

# Global Snow Cover Monitoring: An Update

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## Abstract

Accurate monitoring of the large-scale dimensions of global snow cover is essential for understanding details of climate dynamics and climate change. Presently, such information is gathered individually from ground station networks and satellite platforms. Efforts are in progress to consolidate and analyze long-term station records from a number of countries. To gain truly global coverage, however, satellite-based monitoring techniques must be employed. A 27-year record of Northern Hemisphere continental snow cover produced by the National Oceanic and Atmospheric Administration (NOAA) is the longest such environmental record available. Records of Southern Hemisphere continental cover and snow on top of Arctic sea ice have been produced by similar means for a portion of this interval. The visible imagery charting technique used to generate these data provides information on snow extent but not on snow volume. Satellite microwave analyses over Northern Hemisphere lands show some promise in this regard, however, large-scale monitoring of snow extent with microwave data remains less accurate than visible charting.

This paper updates the status of global snow cover monitoring, concentrating on the weekly snow charts prepared by NOAA and discussing a new and consistent record of monthly snow cover generated from these weekly charts. The NOAA charts show a reduction of hemispheric snow cover over the past five years, particularly in spring. Snow areas from the NOAA product are then compared with values derived using passive microwave data. The latter consistently reports less snow cover than the more accurate visible product. Finally, future snow monitoring initiatives are recommended. These include continuing the consistent NOAA product until an all-weather all-surface product is developed. The latter would use multiple data sources and geographic information systems techniques. Such an integrative product would need extensive comparisons with the NOAA product to ensure the continued utility of the lengthy NOAA observations in studies of climate change. In a retrospective sense, satellite charts from the middle 1960s to early 1970s need reevaluation and techniques to merge satellite products with historic station time series must be developed.

## 1. Introduction

Across the middle and high latitudes of the Northern Hemisphere, the impact of snow on humans and the environment is considerable. Falling snow or snow lying on the ground or on ice influences hydrologic,

biologic, chemical, and geologic processes at and near the surface of the earth. Snow impacts activities as diverse as engineering, agriculture, travel, recreation, commerce, and safety. Empirical and modeling studies show the influential role of snow cover within the global heat budget (Berry 1981; Walsh et al. 1985; Robinson and Kukla 1985; Kukla et al. 1986; Barnett et al. 1989). This is expressed chiefly through increased surface albedo in snow-covered regions. Global models of human-induced climate change suggest enhanced warming in current regions of ephemeral snow cover (Mitchell et al. 1990; Gates et al. 1992). For this reason snow cover has been recommended as a useful index for detecting and monitoring such change (Barry 1985; Schlesinger 1986).

Accurate snow cover information is essential for understanding details of climate dynamics and climate change. Snow observations should be as lengthy and geographically extensive as possible. Ground station measurements of snow cover have been made for up to a century in some countries, and recently we and others have begun to consolidate and quality control these data (Robinson 1993a). The spatial coverage provided by the stations, however, is generally limited to low elevation regions of the Northern Hemisphere midlatitudes and to snow courses in mountainous regions. An urban bias may also exist, resulting in an underrepresentation of snow. A more complete hemispheric view of snow cover needs information from satellite-borne sensors. Currently, visible satellite images provide the most accurate information on snow cover extent; however, this data source extends back only approximately three decades. Microwave-derived estimates of snow extent and volume are relatively accurate over some regions but are available only since the late 1970s.

Only Northern Hemisphere lands have been continuously monitored for snow extent since the late 1960s (Dewey and Heim 1981; Iwasaki 1991), although we have examined snow for select intervals over Southern Hemisphere lands (excluding Antarctica) (Dewey and Heim 1983) and Arctic sea ice (Robinson et al. 1992). There is also a daily U.S. Air Force snow product that relies heavily on surface-based observations as input into a numerical model that creates daily charts with global coverage (Hall 1986). Disadvantages of these charts include a reli-

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ance on extrapolations and climatology in data-sparse regions (McGuffie and Robinson 1988). Recently, an improved interpolation scheme incorporating horizontal and vertical components has been added to the model (Armstrong and Hardman 1991). A method to estimate depth using passive microwave data has also been proposed to reduce the reliance on climatology but has yet to be implemented.

In this paper we examine visible satellite observations of snow cover over Northern Hemisphere lands and, using this information, evaluate monthly snow extents from 1972 to 1992. A discussion of satellite passive microwave efforts to identify snow and a comparison of microwave and visible products follows. Finally, we recommend ongoing and retrospective monitoring initiatives.

## 2. Charting from visible data

Visible satellite data provide continental coverage of snow extent at a relatively high spatial resolution. Snow is identified by recognizing characteristic textured surface features and brightness. Surface albedo and percent of snow coverage (patchiness) are also gleaned from the data. Shortcomings include 1) the inability to detect snow cover when solar illumination is low or when skies are cloudy, 2) the underestimation of cover where dense forests mask the underlying snow, 3) ambiguities in the recognition and demarcation of patchy snow cover, 4) 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 5) the lack of all but the most general information on snow depth (Kukla and Robinson 1981; Dewey and Heim 1982).

### *a. NOAA snow charts*

The National Oceanic and Atmospheric Administration (NOAA) began mapping snow cover over Northern Hemisphere lands in 1966 (Matson et al. 1986). The weekly charts resulting from this effort continue to be generated operationally and remain the only such hemispheric product. They comprise the longest satellite-based environmental record available.

NOAA charts are based on a visual interpretation of photographic copies of visible imagery by trained meteorologists. The subpoint resolution of the meteorological satellites used prior to 1972 was about 4 km. The Very High Resolution Radiometer (VHRR) launched in 1972 provided imagery with a spatial resolution of 1.0 km. Since November 1978 the Advanced VHRR has provided 1.1-km resolution data. Imagery is examined daily and charts show snow boundaries on the last day of the chart week that the

surface in a region is seen (Fig. 1). Since May 1982, the date when a particular region is last observed has been placed on the charts. An examination of these dates shows the snow coverage to best represent that of the fifth day of the chart week.

In early years the snow extent was underestimated on the NOAA charts, especially during fall. Charting improved considerably in 1972 with the deployment of the VHRR sensor and the increased experience among analysts in recognizing snow-covered ground. Since then we consider the charts suitable for continental-scale climate studies (Kukla and Robinson 1981), particularly where 1) skies are frequently clear, as is common in spring near the snow line, 2) solar zenith angles are relatively low and illumination is high, 3) the snow cover is reasonably stable or changes slowly, and 4) pronounced local and regional signatures are present owing to the distribution of vegetation, lakes, and rivers. The NOAA charts are digitized weekly using the National Meteorological Center's primitive equation grid. This is an 89 x 89 cell Northern Hemisphere grid having a polar stereographic projection. Cell resolution ranges from 16 000 km<sup>2</sup> to 42 000 km<sup>2</sup>. Only cells interpreted to be at least 50% snow covered are considered snow covered.

Figure 2 shows the mean position of the North American snow line for four months of the year. Snow lines are derived from 20 years of NOAA digital data by calculating the percentage of time each digitized cell is recognized as snow covered. To acquire accurate monthly snow extents, we have developed a new routine (Robinson 1993b). This follows our discovery of a major inconsistency in NOAA's calculations of monthly snow cover areas (Robinson et al. 1991). Before 1981 NOAA calculated continental areas from monthly summary charts, which consider a cell to be snow covered if snow is present on two or more weeks during a given month (Dewey and Heim 1982). Since 1981 NOAA has produced monthly areas by averaging areas calculated from weekly charts. A comparison of these two methodologies shows areas computed using the monthly approach to be from several hundred thousand to over three million square kilometers greater than those calculated using weekly areas. The offsets are not consistent. Also contributing to the problem are 53 cells (covering 1.8 x 10<sup>6</sup> km<sup>2</sup>) that are not considered consistently in the area calculations throughout the period of record. In 1981 NOAA changed their land mask; 26 land cells were reclassified as water and 27 new land cells were added. As discussed in the following, neither of the NOAA masks is accurate; both fail to accurately identify all land ( $\geq 50\%$  land) and water cells.

Our new consistent methodology (Rutgers routine) weekly calculates areas from the digitized snow files

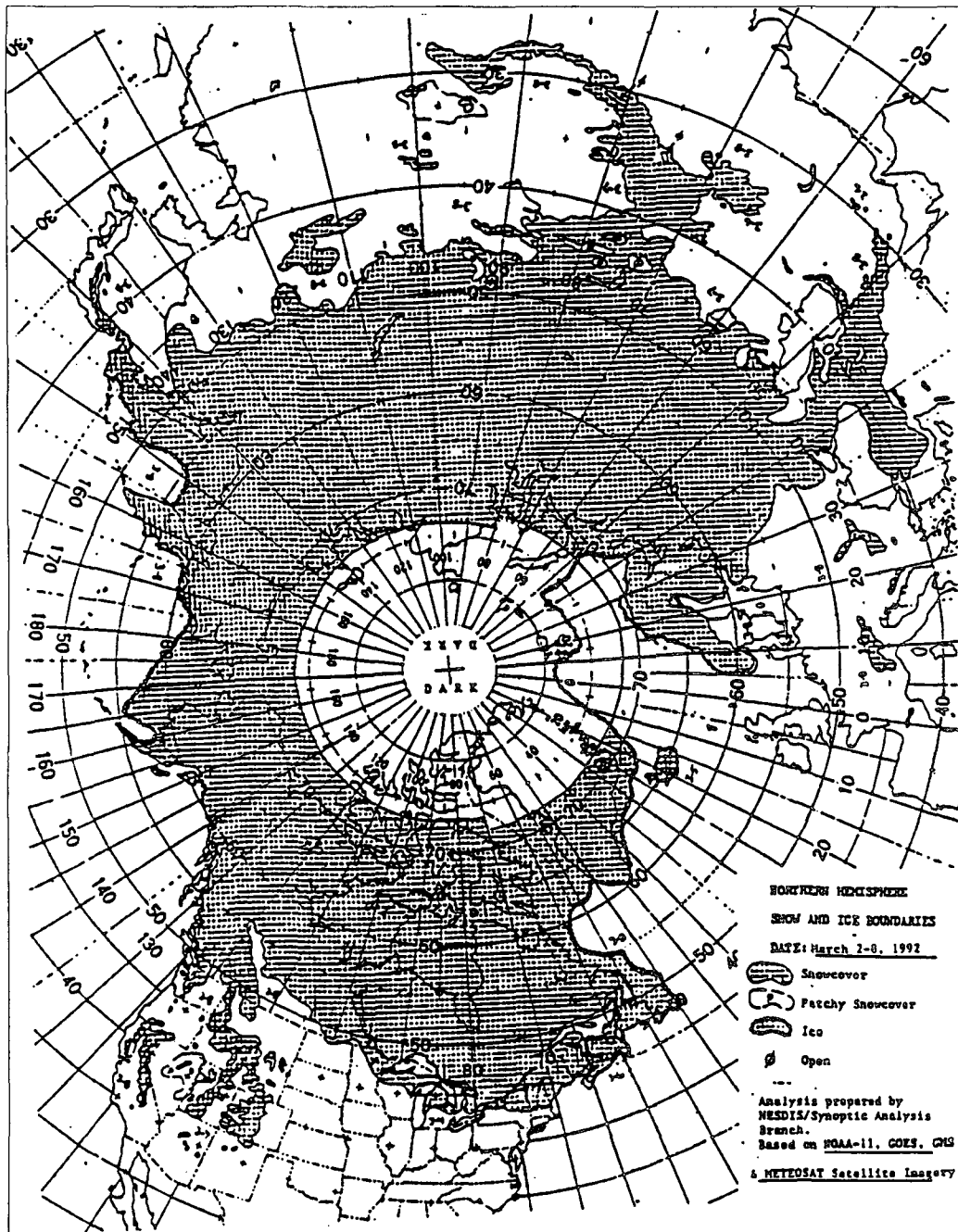


FIG. 1. NOAA snow chart for 2–8 March 1992. The size of the chart shown here is approximately 20% of the original.

and weights them according to the number of days of a chart week falling in the given month. A chart week is considered to center on the fifth day of the published chart week. No weighting has been employed in either of the NOAA routines.

In addition, we have developed a definitive land mask at Rutgers using digital map files analyzed on a geographic information system (GIS). We calculated the percentage of land in each of the 7921 NMC grid

cells using the National Geophysical Data Center's 5-min resolution ETOPO5 file as the primary data source. As this file does not include large interior lakes, the Navy Fleet Numerical Oceanography Center's 10-min resolution Primary Terrain Cover Types file was used to account for these water bodies. Some 48 cells poleward of approximately 30°N, which had been considered land in the pre-1981 NOAA or in the 1981-to-present NOAA mask, are actually predominantly

water covered. Conversely, 54 land cells were considered water on one or both NOAA masks, and these required a first-time analysis to determine whether they might be snow covered. This was accomplished by selecting nearest representative land cells (cells that NOAA has continually charted as land) and assigning their snow status to the "new" land cells. Spot checks of a number of hard copy weekly charts prove this to be an adequate approach. NOAA plans to begin using this mask in the near future.

*b. Continental snow cover from NOAA charts: 1972–1992*

According to values generated using the Rutgers routine, the extent of snow cover over Northern Hemisphere lands is greatest in January. On average, 46.5 million km<sup>2</sup> of Eurasia and North America are snow covered in this month, with February a close second, averaging 46.0 million km<sup>2</sup> (Table 1, Fig. 3). August has the least cover, averaging 3.8 million km<sup>2</sup>, the majority of this being snow on top of the Greenland ice sheet. The past two decades of monthly data are close to normally distributed, and monthly standard deviations range from 1.0 million km<sup>2</sup> in August to 2.9 million km<sup>2</sup> in October. The annual mean cover is 25.3 million km<sup>2</sup> with a standard deviation of 1.1 million km<sup>2</sup>. The snowiest year was 1978 with a mean of 27.4 million km<sup>2</sup>, with 1990 the least snowy at 23.2 million km<sup>2</sup>.

Twelve-month running means of continental snow extent best illustrate the periods of above-normal cover that occurred in the late 1970s and mid-1980s

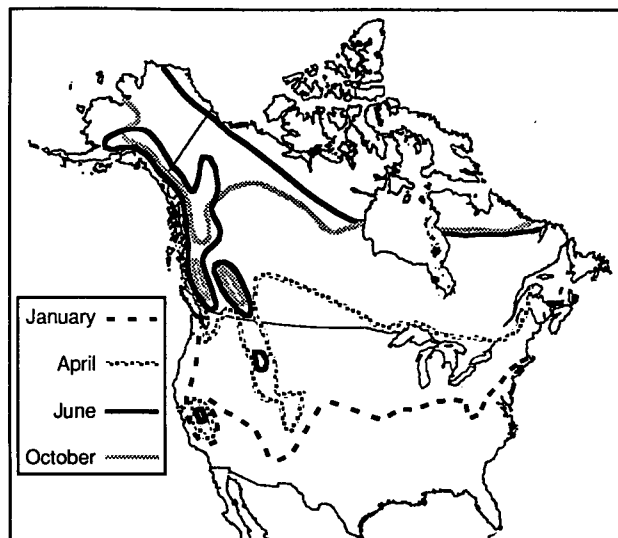


FIG. 2. Mean North American snow lines for October, January, April, and June. Lines are derived from NOAA weekly snow charts covering the interval from January 1971 through June 1990. The mean snow line is defined as the isoline denoting a 50% frequency of snow cover.

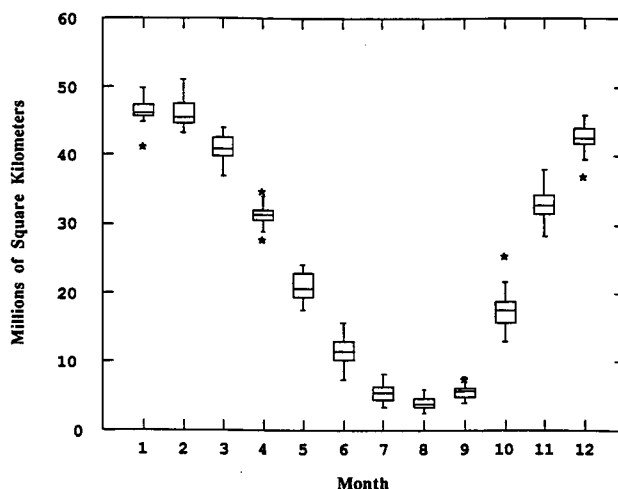


FIG. 3. Monthly snow cover over Northern Hemisphere lands (including Greenland) between January 1972 and December 1992. The median area of cover is the horizontal line within the 12-monthly boxes, and the interquartile range (ICR) is between the top and bottom of the box. Whiskers show the extreme values between +1 and +1.5 ICR and -1 and -1.5 ICR, and asterisks show values in individual years falling outside of the  $\pm 1.5$  ranges. Values are calculated from NOAA weekly snow charts.

(Fig. 4). Intervals with lower snow extents include the mid-1970s and early 1980s; however, neither approach the deficit of snow cover observed in recent years. Of the 65 months between August 1987 and December 1992, only 8 months had above-normal snow cover. Three of these were September, November, and December 1992. The lowest year on record was 1990, when monthly minima occurred in 8 months (Table 1). Spring cover has shown pronounced deficits over the past 5 years in Eurasia and 6 years in North America. Areas in these springs have been at or below lows established before this period (Fig. 5). Fall and summer cover has also been low in recent years, while winter cover has been close to average. The reduced snow extent in recent years has coincided with some of the warmest surface air temperatures of the past century (Jones et al. 1991). We have observed a striking inverse relationship between hemispheric snow extent and surface air temperature over the past two decades (Robinson et al. 1991).

### 3. Charting from passive microwave data

Microwave radiation emitted by earth's surface is largely unobstructed by weather effects as it penetrates the winter atmosphere. This makes the discrimination of snow cover from passive microwave satellite data possible by recognizing differences in emissivity between snow-covered and snow-free sur-

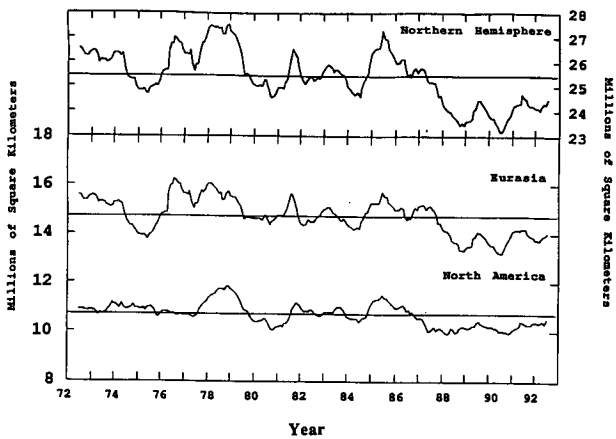


FIG. 4. Twelve-month running means of snow cover over Northern Hemisphere lands (including Greenland) for the period January 1972 through December 1992. Running means are also shown for Eurasia and North America (including Greenland). Values are plotted on the seventh month of the 12-month interval and are calculated from NOAA weekly snow charts.

faces. The spatial extent as well as the depth or water equivalent of the snowpack are estimated using equations that employ radiation sensed by multiple channels in the microwave portion of the spectrum (e.g., Kunzi et al. 1982; Chang et al. 1987; McFarland et al. 1987). Snow estimates from satellite-borne microwave sensor data have been available since the launch of the Scanning Multichannel Microwave Radiometer (SMMR) in late 1978. The spatial resolution of the data is several tens of kilometers. Since 1987 the Special Sensor Microwave Imager (SSM/I) has provided information to determine snow extent and volume. The lack of sufficient coverage of ground truth snow depth or volume data makes an adequate assessment of the reliability of microwave estimates uncertain on regional and larger scales. Therefore, the remainder of this discussion focuses on the microwave monitoring of snow extent.

As with visible products, the microwave monitoring of snow extent has limitations. Data resolution makes the detailed recognition of snow cover difficult, particularly where snow is patchy, and it is difficult to identify shallow or wet snow using microwaves. Because

of region-specific differences in land cover and snowpack properties, a single algorithm cannot adequately estimate snow cover across Northern Hemisphere lands (see the following). Studies of a regional nature that address these differences encompass landscapes as diverse as mountains (Chang et al. 1991), the Tibetan Plateau (Robinson et al. 1984; Robinson and Spies 1993); forest (Hall et al. 1982; Hallikainen and Jolma 1986), tundra (Hall et al. 1986), and prairie (Goodison 1989).

#### a. Continental snow cover from NASA charts: 1978–1987

Monthly charts of Northern Hemisphere continental snow extent have been produced from SMMR data by a team of NASA scientists (Chang et al. 1990). This is the only such time series available to date and covers the interval from November 1978 through August 1987. A single algorithm is used to estimate snow depth on a  $0.5^\circ \times 0.5^\circ$  grid. Monthly values are averages of depths for the five or six pentad charts centered in a given month (SMMR data were gathered every other day and three of these passes are used for each pentad chart; there is a one-day gap between each pentad). Cells having an average depth of 2.5 cm are considered snow covered all month. This results in a positive bias to the snow areas, especially in areas where snow cover fluctuates. Despite this

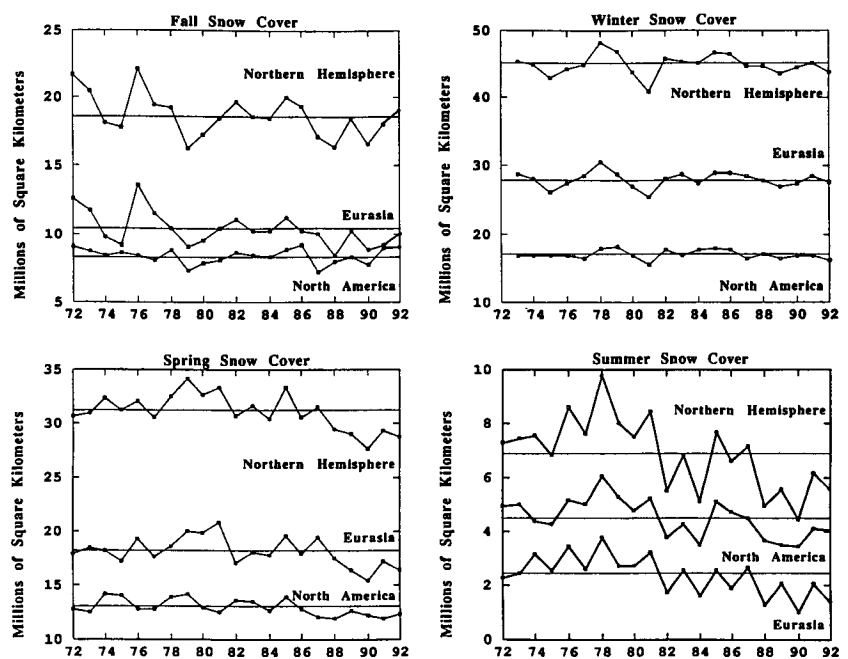


FIG. 5. Seasonal time series of snow cover over Eurasia and North America (Greenland is excluded) (winter: Dec–Feb; spring: Mar–May; summer: June–Aug; fall: Sep–Nov). Values are calculated from NOAA weekly snow charts.

bias, NASA mean monthly snow cover for Northern Hemisphere lands (exclusive of Greenland) runs from less than 1 million to as much as 13 million km<sup>2</sup> below NOAA areas for the nine years of coincidental estimates. These absolute differences are greatest in the late fall and early winter. In a relative sense, NASA microwave areas are between 80% and 90% of NOAA visible values in winter and spring, 20% to 40% of the visible estimates in summer, and 40% to 70% of visible areas in fall (Fig. 6). Wet and shallow snows may explain the significant disparities in the latter two seasons. Both are difficult if not impossible to monitor using a passive microwave approach. Depth may be the most important of these two variables, given the better agreement in spring, although it has been suggested that unfrozen soil beneath the pack is a major contributor to underestimates during fall (B. Goodison 1993, personal communication). There may also be an overestimation of summer continental

snow cover in the NOAA product due to difficulties in distinguishing between frozen water bodies and snow-free land in Arctic regions (e.g., Canadian archipelago).

Snow monitoring employing SSM/I data shows the same strengths and liabilities as the SMMR data (Goodison 1989; Hall et al. 1991). The SSM/I has 19 and 37 GHz channels; thus, SMMR algorithms perform much the same as with the 18 and 37 GHz channels. In addition, the 85 GHz channel on the SSM/I has shown promise in improving the monitoring of shallow (<5 cm) snow cover (Nagler and Rott 1991).

#### 4. Snow monitoring in the 1990s

While useful snow data are increasingly being gathered, the need remains to improve ongoing monitoring and to continue assembling and analyzing past observations. Given limited resources these activities

must be developed to take best advantage of the data and analytic tools available. With this in mind we make the following recommendations regarding snow monitoring activities and projects for the years ahead.

##### a. Near real-time monitoring

###### 1) MAINTAIN THE NOAA VISIBLE

SATELLITE CHARTING EFFORT IN ITS PRESENT FORM

To alter abruptly or, perhaps more seriously, alter subtly the manner in which the NOAA charts are produced would severely weaken what is presently the longest and most consistent satellite-derived dataset of any surface or atmospheric variable. Any alteration would require "restarting the clock" and losing precious years when employing snow cover to identify and monitor climate change.

###### 2) DEVELOP AND PRODUCE ALL-WEATHER, ALL-SURFACE SNOW CHARTS

These charts should incorporate visible and microwave satellite data and station observations and use GIS techniques. At three-to-five-day intervals, these operational global charts would provide the most detailed information pos-

TABLE 1. Monthly and annual (ANN) snow cover (million km<sup>2</sup>) over Northern Hemisphere (NH) lands during the period January 1972 through December 1992. Annual values for Eurasia (EU) and North America (NA) are also included. Areas are calculated using the Rutgers routine.

	Maximum (yr)	Minimum (yr)	Mean	Median	Std. Dev.
Jan	49.8 (1985)	41.7 (1981)	46.5	46.1	1.8
Feb	51.0 (1978)	43.2 (90, 92)	46.0	45.6	2.0
Mar	44.1 (1985)	37.0 (1990)	41.0	40.8	1.9
Apr	35.3 (1979)	28.2 (1990)	31.3	31.4	1.8
May	24.1 (1974)	17.4 (1990)	20.8	20.6	1.9
Jun	15.6 (1978)	7.3 (1990)	11.5	11.4	2.1
Jul	8.0 (1978)	3.4 (1990)	5.3	5.5	1.2
Aug	5.7 (1978)	2.6 (1988, 89, 90)	3.8	3.7	1.0
Sep	7.9 (1972)	3.9 (1990)	5.6	5.6	1.1
Oct	26.1 (1976)	13.0 (1988)	17.5	17.5	2.9
Nov	37.9 (1985)	28.3 (1979)	33.0	32.8	2.3
Dec	46.0 (1985)	37.5 (1980)	42.6	43.0	2.3
ANN: NH	27.3 (1978)	23.1 (1990)	25.3	25.3	1.1
ANN: EU	16.0 (1976)	13.1 (1990)	14.7	14.7	0.8
ANN: NA	11.7 (1978)	10.0 (1990)	10.6	10.7	0.4

sible on snow extent, water equivalent and depth, and surface albedo over land surfaces, and, at a minimum, snow extent and albedo over sea ice and the Greenland ice sheet. This effort should be designed to accommodate future improvements in all the realms of snow monitoring, including increased station coverage, operational satellite monitoring of the surface at  $1.6 \mu\text{m}$  to better distinguish clouds from snow cover (Bunting and d'Entremont 1982), new regional microwave algorithms, or improved GIS techniques. Charts might also benefit from the use of other data such as precipitation and temperature observations. The charts, whenever developed, should not replace the current NOAA visible product until sufficient coincident observations have been made to assure the continued utility of the lengthy NOAA product in climate change studies.

#### b. Retrospective monitoring

##### 1) CONTINUED ASSEMBLY, DIGITIZATION, AND QUALITY CONTROL OF HISTORIC AND RECENT STATION DATA

In addition to addressing data from conventional stations, ground data from snow courses and remote snow measurement networks should be scrutinized. This is exemplified by the current effort to recover snow course data from the former Soviet Union through a cooperative effort between the U.S. National Snow and Ice Data Center at the University of Colorado and A. Krenke of the Russian Academy of Science. All of these data, whether gathered daily or monthly, are needed as ground truth when verifying satellite-based efforts, as well as to provide historic perspective when analyzing recent variations. Associated with the latter, techniques need to be developed to merge satellite products with station historic time series.

##### 2) RECHART NORTHERN HEMISPHERIC CONTINENTAL SNOW COVER FROM 1966 THROUGH 1971

Visible satellite data are available for this interval, albeit at a lower resolution than in recent years. With the improved ability of analysts to recognize snow from clouds or snow-free ground, significant improvements to the early NOAA charts are possible. We also recommend recharting the Tibetan Plateau and adjacent mountains through the middle 1970s and summer high-latitude lands. These endeavors and spot checks across the continents in subsequent years would expand and improve the NOAA time series and would permit establishing quantitative error estimates to this product.

## 5. Conclusions

The recent meager extent of snow cover over Northern Hemisphere lands raises a number of ques-

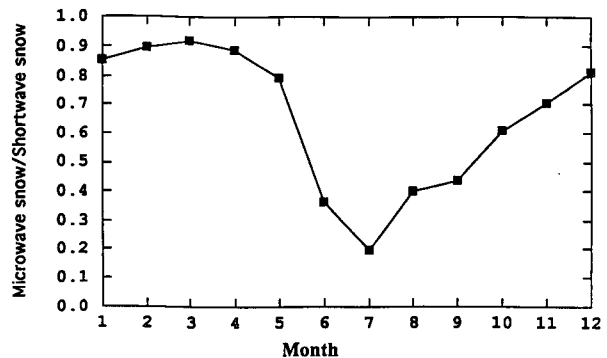


FIG. 6. Ratio of mean monthly snow cover area derived from NASA microwave and NOAA visible charts for Northern Hemisphere lands (excluding Greenland). NOAA values exceed NASA estimates for each month within the November 1978 through August 1987 study period.

tions regarding the natural variability of snow, the potential utility of snow as an indicator of human-induced climate change, and the role of snow in the climate system and in any future climate change. New studies have provided information about interactions between snow and other components of the climate system (e.g., Yasunari 1987; Robinson and Dewey 1990; Gutzler and Rosen 1992; IPCC 1992; Karl et al. 1993; Leathers and Robinson 1993), but they also illustrate the need for additional snow information. With the ongoing development of station and satellite snow datasets and the promise of continued improvements in analytic techniques, more accurate and extensive information on the extent and physical characteristics of snow cover across continents and sea ice will continue to become available. This information will contribute greatly to gaining greater insight and eventually provide answers to the questions posed above, the most important perhaps being whether snow cover is a credible indicator of climate change.

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