ACCURACY OF OPERATIONAL SNOW AND ICE CHARTS

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Abstract

Operational snow and ice cover charts produced by NOAA, the Navy and the U.S. Air Force Global Weather Central (AFGWC) were compared with ground station reports and original satellite imagery. We conclude that the information on the extent of snow covers is sufficiently accurate for use in the recent generation of general circulation models in all seasons except autumn. However, information on surface albedo, on the thickness of snow covers, and on the proportion of open water within the pack ice needs to be considerably upgraded.

Introduction

Snow and ice covers have a large influence on the global heat budget (Fletcher, 1965; Fletcher et al., 1966; Untersteiner, 1961; Radok, 1978; Kukla, 1981). Knowledge of the variation of these covers in time and space is essential for understanding climate fluctuations on all time scales (Kukla and Kukla, 1974; Wiesnet and Matson, 1976; Ackley and Keliher, 1976; Rashke and Preuss, 1979).

The climatic significance of seasonal snow and ice fields is a result of their: a) high shortwave reflectivity; b) very high longwave emissivity; c) latent heat consumed in melting; and d) maintenance of surface temperature at or below 0°C with resulting reduction of evaporation rates and generation of dry air masses.

Three U.S. government agencies produce operational charts of snow and ice covers on a hemispheric and global basis in weekly intervals. They are a) National Environmental Satellite Service (NESS) of the National Oceanic and Atmospheric Administration (NOAA) of the U.S. Department of Commerce, whose products will be referred to as the NESS charts; b) Global Weather Central of the U.S. Air Force, whose computer compiled digitized snow depth maps will be referred to as the Air Force charts; and c) Fleet Weather Facility (FLEWEAFAC) of the U.S. Navy, recently the Navy/NOAA joint center, whose ice charts of both hemispheres are referred to as the Navy charts. More information on the products of all three groups is given in Table 1.

Accuracy of operational snow and ice charts (with G. Kukla). in: (ed. K. Carver) 1981 IEEE International Geoscience and Remote Sensing Symposium Digest, 974-987, 1981.

Each group producing snow and ice charts uses different techniques and different sources of information. NESS uses NOAA satellite images and relies on skilled interpreters recognizing characteristic surface features of the snow-covered land. Images for each consecutive day of the given week are used to update the snowline. Snow cover is placed in one of three relative reflectivity classes depending on the visible surface brightness (cf. Wiesnet and Matson, 1979; Matson and Wiesnet, 1981; Smigielski, 1981).

The Air Force digital charts show the extent and depth of snow on the ground; the data being generated by a sophisticated computer program. Snow depth reported by ground stations is complemented by precipitation and temperature data and by observed satellite brightness fields. Blank spots are reconstructed from climatology (Woronicz, 1981).

Ice cover in both hemispheres is mapped by the Navy. The charts show the ice concentration in octas (eighths) or, more recently, in tenths. Visible, infrared, and microwave imagery gathered during three consecutive days is used. Data are supplemented by ship and coastal station reports (Godin, 1981). We tested the accuracy of the operational charts as sources of information on the: a) position of the snow and ice boundaries; b) surface albedo; c) depth of snow on ground; and d) time accuracy of the plotted information. We focused on the autumn and spring, when the largest regional changes occur in the observed variables. New charts were constructed for selected intervals, using the original satellite imagery as well as high quality satellite products and expanded and verified ground station data sets not available for the preparation of the operational products. We also use regional snow depth charts produced by other national agencies, such as the Weekly Weather and Crop Bulletin, and the British and Canadian snow and sea ice charts, etc. (cf. overview by Crane, 1979).

Accuracy of Snow Cover Boundaries

Snow cover on land is frequently discontinuous. Bare ground may be exposed by melting or drifting. More importantly, the presence, type, height and density of vegetation affect the proportion of snow seen from the nadir, even with a continuous thick snow cover on the ground. A fresh snow field has an albedo of 75%-85%. However, Kung et al. (1964) found the January albedo of a tall dense mixed forest in Menominee County, Wisconsin, with 12 to 25 cm of snow on the ground to be 17.9%, which is only 3.6% higher than in July. On the other hand, a grassland with 5 cm of fresh snow or a frozen lake with only 1-2 cm of snow may have albedos some 60 to 70% higher than in summer. Differing densities of the vegetational canopy and the frequent patchy character of snow fields may lead to different interpretations of snow boundaries.

In order to examine the accuracy of the operational snow charts, we produced new, independent, updated sets of snow maps for selected blocks in the U.S. and Asia, representing flat, hilly and mountainous areas.

Satellite information was recharted and completed by incorporating reports from ground stations. The area covered by snow was measured and expressed as the percentage of the total area of the block (e.g. Fig. 3). Figure 1 shows snow analyses of six mountainous southwestern states (California, Nevada, Utah, Colorado, Arizona, and New Mexico) produced by four independent groups. There was no significant snowfall during the 4 days for which the information was plotted. A gradual dissipation of the snowfields occurred in the March 13-21 period. While the snow covered areas of the Lamont, NOAA, and Weather and Crop Bulletin charts are similar (Table 2), the delimitation of the snow fields differs largely. The Lamont product (A) is plotted in detail from high-resolution NOAA-VHRR imagery and shows a rather complicated outline and reflectivity pattern of the snow fields. The snowline in the other charts is highly generalized, and in the Air Force chart partially incorrect. In general, the Air Force charts tend to overestimate the snow cover extent, especially in the less than 2" class (Kukla and Robinson, 1981).

Similar tests done for the flat and moderately hilly regions showed a rather realistic location of the snowline in all products. This conclusion refers to all seasons except autumn when, particularly in Asia, large differences are found between the NESS and the Air Force products. This is because large zones of persistent cloudiness commonly occur in autumn in the middle and higher latitudes. NESS interpreters only show snow cover visible in cloud-free scenes. They do not plot snow reported at ground stations under clouds (Smigielski, 1981). The Air Force charts, on the other hand, are principally based on ground station reports and chart snow whether cloud covered or not (Woronicz, 1981).

We also found that in the early charts of the NESS series, especially those from the late 1960's, the snow in poorly illuminated scenes was frequently omitted in autumn over substantial portions of northern Asia and parts of North America. This finding modifies the conclusions of Kukla and Kukla (1974) on the considerable increase of the average snow cover between 1970 and

1972. While the average annual snow covers in the Northern Hemisphere did indeed increase from the late 1960's to early 1970's, the change was less extreme and more gradual than the NESS snow charts show, mainly due to the underestimation of the autumn snow cover in the late 1960's.

Snow Cover Changes in Time

Snow and ice cover in the Northern Hemisphere changes from about 10 million Km^2 in summer to about 60 million Km^2 in winter. Between September and December it increases by about 40 million Km^2 in less than 90 days. Thus, a single day represents on the average almost 1% of the total seasonal change from a full summer to a full winter condition. Ten days may amount to about 8% of the seasonal wave.

Obviously, any meaningful monitoring of snow cover variability for climate related studies must be accurately dated. Figure 2 depicts a huge change in the area and reflectivity of the snow cover in Nebraska, Iowa, Kansas, and Missouri in a single day in March. Figure 3 and Table 3 shows similar variations in regional snow cover within a single week in the north central states. In regions close to the margins of the snow cover fields the day-to-day variability of snow extent may be large in all seasons. From Fig. 3 it is seen that the weekly operational charts most accurately depict the snow cover extent on the last two days of a week-long interval.

Our comparisons were done in relatively small blocks and compensations are likely on a hemispheric scale. However, time accuracy of the information presented in the operational charts is obviously in need of significant improvements.

Surface Albedo of Snow Fields

No charts of surface albedo on a real time basis are being produced. Rashke and Preuss (1979) computed the surface albedo at four typical intervals of the year from Nimbus 3 satellite composite minimum brightness fields. Arbitrary corrections for atmospheric transmissivity and undetected clouds decrease the accuracy of their results.

Snow is causing the largest variability of surface albedo on a seasonal basis. Operational snow and ice charts can thus be used to aid in estimating approximate regional surface albedo values of partly snow-covered scenes (Kukla and Gavin, 1979; Kukla and Robinson, 1980; Adem and Donn, 1981).

Only NESS weekly snow charts differentiate the relative brightness of snow fields. This is visually classified in three grades, where 1 is the lowest and 3 the highest.

Batten et al. (1977), analyzing VHRR images from Canada and the U.S., determined the average albedos of Class 1 as 30%, Class 2 as 45% and Class 3 as 65%. The variability in each class may reach ± 20%. Six grades of relative brightness based on the estimated proportion of snow covered to snow free surface elements (Kukla, Robinson, and Brown, 1981) were visually subdivided in our tests (cf. Fig. 2). We have not yet correlated the visual brightness grades with the objectively measured albedo values, however, the comparisons of albedo values computed from the early NESS charts with the more detailed six-grade subdivision show large discrepancies between the two sets (Kukla and Robinson, 1981).

Snow Thickness

Several national agencies produce daily, weekly and monthly snow depth charts for most parts of the Northern Hemisphere. However, the spatial variability of snow depth is so large and the density of the reporting network so light that no realistic regional parametrization of ground station data is as yet possible.

Determination of the snow thickness from the relative reflectivity of snow fields was attempted by McGinnis et al. (1975) who found increasing brightness with the increase of snow depth up to about 10". However, in the area in Ohio studied by Kukla and Robinson (1981) the ratio of woodland to open farmland, not the thickness, caused most of the variance in the observed brightness fields.

If the parametrization of the real snow depth in a flat or moderately hilly region, such as Ohio, causes serious problems, then in the mountainous regions the task is next to impossible. For instance, Fig. 1 illustrates the inadequacy of the spatial representation, and the degree of variability of the snow depth reported in the western United States by the Weather and Crop Bulletin and by the Air Force.

Accuracy of Sea Ice Cover Charts

The Navy operational charts of sea ice cover were checked using the NOAA-VHRR visible and infrared satellite imagery and Defense Meteorological Satellite Program (DMSP) transparencies. In general, the quality of the Navy charts was found to be sufficiently high for use in climate-related studies. The charts relatively accurately show the proportion of ice floes which are either snow covered or formed of white and light grey ice. Open water or young dark ice surrounding floes cannot be easily differentiated.

Therefore, an ice field shown to have a 7/10 concentration may represent an area which is covered by 70% of light or snow covered ice floes, by 20% fresh dark ice, and by 10% open water. The proportion of young dark ice to open water varies with the season. In late spring and summer open water dominates while in fall and winter thin ice dominates.

In several recent publications it was argued that the proportion of open water in the winter pack ice around Antarctica is considerably higher than in the Arctic (Ackley and Keliher, 1976; Zwally et al., 1976). This conclusion was based on the exclusive interpretation of microwave satellite imagery. Our comparison of cloud free infrared VHRR scenes of the Weddell Sea and the Ross Sea in August, 1976 with the simultaneous Nimbus 5 microwave false color products demonstrated that the proportion of open water within the pack ice interior was not noticeably different from the Arctic basin (Kukla and Dehn, 1981).

A considerable change in the surface albedo on top of the Arctic ice occurs in summer. From the end of June through the second half of August, the snow on top of the ice melts and puddles of meltwater develop. The few published albedo measurements taken at ice floe stations indicate that the albedo of such a surface drops from about 80-85% to 50-60% or less. No data yet exist on the areal extent and intensity of the summer melt on top of the Arctic ice and its seasonal and year-to-year variability. Frequent clouds preclude the use of low resolution satellite visible imagery. Microwave charting is being tested by NASA researchers but it is not expected to become operational in the near future.

The shortwave albedo of a bare ice surface ranges widely, from about 8% to 60%. A fresh snow cover only a centimeter thick is sufficient to raise the ice albedo to over 80%. The potential impact of this variability on climate is obvious. Unfortunately, except for broad and inaccurate NESS ice cover reflectivity estimates, no attempt has been made to chart the ice albedo changes on a regular basis. The NESS reflectivity values for the ice surface are not sufficiently detailed for use in climate models. Kuznetsov and Timerev (1972) correlated ice concentrations with albedo values. Kukla and Gavin (1979) and Kukla and Robinson (1980) used these and similar results in the computation of the surface albedo index of the ice fields from Navy charts. While the correlation is realistic for late winter and spring, when the ice is mostly snow covered, it seems less reliable in fall when large portions of the ice are snow free and in the summer in the Arctic when the snow on top of the ice melts.

Results

The tests reported here and in Kukla and Robinson (1979; 1981) lead us to the following conclusions:

a) The NESS snow charts from the 1966 to 1973 interval show snow boundaries with acceptable accuracy for climate studies on a hemispheric scale in winter, spring, and summer but not in autumn. The information on the relative reflectivity of snow fields is inadequate.

b) The NESS charts from 1974 through 1980 show snow boundaries with acceptable accuracy for large scale and even regional climate studies. Snow fields under persistent clouds are consistently not shown, which leads to systematic under-representation of snow extent, particularly noticeable in autumn. The relative reflectivity of snow fields is judged to be accurate enough for gross climate studies on a hemispheric scale, but not on a regional scale. In both the NESS and Air Force charts the detailed outline of snow fields is greatly generalized.

c) The day-to-day changes in the area covered by snow can be very large especially in autumn and in spring. The NESS charts tend to underestimate the snow area in autumn because they do not show snow under persistent clouds; while the Air Force charts in general tend to overestimate the snow extent especially in the category of less than 2" (Fig. 1).

d) The best fit with Lamont daily products of the charted area in the NESS and Air Force products is reached on the last, or the penultimate day of the week. The more recent charts are more accurate. The average areal differences in the 1970's charts were less than 10% of the total area of a given block.

e) The Navy operational sea ice charts present a sufficiently accurate ice boundary and proportion of white or grey ice floes to dark ice and open water. Thin dark ice is frequently not distinguished from open water. Reflectivity is not reported.

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References

Ackley, S., and T. Keliher (1976) Antarctic sea ice dynamics and its possible climatic effects. AIDJEX Bulletin 33, p. 53-76.

Adem, J., and W. Donn (1981) Mean monthly numerical prediction with a thermodynamic grid model. Abstracts, First Conference on Climatic Variations of the American Meteorological Society, p. 19.

Batten, E., J. Soha, and M. Morrill (1977) The albedo of snow covered surfaces determined from NOAA 4 and 5 satellites. Trans. Amer. Geophys. Union 58, p. 400.

Crane, R. (Compiler, 1979) Inventory of snow cover and sea ice data, Glaciological Data Report GD-7, 171 p.

Fletcher, J. (1965) The heat budget of the Arctic Basin and its relation to climate. Rand Corp. Report R-444-PR, 179 p.

Fletcher, J., B. Keller, and S. Olenicoff (1966) Soviet data on the Arctic heat budget and its climatic influence. Rand Corp. Memorandum RM-5003-PR, 205 p.

Godin, R. (1981) Sea-ice charts of the Navy NOAA Joint Ice Center. In: (Kukla, G., Hecht, A. and Wiesnet, D., eds.) Proceedings of Snow Watch 1980 Conference, National Science Foundation, Washington, D.C. (in press).

Kukla, G.J., and Kukla, H.J. (1974) Increased surface albedo in the Northern Hemisphere. Science 183, p. 709-714.

Kukla, G., and J. Gavin (1979) Snow and Pack Ice Indices, Glaciological Data Report GD-6, p. 9-14.

Kukla, G., and D. Robinson (1979) Accuracy of snow and ice monitoring. Glaciological Data Report GD-5, p. 91-97.

Kukla, G., and D. Robinson (1980) Annual cycle of surface albedo. Mon. Wea. Rev. 108, p. 56-68.

Kukla, G. (1981) Climatic role of snow covers. In: Sea Level, Ice and Climatic Change (Radok, U., and I. Allison). Proceedings of the Symposium, XVII General Assembly IUGS, Canberra International Association of Hydrological Scineces Publication (in press).

Kukla, G., and W. Dehn (1981) Comparison of the microwave and IR Antarctic sea ice images. Sea Ice Science. NASA/Goddard Space Flight Center, p. 62-63.

Kukla, G., and D. Robinson (1981) Climatic value of operational snow and ice charts. In: (Kukla, G., A. Hecht, and D. Wiesnet, ed.) Proceedings of Snow Watch 1980 Conference, National Science Foundation, Washington, D.C. (in press).

Kukla, G., D. Robinson, and J. Brown (1981) Lamont climatic snow cover charts. In: (G. Kukla, A. Hecht, and D. Wiesnet, eds.) Proceedings of Snow Watch 1980 Conference, National Science Foundation, Washington, D.C. (in press).

Kung, E., R. Bryson, and D. Lenschow (1964) Study of a continental surface albedo on the basis of flight measurements and structure of the earth's surface cover over North America. Mon. Wea. Rev. 92, p. 543-563.

Kuznetsov, I., and A. Timerev (1973) The dependence of ice albedo changes on the ice cover state as determined by airborne observations. Problems of the Arctic and Antarctic, Israel Program on Scientific Translations 40, p. 67-74.

Matson, M., and D. Wiesnet (1981) New data base for climate studies. Nature 289, p. 451-456.

McGinnis, D., J. Pritchard, and D. Wiesnet (1975) Snow depth and snow extent using VHRR data from the NOAA-2 satellite. NOAA TEch. Memorandum NESS 63, 16 p.

Radok, U. (1978) Climatic roles of ice: a contribution to the International Hydrological Programme (IHP). Hydrological Sciences Bulletin 23, n. 3, p. 333-354.

Rashke, E., and H. Preuss (1979) The determination of the solar radiation budget at the earth's surface from satellite measurements. Meteorol. Rdsch 32, p. 18-28.

Smigielski, F. (1981) Northern Hemisphere snow and ice charts of NOAA-NESS. In: (G. Kukla, A. Hecht, and D. Wiesnet, eds.) Proceedings of Snow Watch 1980 Conference, National Science Foundation, Washington, D.C. (in press).

Untersteiner, N. (1961) On the mass and heat budget of Arctic sea ice. Arch. Meteor. Geophys. Bioklim. A 12, p. 151-182.

Wiesnet, D., and M. Matson (1976) A possible forecasting technique for winter snow cover in the Northern Hemisphere and Eurasia. Mon. Wea. Rev. 104, p. 828-835.

Wiesnet, D., and M. Matson (1979) NOAA satellite-derived continental snow cover data base. Glaciological Data Report GD-6, p. 3-8.

Woronicz, R. (1981) The U.S. Air Force snow cover charts. In: (G. Kukla, A. Hecht, and D. Wiesnet, eds.) Proceedings of Snow Watch 1980 Conference, National Science Foundation, Washington, D.C. (in press).

Zwally, J., T. Wilheit, P. Gloersen, and J. Mueller (1976) Characteristics of Antarctic sea ice as determined by satellite-borne microwave imagers. Proceedings of Symposium on Meteorological Observations from space, 4 p.

Table 1. Current series of snow and ice charts used in the study.

Symbol	Chart Name	Produced By	Area	Projection and Approx. Scale	Interval	Content
NESS	Northern Hemisphere Average Snow and Ice Boundaries	Analysis & Evaluation Branch of the National Environmental Satellite Service, NOAA	Continents of the Northern Hemisphere North of 25°-30°N. Latitude	Polar Stereographic 1:50,000,000	Weekly: 1967-Present	Boundaries of Snow and Ice-Covered Areas in 4 Classes: 1) Least Reflective 2) Moderately Reflective 3) Highly Reflective 4) Scattered Mountain Snow
Air Force	Current Snow and Ice Depth	USAF, Global Weather Central	Both Hemispheres 0-90°N	Polar Stereographic 1:30,000,000	Weekly: 1967-Present	Depth of Snow and Ice for 6 Categories: 1) <2"; 2) >2"; 3) >4"; 4) >6"; 5) >8"; 6) >10"
Weather and Crop Bulletin	Weekly Weather and Crop Bulletin Snow Chart	NOAA and U.S. Dept. of Agriculture	Continental U.S.	Albers Equal Area 1:30,000,000	Weekly: 1934-Present	Depth of snow on ground at 7 a.m. E.S.T. for Monday, December - March only
Navy	Southern Ice Limit	U.S. Navy Fleet Weather Facility	2 Sections, north of 40°N: ∿120°W-90°E ∿90°E-120°W	Polar Stereographic ∿1:15,000,000	Weekly: 1972-Present	Sea Ice Concentration in Oktas (from 1980 in tenths), Ice Age Isoline of +2°C sea surface temperature, and 0°C air temperature
Navy	Northern Ice Limit	U.S. Navy Fleet Weather Facility	Antarctic South of 50°	Polar Stereographic ∿1:18,000,000 1973-74: 1:35,000,000	Weekly: 1973-Present	Same as Above

Table 3. Snow area in the north central USA (figure 3) as measured from Lamont charts for each day of the selected weeks, compared with the area of the corresponding NESS and Weather and Crop Bulletin weekly charts. Areas larger than in the Lamont product shown with positive sign.

	INTERVAL	1	2	3	4	5	6	7
NESS	11/10-16/75	26.5	18.1	-14.6	-17.3	- 4.8	11.8	22.7
	11/17-23/75	63.5	65.8	43.3	15.6	- 4.5	1.2	-13.9
	3/ 1- 7/76	34.6	23.8	19.2	.6	- 4.7	- 1.2	.6
	3/ 8-14/76	-41.7	-28.5	-19.6	-14.0	-26.8	-12.8	- .3
	3/15-21/76	-38.5	-35.4	-19.9	- 8.0	- 4.2	- 6.2	-10.2
Weather and Crop Bulletin	3/ 2- 8/76	3.6	- 1.0	-19.6	-24.9	-21.4	-19.6	-18.7
	3/ 9-15/76	-18.7	- 9.8	- 4.2	-17.0	- 3.0	9.5	- 8.1
	3/16-22/76	-34.8	-19.3	- 7.4	- 3.6	- 5.6	- 9.6	- 2.8

Table 2. Snow cover in percent of the six state area as shown in figure 1.

Date March 1978	Source	Snow Depth	% Cover of the Six State Area
16	Lamont	-	14.7
19	NESS	-	15.1
20	Air Force	all	44.0
20	Air Force	≥2"	18.5
20	Weather & Crop Bul.	all	18.7

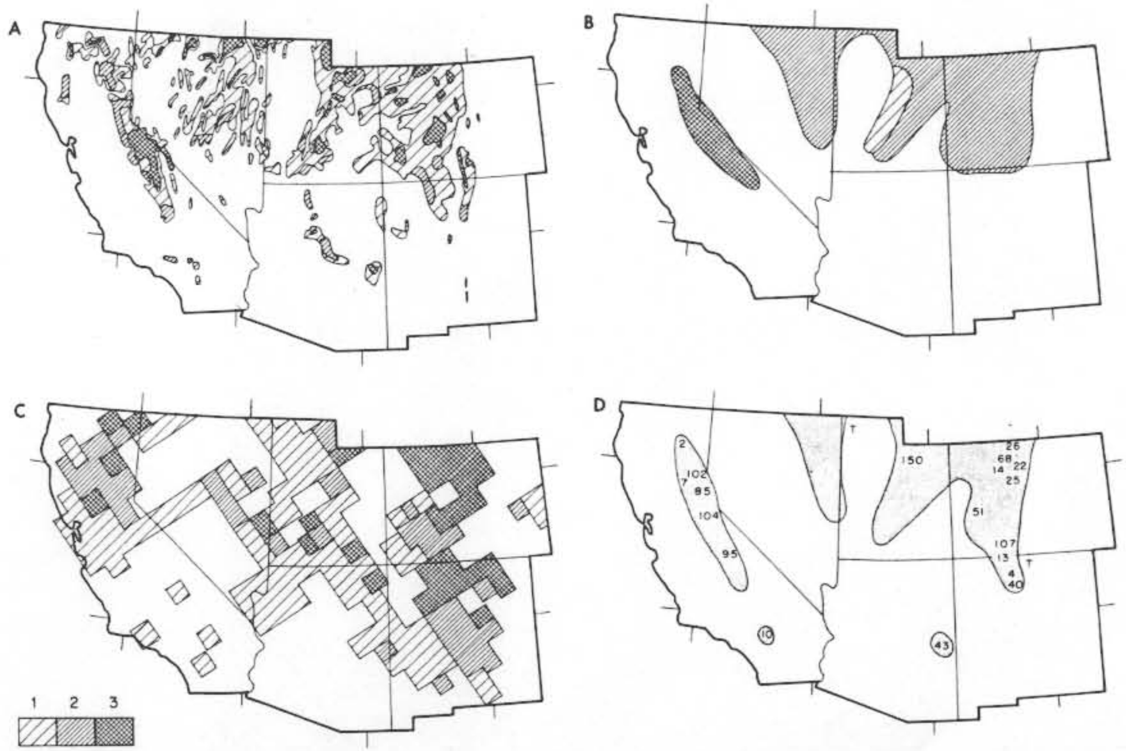

Figure 1. Snow cover in the southwest U.S. in mid-March 1978 as charted on the 16th by Lamont (A), for the week 13-19 by NESS (B), and for the 20th by the Air Force (C) and the Weather and Crop Bulletin (D). Snow field reflectivities in A and B range from low (class 1) to high (class 3). Snow depths in C are <2" for class 1, <6" for class 2, ≥6" for class 3. Depth in D in inches.

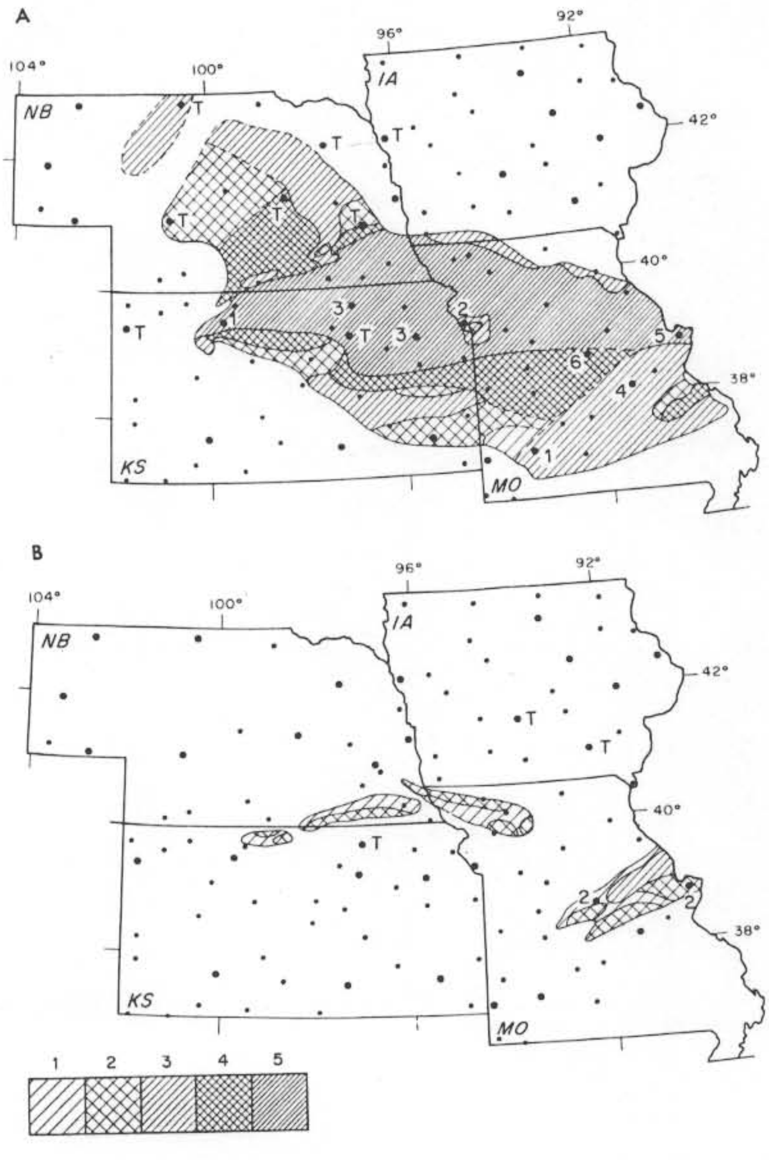

Figure 2. Snow cover in the central U.S. on 3/16 (A) and 3/17 (B), 1976. Constructed from NOAA GOES and VHRR imagery. Ground data (·) used where cloudy (---). WSO stations marked with large dots. Those reporting snow on ground give depth in inches. Reflectivity classes from 1 (low) to 5 (high) as described in Kukla et al 1981.

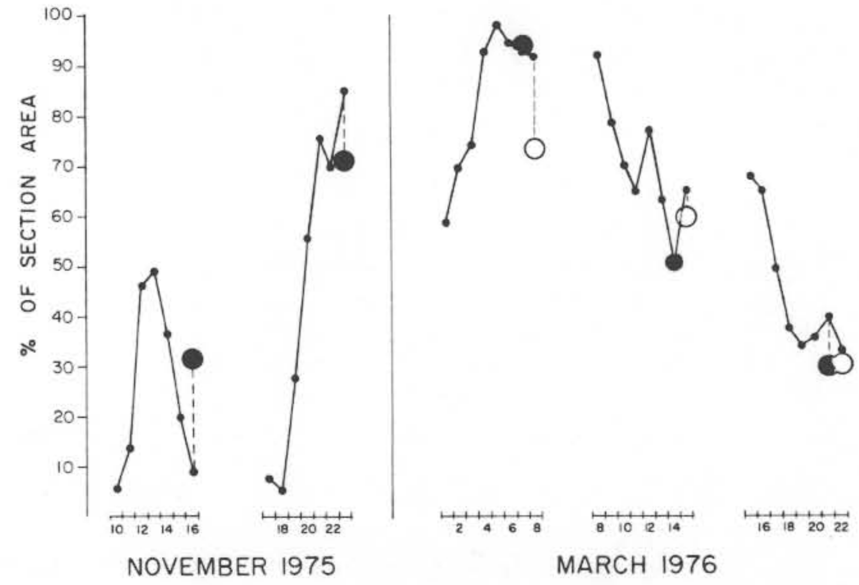

Figure 3. Snow cover in percent of total area of North and South Dakota, Minnesota, Wisconsin, Iowa and Nebraska for each day of selected weeks, compared with the snow extent of corresponding NESS (full circle) and Weather and Crop Bulletin (open circle) charts. Compare with table 3.