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Hemispheric snow cover from satellites

David A. Robinson
Department of Geography, Rutgers University, New Brunswick, NJ 08903, U.S.A.

ABSTRACT. Full hemispheric monitoring of snow cover has been possible since the advent of meteorological satellites in the 1960s. Since that time visible satellite imagery has been used to chart the extent of northern hemisphere snow on a weekly basis. An analysis of monthly snow areas from a consistent U.S. National Oceanic and Atmospheric Administration (NOAA) set, dating back to 1972, finds that hemispheric snow cover has been well below means for the 1972–91 interval since the middle of 1987. Since the late 1970s multichannel data from satellite-borne passive microwave sensors have been used to estimate hemispheric snowpack extent and depth or water equivalent. Microwave extents generally run considerably lower than NOAA visible values due to microwave difficulties in detecting patchy or wet snow, snow lying on unfrozen ground, and snow in forested regions. The relative simplicity of observing hemispheric snow cover from satellites, the potential of integrating these and other sources of data using geographical information system techniques, the critical role that snow cover has in the global heat budget, and the expected role of snow feedbacks in anthropogenic climate change support the continued diligent monitoring of snow cover.

INTRODUCTION

Empirical and modeling studies alike show snow cover to be an important climate variable (Walsh and others, 1985; Barnett and others, 1989), influencing the global heat budget chiefly through its effect of increasing surface albedo (Robinson and Kukla, 1985). Models simulate an amplification of global anthropogenically-induced warming in regions where and when snow cover is currently ephemeral (Manable and Wetherald, 1980; Dickinson and others, 1987). Accurate information on snow cover is essential for understanding details of climate dynamics and climate change. It has been suggested that this information might make snow-cover extent a useful index for detecting and monitoring such change (Barry, 1985). To date, our ability to examine the utility of snow extent as a climate indicator has been restricted due to the limited temporal and/or geographical coverage of available snow-cover data. Efforts are underway to extend regional analyses of snow cover to the beginning of this century (Robinson and Hughes, 1991). However, full hemispheric analyses of snow cover are available only since the advent of meteorological satellites.

In 1966, the U.S. National Oceanic and Atmospheric Administration (NOAA) began to map the snow and ice areas in the northern hemisphere on a weekly basis from the best available visible meteorological satellite imagery (Matson and others, 1986). That effort continues today, and remains the only such visible hemispheric product. In addition, strides have been made since the late 1970s to further understanding of the multichannel returns from passive microwave sensors so they might be employed in monitoring the global snowpack. Hemispheric snow extent has been calculated from microwave data for the period 1978 to 1987, the only such estimates to date (Chang and others, 1990). Here, the strengths and weaknesses of satellite-derived hemispheric snow products, both visible and microwave efforts, are discussed, results from twenty years of visible monitoring presented and recommendations for a future hemispheric product made.

VISIBLE CHARTING

NOAA weekly snow charts

Weekly snow charts produced by NOAA are based on a visual interpretation of photographic copies of satellite imagery by trained meteorologists. Up to 1972, the subpoint resolution of the meteorological satellites commonly used was around 4 km in the visible wavebands. Beginning in October 1972, the Very High Resolution Radiometer (VHRR) provided imagery with a spatial resolution of 1.0 km, which in November 1978, with the launching of the Advanced VHRR (AVHRR), was reduced slightly to 1.1 km. NOAA Geostationary Operational Environmental Satellite images are also used in the middle latitudes of North America. Snow is delimited by recognizing characteristic textured surface features and brightness of snow-covered lands. The charts show boundaries on the last day that the surface in a given region is seen. Since May 1982, dates when a region was last observed have been placed on the charts, and an examination of these dates shows the charts to be most representative of the fifth day of the week.

It is recognized that 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 since then charting accuracy is such that this product is considered suitable for continental-scale climate studies (Kukla and Robinson, 1981).

In addition to the problems imposed by end-of-the-week cloudiness, difficulties in using visible imagery to chart snow cover include: (1) low illumination when the solar zenith angle is high, (2) dense forests masking snow on the ground resulting in the under-representation of cover and (3) difficulty in discriminating snow from clouds in mountainous regions and in uniform lightly vegetated areas which have a high surface brightness when snow covered. The snow charts are quite reliable for certain times and in certain regions. These include regions where: (1) skies are frequently clear, commonly 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 only slowly and (4) pronounced local and regional signatures are present owing to the distribution of vegetation, lakes and rivers. Under these conditions the satellite-derived product will be superior to charts of snow extent gleaned from station data, particularly in mountainous and sparsely inhabited regions. Another advantage of the NOAA snow charts is their portrayal of regionally representative snow extent, whereas charts based on ground-station reports may be biased due to the preferred position of weather stations in valleys and in places affected by urban heat islands, such as airports.

The NOAA charts are digitized on a weekly basis using the NMC Limited-Area Fine Mesh grid. This is an 89×89 cell northern hemisphere grid, with cell resolution ranging from $16\,000\,km^2$ to $42\,000\,km^2$. Whether a cell is categorized as snow-covered or snow-free is determined by laying the grid over a chart and deciding if more than half of the cell lies in a snow-covered region. If so, the entire cell is considered snow-covered, if not it is digitized as being snow-free.

Derivation of monthly snow cover

A new routine to calculate monthly snow areas from the weekly NOAA data has been developed following the discovery of a major inconsistency in the manner in which NOAA has calculated monthly snow-cover areas (Robinsons and others, 1991). Prior to 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 $3 \times 10^6\,km^2$ greater than those calculated using weekly areas. The offsets are not consistent. Also contributing to the problem are 53 cells (covering $1.8 \times 10^6\,km^2$) not considered consistently in the area calculations throughout the period of record. In 1981 NOAA changed their land mask, in the process eliminating 26 cells from consideration of being snow-covered (categorizing them as water), while 27 others began to be examined. As discussed below, neither of the NOAA masks is accurate; both fail to identify all cells, and only those cells, at least half-covered by land.

Our new, consistent methodology (Rutgers Routine) calculates weekly areas from the digitized snow files and weights them according to the number of days of a given week that fall in the given month. A chart week is considered to center on the fifth day of the published chart week (cf. above). No weighting has been employed in either of the NOAA routines.

In addition, a definitive land mask has been developed using digital map files analyzed on a geographic information system (GIS). The percentage of land in each of the 7921 NMC grid cells is calculated using the National Geophysical Data Center's five-minute resolution ETOPO5 file as the primary data source. As this file does not include large interior lakes, the Navy Fleet Numerical Oceanography Center's ten-minute resolution Primary Terrain Cover Types file is used to account properly for these water bodies. Some 48 cells polewards of approximately 30° N, which had been considered land in the pre-1981 NOAA and/or the 1981-to-present NOAA mask, are actually predominantly water-covered (<50% land). Conversely, 54 land cells are found to have been considered water on one or both NOAA masks. Those cells falling under the latter require a first-time analysis to determine whether they might be snow-covered. This is accomplished by selecting nearest representative land cells (cells which NOAA has continuously 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.

Continental snow cover from NOAA charts: 1972–91

According to values generated using the Rutgers Routine, the extent of snow cover over northern hemisphere lands is greatest in January. On average, some $46.6 \times 10^6\,km^2$ of Eurasia and North America are snow-covered in this month, with February a close second with an average of $46.1 \times 10^6\,km^2$ (Table 1). August has the least cover, averaging $3.9 \times 10^6\,km^2$, most 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 $0.9 \times 10^6\,km^2$ in August to $3.0 \times 10^6\,km^2$ in October. The annual mean cover is $25.4 \times 10^6\,km^2$ with a standard deviation of $1.1 \times 10^6\,km^2$. The snowiest year was 1978 with a mean of $27.3 \times 10^6\,km^2$, with 1990 the least snowy at $23.1 \times 10^6\,km^2$.

Twelve-month running means of snow extent over northern hemisphere lands best illustrate the period of above normal cover that occurred in the late 1970s and mid 1980s (Fig. 1). Over Eurasia and North America, 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 49 months between August 1987 and August 1991, only four had above-normal snow cover (January 1988, September

Table 1. Monthly and annual snow cover (million km²) over northern hemisphere lands during the period January 1972 through August 1991. Areas are calculated using the Rutgers Routine

	Maximum (yr)	Minimum (yr)	Mean	Median	Std. dev.
Jan	49.8 (1985)	41.7 (1981)	46.6	46.1	1.9
Feb	51.0 (1978)	43.2 (1990)	46.1	45.7	2.0
Mar	44.1 (1985)	37.0 (1990)	41.1	41.1	1.8
Apr	35.3 (1979)	28.2 (1990)	31.5	31.4	1.7
May	24.1 (1974)	17.4 (1990)	20.9	20.9	2.0
Jun	15.6 (1978)	7.3 (1990)	11.6	11.5	2.1
Jul	8.0 (1978)	3.4 (1990)	5.3	5.5	1.2
Aug	5.7 (1978)	2.6 (1988, '89,'90)	3.9	3.9	0.9
Sep	7.9 (1972)	3.9 (1990)	5.7	5.6	1.1
Oct	26.1 (1976)	13.0 (1988)	17.6	17.5	3.0
Nov	37.9 (1985)	28.3 (1979)	33.0	32.7	2.4
Dec	46.0 (1985)	37.5 91980)	42.5	43.0	2.3
Annual	27.4 (1978)	23.1 (1990)	25.4	25.3	1.1

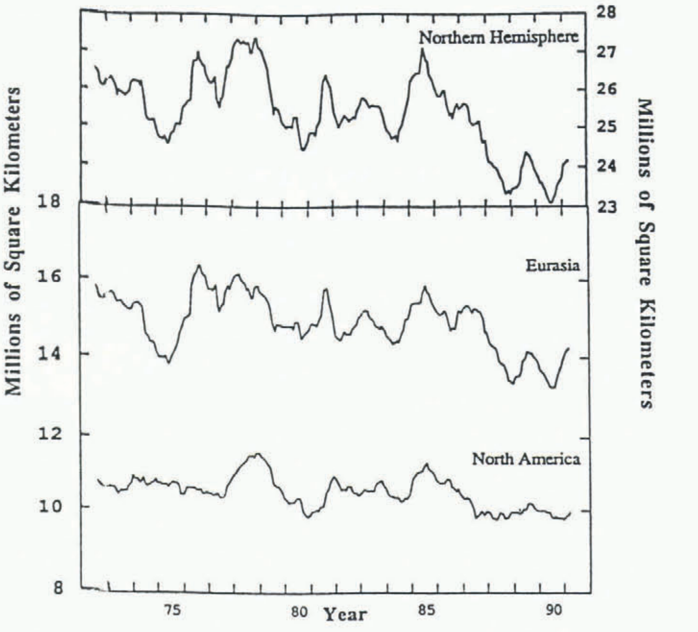

Fig. 1. Twelve-month running means of snow cover over northern hemisphere lands (including Greenland) for the period January 1972 through August 1991. Running means are also shown for Eurasia and North America (including Greenland). Values are plotted on the 7th month of the 12-month interval, and are calculated from NOAA weekly snow charts using the Rutgers Routine.

1989, December 1989, December 1990). Preliminary figures show this continuing through May 1992, with the exception of November 1991, which was above normal. The lowest year on record was 1990, when monthly minima occurred in eight months (Table 1). Through 1991, spring cover has shown pronounced deficits since 1987 in North America and 1988 in Eurasia; areas in these springs have been at or below lows established prior to this period. During the same interval, both continents have had low seasonal cover in the fall and summer, although frequently neither continent has been at or approached record low levels. Winter cover has been close to average over the past five years.

MICROWAVE CHARTING

Microwave radiation emitted by the earth's surface penetrates winter clouds, permitting an unobstructed signal from the earth's surface to reach a satellite. The discrimination of snow cover from microwave data is possible mainly because of differences in emissivity between snow-covered and snow-free surfaces. Estimates of the spatial extent as well as the depth or water equivalent of the snowpack are gleaned from equations employing radiation sensed by multiple channels in the microwave portion of the spectrum (e.g. Kunzi and others, 1982; McFarland and others, 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 on the order of several tens of km. Since 1987, close to the time of SMMR failure, the Special Sensor Microwave Imager (SSM/I) has provided information for the determination of snow extent and volume. The lack of sufficient ground-truth data on snow depth or volume makes an adequate assessment of the reliability of such microwave estimates uncertain. Therefore the remainder of this discussion focuses on the microwave monitoring of snow extent.

As with visible products, the microwave charting of snow extent is not without its limitations. The resolution of the data 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. It is also apparent that because of region-specific differences in land cover and snowpack properties, no single algorithm can adequately estimate snow cover across northern hemisphere lands. Efforts are underway to undertand regional microwave signatures better, and in some cases to develop region-specific algorithms. Landscapes of interest include mountains (Chang and others, 1991; Armstrong and Rango, 1992), forest (Hall and others, 1982; Hallikainen and Jolma, 1986; Foster and others, 1991), tundra (Hall and others, 1986), prairie (Goodison, 1989) and the Tibetan Plateau (Robinson and others, 1990). It remains difficult to validate snow estimates and gain an accurate understanding of conditions within a 25–50 km microwave pixel. This can be a result of sparse networks of stations with daily snow data (Schweiger and Barry, 1989), but can even be a problem in areas where intensive field studies are conducted, particularly if the landscape is highly variable (Chang and others, 1987a).

Continental snow cover from NASA microwave charts: 1978–87

With the exception of select areas such as the Tibetan Plateau (Robinson and others, 1984), microwave algorithms tend to underestimate snow extent. This is apparent when comparing National Aeronautics and Space Administration (NASA) microwave estimates of monthly continental snow extent using the generic algorithm of Chang and others (1987b) with NOAA visible values. The theoretical NASA algorithm uses the difference in brightness temperatures of 18 and 37GHz SMMR data to derive a snow depth/brightness temperature relationship for a uniform snow field. A snow density of $0.3\,g\,cm^3$ and a snow-crystal radius of 0.3 mm are assumed, and by fitting the differences to the linear portion of the 18 and 37 GHz responses a constant is derived that is applied to the measured differences. This algorithm can be used for snow up to one meter deep.

NASA mean monthly snow cover for northern hemisphere lands (exclusive of Greenland) runs from less than one to as much as thirteen million square kilometers below NOAA areas for the nine years of coincidental estimates (Robinson, 1992). These absolute differences are greatest in the late fall and early winter. In a relative sense, microwave areas are between 80 and 90% of visible values in winter and spring, 20 to 40% of the visible estimates in summer, and 40 to 70% of visible areas in fall. A possible explanation for the great disparities in the latter two seasons may be the wet and shallow nature of the snowpack interfering with accurate microwave recognition of snow. Depth may be the most important of the 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 (personal communication from B. Goodison).

While the preceding discussion has dealt with SMMR data, snow monitoring employing SSM/I data shows the same strengths and liabilities as the former (Goodison, 1989; Hall and others, 1991). The SMM/I has 19 and 37 GHz channels, thus SMMR algorithms perform much as they do 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).

CONCLUSIONS

Monthly snow cover across continents of the northern hemisphere has been well below 1972–91 normals since the middle of 1987. Few months during the past four years have exhibited above-normal coverage, and deficits have been particularly large in spring. Low totals have been observed in both Eurasia and North America. This period of reduced extent has occurred during one of the warmest periods of the past century, and throughout the past two decades, twelve-month running means of snow cover and surface air temperature show a striking relationship. Both may in part be due to a snow–albedo–temperature feedback.

Further research is needed to understand better the recent snow deficits and any associations between snow cover and other climate variables. Of primary importance is the increased availability of accurate snow information. This includes maintaining the NOAA satellite charting effort in a consistent manner, to assure temporal continuity. In addition, GIS techniques should be employed to produce an all-weather, all-surface hemispheric snow product that includes information on snow extent, volume and the surface albedo of snow-covered regions. This involves merging visible and microwave satellite input, along with station observations. To succeed, this will require the development of regional microwave algorithms, as a global algorithm has been shown most often to underestimate the coverage of snow. Further consolidation and access to station data sets, including their digitization and quality control is also necessary.

With climatic data sets of snow and other variables in place, detailed analyses of snow kinematics and the dynamic role of snow cover in the climate system can be addressed adequately. Finally, the relative simplicity of observing hemispheric snow cover from satellites, the potential of integrating these and other sources of data using GIS techniques, the critical role that snow cover has in the global heat budget, and the expected role of snow feedbacks in anthropogenic climate change support the continued diligent monitoring of snow cover.

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