THOMAS M. LILLESAND
DOUGLAS E. MEISNER
ANNE LAMOIS DOWNS
RICHARD L. DEUELL
Remote Sensing Laboratory
University of Minnesota
St. Paul, MN 55108

Use of GOES and TIROS/NOAA Satellite Data for Snow-Cover Mapping*

In open agricultural areas, satellite data helped improve the results of the conventional snow mapping process; however, masking effects in forested regions severely impaired the ability to visually interpret snow extent on most dates.

INTRODUCTION

SINCE LATE 1972 environmental satellites have been providing daily, high resolution (1 km) imagery over North America on an operational basis. During 1973 hydrologists at the NOAA National Environmental Satellite Service (NESS) demonstrated that images from these satellites could be used to create timely snow-cover maps over river basins of varying size, location, and topography (Wiesnet and McGinnis, 1973). By 1974, snow mapping had become an "operational" program at NOAA/NESS (Schneider *et al.*, 1976) and the program has continued to expand.

ABSTRACT: *GOES and TIROS-N/NOAA-6 satellite data were evaluated both visually and digitally to assess their potential for aiding the process of statewide snow extent mapping in Minnesota. This state contains a geographic continuum spanning from a large open-agricultural area, through a partially forested transitional zone, to a heavily forested area. The ability to discriminate snow extent statewide was found to be influenced strongly by the date of sensing and the cover types involved. Visual analysis showed that snow extent in the heavily forested area was directly observable only in late spring images. Visual analysis of GOES data covering the open-agricultural area of the state showed that marked improvement in the accuracy of the conventional snow mapping process could be realized by analyzing the imagery in concert with the ground data collected in this area. Snow depth vs. scene radiance correlations were calculated using GOES image data for four cloud-free dates covering the open-agricultural area. Various data normalization techniques were employed, with resulting* R^2 *values ranging up to 0.88. The optimum normalization technique yielded* R^2 *values averaging 0.71. Digital analysis of both GOES and TIROS data was also used to document the relative snow masking influences of the various cover types occurring in the heavily forested area. The results of these efforts are described herein as are the geometric transformations used to merge the ground and satellite data employed in the study.*

The principal image interpretation methodology used in the NESS snow mapping program is visual

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analysis of enlarged hard copy image products from the Geostationary Operational Environmental Satellite (GOES) and the TIROS/NOAA Satellite systems. Visible band images are rectified to a hydrologic basin map utilizing a Bausch and Lomb Zoom Transfer Scope (ZTS). The snow line on the image is traced onto the basin map and snow-covered areas are colored in. Snow extent is then measured using the planimeter function of an electronic density slicer. With the hope of automating this entire process, NESS has supported various research programs aimed at developing methodologies for all digital snow mapping (Schneider, 1979).

A major influence on the accuracy of any visual or digital snow-mapping procedure is the difficulty of detecting snow cover in forested regions. Forest cover in general, and dense coniferous covers in particular, tend to "mask" the presence of snow. This problem was studied in the heavily forested regions of the Adirondack Mountains (Eschner *et al.*, 1977). The research reported herein was aimed at studying the forest cover snow masking effect under the mixed forest-agricultural conditions of the Lake States. More specifically, the study was conducted using Minnesota as a test area to evaluate the imaging characteristics of snow in open agricultural areas, under heavily forested conditions, and in zones of transition between these two cover types. Both GOES and NOAA/TIROS data were analyzed and both visual and digital data analysis techniques were employed. Satellite and ground-based snow survey data were compared on a statewide basis for the winters of 1978-79 and 1979-80. We describe how these data were acquired and analyzed, and the comparative imaging characteristics of snow present under the aforementioned cover conditions.

Data Acquisition

Snow Survey Data

Snow mapping is important in a state such as Minnesota because this information is used in activities such as soil moisture condition assessment, flood forecasting, winter recreation, and wildlife management. Accordingly, the Minnesota Department of Natural Resources (DNR), through the State Climatology Office, publishes snow depth maps for the state on a weekly basis throughout the snow season.* About 15 National Weather Service (NWS) first order reporting stations and 40 DNR Forestry Division stations supply the core of the survey data. In addition, supplemental snow depth measurements are collected weekly from about 200 cooperative volunteers. Each week's point measurements are geographically referenced on a computer generated base map and snow depth isarithms are portrayed manually. Both the raw point data and the generalized snow depth maps were used in this study.

Figure 1 shows the distribution of the reporting stations comprising the snow survey network, the three major land cover zones across the state (from open agriculture in the southwest, through a transition zone, to the dominantly forested area of the northeast), and the locations of test areas within each zone. These areas were used for detailed cover type analyses.

Forest Cover Type Data

The cover type data used in this study were extracted from a statewide forest cover survey compiled previously through the cooperative efforts of the USDA North Central Forest Experiment Station (NCFES) and the Minnesota State Planning Agency. The NCFES acquired the original data for this survey by interpreting the most recent available photo coverage of all areas of the state and reducing this interpretation to 1:24,000 master sheets. In turn, the interpreted data were encoded on a 40 acre grid cell basis into the Minnesota Land Management Information System (MLMIS). Once in this geographic information system, these data were composited digitally to prepare a statewide forest cover map at a scale of 1:1,000,000 (LMIC, 1977). A 50 percent cover criterion was used to determine if any given cell was mapped as dominantly forested. The same criterion was used

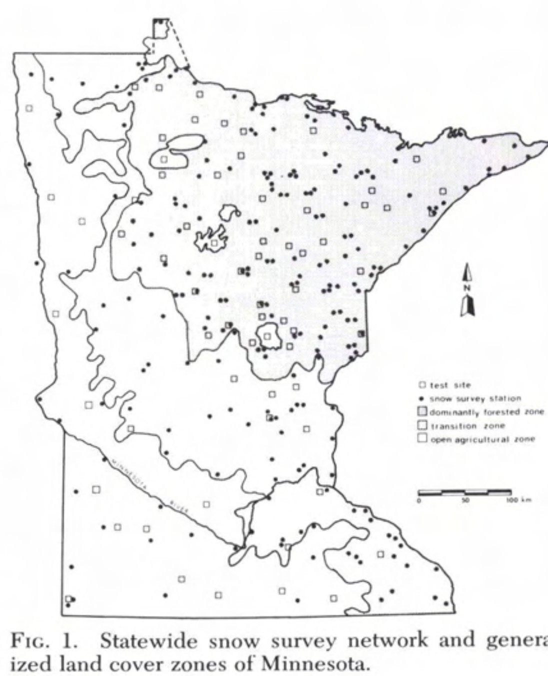

FIG. 1. Statewide snow survey network and generalized land cover zones of Minnesota.

* These data are also summarized annually along with estimated snow water content statistics and statewide soil moisture conditions (DNR 1980).

to portray the dominant forest type within a forest area. While the 1:1,000,000 forest cover map served as a general cover type reference for this study, current (1977-79) statewide quad-centered photographs were used for map verification and detailed cover type analysis over the individual test sites.

The major forest types occurring in the state are pine (white, red, and jack), spruce-fir (balsam fir, white spruce, black spruce, tamarack, and northern white cedar), oak (red, white, and burr), elm-ash-cottonwood (lowland elm, black ash, cottonwood, and red maple), maple-basswood (sugar maple, basswood, yellow birch, upland elm, and red maple), and aspen-birch (aspen, balsam poplar, and paper birch).

IMAGE DATA

Table 1 summarizes the basic characteristics of both the GOES and TIROS-N/NOAA-6 satellite systems and compares them to those of the Landsat satellite series. The GOES system, being geostationary, produces image data of relatively constant geometry. The TIROS-N/NOAA-6 system is polar orbiting, and suborbital tracks do not repeat on a daily basis. Thus, the location and geometric distortion of a given study area varies with each image analyzed (Hussey, 1979).

Images selected for analysis were those on or most proximate to each of the weekly snow survey dates during the snow seasons of 1978-79 and 1979-80. All GOES data were obtained from the Space Science and Engineering Center at the University of Wisconsin-Madison. This facility archives noon (CDT) full-disk GOES hard copy images on a daily basis. A total of 28 clear image dates was selected by previewing such images, and 1000 by 1000 pixel segments centered on Minnesota were extracted from each of these scenes in computer compatible tape (CCT) format. These data were subsequently used to generate hard copy images using a Dicomed Image Recorder at the University of Minnesota Image Processing Center. The images appearing in the remainder of this article are segments (windows) of the archival data film recorded locally in this fashion. Only visible band GOES data were produced in this fashion because the thermal data were available solely at an 8-km resolution—a size judged too coarse relative to the forest cover variation typical of the state.

All TIROS-N and NOAA-6 data were ordered from the Satellite Data Services Division of NOAA's Environmental Data Service. Channel 1 and 4 hard copy images were received in either transparency or paper print form and all channels were ordered in CCT format. Data were ordered for those dates when Minnesota appeared in the center one-third of an image. Of the 22 CCT's requested, only nine were received and only three subsequently analyzed.

Not only were limited amounts of the TIROS-N and NOAA-6 data received, but also cloud cover often prevented analysis of the available data. The few cloud-free dates available in CCT format with accompanying hard copy, however, were of excellent quality.

Visual Image Interpretation

OBJECTIVE/PROCEDURE

The objective of the visual interpretation process was to compare the images of various data to their corresponding snow maps and to determine the relative influence of various cover types in areas of disagreement. A B & L Zoom Transfer Scope (ZTS) was used to correlate the cover type map and respective snow map to each image analyzed. Features such as rivers and lakes were identified to enable the interpreter to "warp" the map or image data into a common geographic base.

Table 1. Basic Characteristics of GOES and TIROS-N/NOAA Data Compared to Landsat Data

Satellite	Altitude	Sensor	Band (μm)	Resolution	Freq[1]
Landsat	920 km	MSS Multispectral Scanner	4 (0.5-0.6) 5 (0.6-0.7) 6 (0.7-0.8) 7 (0.8-1.1)	80 m	18 days
		RBV Return Beam Vidicon	(0.505-0.750)	30 m	
GOES[2]	37,500 km	VISSR Visible/Infrared Spin Scan Rad.	vis. (0.55-0.75) IR (10.5-12.6)	1 km 8 km	24 48
TIROS-N/ NOAA-6	854 km 833 km	AVHRR Adv. Very High Resolution Radiometer	1 (0.55-0.90)[3] 2 (0.73-1.10) 3 (3.55-3.93)[4] 4 (10.5-11.5)	1 km	1 1 2 2

[1] Coverage frequency expressed in repetitions/day (except for Landsat).
[2] Geostationary orbit (others are near-polar sun synchronous).
[3] Changed to 0.55-0.68 μm on NOAA-6.
[4] Channel 3 is excessively noisy on TIROS-N.

This was done with relative ease with the GOES data, becuase of the repeatability of the distortions from date to date. Map-to-image correlation was a much more difficult process for the TIROS/NOAA images. Each image had different distortion characteristics, and the nature of these distortions made it impossible to accurately rectify the image data over the entire study area with the optical stretch feature of the ZTS.

RESULTS

As anticipated, the ability to detect snow extent varied greatly with time and cover type. The presence of snow in the open agricultural and transition zones was very apparent on all dates of analysis. In fact, qualitative differences in snow depth could also be observed in these regions up to depths of approximately 25 cm when a majority of the lower ground vegetation became covered. Beyond this depth, changes in snow brightness were minimal with subsequent increases in depth (also noted in Barnes and Bowley, 1974).

Figure 2 illustrates the general correlation between snow depth and image brightness in the open agricultural area. Both Figures 2 and 3 illustrate the overall masking influence of the forest cover in the northeastern portion of the state. The principal key to the presence of snow in this region is its visibility in open areas (e.g., lakes, open pit mines). Snow depth variations were virtually impossible to discriminate in this region. Likewise, it was extremely difficult to discriminate snowfield boundaries when they occurred in the forested region. However, the overall masking effect of the forest cover was strongly influenced by the date of sensing. In early and mid-season images, masking was found to be extensive and the high reflectance in open areas provided the primary clue that snow was present. But in late March and early April, there was a general increase in image tone within the snow covered forested areas characterized by deciduous types, open bog lands, and low density coniferous stands.

FIG. 2. 2 December 1979 GOES visible band image segment with snow depth overlay for 5 December 1979. Note representative cover type areas of (A) spruce-fir, (B) open bogs, (C) Iron Range, with open pit mines, and (D) aspen-birch.

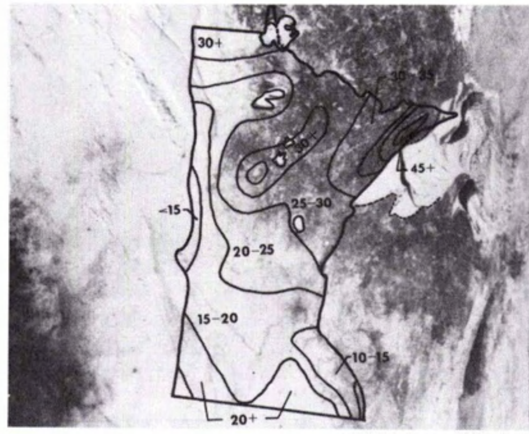

FIG. 3. 11 March 1979 TIROS-N band 1 image segment with snow depth overlay for 14 March 1979 (snow depth in inches).

This decrease in masking may be associated with the more favorable solar altitude during the latter portion of the season. However, by late April and thereafter, little tonal contrast was observable in the forested area. Dense coniferous types strongly masked the presence of snow irrespective of point in the snow season.

The general value of the images in assisting the statewide snow mapping process was apparent throughout this study in spite of the masking influence encountered in the forested areas. For example, interpretation of the ground data in the absence of the satellite imagery often led to inaccurate placement of snow extent and depth lines in the open agricultural areas. Figure 4 illustrates how having the satellite data in hand might assist the snow mapper in making decisions about the placement of snow depth isarithms. The synergism realized from using the ground and satellite data enables much more accurate mapping, and might eliminate the need for such a dense snow survey net in the open and transition areas of the state.

Being available so frequently, the images can also be used to monitor important transient events which are often misrepresented or omitted when using the conventional measurement procedures. Figures 5 and 6 illustrate this point; these images show the aftermath of a storm on two successive days. Note how rapidly melt occurs during this period and how the satellite data greatly improve the depiction of this event in contrast to using the NWS snow-depth data alone.

DIGITAL DATA ANALYSIS

OBJECTIVES

There were two principal objectives of the digital data analyses performed in this study. First, we wished to quantify the extent of the correlation

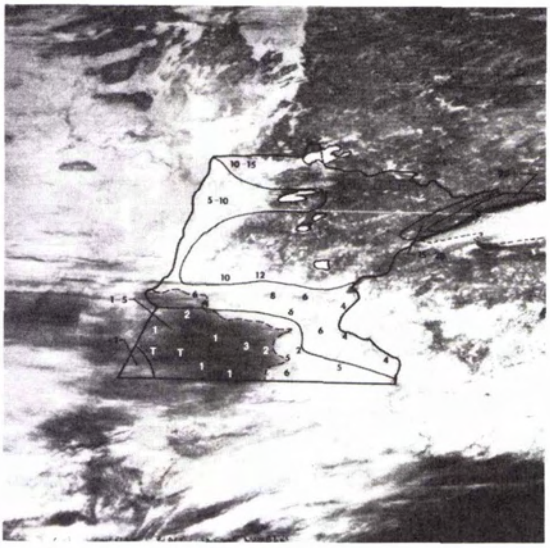

FIG. 4. 8 January 1980 GOES visible band image segment with snow depth overlay for 9 January 1980. Dashed line illustrates probable position of 5 inch (12.6 cm) isarithm from image interpretation. Solid line shows its position estimated from ground data.

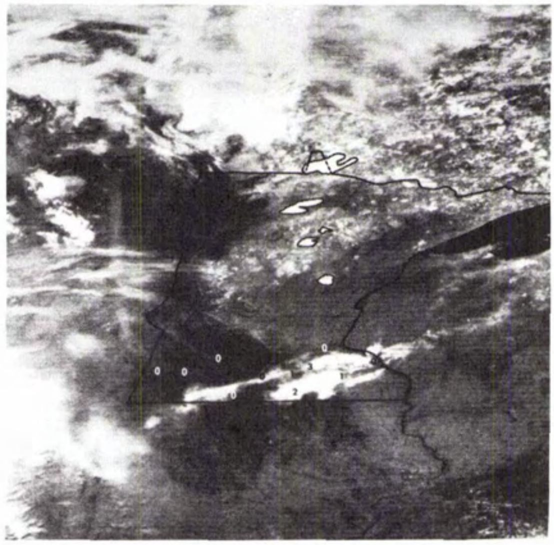

FIG. 6. 5 April 1980 GOES visible band image segment with selected NWS snow depths. Compare to Figure 5 to note transient nature of storm track in southern portion of state.

between image brightness and snow depth observed by means of the visual analysis in the open land cover area. Secondly, we wished to study quantitatively the masking influence attributable to the various forest types found in the study area.

GEOMETRIC CONTROL

Geometric transformations were developed to allow accurate location of ground test sites in the

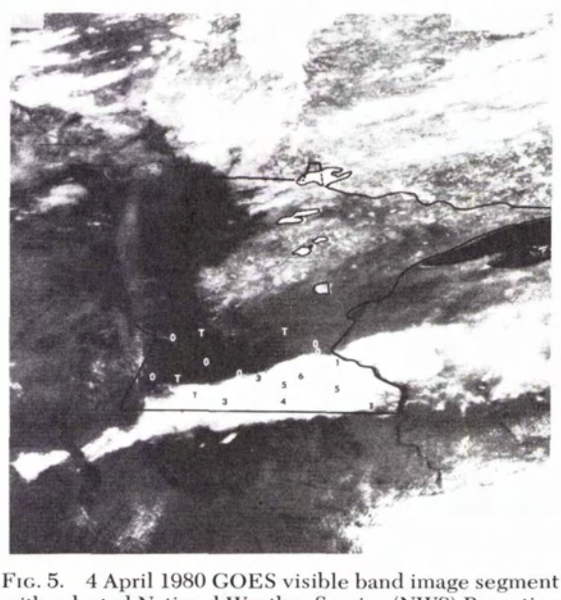

FIG. 5. 4 April 1980 GOES visible band image segment with selected National Weather Service (NWS) Reporting Station snow depths.

image data sets. The TIROS data were first resampled to correct for systematic distortions, and then ground control points were used to provide a least-squares fit to a map base using a two-dimensional, second order polynomial coordinate transformation. The GOES data were analyzed solely by locating ground control points and applying the coordinate transformation.

The systematic correction for the TIROS data was adapted from previous work applied to NOAA-4 data (Meisner *et al.*, 1977), which in turn had been based on work by Legekis and Pritchard (1976). The formulas were modified for the different parameters of the TIROS-N/NOAA-6 systems, described in Kidwell (1979). Table 2a lists the modified parameters and Table 2b gives the revised algorithm used for the panoramic distortion correction. This algorithm was used to generate a lookup table for use in a nearest neighbor resampling of each image. (A more complete discussion of the geometric correction procedures used to analyze the TIROS data is contained in the Appendix of Lillesand *et al.* (1980).)

The effect of the systematic correction was studied on the 11 March 1979 scene. Images covering Minnesota were generated with and without the geometric correction, and control points were measured and submitted to a least squares affine fit. Residuals of 1.60 pixels RMS in x(EW) and 0.92 in y(NS) were found for eleven points on the uncorrected image. On the corrected image, these improved to 0.62 and 0.69 pixels RMS. This was not a comprehensive test of the correction, since the image column coordinates of the control points

TABLE 2A. TIROS-N/NOAA-6 PARAMETERS APPLICABLE TO PANORAMIC CORRECTION

Satellite:	orbital period	102 minutes*
	mean altitude	852 km (TIROS-N)/ 813 km (NOAA-6)*
	nominal line spacing	1.09 km
	inclination	98.9°
Scanner:	line rate	6 Hz
	sample rate	39,936 Hz

*(these values are updated regularly)

TABLE 2B. REVISED PANORAMIC CORRECTION FORMULAS

given: x' (column number in panoramic corrected grid)
alt (satellite altitude divided by earth radius)
find: x (raw image column number)

$$\emptyset = (x' - 1024)/5844.17$$
$$\alpha = \tan^{-1} (\sin\emptyset/(1 - \cos\emptyset + \text{alt}))$$
$$x = \alpha \cdot 1059.335 + 1024$$

(for derivation see Appendix of Lillesand *et al.* (1980))

ranged only between 615 and 833. Within this limited width (about 10 percent of the full scene width of 2048 pixels), the panoramic distortion is essentially linear. Tests covering a greater width nearer the edge of the scene are the subject of continuing research on the TIROS geometric correction procedures.

Geometric analysis of the GOES images was simplified by the consistent nature of their geometry. One scene (20 October 1978) was fit to the base map using 19 control points and a second order polynomial coordinate transformation. Resulting residuals were 1.20 pixels RMS in x and 0.88 in y. Subsequent scenes were found to be offset in x and y (origin translation) but otherwise equivalent to the first scene (in scale and rotation). By locating a sample of the original 19 control points on each scene, the offsets could be quickly determined.

DATA EXTRACTION

The actual digital analysis of the imagery commenced by locating study sites (Figure 1) containing 10 to 40 km² areas of reasonably uniform cover type on the statewide 1:1,000,000 scale forest cover type map. Where possible, the cover characteristics of each site were verified using high altitude quad-centered aerial photography. Polygons enclosing the sites were drawn and coordinates of the vertices were measured on the same overlay grid used in the geometric analysis. This allowed the polygon vertex coordinates to be transformed into the coordinate system for each image date. Next, a supervised training program was run to extract the pixel values for each polygon and to derive the attendant mean, variance, and covariance data. These data were then used to study the quantitative relationship between snow depth and digital brightness in the open area and to study the different cover type/snow depth characteristics in the forested area.

OPEN AREA ANALYSIS

The relationship between snow depth and image brightness was studied using the digital GOES visible data. Thirteen test sites were located in nonforested, nonurbanized areas proximate to the National Weather Service Stations in the southern and eastern regions of the state. These stations record snow depth on a daily basis, insuring concurrence with the image dates. The test sites contained between 11 and 40 pixels, averaging 23 each. Test site pixel values were extracted from four dates of GOES imagery, which necessitated some between-date normalization for atmospheric effects, illumination changes, etc. To assess different normalization strategies, the raw pixel values for each test site were converted to seven forms of brightness expression as follows:

(1) DN: the mean digital number (DN) within the site.
(2) DN_{max}: the brightest pixel in the site (this was used to screen out any forest cover).
(3) $DN\text{-}DN_0$: Mean DN minus the digital number representing the darkest 2 percent of the scene (a nominal atmospheric correction).
(4) Normalized: mean DN normalized using the mean and standard deviation for the entire image segment.
(5) Percentile: mean DN expressed as percentile rank in the distribution of the full segment.
(6) Mean-Oct.: mean DN minus the corresponding DN from a pre-snow image (20 October '78).
(7) Max-Oct.: max DN minus the October value.

Table 3 gives the R^2 results of regression fits applied to the data. Both linear (snow depth versus brightness) and second order (snow depth versus brightness and brightness squared) fits were applied. On all dates, the "October subtraction" procedures provided the best results, with a maximum R^2 value of 0.86 realized on the 4 April date (method 6).

The data set combining all dates (A, B, C, D in Table 3) yielded poor R^2 values, particularly with the normalized data. A combination of two proximate dates (A and B) gave better results, suggesting that the relationship changes throughout the season. This is also indicated in Figure 7, which is a plot of Mean-Oct. brightness values versus snow depth for 1 December 1978 and 9 January 1979. (One test area was cloud covered on the 1 December scene, so only 12 points are shown on the plot for this date).

In a comparable study using NOAA-2 data, McGinnis (1975) reported a correlation coefficient

TABLE 3. R^2 RESULTS OF SNOW DEPTH VS. IMAGE BRIGHTNESS REGRESSION ANALYSIS, GOES VISIBLE CHANNEL

		form of brightness expression						
Date	form of regression	1. mean	2. max.	3. atmos.	4. norm.	5. %tile	6. mean-Oct	7. max-Oct.
A. 1 Dec 78	linear	0.33	0.48	0.33	0.33	0.43	0.45	0.61
	2nd order	0.56	0.73	0.56	0.56	0.65	0.73	0.76
B. 9 Jan 79	linear	0.52	0.49	0.52	0.52	0.37	0.58	0.54
	2nd order	0.66	0.55	0.66	0.66	0.58	0.68	0.64
C. 2 Dec 79	linear	0.54	0.50	0.54	0.54	0.55	0.55	0.53
	2nd order	0.61	0.60	0.61	0.61	0.59	0.58	0.62
D. 4 Apr 80	linear	0.80	0.69	0.80	0.80	0.65	0.82	0.73
	2nd order	0.85	0.81	0.85	0.85	0.88	0.86	0.82
combined (A,B,C,D)	linear	0.33	0.31	0.27	0.16	0.16	0.37	0.36
	2nd order	0.35	0.32	0.33	0.22	0.17	0.40	0.37
(A,B)	linear	0.30	0.31	0.25	0.36	0.39	0.41	0.39
	2nd order	0.41	0.36	0.26	0.53	0.49	0.54	0.45

of 0.86 using a 2nd order fit. The generally lower values obtained here were likely due to a greater variability in the age of the snowpack. In the McGinnis study, a single image date immediately following a large snowstorm was used.

FOREST SITE ANALYSIS

For the forest masking effect analysis, 39 study sites were located in the predominantly forested region of the state. They were grouped under five general forest cover categories. In addition, two nonforested classes were included for comparison purposes. The categories are listed below in order of increasing image brightness:

(1) Conifer (six sites): dense stands of pine, spruce, fir, and tamarack.
(2) Hardwoods (eleven sites): dense stands of aspen/birch, elm/ash/cottonwood and maple/basswood associations.
(3) Mixed (three sites): sites containing both coniferous and deciduous forest.

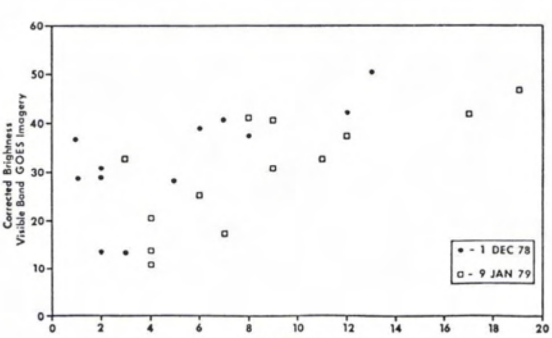

FIG. 7. Plot of corrected brightness vs. snow depth (corrected brightness: mean DN minus corresponding DN from a pre-snow image, 20 October 1978).

(4) Oak (three sites): considered separately because of leaf persistence.
(5) Wetland Conifer (three sites): bog areas containing dense conifer stands interspersed with open marshaland.
(6) Scattered Deciduous (eight sites): forest patches mixed with open areas.
(7) Open (two sites): nonforested sites located in the dominantly forested region.
(8) Lakes (three sites): located on large lakes (generally snow covered but potentially could be blown clear).

Analysis of the TIROS/NOAA data was hindered by cloud cover. As a result, digital analysis was focused on a single image date, 11 March 1979. Snow depths ranged from 50 to 90 cm in the forested region on this date. Thus, all sites may be considered to be in a "heavily snowcovered" state.

It was our intention to study the utility of the four-channel multispectral data provided by the Advanced Very High Resolution Radiometer (AVHRR). Unfortunately, the system on board TIROS-N is still virtually a two-channel scanner. Channels 1 and 2 were found to be highly redundant for our scenes, with correlation coefficients in the training sites averaging 0.95. This is due to spectral overlap in the bandwidths (0.55 to 0.90 μm for channel 1 and 0.73 to 1.10 μm for channel 2), a situation rectified on NOAA-6 by reducing the channel 1 band to 0.55 to 0.68 μm. NOAA-6 digital data sets were not available on clear days in our study period, so the degree of improvement in spectral resolution could not be assessed. Channel 3 data (3.55 to 3.93 μm) from TIROS-N is very noisy due to system problems (Kidwell, 1979, p. 2.3-1) and was found to be unusable.

Table 4 lists the mean brightness values observed within the test sites after grouping by cover category. This table also lists the channel 1 versus

TABLE 4. TIROS-N PIXEL VALUES GROUPED BY FOREST TYPE

	channel	1. Conifer	2. Decid.	3. Mixed	4. Oak	5. Wet Con.	6. Scattered	7. Open	8. Lake
mean	1	3	20	25	37	90	91	160	179
	2	22	55	57	67	111	110	159	175
	4	139	132	137	122	142	135	130	150
ch. 1 vs. 2 correlation		0.99	0.96	0.78	0.99	0.95	0.99	0.99	0.95

channel 2 correlation coefficients. Four dates of GOES data were also analyzed, and the same mean brightness ranking of cover type categories was found on all dates. In spite of this consistent ranking, the ranges within each category were very broad, causing considerable overlap. Thus, even within the homogenous test sites, image response is only partially dependent on cover type. This precludes the use of a cover-type based normalization to remove masking effects.

In an attempt to better compensate for variability due to site characteristics, a modification of a technique reported by Tarpley *et al.* (1979) was applied to the GOES data. The procedure followed was

- Using a pre-snow data set (20 October 1978), the darkest pixel in each cover category was found. This established a "reference dark" level for each category. Next, a "delta factor" was computed for each site by taking the difference between the site mean and the reference dark level for its cover category.
- On a snowmelt date (17 April 1980), the darkest pixel in each cover category was again found. The delta factors from the first step were then added to the revised reference dark levels. The resulting values were taken as estimates of the nonsnow brightness level for each site.
- If the actual April image brightness exceeded the estimate from the second step, it was classified as snow covered. Otherwise, it was classified as "clear."

This procedure compensates for cover type by treating each category independently, for variations within cover type with the delta factor for each site, and for between-date variation with the reference dark level.

Table 5 indicates the general success of applying the classification to our limited number of study sites. An average per-class accuracy of 78 percent was realized along with an overall accuracy of 69 percent (25/36). These results look promising, but they exceed those that would be expected in a statewide application. Whereas the test sites are homogeneous with respect to cover type, most pixels in a statewide application would contain a mixture of types. Instead of using cover type categories *per se*, it may be preferable to determine "image brightness regimes" directly from the GOES data by averaging many dates of imagery. These brightness groups could then be used instead of the cover categories in the above procedure.

CONCLUSIONS

- Visual interpretation of snow extent in nonforested regions would provide very useful input to the snow mapping techniques currently used in Minnesota. Several examples were found where the traditionally prepared snow map disagreed with a snow extent line clearly visible on the satellite image. The satellite data provide an improved portrayal of the spatial distribution of snow when used in conjunction with ground data.
- GOES images were found to be more useful than TIROS/NOAA images due to the consistent geometric characteristics and greater frequency of GOES coverage. This coverage frequency offers improved observation of important snowmelt events which are often poorly described by ground survey data.
- Masking effects in the forested regions severely impair the ability to visually interpret snow extent on most dates. Late spring images exhibited less masking influence, but the interpretation is still frequently inaccurate. Increased brightness in open areas contained within forested areas is the primary clue that snow is present.
- Quantitative relationships were found between GOES visible band brightness and snow depth in nonforested test sites. The highest correlations

TABLE 5. RESULTS OF SNOW/CLEAR CLASSIFICATION FOR 17 APRIL 80

	# correct snow	# correct clear	# errors snow	# errors clear	percent accuracy
1. Conifer	4	–	2	–	67%
2. Deciduous	0	7	3	1	64%
3. Mixed	2	1	0	0	100%
4. Oak	–	2	–	1	67%
5. Wetland Conifer	2	1	0	0	100%
6. Scattered Decid.	0	4	1	3	50%
7. Open	–	2	0	0	100%

were found with data normalized by subtracting pre-snow image values to correct for site characteristics. Second order regressions yielded R^2 values up to 0.86 using this procedure.

- On TIROS-N, channels 1 and 2 were redundant for our scenes and channel 3 was extremely noisy, making the current scanner essentially a two-channel system. NOAA-6 segments were not available on clear dates in this study, so an evaluation of the utility of its multispectral data was impossible.
- The ranking of forest cover type categories arranged by increasing brightness was fairly consistent between dates and imaging systems. However, the ranges of values within each category overlapped considerably. This variability likely characterizes many of the mixed forested regions of the Lake States and would appear to preclude digital snow mapping in forested areas in this region using "type specific" normalization strategies.
- A digital snow-mapping technique reported by Tarpley *et al.* (1979) was modified and applied to the forested test site data. The procedure corrects for cover type, image date, and site characteristics. An average per-class accuracy of 78 percent was realized. It is suggested that variations of this approach be evaluated in future research.

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