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A discussion of the accuracy of NOAA satellite-derived global seasonal snow cover measurements

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ABSTRACT The first weekly charting of snow cover in the Northern Hemisphere using meteorological satellite images was begun by the U.S. National Oceanic and Atmospheric Administration (NOAA) in November 1966. While this long-term data base is a significant improvement over ground charts produced solely from ground station data, several real and potential sources of error affect it. Because climatologists who study the effect of large-scale snow cover on the global heat budget utilize these data, evaluation of their accuracy is in order. This paper reviews the results of investigations which have attempted to quantify the noise level in the data and concludes that, except for the fall season, the data are accurate enough for climate-related studies on continental or hemispheric scales. However, care should be exercised and additional verification with station data is recommended before using the product in local or regional studies of snow cover variation. Recommendations are also made for integrating satellite and ground station data and for further development of sensors and remote-sensing techniques from which estimates of snow depth and snow water equivalent can be developed.

Étude de l'exactitude des mesure de la couverture saisonnière mondiale de neige effectuée à partir du satellite de la NOAA

RÉSUMÉ En novembre 1966, la NOAA a commencé d'établir, de semaine en semaine, la carte de la neige et de la glace de l'hémisphère nord à partir des données satellitaires de météorologie. Aujourd'hui, elle continue cette tâche. Les climatologistes ont déterminé la nécessité de mesures exactes de cette variable clé, qui influence le bilan thermique du globe. Des sources d'erreurs, effectives ou éventuelles, touchent cette base de données à long terme. Dans quelle mesure les données sont-elles exactes et les climatologistes peuvent-ils les utiliser pour la modélisation du globe et d'autres études liées au climat? Des examens antérieurs ont mesuré des erreurs systématiques et des fluctuations dans les données, mais concluent qu'à l'exception d'une divergence saisonnière à l'automne, les données sont généralement utiles pour les études liées au climat à l'échelle mondiale. Toutefois, il faut prendre des précautions pour tenter des études de l'étendue de neige. On donne des conseils pour intégrer les données satellitaires et les données des stations météorologiques et pour étudier, par la recherche, l'amélioration du rendement des capteurs pour la mesure de la hauteur de neige et l'équivalent en eau de la neige.

INTRODUCTION

Before the global data gathering capability of meteorological satellites, snow-cover extent was a climatic variable determined on the basis of synoptic weather station reports. The resulting maps were highly generalized. In most mountainous or poorly inhabited areas, regionally-representative data were not available. In November 1966, the U.S. National Oceanic and Atmospheric Administration/ National Environmental Satellite Service (NOAA/NESS), the forerunner of today's NOAA/National Environmental Satellite, Data and Information Services (NESDIS), began to map the snow and ice areas in the Northern Hemisphere from the best available meteorological satellite imagery on a weekly basis. That effort continues today.

Interest in global climate is growing, not only because of potential CO_2-induced changes, but also because of concern over possible changes of the ozone layer and the debate concerning potential climatic consequences of nuclear war. This interest extends also to the areal extent of snow and ice, which is one of the key variables in the global climate system. It influences the global heat budget, chiefly through its effect of increasing global albedo (Untersteiner, 1961; Kung *et al.*, 1964; Radok, 1978; Robinson & Kukla, 1985). Accurate measurement of global snow and ice cover is essential for understanding the details of climatic change (Kukla & Kukla, 1974; Wiesnet & Matson, 1976).

The objective of this paper is to discuss the real and potential sources of error that affect this important data base. The following elements need to be evaluated regarding the recognition of snowfields: the influence of satellite and sensor characteristics (e.g. field of view, wavelength, resolution, etc.), interpreter biases, the impact of cloud covered areas, the statistical treatment of data, snow covers of a short duration, snow under forest canopies, snow in mountainous areas, map scales and projections, consistency of analysis techniques, winter darkness, etc. The brevity of this paper precludes meaningful discussion of some of these elements.

PREPARATION OF THE SNOW AND ICE CHARTS

The snow charts are produced from a visual interpretation of photographic copies of NOAA satellite imagery by trained meteorologists. The NOAA satellites and sensors used in the mapping are listed in Table 1. The subpoint resolution of the NOAA meteorological satellites commonly used has ranged from 1.0 km to 7.4 km. Up to 1972, the resolution 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. Since January 1970, the thermal IR has also been used for night-time snow-cover observations. NOAA Geostationary Operational Environmental Satellite (GOES) images are also used in the middle latitudes of North America.

By recognizing characteristic textured surface features and brightnesses of snow-covered lands, the interpreters delimit the snow boundary and plot it on a 1:50,000,000 polar stereographic base map. Boundaries are plotted daily where the surface is visible. Where skies are cloudy, the boundary is considered stable, with no adjustments made until the surface is once again observed. The final weekly chart thus contains observations plotted over at least the last several days of the week (Fig. 1).

The NOAA charts have always delimited the boundary between snow covered and snow-free land surfaces. Until May 1982, one of three categories of relative surface brightness was assigned to a region with snow cover (Fig. 2). This practice was dropped, as it was felt to be too subjective. Since May 1982, areas of patchy cover have been differentiated from "full" snow cover. Also, since May 1982, the dates when portions of the snow boundary are last detected on the satellite imagery were first noted. Figures 1 and 2 show recent and early examples of a NOAA chart. Recently, these snow charts were digitized using the National Meteorological Center's standard 89-by-89 element matrix superimposed on a polar stereographic Northern Hemisphere chart. The data are updated annually. They are summarized in the Atlas of North American Snow Cover of NOAA-NESDIS, which shows monthly frequency maps (Matson *et al.*, 1986) (Fig. 3).

TABLE 1 NOAA/NESDIS Satellites and Sensors used in Mapping Northern Hemisphere Snow and Ice Cover (after Matson et al., 1986)

SATELLITE	SENSOR[a]	SPECTRAL BAND (μm)	SUBPOINT RESOLUTION (km)	PERIOD OF OPERATIONS
ESSA 3	AVCS	0.5 - 0.75	3.7	2 Oct 1966- 9 Oct 1968
ESSA 4	APT	0.5 - 0.75	3.7	26 Jan 1967- 6 Dec 1967
ESSA 7	AVCS	0.5 - 0.75	3.7	15 Aug 1968-19 Jul 1969
ESSA 8	APT	0.5 - 0.75	3.7	15 Dec 1968-12 Mar 1976
ESSA 9	AVCS	0.5 - 0.75	3.7	26 Feb 1969-15 Dec 1973
ITOS 1	AVCS	0.5 - 0.75	3.7	23 Jan 1970-17 Jun 1971
	APT	0.5 - 0.75	3.7	
	SR	0.52 - 0.73	3.7	
		10.5 -12.5	7.4	
NOAA 2	VHRR	0.6 - 0.75	1.0	15 Oct 1972-30 Jan 1975
		10.5 -12.5	1.0	
	SR	0.52 - 0.73	3.7	
		0.50 - 0.94	3.7	
		10.5 -12.5	7.4	
NOAA 3	VHRR	0.6 - 0.74	1.0	6 Oct 1973-17 Dec 1974
	SR	0.52 - 0.73	3.7	
		10.5 -12.5	7.4	
NOAA 4	VHRR	Same as NOAA 3		15 Nov 1974-15 Sep 1976
	SR	Same as NOAA 3		
NOAA 5	VHRR	0.6 - 0.75	1.0	29 Jul 1976- 1 Mar 1979
		10.5 -12.5	1.0	
	SR	0.52 - 0.73	3.7	
		0.50 - 0.94	3.7	
		10.5 -12.5	7.4	
TIROS-N	AVHRR	0.55 - 0.90	1.1-4.4	6 Nov 1978-20 Jan 1980
		0.725- 1.10	1.1-4.4	
		3.55 - 3.93	1.1-4.4	
		10.5 -11.5	1.1-4.4	
NOAA Series	AVHRR	0.55 - 0.68	1.1-4.4	16 Jul 1979-present
		0.725- 1.10	1.1-4.4	
		3.55 - 3.93	1.1-4.4	
		10.5 -11.5[b]	1.1-4.4	
		10.3 -11.3[c]	1.1-4.4	
		11.5 -12.5[c]	1.1-4.4	
GOES Series	VISSR	0.55 - 0.70	1-7.4	17 May 1975-present
		10.5 -12.5	7.4	

a) Cameras and sensors: AVCS, Advanced Vidicon Camera System; APT, Automatic Picture Transmission; SR, Scanning Radiometer; VHRR, Very High Resolution Radiometer; AVHRR, Advanced Very High Resolution Radiometer; VISSR, Visible and Infrared Spin Scan Radiometer
b) Four-channel AVHRR
c) Five-channel AVHRR

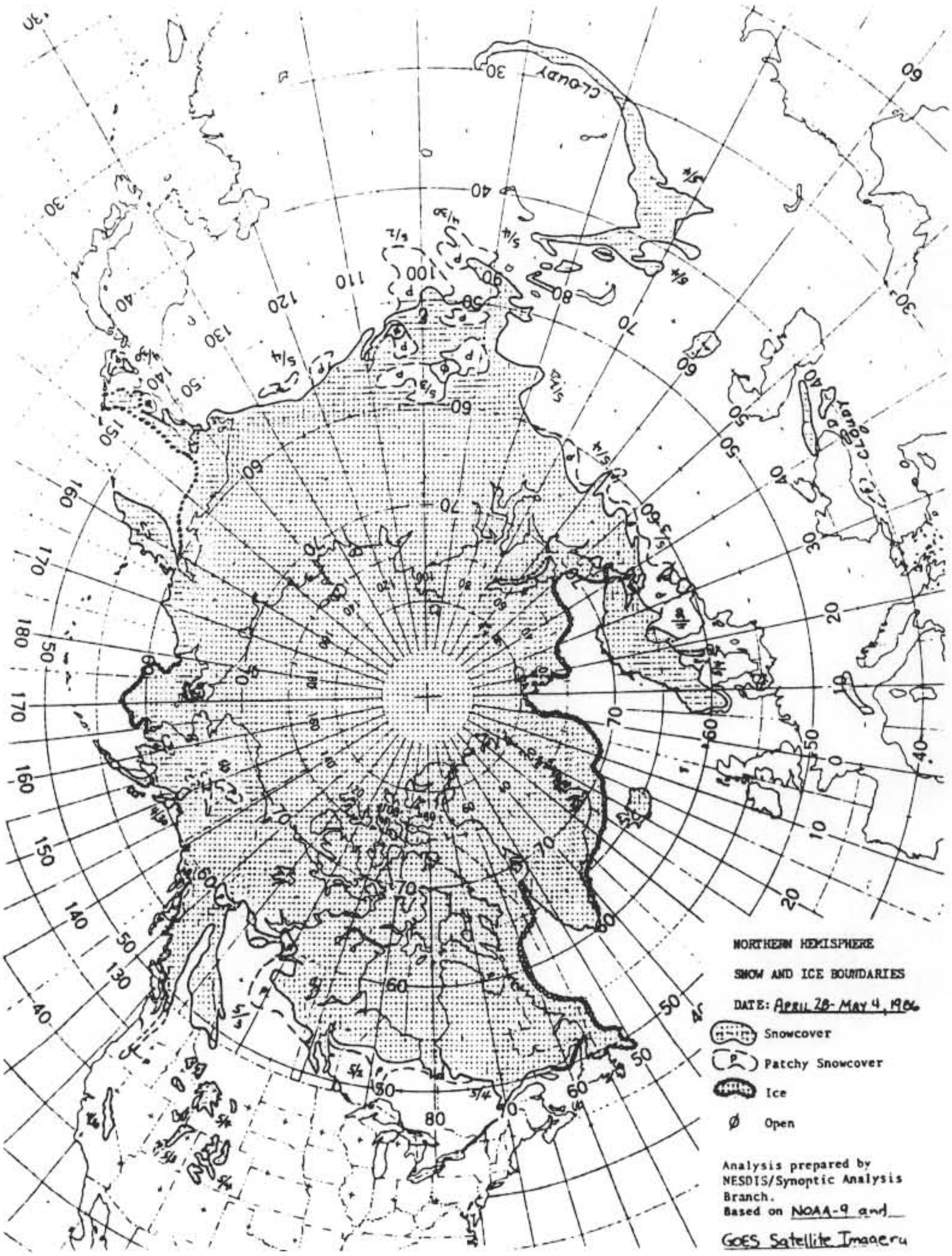

FIG. 1   NOAA Snow chart for April 28 - May 4, 1986

POTENTIAL SOURCES OF ERROR

The potential sources of error within the NOAA snow chart set fall into three broad categories: procedural, seasonal, historical.

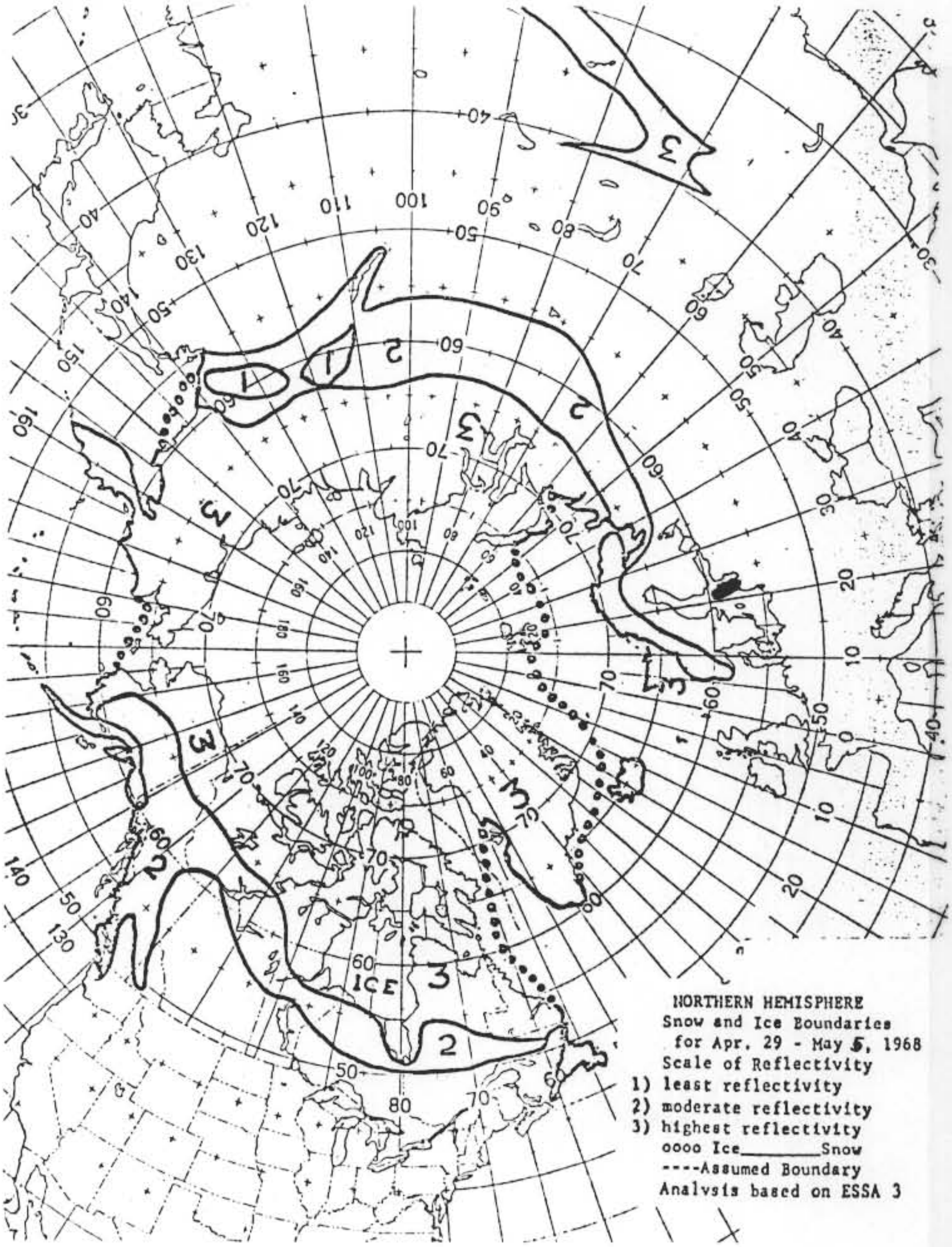

FIG. 2 NOAA snow chart for April 29 - May 5, 1968

Procedural

Tests have shown that the NOAA charts best represent snow cover conditions over the United States on the penultimate day of the chart week (Fig. 4) (Kukla & Robinson, 1981). However, for Eurasia and the high latitudes of North America, where GOES images are not available, the average lag in charting snow cover changes is probably considerably larger.

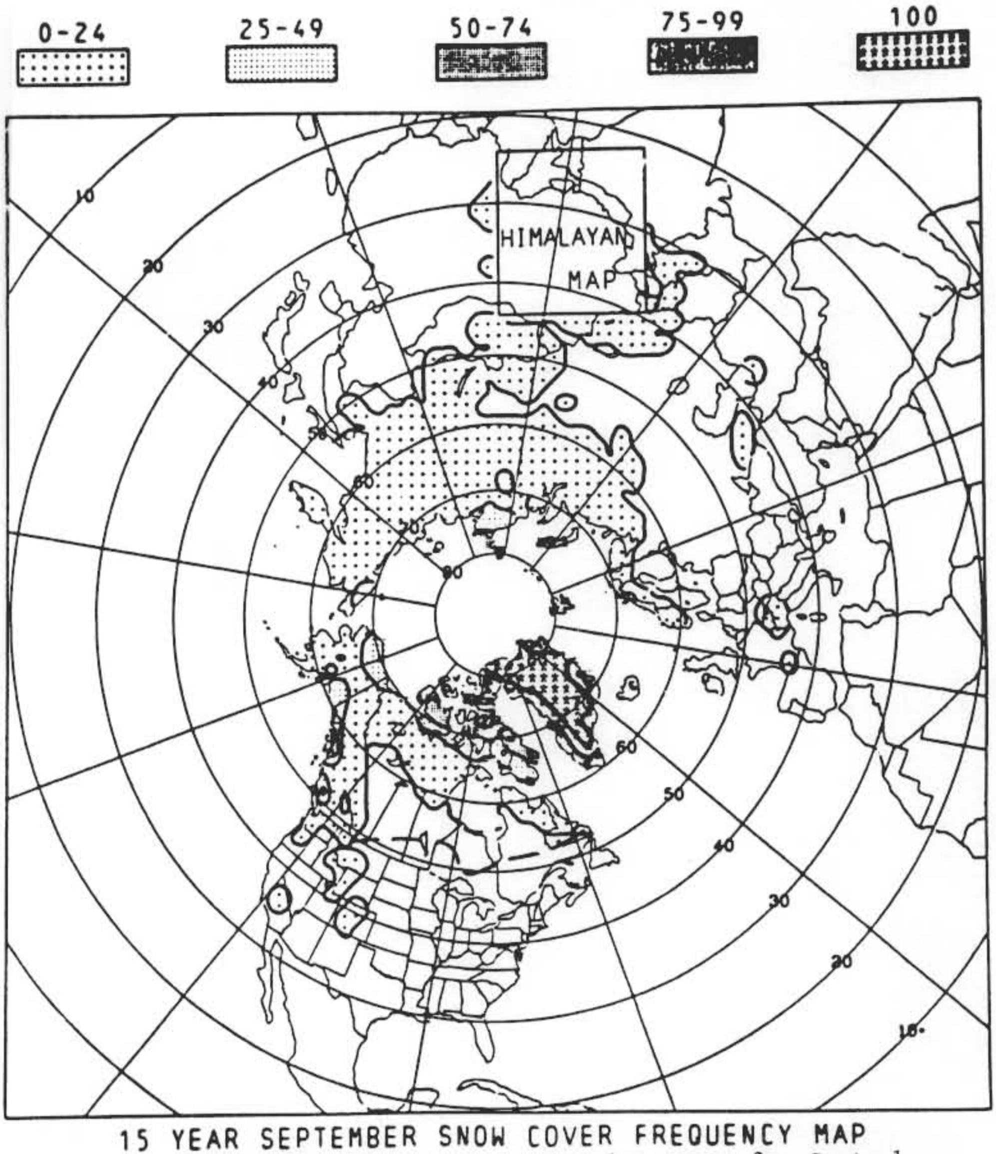

FIG. 3 Satellite-derived snow cover frequency for September, (Matson et al., 1986). The dashed line in Canada shows the 0% probability of one inch or more of snow cover (Dickson & Posey, 1967)

An example of procedural-induced bias leading to systematic underestimates of satellite-derived snow cover in Eurasia for the 1966 to 1974 period has been documented by Ropelewski (1984) and Matson *et al.*, (1986). The bias in the Eurasian data was clearly identified in time-series plots of snow cover area. Other procedural biases are not obvious in the time series and, if they exist, are smaller than the natural variability, i.e., real climate variability plus cloud-induced noise, in the snow cover data, or have been masked by "real" climate drift of the opposite sign.

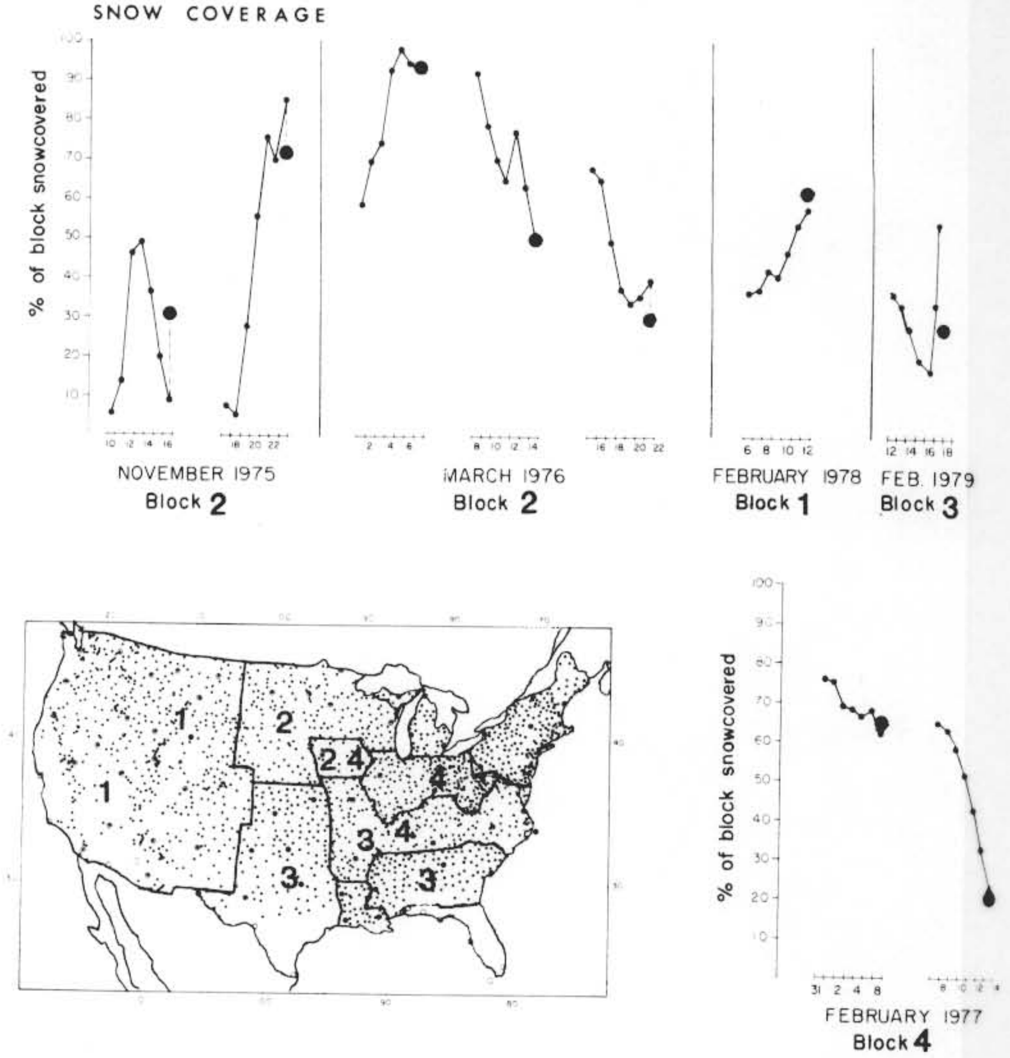

FIG. 4 Snow coverage, in percent of total area, of selected U.S. geographic blocks. Blocks, some overlapping, are shown on the map. Daily values (small connected circles) were obtained from Lamont charts, which are based on ground station (locations shown on map) and satellite information. NOAA snow chart coverage is plotted on the last day of the charted week (after Kukla & 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 underrepresentation 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 time of day at which the NOAA polar orbiters pass over the Northern Hemisphere has varied from early to midday over the years. The resultant variations in solar zenith angle, thus illumination, may have introduced an unknown bias in the product.

The relatively small scale of the imagery and even smaller scale of the base map makes the accurate charting of snow in regions of patchy snow cover (e.g. mountains) difficult (Fig. 5).

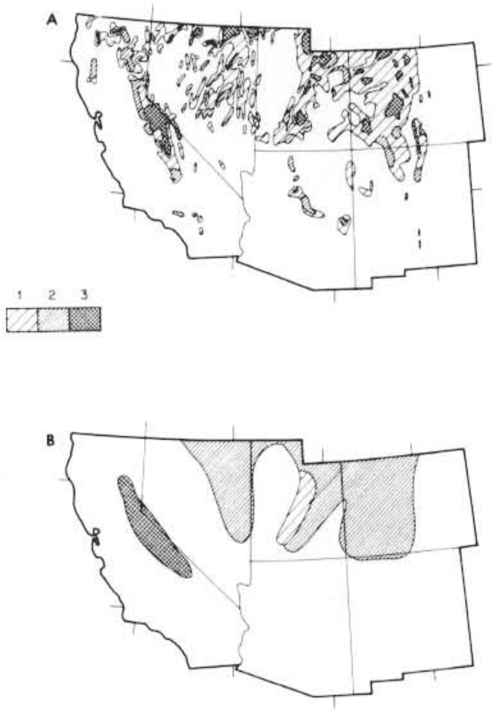

FIG. 5 Snow cover in the southwest U.S. as charted: a) on March 16, 1978 by Lamont using satellite imagery and b) for the week of March 13-19, 1978 by NOAA. Snow-field reflectivities range from low (1) to high (3) (after Kukla & Robinson, 1981)

Seasonal

There are serious deficiencies in the NOAA snow charts in autumn. Figure 6 illustrates this over central Asia, where ground station data indicate an extensive snow-covered zone far to the south of the NOAA snow boundary. This problem is related to the difficulty of detecting snow in the autumn owing to low solar illumination, high solar zenith angle, the presence of dense coniferous forests in the snow margin belt, the absence of frozen snow-covered water bodies in the forested zones and frequent dense clouds along the

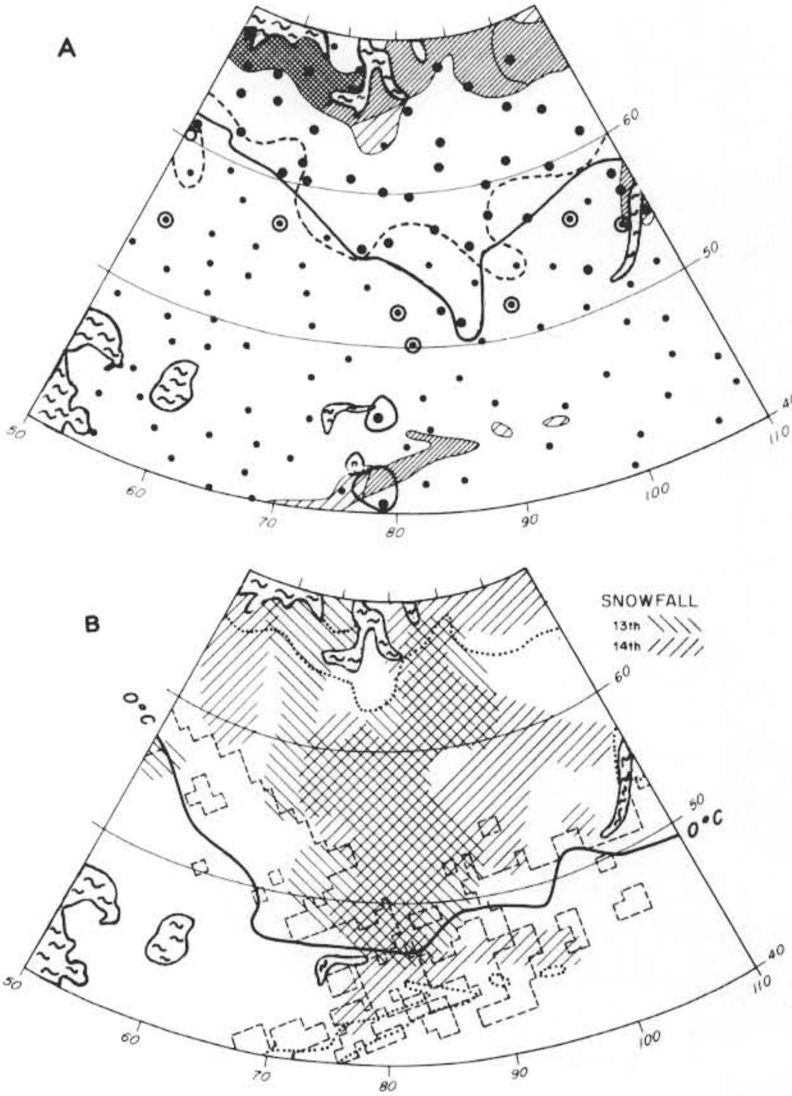

FIG. 6 a) Central Asia snow cover for the week of October 8-14, 1979, using the same reflectivity classes as in Fig. 5. WMO stations reporting snow cover on the 17th are shown in large full circles, those reporting no snow on the ground with open circles. Snow cover of < 2 cm on the 17th is found north of the solid line, on the 12th north of the dashed line. Small full circles mark additional WMO stations used in 6b

b) Regions where WMO stations report snowfall at 0000 GMT on October 13 and 14, 1978 are hatched. Stations north of the 0°C isotherm had below freezing morning surface air temperature on both days. The NOAA snowline from 6a is dotted, the Air Force snowline on the 15th (based primarily on station data) is dashed (from Kukla & Robinson, 1981) snow margin. Heavy cloudiness is also a problem when attempting to chart snow cover in the Arctic regions in summer.

Historical

The quality of the NOAA snow charts has improved with time because of improved sensors, increased interpreter expertise in recognizing snow-covered land from clouds and snow-free land, less frequent changes of the personnel involved in the charting and improved mapping techniques. The early maps have been found to be considerably less reliable, most often underestimating the extent of snow cover. This lack of consistency has been particularly pronounced in autumn as shown in Figure 7 and Table 2. Kukla & Gavin (1984) concluded that the errors in the NOAA charts were largest during the first five years of observation and that, consequently, Kukla & Kukla's (1974) conclusion on the sharp increase of average annual Northern Hemisphere snow cover between 1970-1972 should be revised. The early (1966-1974) mapping of the Tibetan Plateau region was also determined to have been mapped with varying accuracy (Ropelewski, 1984; Matson *et al.*, 1986).

TABLE 2 Differences in millions km^2 between the revised (Lamont) and original (NOAA) snow charts (from Kukla & Gavin, 1984)

	October		*November*	
	Beginning	*End*	*Beginning*	*End*
EURASIA				
1968	*+8.2*	*+12.6*	*+9.4*	*+5.6*
1969	*+6.1*	*+ 3.7*	*+3.4*	
1970	*+6.9*	*+ 3.3*	*+7.0*	*+6.0*
1971	*+5.0*	*+ 0.1*	*+4.9*	*-3.8*
1972	*-1.9*	*+ 0.1*	*-0.6*	
NORTH AMERICA				
1968	*+2.7*	*+ 3.5*	*+5.0*	*+1.0*
1969	*+2.1*	*+ 4.6*	*+0.5*	
1970	*+0.7*	*+ 0.4*	*+0.6*	*+0.2*
1971	*+0.2*	*+ 0.7*	*+3.1*	*+1.4*
1972	*+0.4*	*+ 1.4*	*+2.0*	

Note: Eurasian data for the region north of latitude 40 N. (Tibetan Plateau excluded)

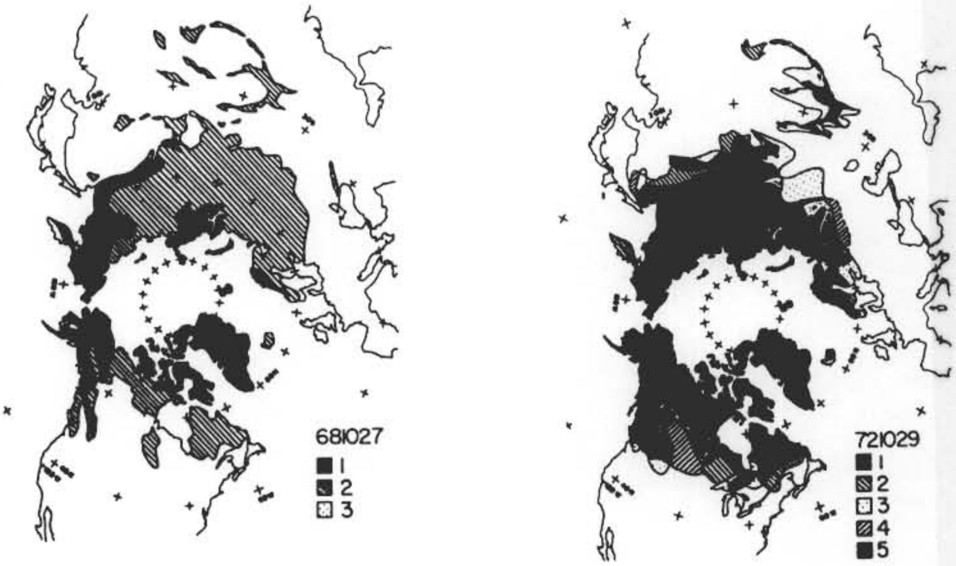

FIG. 7 a) Comparison of the revised Lamont snow cover chart for the end of October 1968, (10/21-10/27 data analysed) with the NOAA original. (1) snow shown in both charts, (2) snow detected in satellite imagery analysed at Lamont but not shown in the original NOAA chart, (3) snow shown in the NOAA original but not detected in the Lamont revision

b) Same as in 7a except for 23-29 October 1972. (1-3) same as in 7a, (4) snow on ground under persistent cloud cover as reported by the WMO network but not shown in the original NOAA chart, (5) ditto, but charted as snow in the NOAA map (from Kukla & Gavin, 1984)

RELIABILITY, ACCURACY AND USEFULNESS OF NOAA SNOW CHARTS

The weak points of the NOAA snow charts have been emphasized in order to make the user aware of potential limitations. However, 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 that they show 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.

COMPARISON WITH AN EARLIER SNOW COVER CLIMATOLOGY

Dickson & Posey (1967) published maps of snow cover probability based on available ground-station records. Their monthly maps portrayed the probability of occurrence of one inch (2.5 cm) or deeper snow cover at the end of September through May. Both this analysis and that of Matson *et al.*, (1986) are restricted to the Northern Hemisphere. While these two are different measures of snow cover, some crude comparisons can be made. In particular, the 0% probability isoline of one inch or more snow depth in the Dickson & Posey study should lie close to the 0-20% probability of snow cover isoline of the Matson *et al.*, atlas if the two data sets are consistent and there has been no trend in the extend of snow cover. Actual comparisons show this to be the case in North America with the exception of September which shows the snow line 5° to 10° of latitude south of the position indicated on the satellite-based mean chart (Fig. 3). This difference is in agreement with the systematic underestimation inherent in the satellite-derived snow cover in autumn. No other months show such a large difference between the two analyses. A comparison was not made for the Eurasian sector because the Dickson & Posey data were interpolated over large areas of Eurasia which were devoid of data.

RECOMMENDATIONS

The need for global climate studies and global climate models continues undiminished on a planet where greenhouse gases may induce a major warming, where the ozone layer is presumably being depleted, and where natural forests are being cut down. Climate model results indicate that snow cover variations play an important role in climatic change. Despite current "growing pains" in the development of the satellite-derived data base, it is important not only to continue with the effort but also to improve the quality of the monitoring.

Research should be oriented towards the integration of satellite information with conventional meteorological station data. In this way, a much greater temporal and spatial precision could be achieved and snow depths could be included in the charts. It is also recommended that research into microwave satellite sensors be intensified to assist in the collection of data on snow depth and snow water equivalent as well as the distribution of melting snow cover.

CONCLUSIONS

The NOAA data are currently the best snow cover information available for the post-1966 period on continental or hemispheric scales

The accuracy of the charts and the derived digitized data base is sufficiently high in winter and in spring for large-scale climate-related studies. Users of this set, however, must be aware of its limitations, so that the data are not misinterpreted.

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