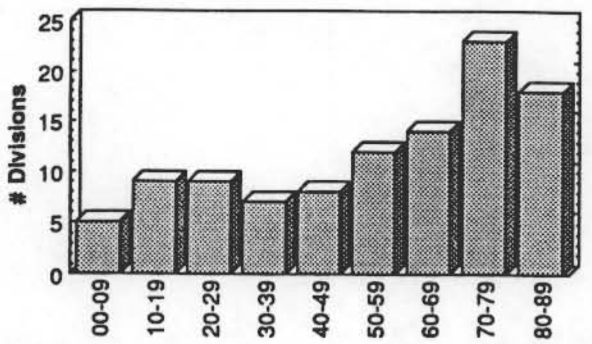

Figure 4. Decadal summary of study divisions in the central United States (cf. Figure 3) with more than half of the days in January having a snow cover of greater than or equal to 2.5 centimeters in at least five years. Pre-1980 data from the station network; 1980 to 1989 data from National Oceanographic and Atmospheric Administration weekly snow charts.

four (Figure 4). This is particularly notable in the central Great Plains.

Conclusions

Should model projections of future climate warming prove accurate, the mean North American snowline will retreat poleward and toward mountain peaks in all seasons. This will have wide-ranging consequences on water supplies, agriculture, tourism, and many other processes and activities. The significant year-to-year variability in the snowline over past decades has provided glimpses of snow-drought effects that would become more common with warming.

Despite a recent decrease in spring snow cover, there is no indication of any wide-scale retreat of the North American snowline in the past several decades. In fact, if the January snowline in the central United States is any indication (caution: it may not be, particularly in other seasons), a precipitous retreat of the line would have to occur before conditions exceeding the first half of the century were surpassed. Clearly, we must continue to observe the snowline from ground and satellite platforms to gain a better understanding of its role in future climate change and the identification of such change.

Acknowledgments

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