# Seasonal Variability of Northern Hemisphere Snow Extent Using Visible Satellite Data*

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In this paper we use a satellite-derived data set to explore spatial and temporal variations of snow extent across Northern Hemisphere continents during the last three decades. These weekly visible-wavelength satellite maps of Northern Hemisphere snow extent produced by the National Oceanic and Atmospheric Administration constitute the longest consistently-derived satellite record of any environmental variable. We document the considerable intra-annual variability of snow extent, and show that during each month, fluctuations over relatively small areas are responsible for the majority of the year-to-year variability. Regions that cover less than 6% of Northern Hemisphere lands north of 20°N explain 62%–92% of the interannual variance across the continents. On average, snow was more extensive across both Eurasia and North America from the 1970s to middle 1980s than during the late 1980s to late 1990s. During late winter, spring and summer, snow extent has decreased since the middle 1980s, while during fall to middle winter, snow extent has remained relatively constant. Accurate information on continental snow extent is critical for weather and hydrologic forecasting; for understanding hemispheric-scale atmospheric circulation, thermal variations, and regional snow extent; and for using snow as a credible indicator of climate variability and change. **Key Words: snow extent, Northern Hemisphere, climatology.**

## Introduction

The large-scale distribution of snow cover over Northern Hemisphere lands has received considerable attention in recent years. This interest has been spurred by concerns related to potential changes in the global climate system associated with anthropogenic and natural causes. Accurate information on snow extent is critical for understanding the role of snow in the climate system, for developing accurate weather and hydrological forecasts, and for parameterizing and verifying climate models (Berry 1981; Steppuhn 1981; Barry 1985; Shine et al. 1990). The availability of satellite-derived maps of snow extent over Eurasia and North America has been another impetus for this interest, at this time providing almost three decades of information for use in addressing these issues. This makes this data set the longest consistently derived satellite record of any environmental variable (Wiesnet et al. 1987).

From the late 1960s up to May 1999, weekly visible wavelength satellite maps of Northern Hemisphere snow extent produced by the National Oceanic and Atmospheric Administration (NOAA) provided an extremely useful means of assessing hemispheric snow extent (continental area covered by snow, regardless of depth, water content, or age). These maps provide acceptable information from 1972 to 1999. They are no longer produced, having been replaced in June 1999 by daily Interactive Multisensor Snowmap (IMS) initiative maps that rely heavily on visible imagery but also utilize satellite microwave and station data (Ramsay 1998). A 15-month overlapping period of traditional weekly and IMS mapping took place, and validation studies are underway to assure that the mapping transition is as seamless as possible (Robinson et al. 1999). A reanalysis of satellite data from 1967–1971 is underway at Rutgers University, and results of this study will soon be appended to the 1972–1999 weekly time series.

Studies which have utilized the NOAA snow data for understanding snow extent kinematics

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include Matson and Wiesnet (1981), Dewey and Heim (1982), Barry (1990), Robinson et al. (1991), Iwasaki (1991), Gutzler and Rosen (1992), Masuda et al. (1993) and Frei and Robinson (1999). Recent studies that use NOAA snow data to investigate snow cover synergistics within the climate system include Leathers and Robinson (1993, 1997), and Karl et al. (1993). While visible imagery is recognized as an effective means of assessing regional snow extent, it does have some shortcomings in certain areas and at certain times of the year. These include: 1) the inability to detect snow cover when solar illumination is low or when skies are cloudy, 2) the underestimation of snow extent where dense forests mask the underlying snow, 3) difficulties in discriminating snow from clouds in mountainous regions and in uniform lightly-vegetated areas that have a high surface brightness when snow covered, and 4) the lack of all but the most general information on snow depth (Dewey and Heim 1982).

Since the late 1970s, passive microwave sensors on board polar orbiting satellites also provided information on the distribution of hemispheric snow (Chang et al. 1990; Basist et al. 1996; Grody and Basist 1996; Tait and Armstrong 1996; Tait 1998). Passive microwave measurements are not sensitive to the solar illumination angle, and are generally unaffected by clouds. In some regions they also show promise in estimating snow water equivalent. However, microwave approaches have difficulties in recognizing snow in heavily vegetated areas or where snow is patchy, shallow, and/or wet.

Integrated snow products that include visible and microwave satellite data along with ground station data are beginning to be produced (i.e., the previously mentioned IMS product). This approach takes advantage of the strengths of each source of information and compensates for weaknesses. However, no other snow maps have a combination of the longevity, consistency, and accuracy of the weekly NOAA maps. The data from these maps are used to obtain the results reported in this paper. Following a discussion of map production, we show an example of how NOAA maps can be used to evaluate the spatial and temporal characteristics of continental snow extent from hemispheric to regional scales. In a concluding section we briefly discuss where satellite snow mapping is headed in the coming years.

## NOAA Weekly Snow Maps

NOAA meteorologists produced the weekly maps of snow extent across Northern Hemisphere lands from a visual interpretation of photographic copies of visible-band satellite imagery. Imagery from the Very High Resolution Radiometer (VHRR: launched in 1972, with a spatial resolution of 1.0 km), and after October 1978 the Advanced VHRR (1.1 km resolution) provided much of the information for the weekly mapping. Imagery from geostationary satellites was also utilized. Imagery was examined daily, and maps depict snow boundaries on the last day of the map week that a region was cloud free. Dates were placed on the maps after April 1982, and suggest that the snow extent on the maps best represents the fifth day of the map week.

The weekly maps were digitized to the National Meteorological Center Limited-Area Fine Mesh grid. This is an 89 × 89 cell Cartesian grid laid over a polar stereographic projection of the Northern Hemisphere. Cell resolution ranges from 16,000 to 42,000 square kilometers (this product has also been regridded to the equal area EASE-grid in a CD rom for 1978–1995 and is distributed by the National Snow and Ice Data Center). Each grid

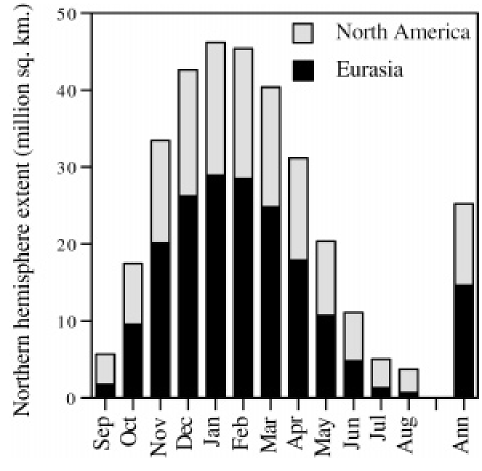

**Figure 1:** *Mean monthly snow extent over Northern Hemisphere continents, using data from January 1972 through May 1999. Means are divided into Eurasian and North American (including Greenland) extents. Annual (Ann) values are also shown.*

cell in the digitized product has a binary value. Cells with at least 50% of their surface covered with snow were considered snow covered. All other cells were considered snow free. In this paper we use monthly means of snow cover extent calculated using a routine described fully in Robinson (1993). In this procedure, weekly areas are calculated from digitized snow files, and monthly values are calculated by weighting the weekly areas according to the number of days of a map week falling in the given month.

## The Seasonal Snow Cycle

### *Monthly Means*

Snow extent over Northern Hemisphere lands reaches a maximum of approximately 47 million square kilometers during January and February, and a minimum of about 4 million sq. km. in August. During October and November, snow accumulates rapidly over the continents (Fig. 1). By December snow covers more than 53% of the land polewards of 20°N, and remains above 50% through March. Using March as an example, snow extent averages 40.8 million sq. km., and ranges from 37.0 (1990) to 44.1 (1985) million sq. km. (Fig. 2). Spring ablation occurs more gradually than fall accumulation. By the end of April, 39% of the land polewards of 20°N remains covered; this decreases to 26% in May and 14% in June. During winter, 62% of Northern Hemisphere snow covered land is found over Eurasia; during fall and spring the snow covered areas are closer to equal over the two major land masses; during summer, snow covered lands are restricted to the Greenland ice sheet and smaller high latitude ice caps.

### *Monthly Active Areas*

Each month, as snow cover advances and retreats across the continents, there are geographic areas over which snow extent is ephemeral. Frei and Robinson (1999) define "active areas" to include those grid cells with snow cover frequencies between 10% and 90% for at least eight of 23 years (using 1972–1994 observations). Areas north of the active area are usually snow covered and to the south are usually snow free. Between September and June,

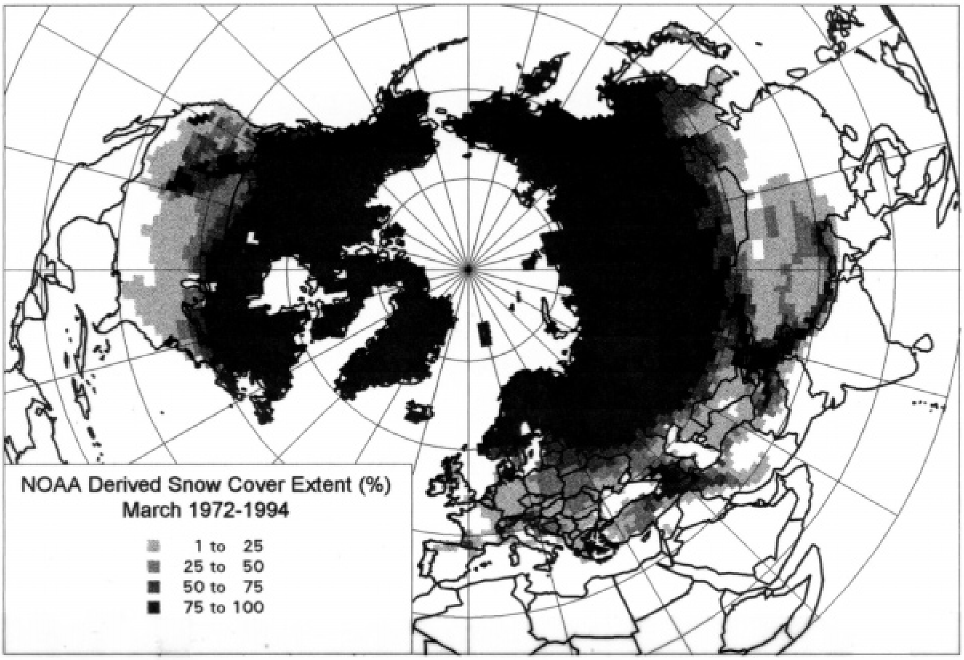

**Figure 2:** *Frequency of snow coverage over Northern Hemisphere lands during March. Percentages are based on analyses of NOAA weekly maps between 1972 and 1994.*

monthly active areas cover between 11% and 28% of the Northern Hemisphere land area north of 20°N.

We illustrate the seasonal progression of snow accumulation in Figure 3, which shows the active grid cells (indicated by black dots) for September, November, January, and March. In September, snow begins to cover the northernmost portions of the land masses. The accumulation season picks up during October and November, the months with the largest active areas. From December through March, active grid cells are found over approximately the same mid-latitude areas, although there are some differences in location and total area. These winter active areas are those over which snow cover is variable.

Spring ablation (not shown in figure) occurs more gradually than fall accumulation. Active grid cells during April are generally found to the north of the March active area, except over elevated regions, and cover more area than any months except October and November. During May the spring ablation zone, indicated by active areas, continues to shift gradually northward. By June, active grid cells cover only the northernmost areas, but still cover significantly more area than during September. By August, only Greenland and high latitude ice caps remain snow covered.

### *Coherent Regions*

Within monthly active areas, Frei and Robinson (1999) apply an S-mode (cf. Yarnal 1993, p. 76 for definition) Principal Component Analysis (PCA) with a Varimax rotation to identify regions within which interannual fluctuations of snow extent are temporally correlated ("coherent regions"). Key regions over Eurasia and North America explain a majority of the monthly variance in snow extent.

Key, or "coherent," regions are identified by

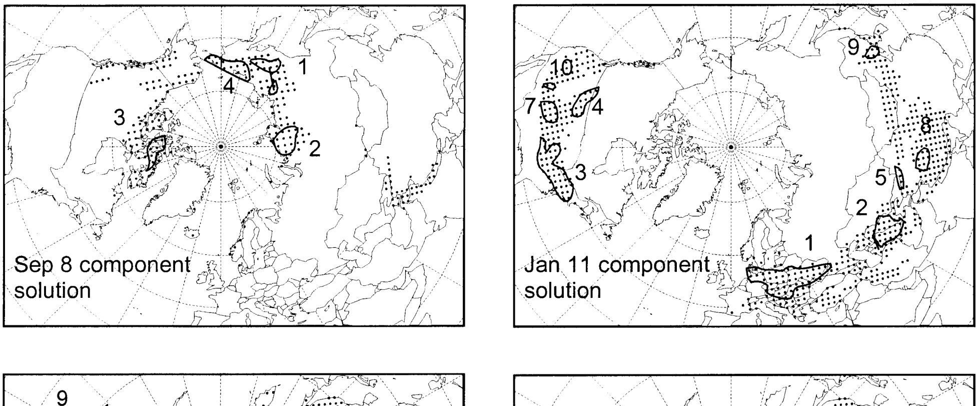

**Figure 3:** *Active areas of snow coverage in September, November, January, and March (1972–1994) are shown with dots (see text for explanation). Regions of coherent snow extent fluctuations are outlined with bold lines. These are regions within which interannual fluctuations of snow extent have greater than 50% of their variance explained by a common signal. Adapted from Frei and Robinson, 1999.*

retaining only those components that explain $\geq 50\%$ of the variance (component loading $\geq 0.71$) of at least three adjacent grid cells. Using this criterion, coherent regions do not overlap geographically, and all grid cells within coherent regions have $\geq 50\%$ of their variance explained by one common time series (the score time series).

Over Eurasia (North America), 2–6 (1–4) coherent regions per month are identified. They cover between 12% and 27% of the monthly active areas, thus 2% to 6% of the Northern Hemisphere land area north of 20°N. The average coherent region covers approximately 0.4 million sq. km., with the largest (PC1 of October) covering about 1.9 million sq. km. of northeastern Russia. Linear multiple regression analyses between continental (dependent variable) and regional (coherent regions: independent variables) snow extents indicate that much of the variance in continent-wide snow extent can be explained by regional signals. Over Eurasia, during most months greater than 50% of continental-scale variance is explained by regional signals (Table 1). Over North America, explained variances are higher.

Coherent regions for September, November, January, and March are indicated in Figure 3. Certain regions are identified as key regions during several months. These include the northern U.S. Great Plains/southern Canadian Prairies, the eastern U.S., and northeastern Europe. Two properties of these regions—their ability to explain much of the variance in continental snow extent, and their coherency with respect to interannual fluctuations—allow this sort of information to be used in conjunction with pre-satellite era station observations to estimate historical variations at regional and continental scales (e.g., Brown 1997; Frei et al. 1999).

***Table 1*** *Linear Multiple Regression Analyses of Monthly Continental Snow Extent (adapted from Frei and Robinson 1999)*

| | **Eurasia** | | **North America** | |
|---|---|---|---|---|
| **Month** | **# Reg*** | **$r^2$**** | **# Reg** | **$r^2$** |
| Sep | 3 | 23 | 1 | 6 |
| Oct | 2 | 62 | 4 | 81 |
| Nov | 6 | 44 | 4 | 72 |
| Dec | 5 | 58 | 2 | 76 |
| Jan | 5 | 59 | 4 | 62 |
| Feb | 3 | 74 | 1 | 92 |
| Mar | 3 | 74 | 2 | 83 |
| Apr | 5 | 62 | 2 | 88 |
| May | 3 | 33 | 2 | 64 |
| Jun | 3*** | 79 | 2*** | 66 |

** Number of coherent regions.*

*** Percent of variance in observed snow extent explained by predicted continental signal (all values shown are significant at $\geq 95\%$, 1-tailed, $n = 23$). Cross-validated.*

**** Only month where one PC was associated with a coherent region on each continent.*

### *Temporal Characteristics of Snow*

Considerable interannual variability has been observed in continental snow extent over the satellite era. While much smaller than seasonal variations, interannual variations are sufficiently large to have substantial impacts on regional hydrology and radiative regimes. Monthly anomalies are generally less than 2 million sq. km., but occasionally exceed 4 million sq. km. (Fig. 4). Fall has the highest interannual variability and winter the least.

A pronounced stepwise change in snow extent occurred in the middle 1980s. Running annual means of extent from 1987 to 1999 fluctuated around a mean of 24.5 million sq. km. That is 1.4 million sq. km, or 6%, less than the earlier portion of the satellite era (Fig. 4). The means of these two periods (1972–1986 and 1987–1999) are significantly different (T test, $p < 0.01$) at the annual time scale, as well as during late winter, spring, and summer (Fig. 5). No significant change is observed in fall through the middle of winter. Decreases in spring and summer snow extent are observed over both continents. Monthly observations show the decrease beginning in February. During seven of the first 15 years of record (1972–1986), February snow extent exceeded the January value, while this occurred only once between 1987 and 1999.

Fall snow extent was particularly low across the continents in 1979, 1988, and 1990, and extensive in 1972, 1976, and 1993. Winter extent was exceptionally low in 1981 (December 1980–February 1981), with 1975 having the second least extensive cover, closely followed by 1997. Snow cover was extensive in the winters of 1978 and 1979 and again in 1985 and 1986. Spring extent was unusually low in 1990. From 1987 to 1999 only two springs had more extensive snow than 1977, which was the year between 1972 and 1987 with the least coverage of spring snow. A similar situation is apparent

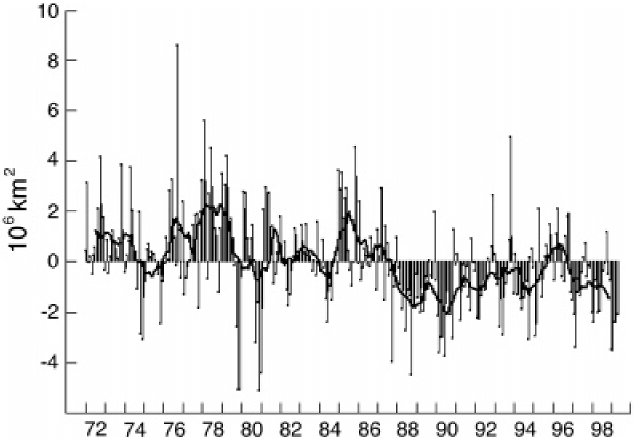

**Figure 4:** *Anomalies of monthly snow cover extent over Northern Hemisphere lands (including Greenland) from January 1972 through May 1999. Also shown are twelve-month running anomalies of hemispheric snow extent, plotted on the seventh month of a given interval. Anomalies are calculated from NOAA weekly maps. Mean hemispheric snow extent is 25.3 million sq. km. for the full period of record.*

in summer, with less extensive snow in every year from 1988 to 1999 than in all but two years prior to that time.

The month-to-month persistence of regional snow anomalies was quantified using Pearson and Spearman correlation coefficients between PC score time series from consecutive months (Frei and Robinson 1999). Western North America and Europe are the only sectors, and January to April the only months, with anomalies that tend to persist longer than one to two months. Over both of these regions, significant correlations are observed from January-February through March-April. This corroborates the results of Walsh et al. (1982), who showed that the Pacific and Midwest U.S. have higher one- and two-month persistences than the eastern U.S. Even over western North America and Europe, where significant persistence is found, anomalously high or low snow extent is not usually maintained throughout the entire snow season. However, there are some exceptions to this: over western North America, high (low) extent persisted for most of the 1978–1979 (1980–1981) season; over eastern North America, high (low) extent persisted during most of the 1977–1978 and 1978–1979 (1982–1983) seasons.

## Conclusions

The 27-year record of Northern Hemisphere snow extent derived from weekly NOAA maps has permitted regional and hemispheric climatologies to be generated. This provides useful information on the spatial distribution of snow, including its variability. We found that areas covering less than 6% of Northern Hemisphere lands north of 20°N explain 62–92% of the interannual variance across the continents. On average, snow was more extensive across both Eurasia and North America from the 1970s to middle 1980s than from the late 1980s to late 1990s. This is most pronounced from late winter to summer.

Given the relatively short time in which hemispheric monitoring of snow extent from space has been possible, it is difficult to fully understand the significance of the apparent stepwise change in snow extent in the middle 1980s. It is noteworthy, however, that the extent of snow appears to be inversely related to hemispheric surface air temperature (Robinson and Dewey 1990), and, particularly in spring, the extent of snow may be strongly influencing temperature through a feedback mechanism (Groisman et al. 1994).

The upcoming extension of hemispheric maps back to late 1966 will provide additional useful information; however it will likely remain impossible to fully understand why these fluctuations in extent have occurred. Other sources of snow information continue to be evaluated and have begun to be incorporated with visible input into operational and research-oriented snow products. They include passive microwave-derived estimates of snow extent and snow water equivalent. Also, useful data sets of ground observations have been assembled in recent years to supplement satellite

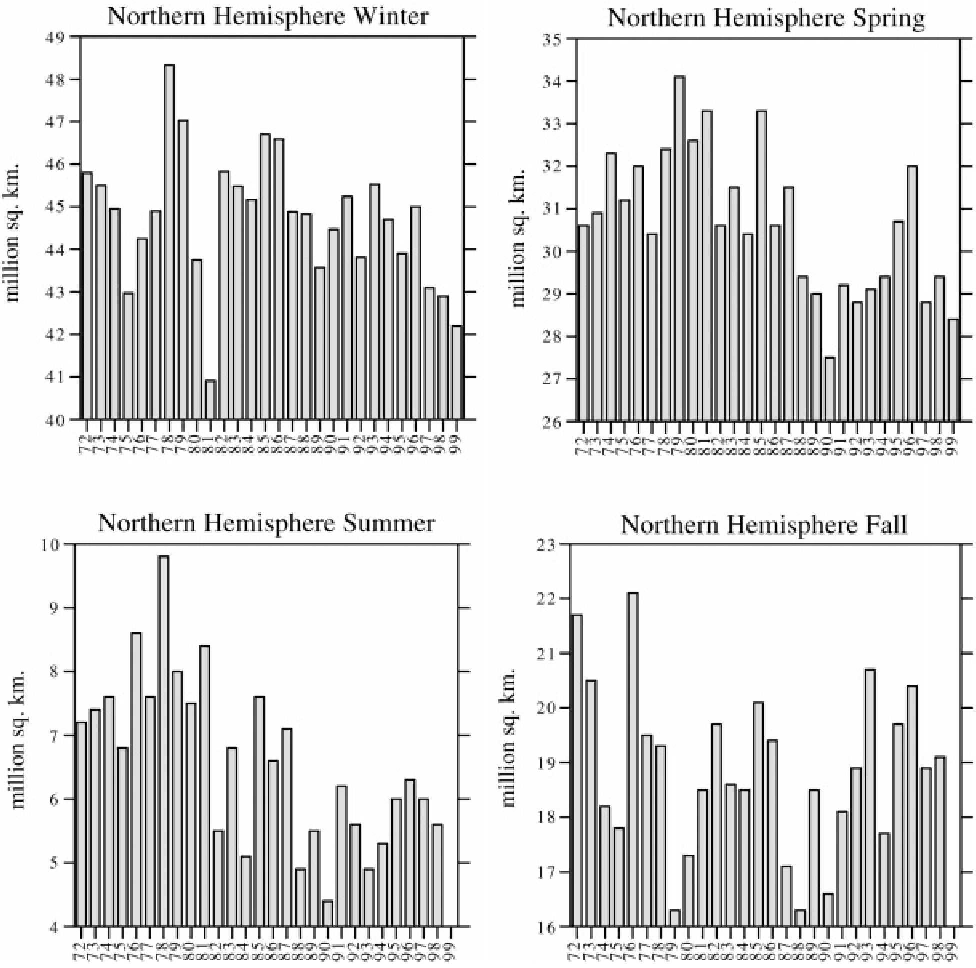

**Figure 5:** *Extent of seasonal snow cover over Northern Hemisphere lands (including Greenland) from the winter of 1971–1972 (December-February) through the spring of 1999. (Spring: March-May; summer: June-August; fall: September-November)*

mapping, as well as in efforts to extend regional records back to much earlier in the century (Brown and Goodison 1996; Hughes and Robinson 1996; Fallot et al. 1997; Frei et al. 1999).

The Interactive Multisensor Snowmap (IMS) initiative currently underway at NOAA is producing daily integrative maps that will soon be linked with the earlier weekly snow maps to continue the lengthy hemispheric time series. The operational IMS effort is being driven by the weather forecasting community, which is convinced that a daily hemispheric map will improve forecast accuracy. Operational maps of snow extent are also planned from data collected from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor flown on the EOS-AM platform (Hall et al. 1995). Accurate snow extent information is critical for weather and hydrologic forecasting, for understanding the synergistic relationships between hemispheric-scale atmospheric circulation, thermal variations, and regional snow extent, and for using snow as a reliable indicator of climate variability and change. ■

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