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Climatic Value 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. Our objective was to find out how accurately snow presence and thickness, as well as the snow impact on surface albedo, are depicted in space and time.

We conclude that the information on snow line postion is sufficiently accurate for use in the current generation of global circulation models in all seasons except autumn.

However, the quality of the information on surface albedo, on the thickness of snow covers, and on the proportion of open water within the pack needs radical improvements.

Introduction

It is well know that snow and ice covers have a large influence on the global heat budget (Hummel and Reck, 1978; Fletcher, 1965; Untersteiner, 1961; King, et al., 1964; Radok, 1978). Knowledge of the variation of these covers in time and space is essential for understanding climate changes (Wiesnet and Matson, 1976; Kukla and Kukla, 1974; Kukla, 1981).

The climatic significance of seasonal snow and ice fields is a result of their:

1. maintenance of low surface temperature of 0°C, or lower,
2. high shortwave reflectivity,
3. very high longwave emmisivity,
4. latent heat consumption in melting,
5. maintenance of a low evaporation rate, and
6. generation of cold, dry high pressure atmospheric masses, resulting from 1-5.

Since our team analyzes NOAA, Navy, and Air Force snow and ice charts in order to generate a series of climate related cryospheric indices (see Kukla and Gavin, 1979; Kukla and Gavin, p.145 this volume), we decided to test the accuracy of the operational charts as sources of information on the:

1. position of the snow and ice boundaries,
2. surface albedo,
3. depth of snow on ground, and
4. time accuracy of the plotted information.

We emphasized periods when maximum regional changes occur in the observed variables. Charts were constructed and compared with operational products. Additional information unavailable at the time of operational chart construction was often used. Both NOAA/NESS, Navy-FLEWEAFAC, and NOAA /Navy interpreters cooperated in the work and frequently provided the original satellite imagery used in generating the charts. The main focus was directed at this stage to the quality of snow charts. This is because the regional changes in the extent and character of snow covers occurring during a single day are much larger than those of sea ice.

Each group producing snow and ice charts uses different techniques. These are described in more detail in other papers presented at this workshop (see Smigielski, p.59 this volume; Godin, p.71 this volume; Woronicz, p. 63 this volume) and reviewed in table 1 of this paper. NESS uses satellite images and relies on skilled interpreters recognizing characteristic textured surface features of the snow-covered land. Images for each day of the particular week are used. The snow areas are placed in one of three relative reflectivity classes depending on the visible surface brightness (See Wiesnet and Matson, 1979; Matson and Wiesnet, 1981; Smigielski, p.59 this volume).

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
NOAA NESS	Northern Hemisphere Average Snow and Ice Boundaries	Synoptic Analysis Branch of the National Earth 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"
Weekly 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 Bulletin	2 sections north of 40°N: ~120W-90E ~90E-120W	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	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

The Air Force charts show the extent and depth of snow on the ground, the data being generated by a sophisticated computer program. The depth of snow is determined by combining and comparing ground reports, precipitation and temperature data, etc. with satellite brightness fields. Blank spots are reconstructed from climatology (See Woronicz, p.63 this volume). The Weekly Weather and Crop Bulletin reports snow cover extent and depth once a week from December through March in the continental United States at 7 a.m. e.s.t. on the chart date. The map is produced from telegraphic reports of selected stations across the country.

Additional operational charts are produced by various agencies from outside the U.S. We used them in tests for comparisons. They all show the depth of snow in winter in selected regions.

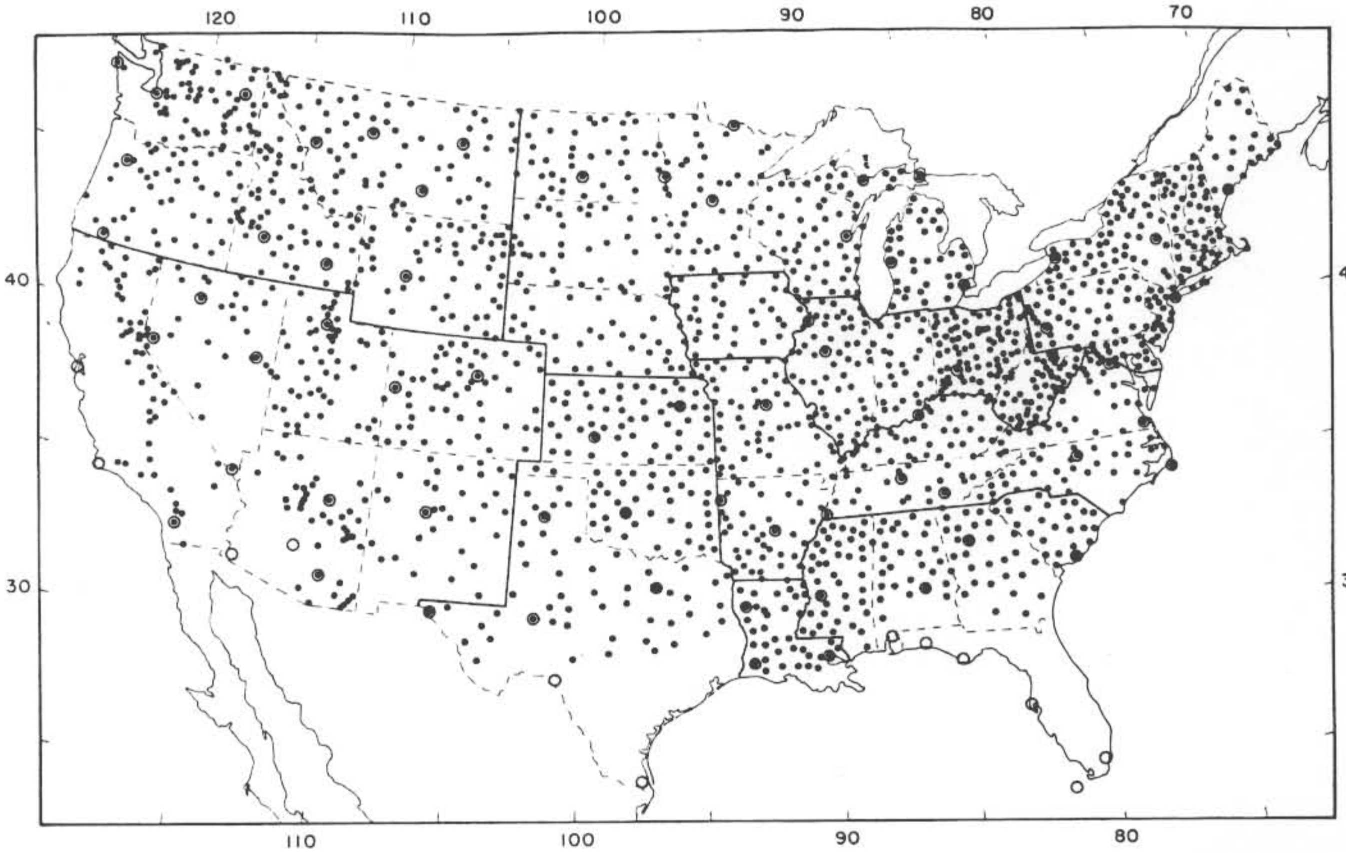

Figure 1. Location of the ground stations reporting snow used in the Lamont study shown in dots. Stations of the WMO network included in the snow depth charts of the British Meteorological Office are marked in circles.

Table 2. Difference in percent of ground snow covered within selected U.S. blocks (see also figure 3) as reported in operational charts (last one in period) and in Lamont daily snow charts. Numbers without the minus sign show operational result to be larger.

NESS	BLOCK	1	2	3	4	5	6	7
11/10-16/75	3	26.5	18.1	-14.6	-17.3	- 4.8	11.8	22.7
11/17-23/75	3	63.5	65.8	43.3	15.6	4.5	1.2	13.9
3/ 1- 7/76	3	34.6	23.8	19.2	.6	- 4.7	- 1.2	.6
3/ 8-14/76	3	-41.7	-28.5	-19.6	-14.0	-26.8	-12.8	- .3
3/15-21/76	3	-38.5	-35.4	-19.9	- 8.0	- 4.2	- 6.2	-10.2
1/31-2/6/77	5	-10.7	- 9.9	- 3.6	- 3.0	- 1.2	- 2.7	3.0
2/ 7-13/77	5	-45.1	-43.0	-38.5	-31.2	-20.6	-12.4	- 2.6
2/ 6-12/78	1	-26.7	26.0	21.1	22.8	16.5	- 9.3	5.5
2/12-18/79	4	- 9.4	- 8.6	1.5	5.8	10.7	- 7.6	-29.0
AIR FORCE		1	2	3	4	5	6	7
2/ 1- 7/77	5	1.3	7.6	8.2	10.0	8.5	14.0	11.5
2/ 8-14/77	5	-18.8	-14.3	- 7.0	3.6	11.8	21.6	14.0
2/ 7-13/78	1	23.4	18.5	20.2	13.9	6.7	2.9	2.9
2/13-19/79	4	28.9	36.0	43.3	48.2	29.9	8.5	22.9
WEATHER AND CROP BULLETIN		1	2	3	4	5	6	7
3/ 2- 8/76	3	- 3.6	- 1.0	-19.6	-24.9	-21.4	-19.6	-18.7
3/ 9-15/76	3	-18.7	- 9.8	- 4.2	-17.0	- 3.0	9.5	- 8.1
3/16-22/76	3	-34.8	-19.3	- 7.4	- 3.6	- 5.6	- 9.6	- 2.8
2/ 1- 7/77	5	-17.1	-10.8	-10.2	- 8.4	- 9.9	- 4.2	- 6.9
2/ 8-14/77	5	-40.0	-35.5	-28.2	-17.6	- 9.4	.4	- 7.2
2/14-20/79	4	- 1.2	6.1	-11.0	- 7.3	-28.7	-14.3	- 8.5

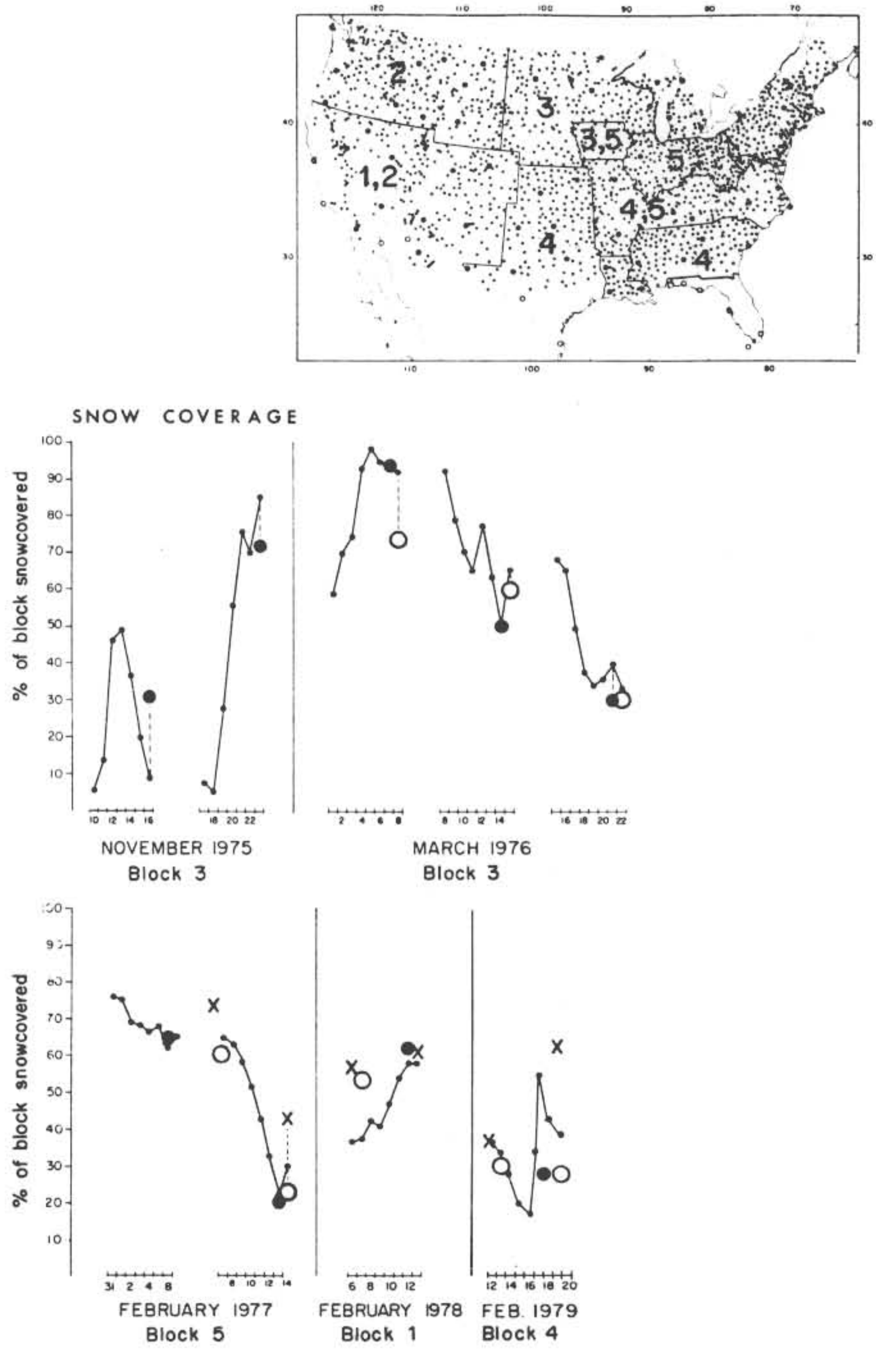

Figure 2. Snow coverage, in percent of total area, of selected U.S. geographic blocks. Blocks, some overlapping, are shown in the upper right. Daily data obtained from Lamont charts are shown by dots; area in the weekly NOAA/NESS snow chart is shown by a full circle plotted on the last day of the charted week; areas from the <u>Weekly Weather and Crop</u> Bulletin are shown by an open circle; and areas in the Air Force charts are shown by a cross.

Figure 3. 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), for the 20th by the Air Force (C), and the Weekly 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 <2in. for class 1, and <6in. for class 2, ≥6 in. for class 3. Depth in D is in inches.

Table 3. Snow cover in percent of the six state total area as shown in figure 3. This includes California, Nevada, Utah, Colorado, Arizona, and New Mexico.

Date in March 1978	Source	Snow Depth	Percent Cover of the Six State Area
16	Lamont	-	14.7
Week of 13-19	NESS	-	15.1
20	Air Force	≥ Trace	44.0
20	Air Force	≥2"	18.5
20	Weather & Crop Bulletin	Scattered reports	18.7

For instance, the snow depth in centimeters over Canada is published once a week by the Canadian Climate Centre in Ontario (Climate Perspectives, 1972-). Depth of snow cover in the Northern Hemisphere as reported by the World Meteorological Organization network is charted every 5-10 days by the British Meteorological Office in Bracknell (see Crane, 1979).

Ice cover in both hemispheres is mapped weekly in relative detail by the Navy, recently joined with NOAA. The ice concentration is reported in octas (eighths) or, recently, in tenths (Godin, p.71 this volume). Visible, infrared, and microwave imagery, the majority of which is gathered during three consecutive days, is used to construct the charts. Data are supplemented by ship and coastal stations. On a less detailed scale, the extent of sea ice is also shown in the NOAA/NESS snow charts, the only source which shows the relative reflectivity of the combined snow and ice cover. The Air Force snow charts depict the outline of the sea ice covered by snow.

Several other agencies around the world produce regional ice cover charts (see Godin, p.71 this volume). These, without exception, classify the ice according to its concentration and/or age. An overview of the availabe data sets is in Crane (1979).

Snow Cover Outline and Areal Density

The snow cover on land is frequently discontinuous. For example, south facing slopes are commonly exposed more rapidly than horizontal surfaces or north facing slopes. Bare ground may be exposed by drifting. More importantly, the presence, type, height, and density of vegetation affect local and regional albedos, even with an otherwise thick snow cover on the ground. A dense coniferous forest with 30 cm of snow on the ground, but with a dark canopy, or steep rock cliffs may not look too different in winter than in summer. Conversely, grass-covered pasture land with even 5 cm of fresh snow may reach an extremely high brightness, comparable to that found over Antarctica and Greenland.

To examine the accuracy of the operational snow charts, we produced a new, independent, updated set of snow maps for selected blocks in the United States and Asia.

Satellite information was recharted and completed by incorporating reports from ground stations. The U.S. ground station network is shown in figure 1. The area covered by snow was measured and expressed as the percentage of the total area of the block. Results were then compared to the area of snow shown in the tested operational charts. Selected results are shown in table 2 and figure 2 . It is seen from the results that:

1. the best fit is reached on the last, or the penultimate day of the week;

2. the departures between the Lamont snow values and those shown in the operational charts tend to be smaller in the more recent years; and

3. the average differences were less than 10 percent of the area of the block.

It must be added that the location of the snowline within individual blocks was quite similar in all tested products, with the exception of the mountainous west. Figure 3 shows snow in six southwestern states (see figure 3, block 2) as charted by four independent groups. There was no significant snowfall during the four days for which the information was plotted. A gradual dissipation of the snowfields occurred in the period between March 13 and 20. While the area of snow cover as found in the Lamont, NOAA/NESS, and Weekly Weather and Crop Bulletin charts is similar (table 3), the geographic distribution of the snow fields differs. The Lamont outline, delimited from NOAA-VHRR imagery, shows a rather complicated patchy structure of snow fields whereas the other charts are highly generalized. The Air Force product also overestimated the cover and extended it into areas where we were unable to locate any snow on the ground either in satellite images or in ground station reports. Excluding the under-two-inch class, the Air Force areal coverage comes closer to the other groups, but the areal distribution fails to improve significantly.

The previously discussed tests in the United States include only one month in autumn. Additional autumn tests, particularly those done over Asia, show frequent large differences between the snowline plotted in the NOAA charts and that shown in the Air Force set. The Air Force charts correlate better with meteorological reports. This is because the middle and high latitudes are frequently covered by persistent clouds in autumn. NOAA interpreters show snow cover only if it is visible in cloud-free scenes. They do not plot snow reported by ground stations which are covered by clouds, and whose relative brightness therefore cannot be determined (Smigielski, p. 59 this volume). The Air Force charts, on the other hand, are principally based on the ground station reports and snow is charted whether cloud covered or not (Woronicz, p.63 this volume).

Figure 4 shows the difference of snow coverage as plotted in Central Asia by NOAA/NESS and the Air Force. Figure 5 shows that large-scale snowfalls occurred within the area one day before and on the day of the NOAA chart as well as earlier in the week. Temperatures were below 0°C both days over the area in question so that the difference between the NOAA and Air Force charts cannot be explained by timing. Rather persistent clouds prevented the NOAA interpreters from determining the state of the ground from the satellite imagery.

Large discrepancies were also found in the early NOAA snow cover charts for autumn between 1967 and 1972. In this case, however, the relatively low quality of the earlier satellite imagery and the lack of sufficient experience with the recognition of snow in poorly illuminated scenes contributed to the omission of the snow fields over substantial portions of northern Asia and sometimes also North America. This finding has direct implications for the conclusions of Kukla and Kukla (1974) on the considerable increase of the average annual snow cover between 1970 and 1972. While the average in the Northern Hemisphere did indeed increase, the change was less extreme and more gradual than the NOAA snow charts indicate. This is, to a large degree, due to the underestimation of the autumn snow cover extent in the carts of the late 1960's.

Sea Ice Edge and Concentration

The Navy (now NOAA/Navy) operational charts of sea ice cover were checked in a manner similar to the snow charts. VHRR visible and infrared NOAA satellite imagery and DMSP (Defense Meteorological Satellite Program) transparencies were used in the checks. An example may be seen in figure 6, a and c. In general, the quality of Navy charts was found to be sufficiently high for use in climate-related studies. They relatively accurately indicate the median proportion of ice floes which are either snow covered or formed of white and light grey ice.

Open water or young dark ice surrounds such floes. In most situations the thin dark bare ice cannot be reliably distinguished from the open water. Thus, an ice field shown to have a 7/10 concentration represents an area with 70 percent of light grey or snow-covered ice floes, but additional fresh dark colored ice may be present in the area. 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 in winter ice dominates.

In some 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 interpretation of microwave satellite imagery. Our comparison of the enhanced cloud free infrared scenes of the Weddell Sea and of the Ross Sea in August 1976 with the simultaneous Nimbus 5 microwave brightness fields indicated that the proportion of open water within the pack ice interior in winter is not noticeably different from the Arctic basin (Kukla and Dehn, 1981). There the range is <1-5 percent at most.

The Albedo of Snow Fields

Surface albedo is not yet charted on a real-time basis anywhere in the world. Kung et al. (1964) measured the surface albedo over a fixed flight path in Wisconsin in monthly intervals throughout a single year. This is the most detailed observance of time-related changes in surface albedo on a regional scale to date. Rashke and Preuss (1979) computed the surface albedo at four typical intervals of the year from Nimbus 3 satellite composite minimum brightness fields. However, arbitrary corrections which had to be made for atmospheric transmissivity decrease the accuracy of their results.

Because snow causes by far the largest variability of surface albedo on a seasonal basis, operational snow and ice charts can be used to aid in estimating approximate regional surface albedo values (Kukla and Robinson, 1980; Robock, 1980; Adem and Donn, 1981). So far, only the average monthly values for a year have been published.

Kukla and Gavin (1979 and p.145 this volume) generate, on a weekly basis, an index related to the short term variations of surface albedo. This is based on the NOAA weekly products which indicate the relative reflectivity of snow fields (Smigielski, p.59 this volume). The large scale brightness of the snow fields is visually classified in three grades, where 1 is the lowest, and 3 the highest. Batten et al. (1977) analysed VHRR images from Canada and the United States and determined the average albedo of class 1 as 30 percent, class 2 as 45 percent, and class 3 as 60 percent. The variability in each class may reach ± 20 percent.

Six grades of relative reflectivity are visually subdivided from satellite imagery in the Lamont climatic charts (Kukla et al., p.87 this volume). We have not yet had an opportunity to correlate these reflectivity grades with synchronously-measured albedo values.

Figure 7 shows a comparison of the three NOAA relative reflectivity classes of the Eurasian snowfields with the six reflectivity classes of the Lamont chart. The NOAA charts depict the snow outline quite well. However, the distribution of the relative brightness field is greatly generalized. Our sample represents the early gneration of the NOAA/NESS

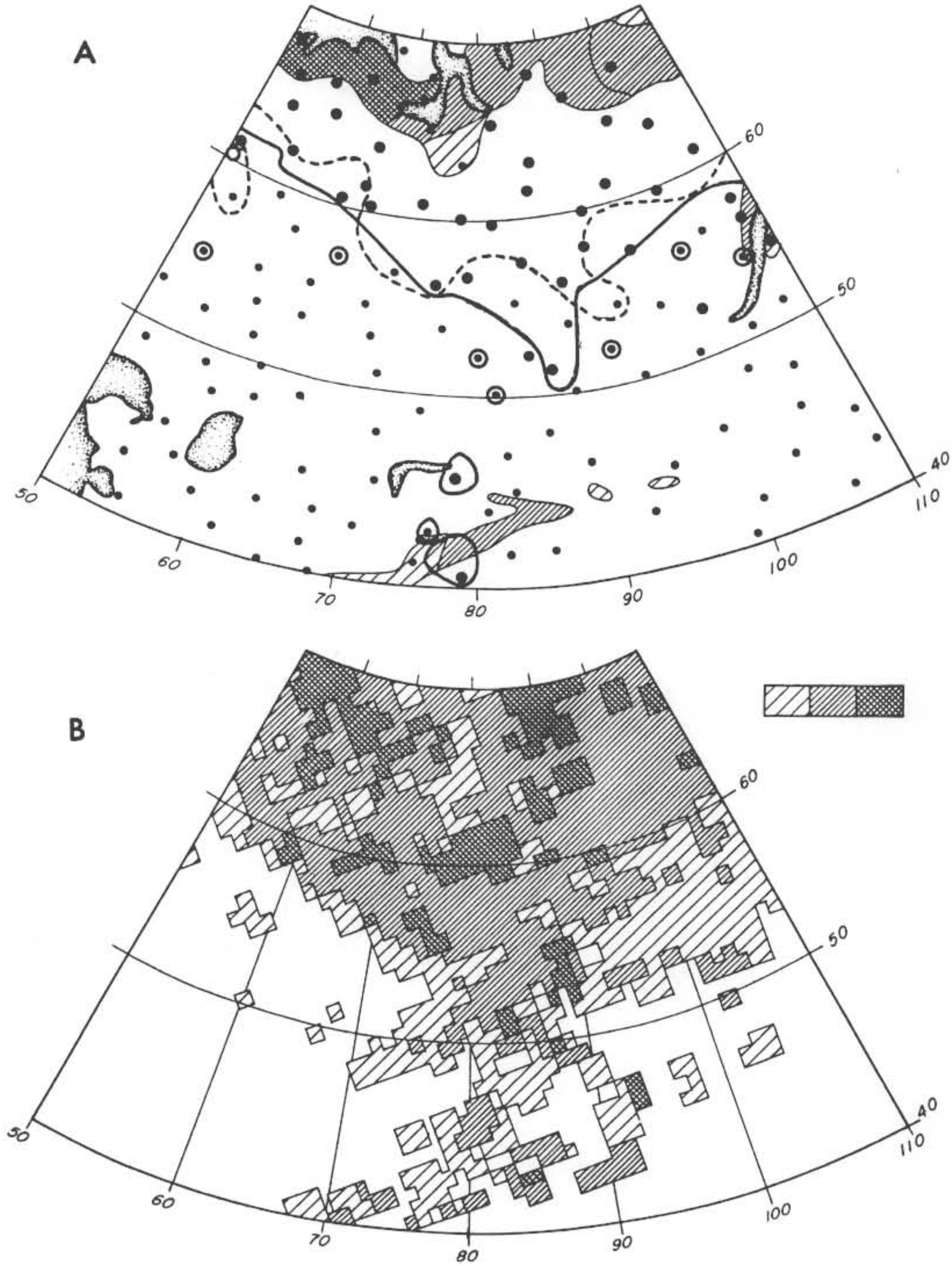

Figure 4. Snow cover plotted in Central Asia for mid-October, 1979. NOAA results for the week ending on the 14th are shown in (A) using the same reflectivity classes as in figure 3. Air Force, for the 15th, is shown in (B). Depth classes are the same as in figure 3. WMO stations reporting snow cover in British charts on the 17th are shown with large dots, those reporting no snow on the ground, with open circles. Snow cover >2cm on October 17 are enclosed within the solid line, on the 12th within the dashed. These and remaining WMO stations (small dots) are used in figure 5.

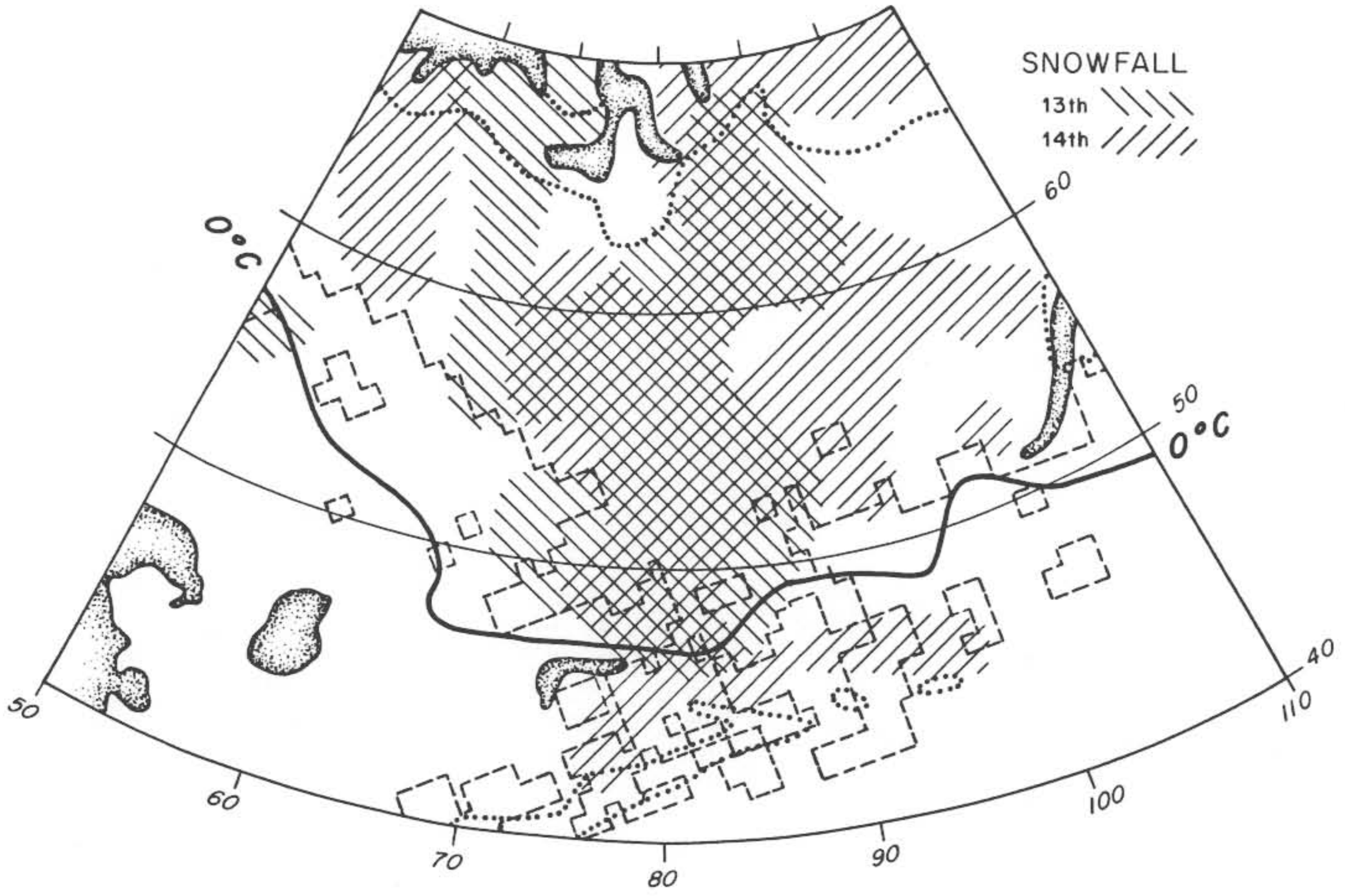

Figure 5. Areas of snowfall reported by WMO ground stations at 00 Gmt (see figure 4A for location) on October 13 and 14 (hatched). Stations north of the 0°C isoline had below freezing morning surface air temperatures on both days. The NOAA/NESS snow outline is dotted, the Air Force dashed. Lakes are stippled.

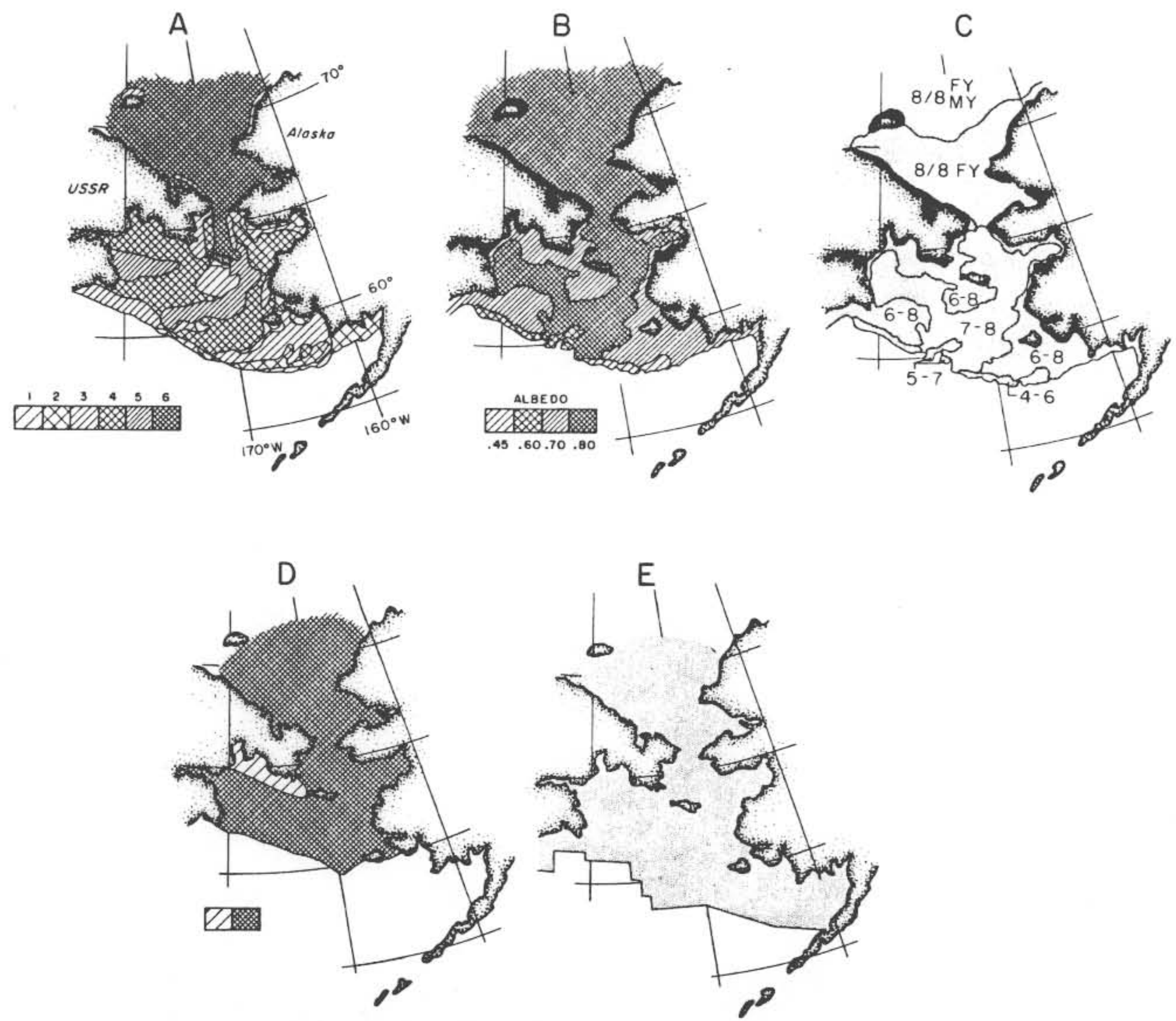

Figure 6. Sea ice extent, concentration, and surface reflectivity in the Bering Sea in March 1978. Lamont chart (A) is constructed from the NOAA/VHRR visible and infrared imagery taken on the 21st. It shows lowest (1) to the highest (6) relative reflectivity. The Navy chart (C) for the three days ending 21 March shows snow concentration in octas. FY is first-year ice. MY is multi-year ice. Albedo estimated from the Navy product by the method of Kukla and Robinson (1980) is shown in (B). The NOAA chart for the week ending 19 March (D) has reflectivity classes the same as in figure 3. Air Force chart for the week ending 20 March (E) shows stippled area with snow over 10 in. thick.

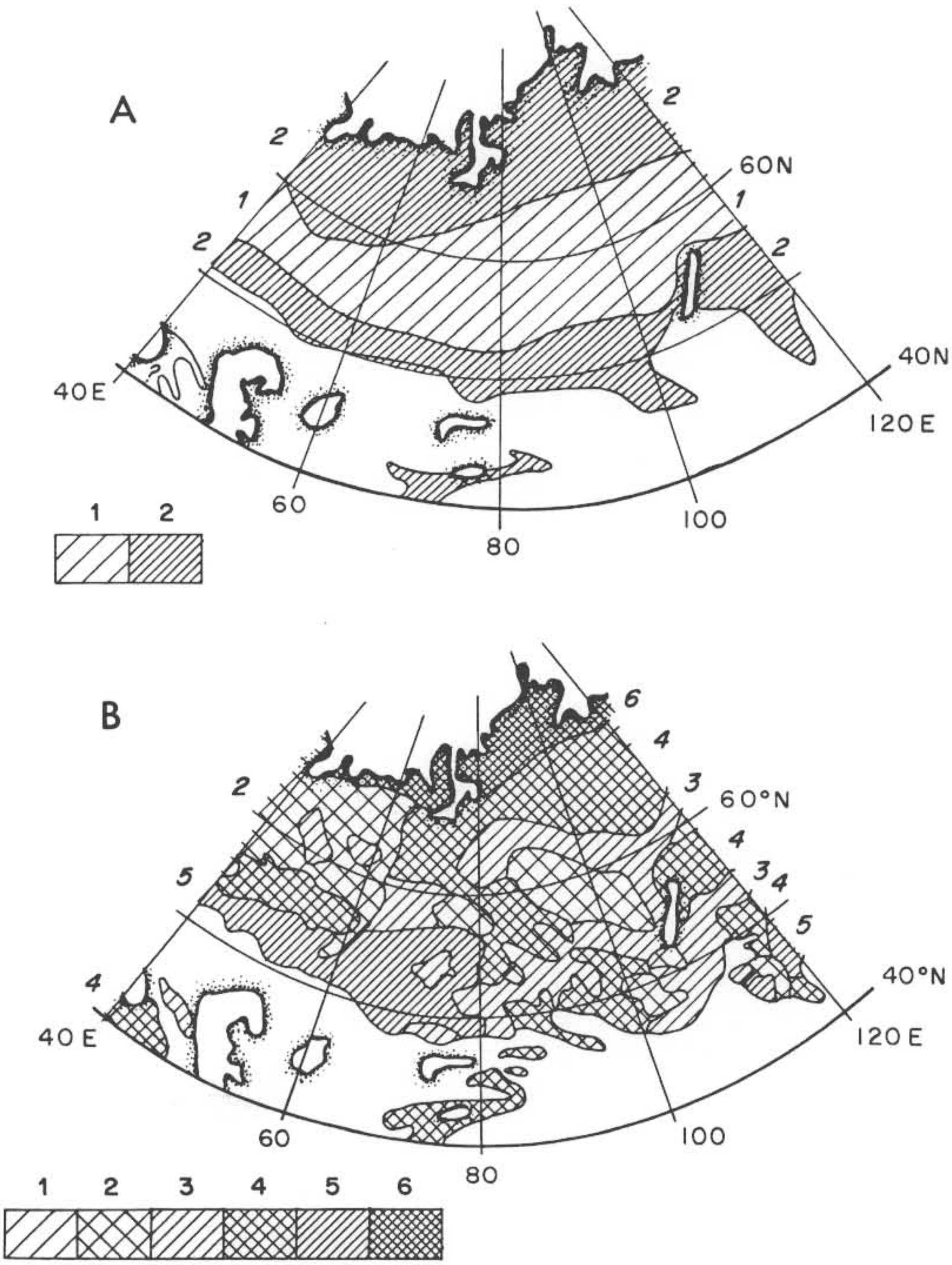

Figure 7. Relative reflectivity of snow cover as shown by Lamont (B) and NOAA (A) for the week ending 29 March 1970. NOAA reflectivities are the same as in figure 3. Lamont reflectivities form 1 (low) to c (high) are described in Kukla et al., p. 87 this volume. Corresponding albedo estimates are shown in table 4.

series. The charts produced after 1973 show the distribution of relative brightness fields in much greater detail. Using the approximate estimates of average surface albedo values corresponding to the NOAA and to the Lamont classes (table 4), the surface albedo of the studied segment is 39 percent from the NOAA and 50 percent from the Lamont product. This large discrepancy is caused by the highly generalized boundaries and high range of albedo values corresponding to reflectivity class 2 in the early NOAA products (pre-1973).

Mountainous zones present a quite complicated surface albedo distribution (figure 3). This is, firstly, because of the irregular and patchy form of the snowfields and, secondly, because of the intricate interfingering of dense forests, bare basins, rocky slopes, and alpine tundras. In the example shown, the snow outline is relatively accurately delimited in the Lamont chart for the 16th of March, but highly generalized in the NOAA/NESS and the Weekly Weather and Crop Bulletin products. The relative reflectivity of the snow fields in the NOAA/NESS chart is overestimated.

The Albedo of Ice Fields

The shortwave albedo of a bare ice surface ranges from about 8 to 60 percent. A fresh snow cover only a few millimeters thick is sufficient to raise the ice albedo to over 80 percent. The potential impact of this variability on climate is obvious. Unfortunately, except for NOAA snow and ice cover charts, no attempt has been made to chart the sea ice albedo changes on a regular basis.

An example of the relative reflectivity distribution of the sea ice cover in the Bering Sea is shown in figure 6. The relative brightness of the sea ice in 6 grades was charted at Lamont (A) from the NOAA-VHRR satellite images in the visible band. This product is compared with the NOAA/NESS representation of the same areas distinguishing two classes of relative reflectivity (D). It appears that NOAA class 1 correlates with the Lamont classes 3 and 4, whereas the darker ice is not shown at all in the NOAA product. The ice concentration classes shown in the weekly operational product of the Navy (C) are transformed into an albedo index (B) after a formula described in Kukla and Robinson (1980). The Air Force (E) reported more ice than was actually present and the ice is charted as if covered by snow at least 10 inches thick. Independent data on snow depth on top of the ice are not available, so the corresponding accuracy of the Air Force chart cannot be established.

The albedo index in version B is higher than the estimated reflectivity in the product A. A comparison of variants A and C shows that this is due to the fact that the ice concentration does not accurately correlate with the brightness distribution.

A considerable change of surface albedo 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 develops puddles of meltwater. The few published measurements taken at ice floe stations indicate that the regional albedo of such a surface drops from about 80-85 percent to 50-60 percent or less. No data yet exist on the areal extent and intensity of the summer melt on top of the Arctic ice and on its seasonal and year-to-year variability. Frequent clouds reduce the utility of satellite imagery in visible bands. There is a potential for microwave charting of the summer melt progression, but no demonstration was yet made of an operationally applicable method.

Table 4. Albedo of March 29, 1970 central Asia sector (figure 7) derived from NOAA and Lamont reflectivity classes.

Class	Percent of Snow Covered Area	Average Albedo: Percent	Albedo of Snowcovered Region: Percent
LAMONT			
2	30.6	32	
3	23.6	43	
4	35.3	54	
5	13.2	65	
6	7.4	75	50
NOAA			
1	43.0	30	
2	57.0	45	39

Snow Thickness

Several national agencies produce daily, weekly, and monthly snow depth charts for different parts of the Northern Hemisphere. The British Meteorological Office in Bracknell produces comprehensive snow depth charts of the whole Northern Hemisphere. However, the spatial variability of snow depth is so large that a reliable regional parametrization based on ground station data is next to impossible.

Figure 8 shows the mid-month depth in February 1977 in Ohio. The thickness measured at ground stations is shown for February 14 (C). This is also the date of the Weekly Weather and Crop Bulletin chart (D), and the Air Force snow depth chart (E).

Determination of the snow thickness from the relative reflectivity of a snow field was attempted by McGinnis et al. (1975) who found increasing regional brightness with increasing depth of fresh snow. A thickness greater than about 25 cm resulted in little further increases of albedo. In our example from Ohio, the forested area (B) in the eastern and southeastern portion of the state displays a low brightness, even though the snow is relatively thick, while farmland with only 3-5 cm of snow displays a high surface albedo. 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.

Figure 3 illustrates how inadequate the data spacing is reported by the Weekly Weather and Crop Bulletin and by the Air Force in the western United States given the high regional variability of the snow depth. In selected mountain ranges, state hydrologic services collect and evaluate data on the snow thickness and water equivalent. However, even if the existing network were used, it is not dense enough to substantially upgrade the continental or hemispheric snow depth charts.

Snow Cover Changes in Time

The snow-and ice-covered area in the Northern Hemisphere changes from about 10 million km^2 in summer to about 60 million km^2 in winter (Kukla and Kukla, 1974; Kotliakov and Krenke, 1981). Between September and December, it increases by about 40 million km^2 in less than 90 days. Thus, a single day represents almost 1 percent of the total seasonal change from a summer to a full winter condition.

Obviously, any meaningful monitoring of snow cover variability for climate related studies must be accurately dated. Figure 9 depicts a huge change of the snow extent in Nebraska, Iowa, Kansas, and Missouri in a single day in March. Figure 2 shows similar large variations in regional snow cover within a single week in autumn and in winter. The day-to-day variability of snow cover in the middle latitudes may be large in all seasons. This fact may significantly influence the precision of the weekly and monthly snow cover charts.

We have tried to determine on which day of the week the charted information comes closest to the real situation. As stated earlier, we have independently charted, from satellite and ground station data, and measured the snow cover area in various parts of the United States. We did it for every day of the week and then compared our results with the area shown in the operational weekly maps (figure 2 and table 2). We found that the operational charts most accurately depict the snow extent on the last two days of a charted week. Our comparisons were done in relatively small blocks and compensations are likely on a hemispheric scale. Thus, the time accuracy of the operational charts is judged sufficient for use in global general circulation models. However, for regional studies considerable improvements are needed.

Results

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

1. The NOAA snow charts for the 1966 to 1973 interval show snow boundaries with acceptable accuracy for large scale climate studies in winter, spring, and summer, but not in the fall. The information on the relative reflectivity of snow fields is inadequate throughout the year.

2. The NOAA charts from 1974 through 1980 show snow boundaries with acceptable accuracy for large-scale climate studies. However, users must keep in mind that snow fields under persistent clouds are systematically not shown, which leads to the under-representation of snow extent, particularly noticeable in autumn. The relative reflectivity of snow fields is depicted with acceptable accuracy for gross climate system studies on a hemispheric scale, but not on regional scales.

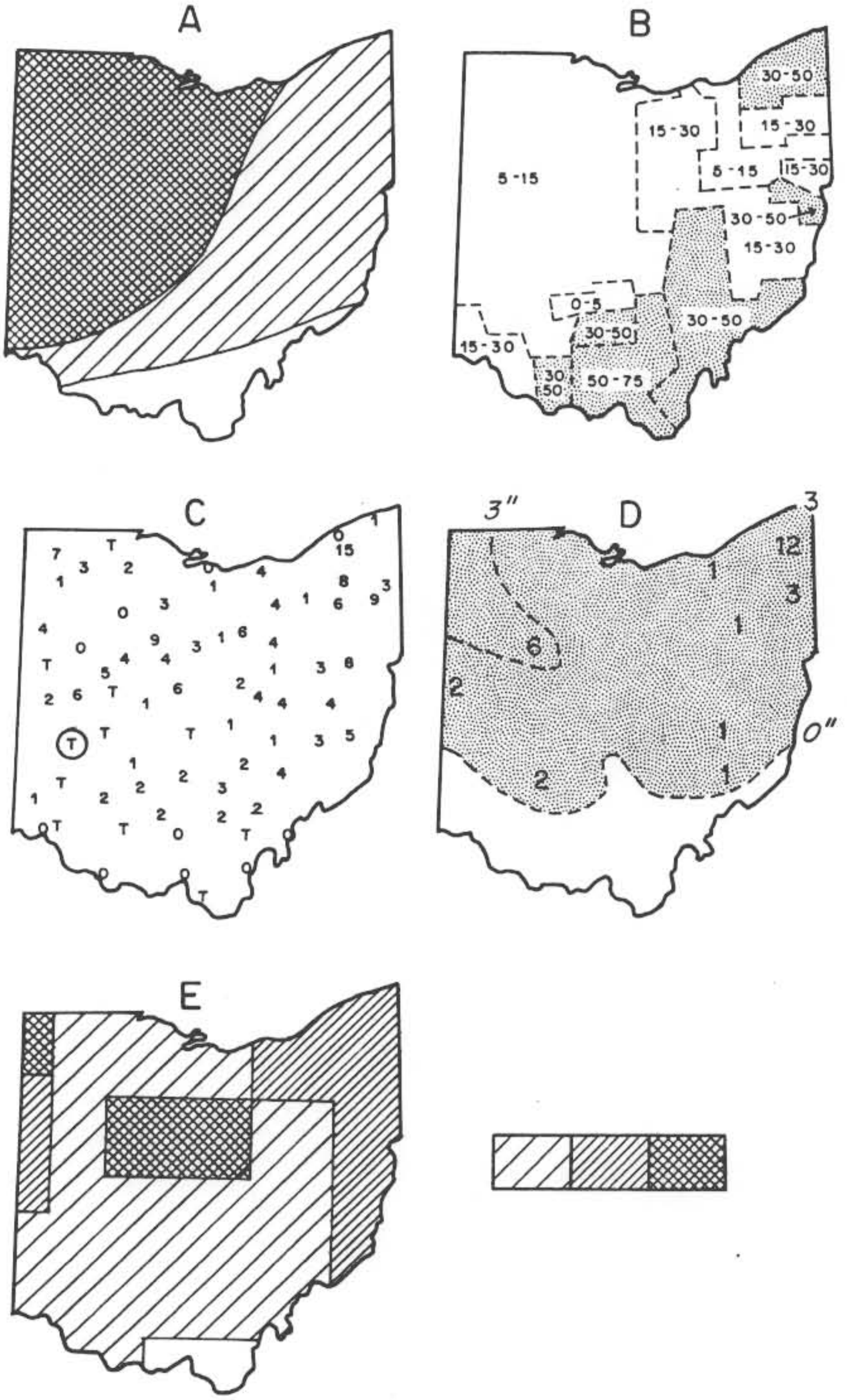

Figure 8. Snow cover in Ohio in mid-February 1977. The NOAA chart (A) for the week ending the 13th shows relative reflectivity the same as in figure 3. Reported snow depth in inches (C) from NOAA climatological data and from the Weekly Weather and Crop Bulletin (D) are shown for the 14. Air Force snow depth is the same as shown in figure 3 for the week ending 14 February. Percent of forest cover (B) is from the World Forestry Atlas (Wiebecke, 1971). WMO stations reporting snow depth are circled in (C).

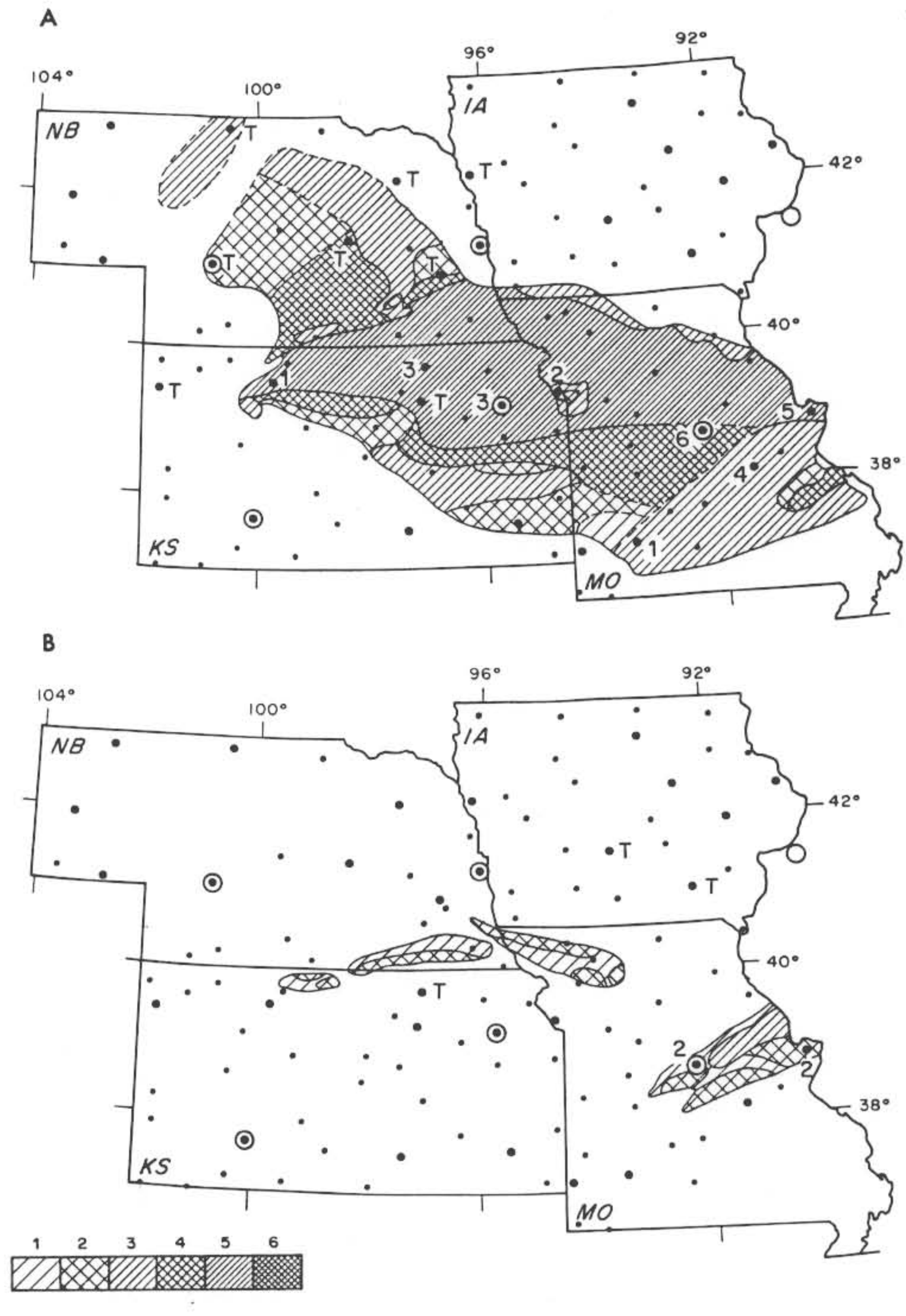

Figure 9. Snow cover in the central U.S. on 16 March (A) and 17 March (B), 1976, constructed from NOAA, GOES, and VHRR imagery. National WSO stations are marked with large dots, WMO stations with circles. Those reporting snow on the ground give depth in inches.

3. The Navy and NOAA/Navy operational sea ice charts present, with sufficient accuracy for climate studies, the ice boundaries and the proportion of white or grey ice to dark ice and open water. Thin dark ice is frequently not distinguished from open water. Reflectivity is not reported, nor is any information given on the thickness and state of the snow on the ice.

4. The Air Force weekly snow depth charts in most cases overrepresent the snow cover extent, especially in the thickness class below two inches. They do not seem to reliably parametrize the real snow depth on a regional scale. They are less suited for climate-related studies involving albedo than the NOAA and Navy charts in winter, spring, and summer, but are the best existing operational source on snow edge position in autumn. We noted that the quality of the recent charts is considerably higher than those produced a few years ago.

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References

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

Adem, J.; Donn, W. (1981) Mean monthly numerical prediction with a thermodynamic grid model. Abstract. (In: Conference on Climatic Variations, 1st, Abstracts. American Meteorological Society, p.19.)

Batten, E.; Soha, J.; Morrill, M. (1977) The albedo of snow covered surfaces determined from NOAA 4 and 5 satellites. American Geophysical Union. Transactions, v.58, p.400.

Climatic Perspective; a weekly review of Canadian climate (1979-) Canadian Climatic Centre, Atmospheric Environment Service.

Crane, R., comp. (1979) Inventory of snow cover and sea ice data. Boulder, CO, World Data Center-A for Glaciology (Snow and Ice). Glaciological Data, Report GD-7, 171p.

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

Godin, R., p.71 this volume.

Hummel, J.; Reck, R. (1979) A global surface albedo model. Journal of Applied Meteorology, v.18, p.239-253.

Kotliakov, V.; Krenke, A. (In press) The data on snow cover and glaciers for the global climatic models. (In: Eagleson, P., ed. Study Conference on Land-Surface Processes in Atmospheric Circulation Models. Greenbelt, Maryland, NASA.)

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

Kukla, G.; Gavin, J. (1979) Snow and pack ice indices. Boulder, CO, World Data Center-A for Glaciology (Snow and Ice). Glaciological Data, Report GD-6, p.9-14.

Kukla, G.; Robinson, D (1979) Accuracy of snow and ice monitoring. Boulder, CO, World Data Center-A for Glaciology (Snow and Ice). Glaciological Data, Report GD-5, p.91-97.

Kukla, G.; Robinson, D. (1980) Annual cycle of surface albedo. Monthly Weather Review, v.108, p.56-68.

Kukla, G. (1981) Climatic role of snow covers. (In: Allison, I., ed. Sea Level, Ice and Climatic Change. Proceedings of the Symposium, XVII General Assembly IUGS, Canberra. International Association of Hydrological Sciences. Publication, no. 131, p.79-107.)

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

Kukla, G.; Gavin, J., p.145 this volume.

Kukla, G.; Robinson, D.; Brown, J., p.87 this volume.

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

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

McGinnis, D.; Pritchard, J.; Wiesnet, D. (1975) Snow depth and snow extent using VHRR data from the NOAA-2 satellite. U.S. National Atmospheric Administration. Technical Memorandum NESS 63, 16p.

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

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

Robock, A. (1980) The seasonal cycle of snow cover, sea ice and surface albedo. Monthly Weather Review, v.108, p.267-285.

Smigielski, F., p.59 this volume.

Untersteiner, N. (1961) On the mass and heat budget of Arctic sea ice. Archiv fur Meteorologie Geophysik und Bioklimatologie, v.A 12, p.151-182.

Weekly Weather and Crop Bulletin (1914-) U.S. National Oceanic and Atmospheric Administration. Environmental and Data Information Service.

Wiebecke, E., ed (1971) Weltforstatlas. Hamburg und Berlin, Paul Parey.

Wiesnet, D.; Matson, M. (1976) A possible forecasting technique for winter snow cover in the Northern Hemisphere and Eurasia. Monthly Weather Review, v.104, p.828-835.

Wiesnet, D.; Matson, M. (1979) NOAA satellite-derived continental snow cover data base. Boulder, CO, World Data Center-A for Glaciology (Snow and Ice). Glaciological Data, Report GD-6, p.3-8.

Woronicz, R., p.63 this volume.

Zwally, J.; Wilheit, T.; Gloersen, P.; Mueller, J. (1976) Characteristics of Antarctic sea ice as determined by satellite-borne microwave imagers. (In: Symposium on Meteorological Observations from Space: Their Contribution to the First GARP Global Experiment, Proceedings. Boulder, CO, National Center for Atmospheric Research, p.94-97.)