Evaluating Snow Cover Over Northern Hemisphere Lands Using Satellite and *In Situ* Observations

D.A. ROBINSON[1]

ABSTRACT

Snow cover is a sensitive indicator of climate dynamics and climate change, and an integrator of basic climate elements. As such, it is important that accurate snow information be available for study. Analyses of weekly National Oceanic and Atmospheric Administration (NOAA) snow charts, that are derived from visible satellite imagery, show two pronounced regimes of snow extent during the 1972-present period over both Eurasia and North America. These charts show that between 1972 and 1985, annual means of snow extent fluctuated around a mean of 25.9 million square kilometers. An abrupt transition occurred in 1986 and 1987, and since then the mean annual extent has been 24.2 million sq. km. Recent decreases in snow extent are large during the spring and summer, while winter and fall extents show no statistically significant change.

The NOAA visible snow product is part of a new integrated dataset that utilizes visible wavelength and microwave satellite derived snow estimates and *in situ* ground station sources. This new set, which is nearing completion, has been developed for the detailed analysis of continental snow cover at regional to hemispheric scales. Data files of snow extent and depth covering five-day intervals are being assembled in a geographic information system. Visible wavelength satellite data and station observations extend from 1972 to present, and microwave data from 1979 to present. The 1° x 1° gridded product will permit the strengths and weaknesses of the individual data sources to be identified and quantified. For instance, according to preliminary analyses of visible, microwave and *in situ* data, microwave estimates of snow extent tend to be too low in all but arid, particularly high-altitude arid, regions.

Key words: snow, climate, Northern hemisphere.

INTRODUCTION

The large-scale distribution of snow cover over Northern hemisphere lands is a topic that has received 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 and depth (or water equivalent) is also 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.

Since 1972, weekly visible wavelength satellite maps of Northern hemisphere snow cover produced by the National Oceanic and Atmospheric Administration (NOAA) have provided an extremely useful means of assessing hemispheric snow cover. This paper will examine means and fluctuations of hemispheric snow extent in recent decades using this information. Studies which have utilized the NOAA snow data for understanding snow cover kinematics include Matson & Wiesnet (1981), Dewey & Heim (1982), Barry (1990), Robinson et al. (1991), Iwasaki (1991), Gutzler & Rosen (1992), and Masuda et al. (1993). Recent studies that use NOAA snow data to investigate snow cover synergistics within the climate system include Leathers & Robinson (1993; 1995), and Karl et al. (1993).

To measure the accuracy of regional to hemispheric-scale estimates of snow extent, as well as to estimate snow depth, the NOAA set is being combined with other sources of snow information. These include microwave satellite estimates and *in situ* station observations of snow depth. Examples of some preliminary data from this integrated set, which is nearing completion, will be discussed below.

[1] Department of Geography, Rutgers University, New Brunswick, New Jersey 08903 USA

INTEGRATED SNOW PRODUCT

Visible satellite observations

Data files of snow extent and snow depth covering five-day intervals (pentads) are being assembled for 1° latitude by 1° longitude cells using geographic information system techniques. A person skilled in image interpretation produced the NOAA snow charts from the visible-band satellite imagery. Charts are digitized weekly using the National Meteorological Center Limited-Area Fine Mesh (LFM) grid (cf. Matson et al., 1986, and Robinson, 1993a for further details on NOAA charts). While NOAA charts have been produced since 1966, early ones tended to underestimate snow extent, particularly during the fall. The accuracy of the data improved considerably in 1972, with the acquisition of higher resolution imagery (Wiesnet et al., 1987).

The results of snow extent discussed in the next section use monthly means of snow cover calculated using a routine described fully in Robinson (1993a). This routine calculates weekly areas from the digitized snow files, and then to obtain a monthly value, weights them according to the number of days of a chart week falling in the given month. A chart week (the routine will be adjusted to use pentad input once the new set is completed) is considered to center on the fifth day of the published chart week. Prior to the calculations, the digital files are standardized to a common land mask. Only those LFM cells that contain more than 50% land are included. This corrects an inconsistency in the original NOAA files.

Microwave satellite observations

Estimates of the spatial extent and the depth or water equivalent of a snowpack are gleaned from measurements in multiple microwave channels (e.g., Kunzi et al., 1982; McFarland et al., 1987; Chang et al., 1987; Grody & Basist, 1996). Microwave radiation emitted by the earth's surface is unaffected by most winter clouds, permitting an unobstructed signal from the surface to reach the satellite. The discrimination of snow cover and depth using microwave data is possible mainly because of differences in emissivity between snow covered and snow free surfaces. Differences in microwave scattering between snowpacks is generally a function of snow mass, although other factors, such as ice layers within the pack, or depth hoar at the base, also influence scattering. Vegetation protruding though the pack also influences microwave signals reaching the satellite sensor, making estimates of snow difficult in forested regions. Snow estimates from satellite-borne microwave sensors have been available since the launch of the Scanning Multi-channel Microwave Radiometer (SMMR) in late 1978. 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/depth. The spatial resolution of the data from these sensors ranges from approximately 15-40 kilometers. The integrated dataset discussed here includes SMMR snow estimates based on the algorithm of Chang et al. (1987) and SSM/I estimates derived from the algorithm of Grody and Basist (1996).

In situ station observations

Data files for station observations are the final component to be added to the integrated analysis. These data will include Global Telecommunication System snow depth observations from across the Northern hemisphere (available during most of the 1980s) and data from western China. To date, the file contains data from the United States Historical Daily Climate Dataset (Robinson, 1993b), Canada, and the former Soviet Union.

Comparison of products

The integrated product will provide more accurate snow information than any one source alone, as the strengths of one source will compensate for the weaknesses of another. In the process, how well each product depicts snow cover will be better understood. Clearly, where the visible and microwave products report similar spatial frequencies of snow coverage, confidence is high. A comparison of frequencies of snow extent for the first six pentads of 1979 is shown in figure 1. There is considerable agreement over most Northern hemisphere lands. However, there are some notable exceptions, particularly in regions where snow coverage is between 10% and 90% (the snow transition zone). Firstly, the microwave product reports more extensive snow cover than the visible charts over the Tibetan plateau and the arid lowlands of east Asia, as well as over the higher elevations of western North America. The Chang et al. (1987) SMMR algorithm overestimates snow extent in cold and arid regions, particularly at high elevations (Robinson & Spies, 1995). This is due to surface and atmospheric conditions in these regions differing from those assumed in the development of the global snow algorithm, thus the brightness temperatures measured by the satellite and incorporated in the algorithm do not provide an accurate assessment of snow cover.

Secondly, the visible product generally shows more snow cover than the microwave over the eastern two thirds of North America, western Asia and Europe. Station data indicate that here also the visible product is the more accurate of the two (figure 2). A combination of four factors may explain this: 1) vegetation protruding through the snow pack affects the brightness temperatures recorded by the microwave sensor, 2) the snowpack may be shallow and patchy, again affecting brightness temperatures,

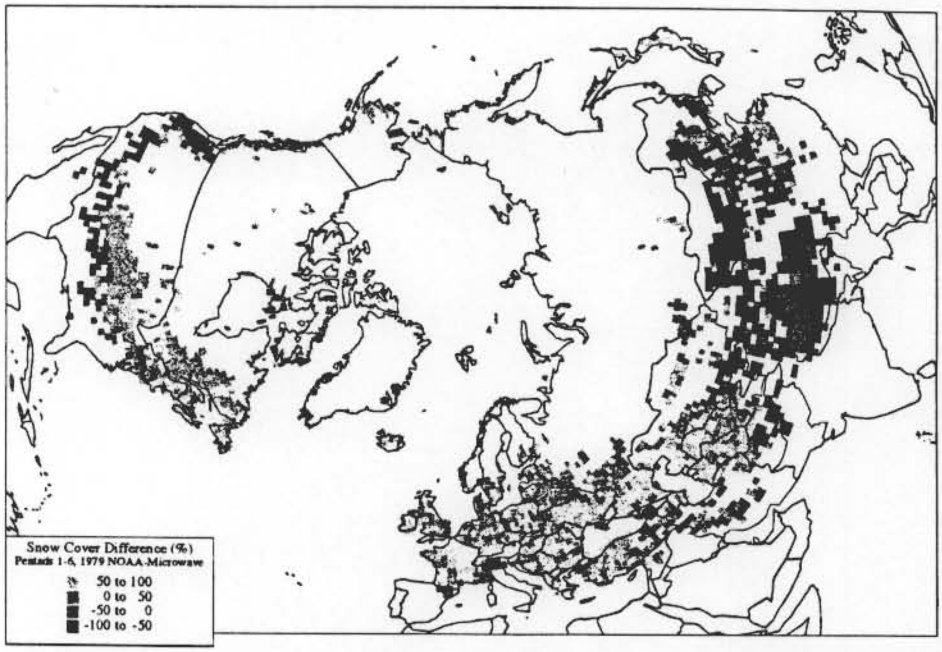

Figure 1. Difference of visible and microwave snow cover frequencies for the first six pentads of 1979. Values are positive where visible (NOAA) analyses show more frequent cover than microwave (SMMR) analyses.

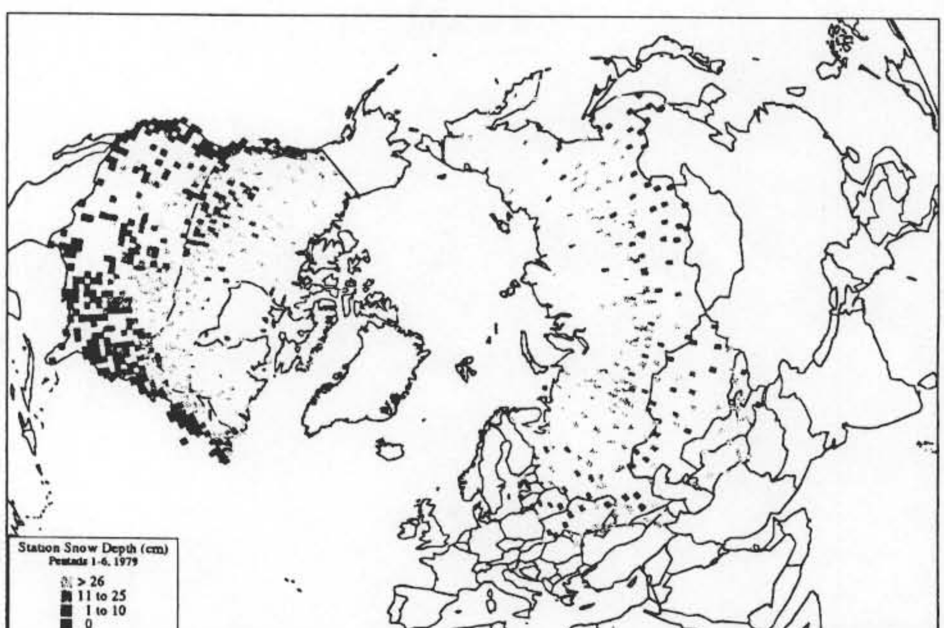

Figure 2. Average snow depth derived from ground station observations for the first six pentads of 1979. Observations from all stations within a 1° x 1° cell are averaged to obtain a pentad cell mean. In turn, the mean cell depths for the six pentads are averaged.

3) the snow pack may be wet, resulting in brightness temperatures similar to snow free ground, and 4) the water content of clouds may be high enough to interfere with or obscure the microwave signal from the surface. A more detailed analysis of all three datasets is required to quantify all of the differences.

A benefit of both the station and microwave data over visible image observations are their estimates of snow depth (also may be expressed as volume or water equivalent). An investigation at Rutgers, conducted over extensive spatial and temporal dimensions, is helping to quantify the limitations of these products. Preliminary comparisons of SMMR and HDCD data over the United States (not shown) indicates that station-measured snow depths are greater than microwave estimates east of the Mississippi basin, while the opposite situation is seen over the Great Plains. A mixed signal is observed in the mountainous West. Speculation is that the protruding vegetation in the East results in an underestimation of microwave depths, and blowing and drifting snow results in an underestimation of regional snow depth at stations in the Plains.

SNOW COVER VARIABILITY: 1972-PRESENT

NOAA satellite charts give the most accurate and appropriate data for assessing variability of snow cover on a continental scale (Wiesnet et al., 1987). An analysis of the NOAA data finds that mean annual Northern hemisphere snow cover extent is 25.3 million square kilometers, with 14.7 million sq. km. over Eurasia and 10.6 million sq. km. over North America (including Greenland) (table 1).

Table 1: Monthly and annual (ANN) snow cover (million sq. km.) over Northern hemisphere (NH) lands during the period January 1972 through September 1996. Annual values for Eurasia (EU) and North America (NA) are also included. Areas are calculated using the Rutgers method.

	MAX	*(yr)*	*MIN*	*(yr)*	*MEAN*	*MEDIAN*	*STD. DEV.*
Jan	49.8	(1985)	41.7	(1981)	46.5	46.6	1.8
Feb	51.0	(1978)	42.5	(1995)	45.7	45.2	2.0
Mar	44.1	(1985)	37.0	(1990)	40.8	40.7	1.9
Apr	35.3	(1979)	28.2	(1990)	31.2	31.2	1.8
May	24.1	(1974)	17.4	(1990)	20.6	19.9	1.9
Jun	15.6	(1978)	7.3	(1990)	11.2	11.3	2.1
Jul	8.0	(1978)	3.4	(1990)	5.1	5.2	1.2
Aug	5.7	(1978)	2.6	(1988-90)	3.7	3.5	1.0
Sep	7.9	(1972)	4.0	(1990)	5.6	5.4	1.1
Oct	26.1	(1976)	13.0	(1988)	17.4	17.5	2.9
Nov	38.3	(1993)	28.3	(1979)	33.4	33.5	2.3
Dec	46.0	(1985)	37.5	(1980)	42.7	43.2	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

Monthly anomalies of greater than 4 million sq. km. have been observed occasionally throughout the past two and a half decades, although they are generally less than 2 million sq. km. (figure 3).

The NOAA time series indicates that recent years have less snow cover than the earlier part of the satellite record over both Eurasia and North America (figure 3). This difference is not associated with a steady decrease of snow extent, but with a step change. Between 1972 and 1985, twelve-month running means of snow extent fluctuated around a mean of 25.9 million sq. km. A rather abrupt transition occurred in 1986 and 1987, and since then mean annual extent has been 24.2 million sq. km. The means of these two periods are significantly different (T test, $p < 0.01$). Recent decreases in snow extent are large during the spring and summer, while winter and fall extents show no statistically significant change (figure 4). Monthly observations show the decrease beginning in February (figure 5). During 7 of the first 15 years of record, February snow extent exceeded the January value. Only once has this occurred in the past decade.

Occasional extremes in snow extent differences from one month to the next are also observed in figure 5. Such a situation occurred in 1995, where the decrease in hemispheric snow cover extent from March to April was considerably less than in any of the other 24 years of record. Subsequently, the April to May 1995 loss of snow cover was the maximum

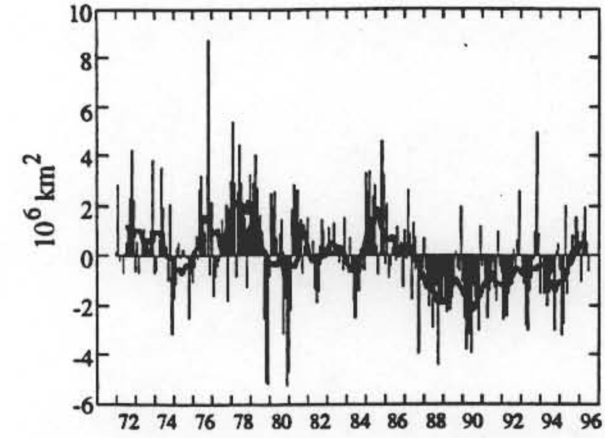

Figure 3. Anomalies of monthly snow cover extent over Northern hemisphere lands (including Greenland) between January 1972 and September 1996. Also shown are twelve-month running anomalies of hemispheric snow extent, plotted on the seventh month of a given interval. Anomalies are calculated from NOAA visible charts. Mean hemispheric snow extent is 25.3 million sq. km. for the full period of record.

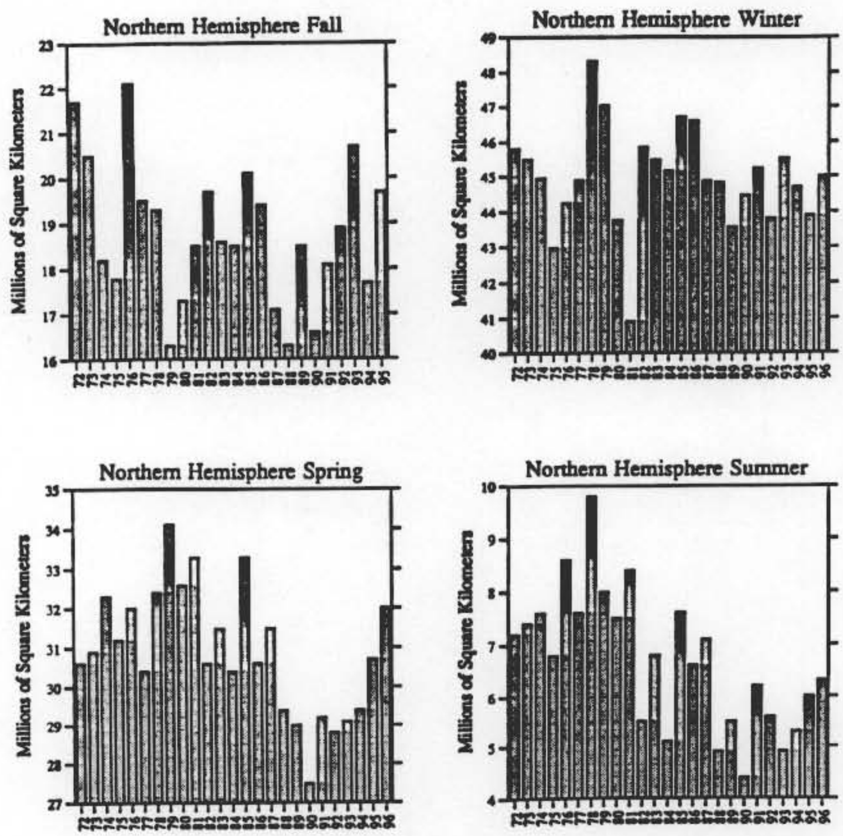

Figure 4. Seasonal snow cover extent over Northern hemisphere lands (including Greenland) between winter (Dec '71-Feb '72) 1972 and summer (Jun - Aug) 1996. Calculated from NOAA visible charts.

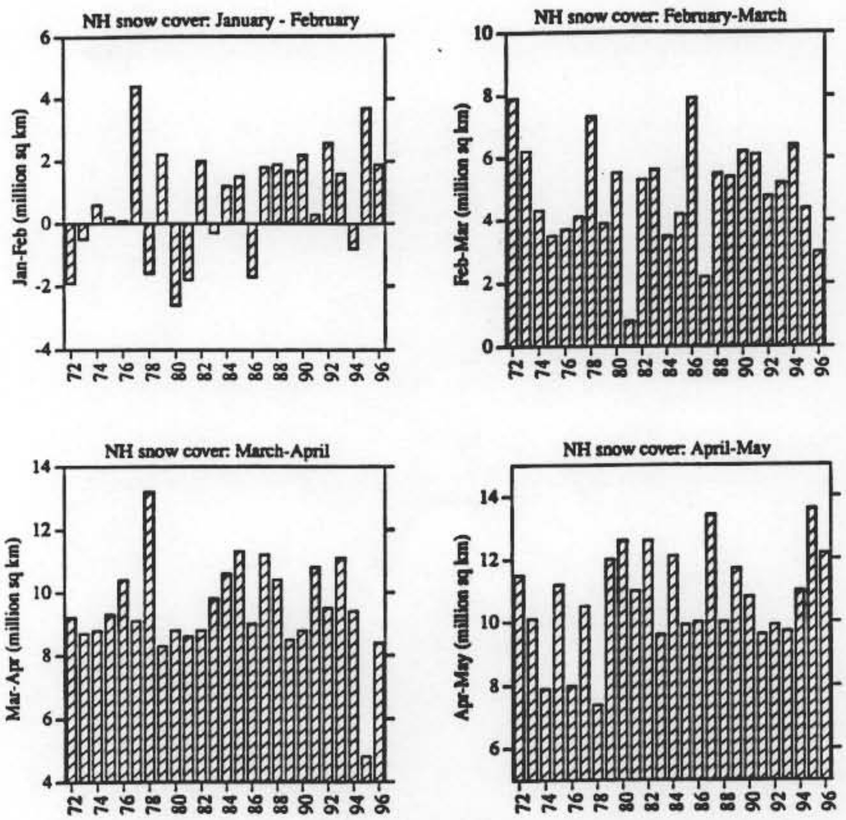

Figure 5. Change in snow cover extent over Northern hemisphere lands from one month to the next, from January to May, for the period January 1972 through May 1996. Calculated from NOAA visible charts.

on record. These fluctuations appear to be largely influenced by continental-scale synoptic events, and must be taken into account when diagnosing recent decreases in late season snow.

CONCLUSIONS

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

Studies using the new integrated snow set, in conjunction with other climatic information, are helping us to place recent variations in historic perspective (cf. Hughes et al., this volume) and to better understand the synergistic relationships between hemispheric-scale atmospheric circulation and thermal variations and continental snow extent (Frei et al., this volume). These and future snow investigations will help establish more meaningful projections of future climatic states.

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