OPERATIONAL SNOW MAPPING FROM SATELLITE PHOTOGRAPHY

by

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Summary

Snow cover is an earth resource that has been observed from space since the first meteorological satellite, nearly a decade ago. In the near future, continued observation of this resource will be a prime use of satellite systems designed specifically to view the earth's surface. In fact, a survey of snow and ice on a world-wide basis, as planned in the International Hydrological Decade, appears economically feasible only through satellite observations.

Recent studies of the use of satellite photography to map snow cover distributions in the Upper Mississippi-Missouri River Basins Region are described in this paper. The techniques presented for identifying and mapping snow distributions, and for estimating snow depths, were developed originally from TIROS photography,[1] and were tested on a data sample obtained from the ESSA satellites.[2] Additional research, currently in progress to determine whether these techniques are also applicable to mountainous areas, is briefly reviewed, and the outlook for operational snow surveillance from space is discussed.

Introduction

Advantages and Limitations of Satellite Snow Surveillance

Progress reports on satellite applications to snow hydrology have been given at the 1963 and 1966 meetings of the Eastern Snow Conference.[3,4] Despite the several studies reviewed in those reports, however, little operational application of snow cover mapping from satellite photography was achieved with the earlier data, owing in part to the uncertainty of obtaining an observation over a specified region. The daily global satellite coverage now available has eliminated this problem.

Satellite data can now be used by the hydrologist to assist in the operational mapping of snow cover distributions. In most cases snow can be reliably identified in satellite photography, and can be differentiated from cloud. Snow distributions can often be mapped in greater detail from these observations than is possible from existing station networks, and in non-forested areas, qualitative estimates of snow depth can be obtained for accumulations up to about four inches.

Nevertheless, current satellite data have limitations and should not be expected to satisfy completely the various operational requirements for snow cover and depth information. Cloud interference, limiting the number of useable satellite observations, remains a major problem, and estimates of snow depths of more than a few inches are not currently possible.

Upper Mississippi-Missouri River Basins Region

The snow mapping techniques described in this paper, although developed for the region of relatively flat terrain within the Upper Mississippi and Missouri River Basins (east of about 105°W), can also be applied to other areas with similar terrain, and are applicable, at least in some degree, to regions of characteristically different terrain and vegetation.

Nearly the entire Missouri Basin and a large part of the Upper Mississippi Basin are non-forested, with the land being used mostly as grassland or cropland. Snowfall increases toward the northeastern part of the region, ranging from an annual value of about 20 inches in the southern Missouri Basin to more than 60 inches in the northeastern Mississippi Basin.

In the north-central United States the frequency of cloud-free observations is sufficient for satellite snow surveillance. A cloud-free observation during winter can be expected in any one area on nearly 50 percent of the days. Two or more consecutive cloud-free days are not uncommon, and seldom will a period of more than a week pass without a useful observation.

Data Characteristics

Observations from the TIROS VII, VIII and IX, and the ESSA-2 and -3 satellites were used in these studies. The ESSA-3 AVCS (Advanced Vidicon Camera System) photographs, which formed the principal data sample, are representative of presently available satellite data. The maximum camera resolution from these satellites is about 2 nm, which appears to be the limiting resolution for obtaining useful snow cover data for hydrologic purposes.

Although APT (Automatic Picture Transmission) data would appear to be the most suitable for operational purposes, because of real time availability at forecasting centers, the rather poor quality of the facsimile reproduction makes their use doubtful. Principal difficulties are due to poor contrast and variations in brightness, both from picture to picture and from one part of a picture to another. Also, most facsimile receivers are not equipped with tape recorders that would enable re-running for better contrast control, nor are they equipped to produce polaroid type prints, which can be of excellent quality (Fig. 5a). At this time, therefore, AVCS data appear to provide the most useable snow cover information to the hydrologist.

Since correct geographical location is essential for obtaining accurate mapping from satellite photography, the accuracy of the initial placement of the latitude-longitude grid must be carefully checked through comparison with known geographic reference points. This applies both to APT pictures, which must be gridded after they are received, and to AVCS pictures, which are electronically gridded. In the AVCS pictures, major geographic features and state boundaries are given in addition to the latitude-longitude grid lines. Although these grids have been assigned an accuracy of $\pm 0.5^\circ$, they may at times be in error by as much as 60 nm or more.

Conventional snow data used for comparison with the satellite observations consist primarily of Monthly Climatological Data, compiled by state (published by Environmental Data Service, ESSA). These data provide the most complete conventionally acquired snow cover information readily available, although more complete data for specific areas may exist at some River Forecast Centers. Accordingly, the number of reports is typical of that which would be available in an operational situation.

Techniques for Identifying Snow Cover

Reference to Concurrent Cloud Observations

Since snow and cloud can have nearly identical reflectivities, differentiation between the two can be a serious problem when analyzing satellite photography. This is equally important for meteorological purposes; in more than one instance, it was found that cloud-free snow-covered areas had been mapped in operational analyses as being cloud-covered.

Reference to standard weather observations can be used principally to determine when major cloud systems cover the region of interest. Under such conditions, little useful snow cover information can be anticipated from satellite photography. When no cloud data are available or when concurrent cloud observations indicate a partial cloud cover, snow can be reliably identified by the techniques discussed below.

Recognition of Terrestrial Features

Recognition of terrestrial features is perhaps the most important technique for identifying snow, since it immediately indicates that no clouds are present in the vicinity of the visible feature. Coastlines, lakes, and rivers are easily recognized features, and can be readily verified on standard maps. Fortunately, in many cases, the appearance of terrestrial features is greatly enhanced with snow on the ground.[5]

In the region studied, the Great Lakes are perhaps the most prominent feature. In Fig. 1a, Lake Michigan can easily be recognized, appearing black since it is not frozen. Other frozen lakes, such as Nipigon and Winnipeg, can also be seen. In the photograph shown in Fig. 5a, identification of the Mississippi River was a principal factor used in determining that the bright area in the western part of the picture was snow and not cloud. The river stands out as a dark line just west of the cloud edge of the storm, centered over the Great Lakes at the picture time.

Other features not so obvious on conventional maps afford equally reliable assistance in snow identification. Among these are boundaries between forested and non-forested areas and boundaries between areas with different land usages. These features form patterns with different tones that could cause inexperienced personnel to misinterpret the snow cover. To the trained analyst, however, the patterns are a valuable tool in differentiating snow from cloud.

In Fig. 1a, the most prominent feature, aside from the Great Lakes, is an area around Lake Superior that appears dark, despite a snow cover of considerable depth (Fig. 1b). From land-usage and forest-type maps, this dark pattern was identified as the forested area of northern Wisconsin and Minnesota. Earlier investigations have shown that the reflectivity of a snow surface can vary over a wide range depending on the amount and type of forest cover, as well as the condition of the snow itself.[6] The forest in question is largely deciduous, and appears gray since snow can be seen through the leafless trees. The darker spots are areas of coniferous growth.

Another dark pattern, near 44°N, 91°W, is associated with a dis-

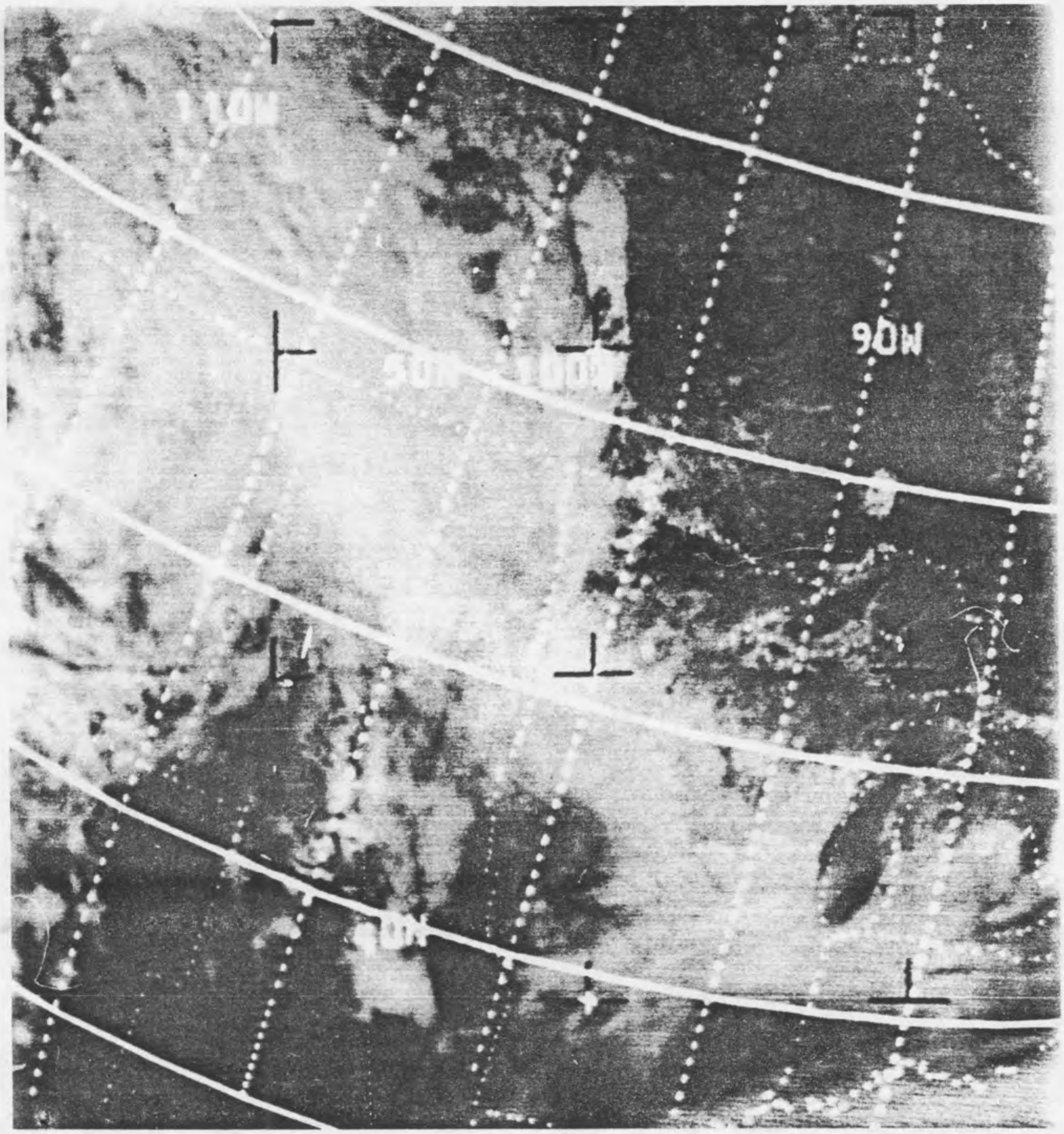

Figure 1a ESSA-3 AVCS photograph (6 February 1967) showing Upper Mississippi-Missouri River Basins region with substantial snow cover. Many terrestrial features, including Lakes Michigan (unfrozen), Nipigon and Winnipeg, can be recognized indicating cloud-free conditions. Darker, forested areas near Lake Superior and in central Wisconsin can also be seen.

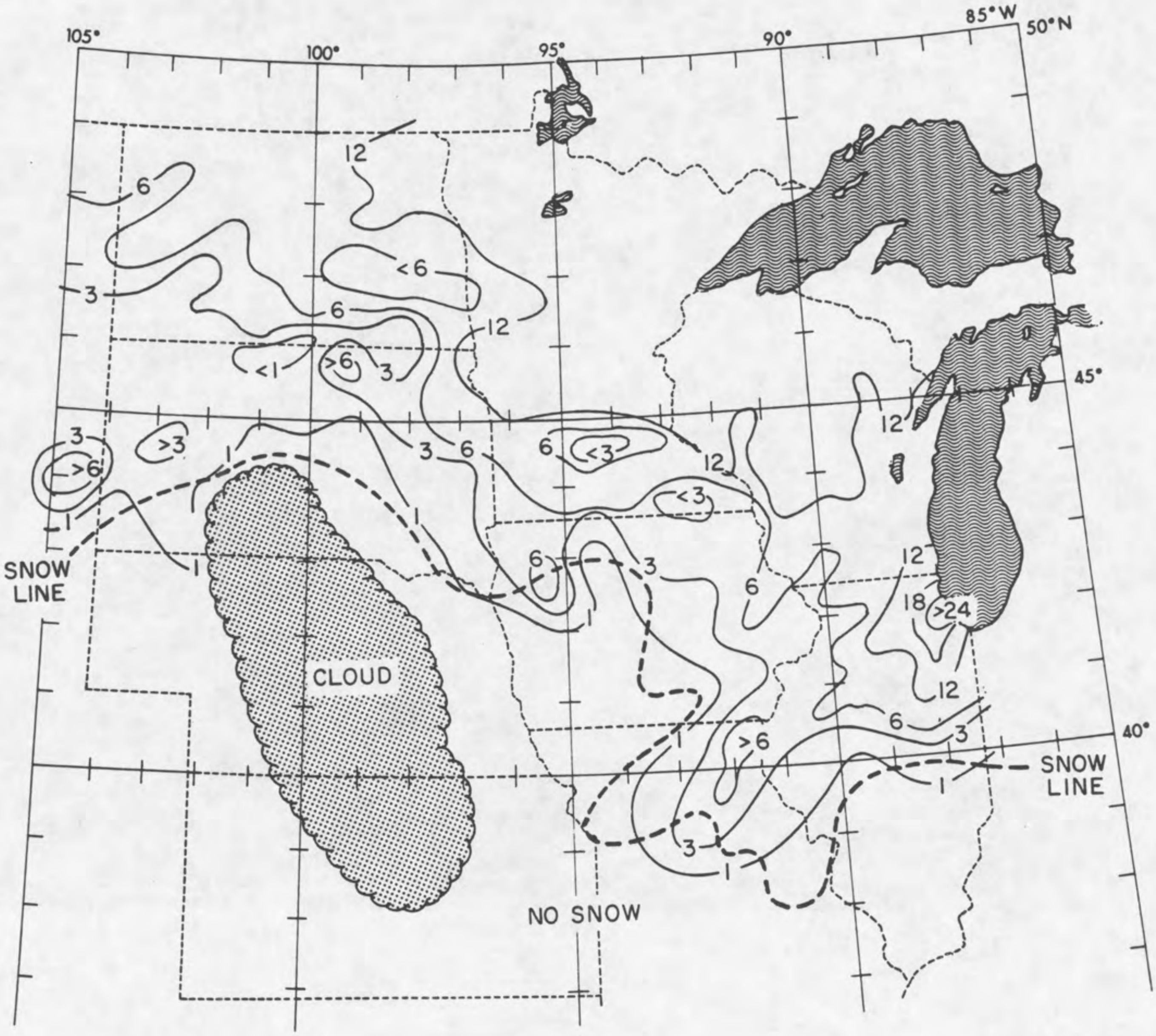

Figure 1b Comparative data for 6 February 1967. Edge of snow cover as mapped from satellite observation is indicated by broken line, and the analysis from conventional data by thin solid lines (snow depths are in inches; gray areas indicate cloud).

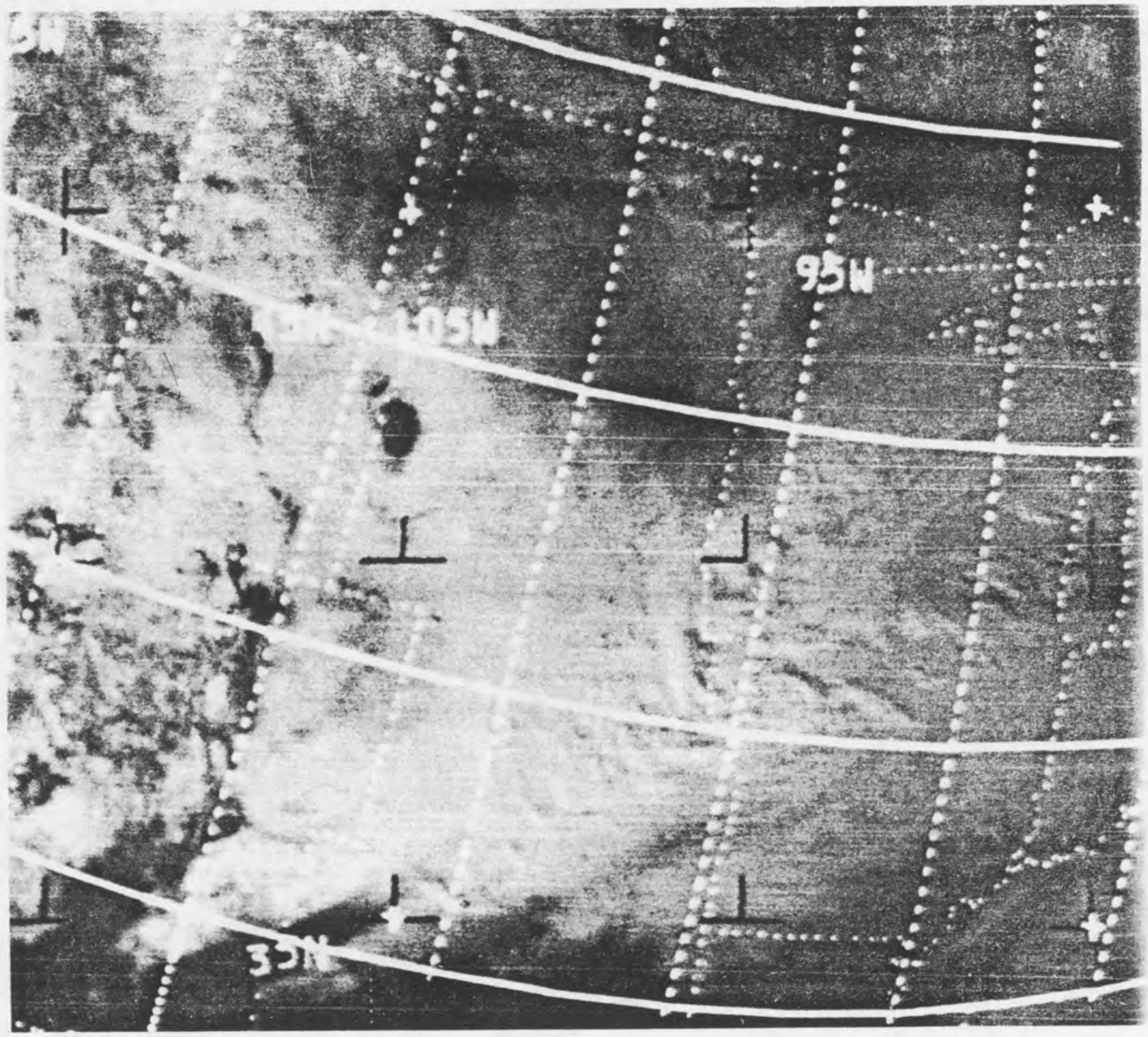

Figure 2a ESSA-3 AVCS photograph (28 December 1966). Pattern stability with the observation on the following day (Fig. 3a) and recognition of the Black Hills 44°N, 104°W) were used to identify and map snow cover. Clouds near 95°W have a rougher texture than the snow due to shadows.

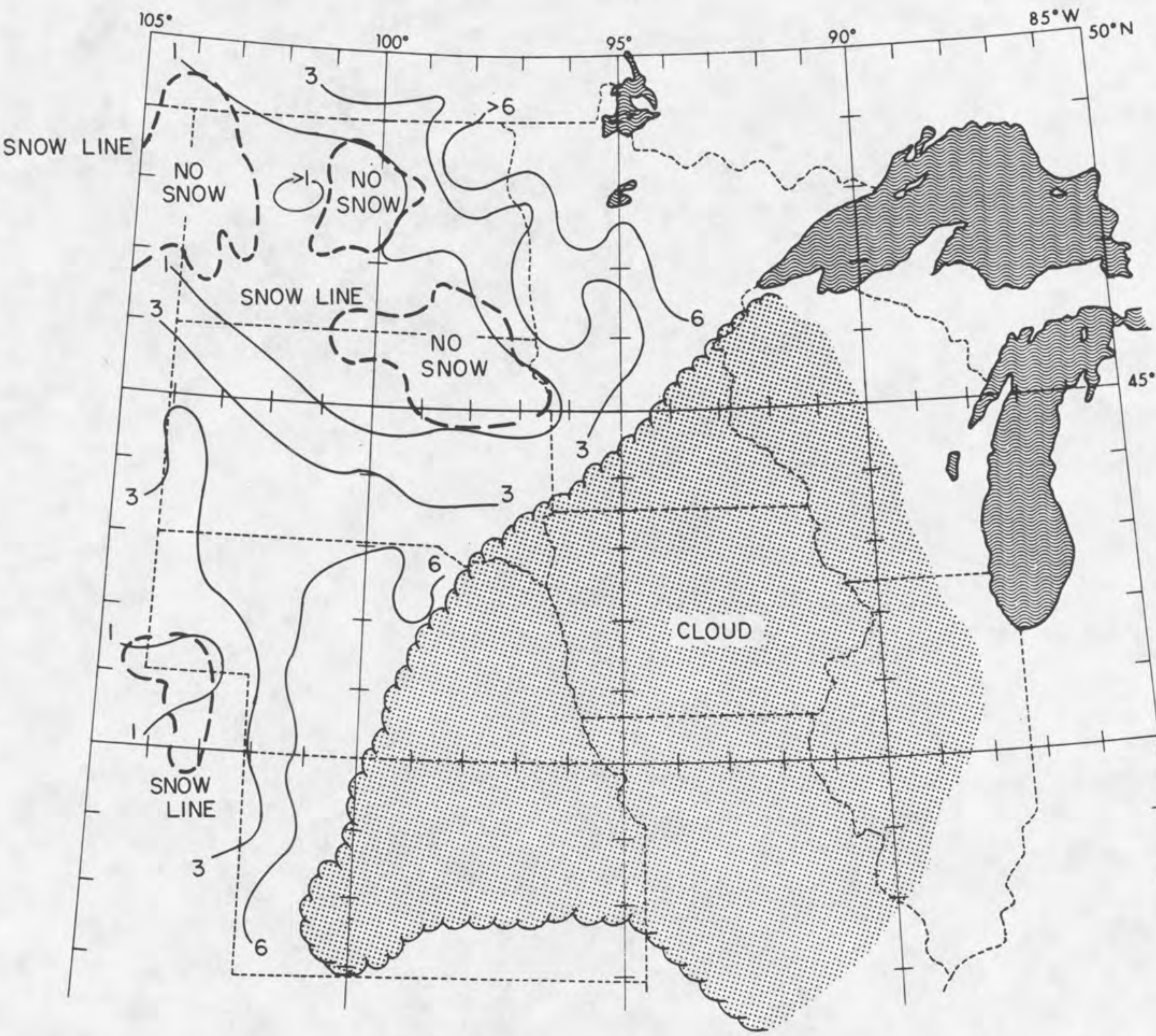

Figure 2b Comparative data for 28 December 1966. Edge of snow cover as mapped from satellite observation is indicated by broken line, and the analysis from conventional data by thin solid lines (snow depths are in inches; gray areas indicate cloud).

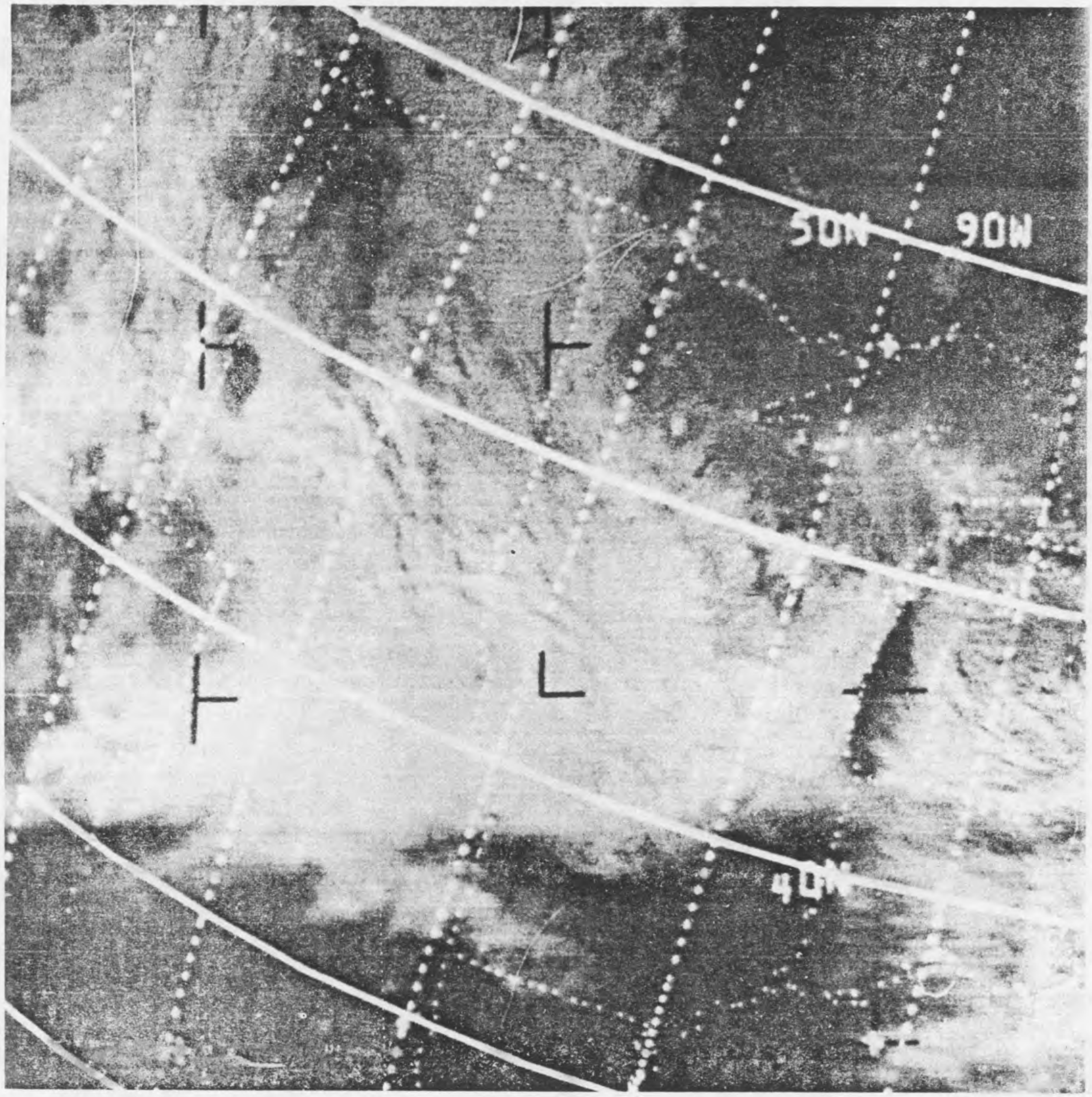

Figure 3a ESSA-3 AVCS photograph (29 December 1966) in which Black Hills, Lake Michigan, and forested areas are visible (clouds between 95° and 100°W can be established by the rougher texture); snow cover was identified through recognition of terrestrial features and pattern stability with the previous observation (Fig. 2a).

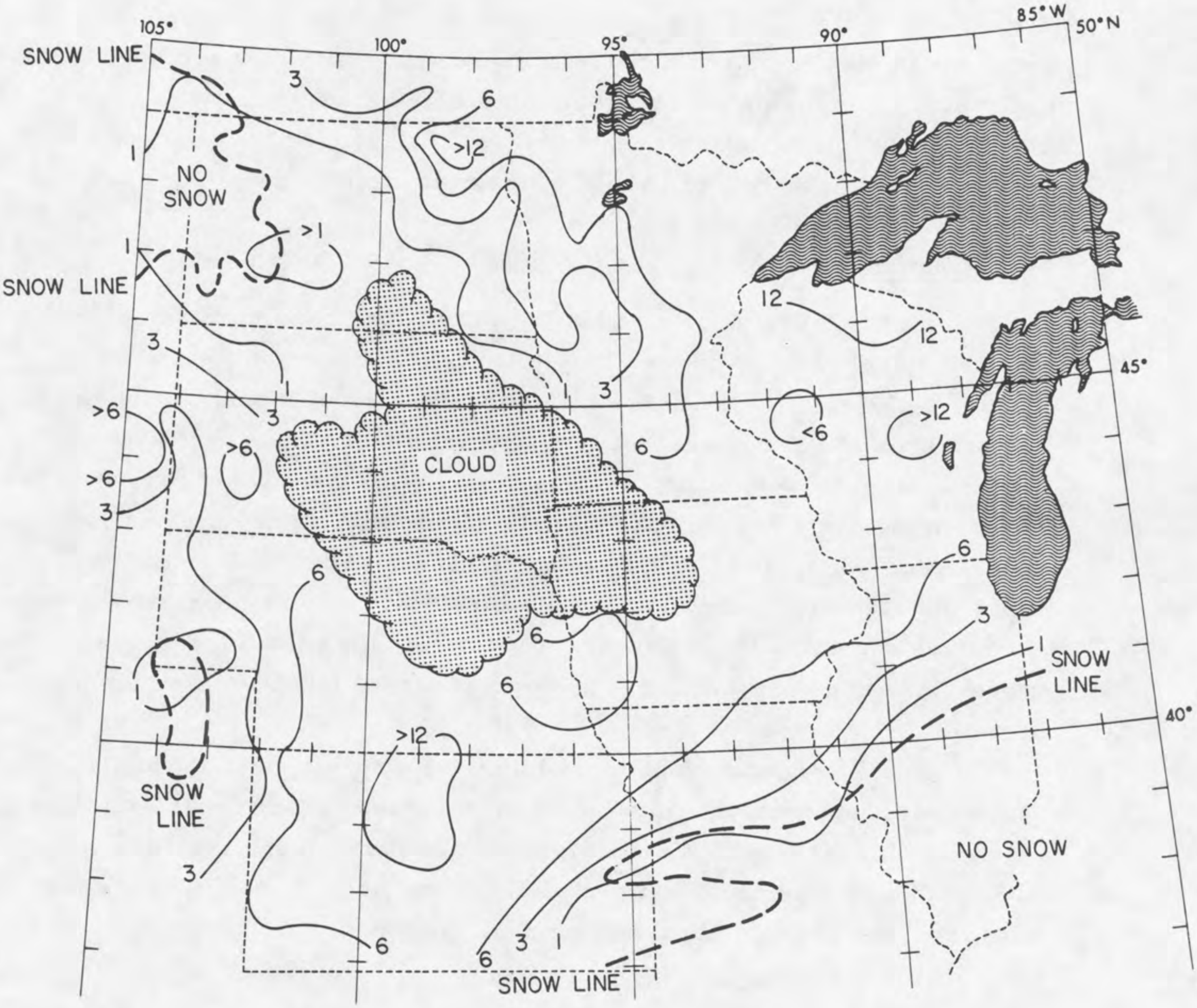

Figure 3b Comparative data for 29 December 1966. Edge of snow cover as mapped from satellite observation is indicated by broken line, and the analysis from conventional data by thin solid lines (snow depths are in inches; gray areas indicate cloud).

tinctively shaped forested area in Wisconsin. A lighter tone pattern south of this area is also visible in most pictures (Figs. 1a, 3a), and apparently is the result of land used as "cropland, woodland, and grazing land" compared with the "cropland and pasture land" farther to the south.[7] In the Missouri River Basin the forest covered Black Hills, near 44°N, 104°W, form an easily recognizable feature (Figs. 2a, 3a), and to the north the forested hills just west of Lake Winnipeg can often be seen (Fig. 1a).

Pattern Stability

Since clouds seldom retain the same shape for more than a few hours, stable patterns viewed by satellite are indicative of snow cover (Figs. 2a, 3a). Naturally, to employ this technique, observations a day or more apart are required, unless several observations per day from an earth synchronous satellite, such as ATS-3, are available. Two observations on the same day only a few hours apart, such as are presently available from ESSA-7 and ESSA-6, must be used with caution, since the apparent stability of slow-moving cloud patterns may be mistaken for snow. When the observations are several days apart, the possible changes in snow cover, due to either melting or a storm passage, must be taken into consideration.

In one sequence of pictures following a spring storm, which dropped substantial snow amounts in a fairly narrow band across the Missouri Basin in early May 1967, a useful observation was obtained on every day but one over a nine-day period. Pattern stability was used to map the snow distribution from the storm event until complete snow melt.

Pattern Appearance

Although having nearly the same reflectivities, snow often appears "smoother" than clouds in satellite photographs. In Fig. 2a, the difference between the two is clearly demonstrated. Recognition of the Black Hills and pattern stability with the observation a day later (Fig. 3a), in which some "lumpy" clouds can also be seen, indicate the cloud-free area in this picture. The lumpy texture is due to shadows of higher clouds on lower clouds or shadows from clouds with greater vertical development. Also, cloud shadows can occasionally be detected on an underlying snow surface.

Snow Mapping

Identification of Snow Line

In the analysis of the satellite photography, all areas with a continuous brightness distinctively greater than the normal dark background, that were identified as being essentially cloud-free, were mapped as being snow-covered. The snow line enclosing such areas was found to represent the limit of a snow accumulation of one inch or more.

In Fig. 5a, at the northern boundary of the snow cover, a sharp gradient exists between the normal background and a very bright tone, enabling the snow line to be easily identified. The analysis of concurrent snow reports indicates a rapid increase from no snow to accumulations of more than 6 inches (Fig. 5b). The southern limit of the snow cover is less definite. In places, an area of intermediate gray tone is observed between the dark background and the brightest tone; conventional data show this area to be covered with about an inch of snow. In Fig. 2a, mottled areas in the northern Missouri Basin, where in general,less than an inch of snow is reported, are mapped as non-continuous snow cover.

Mapping Accuracy

The results of a test using 36 ESSA-3 pictures showed a mean difference of 20 nm (0.33° lat.) between the satellite-observed snow line and the one-inch isoline as analyzed from conventional data. Since the stations used in the "ground truth" data may be separated by as much as 30 miles, however, a certain amount of subjectivity exists in the placing of the one-inch isoline between stations. To estimate the magnitude of this subjectivity, a sample of maps was re-analyzed, without violating any data, to fit as closely as possible, the satellite observed snow line. The re-analysis reduced the difference between the satellite and conventional snow analyses by 60 percent.

Thus, taking into account the subjectivity of the analysis drawn from ground-truth data, the snow line in relatively flat terrain can be mapped from existing satellite photography with an accuracy within ten miles (about 8 nm). This accuracy indicates that satellite data can be useful for mapping snow cover in river basins as small as 100 square miles (10 miles on a side).

The principal difficulty in mapping small river basins is not in determining the size and relative shape of the snow covered area, but rather, in exactly locating the area. When working with patterns that are as small as 10 miles on a side, an error ± 10 miles in the geographical grid of the picture would be critical. If satellite observations are available from more than one satellite on the same day, the multiple views and independently determined geographic referencing grids provide a means for improving the reliability with which small areas can be located.

Estimation of Snow Depth

An apparent relationship exists, at least at times, between snow depth and the brightness as seen in satellite photography. In Fig. 2a, North Dakota is gray in tone; one inch of snow or less is reported in the area. In Fig. 1a, with more than 6 inches of snow in the same area, the brightness is much greater.

An analysis of subjectively estimated brightness and reported snow depth indicated that, in non-forested areas, brightness can qualitatively be related to snow depth for accumulations up to about four inches (Fig. 4). For accumulations greater than four inches, no change in brightness was detectable. In forested areas, little variation in brightness occurs with increasing snow depth. In deciduous forest, all snow depths greater than about one to two inches appear approximately the same tone of gray. Therefore, in satellite photography snow covered forest can be distinguished from non-snow-covered, but little information can be obtained on snow depth. An example of a snow depth analysis is given in Fig. 5.

The relationship between brightness and snow depth (in non-forested areas) can be affected by several factors, including the age of the snow, rainfall, type of terrain, and type of vegetation. Reflectivity decreases with the age of the snow cover, such that two inches of new snow may appear as bright as four or more inches of old snow. Similarly, rainfall may reduce the reflectivity of the snow, although a significant decrease generally results from a complete melting of a part of the snow cover, rather than a decrease in reflectivity of the snow itself. For small snow accumulations, the roughness of the terrain can influence the reflectivity. Also the height of the grass or grain stubble can be a factor determining the snow depth that will appear as continuous cover in a satellite picture.

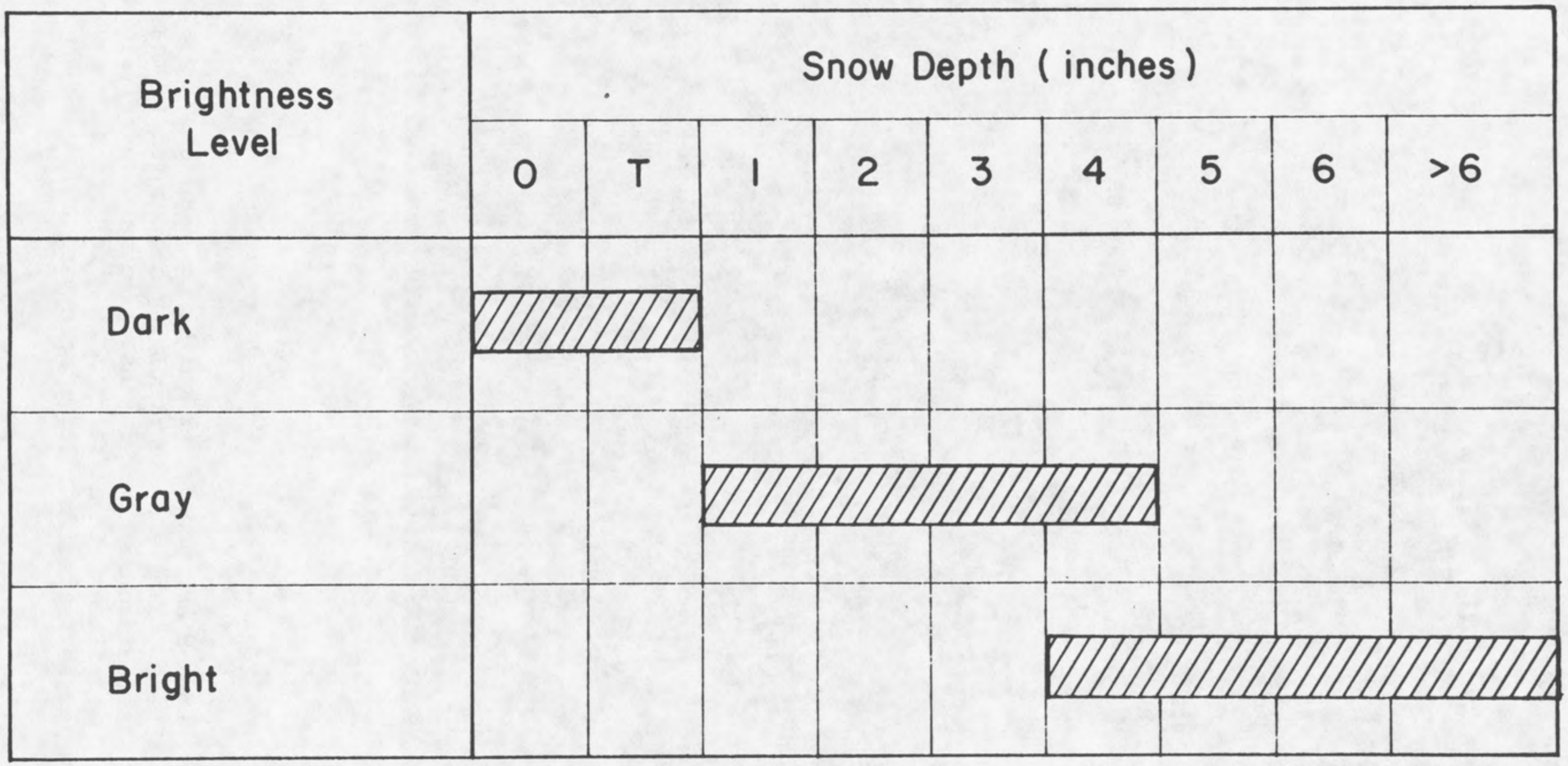

Figure 4 Relationship between snow brightness and snow depth for non-forested area.

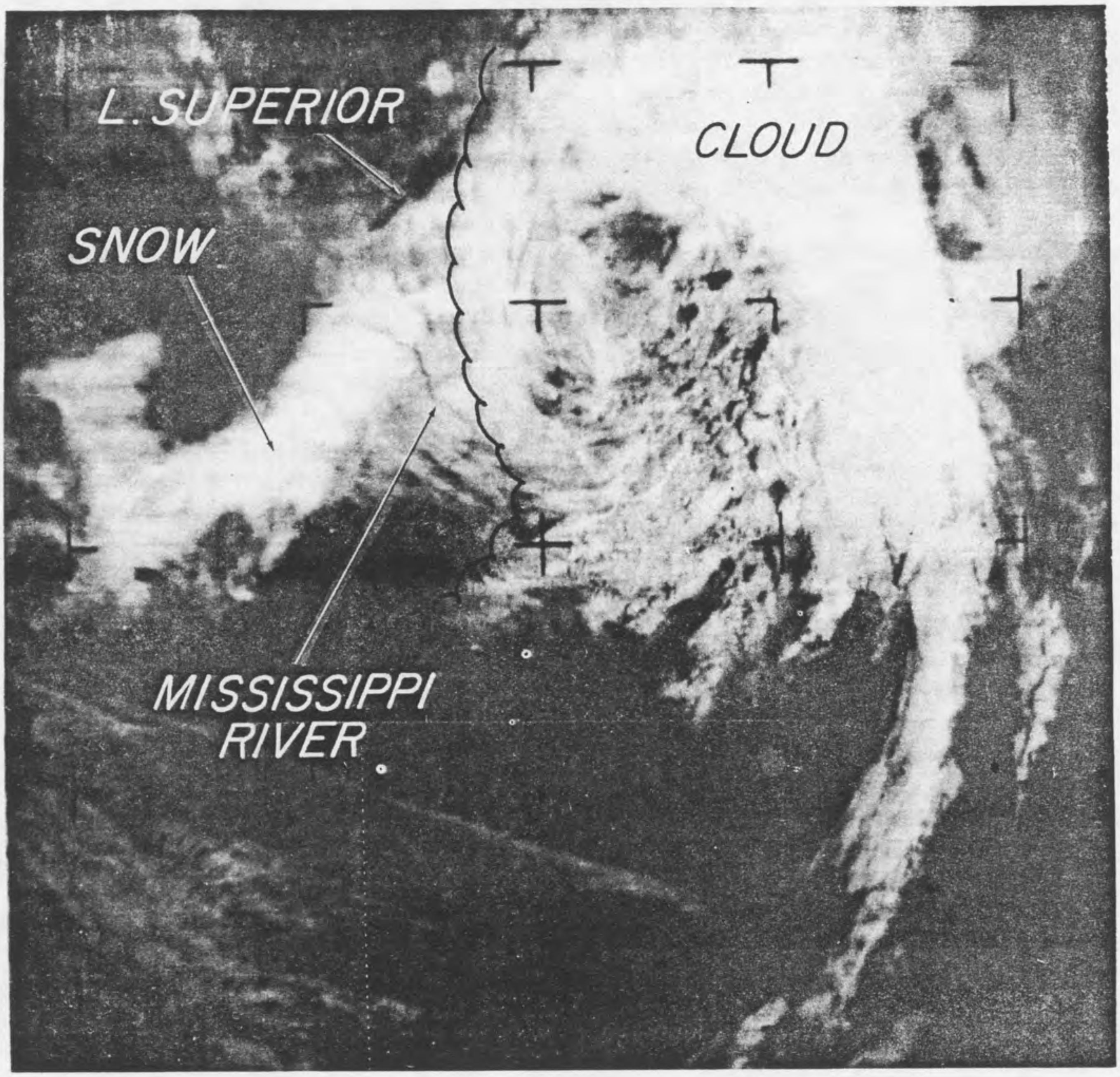

Figure 5a ESSA-2 APT photograph (24 March 1966) showing storm system over Great Lakes and the resulting snow cover in the Upper Mississippi and Missouri River Basins. Recognition of Mississippi River was significant in differentiating between snow and cloud. Snow depth, as estimated from brightness variations, is shown in Figure 5b.

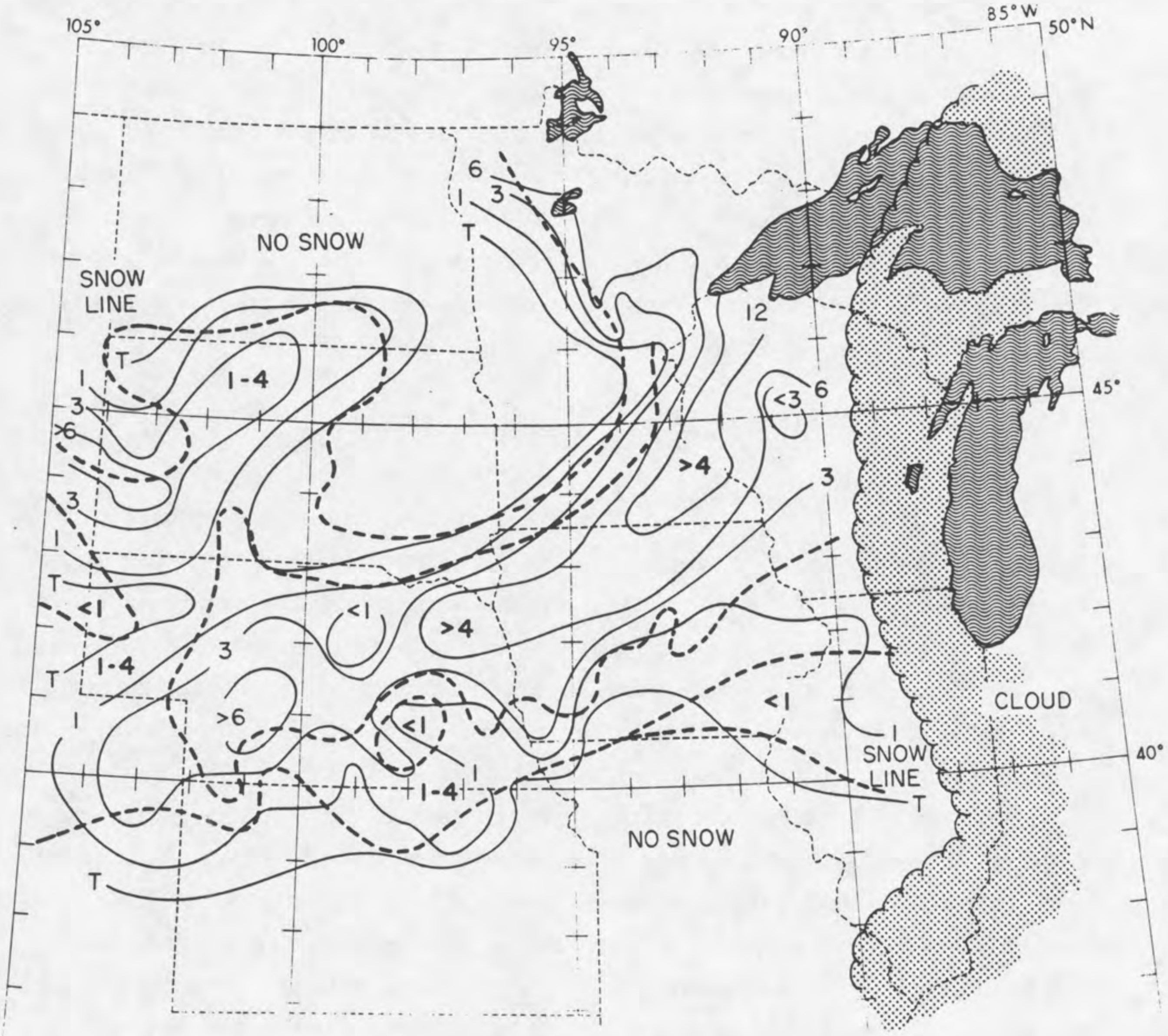

Figure 5b Comparative data for 24 March 1966. Snow depth as mapped from satellite observation is indicated by broken line, and the analysis from conventional data by thin solid lines (snow depths are in inches; gray areas indicate cloud).

Two additional factors are also significant. The first is the camera system itself. Characteristics of the cathode ray tube and lens of the satellite camera system can result in a non-uniformity of film density, such that the brightness of a source of certain intensity may vary over the resulting picture.[8] The second is the solar angle. Since snow is not symmetrical in reflectance,[9] the apparent brightness is a function of sun angle (especially for angles below 45°), and therefore is dependent on the camera angle of the satellite, the time of day, and the time of year. Because of the effect of solar angle, reference should be made to more than one picture from the same orbital pass and/or to pictures from two successive passes. If available, pictures from two different satellites taken several hours apart (such as an AVCS and an APT picture) can be compared.

Application to Mountainous Terrain

Additional research is in progress to investigate the applicability of satellite snow mapping techniques to areas of mountainous terrain. Snow cover in the western United States, where conventional measurements are more difficult to obtain, is of particular hydrologic interest. While it is doubtful that satellite pictures can directly provide even qualitative estimates of the snow depths common in mountain areas, these data can provide valuable information on the areal distribution of snow.

A cloud-free mosaic of the western part of the country is shown in Fig. 6. The bright areas are the result of snow cover; most of the prominent ranges and some individual mountains can be identified. In this region, snow cover tends to follow contours, forming stable patterns that can immediately be recognized by the trained analyst. This technique of recognizing snow by the shape of the pattern cannot be used in regions of flatter terrain, where the snow distribution depends on particular storms.

To be of use in operational forecasting, snow mapping accuracy in mountainous areas is more critical than in the central part of the country, since a slight horizontal displacement of the snow line may result in a significant change in the snow line elevation. Even if existing data cannot provide the required accuracy, techniques developed from these data can be applied to future, higher resolution photography.

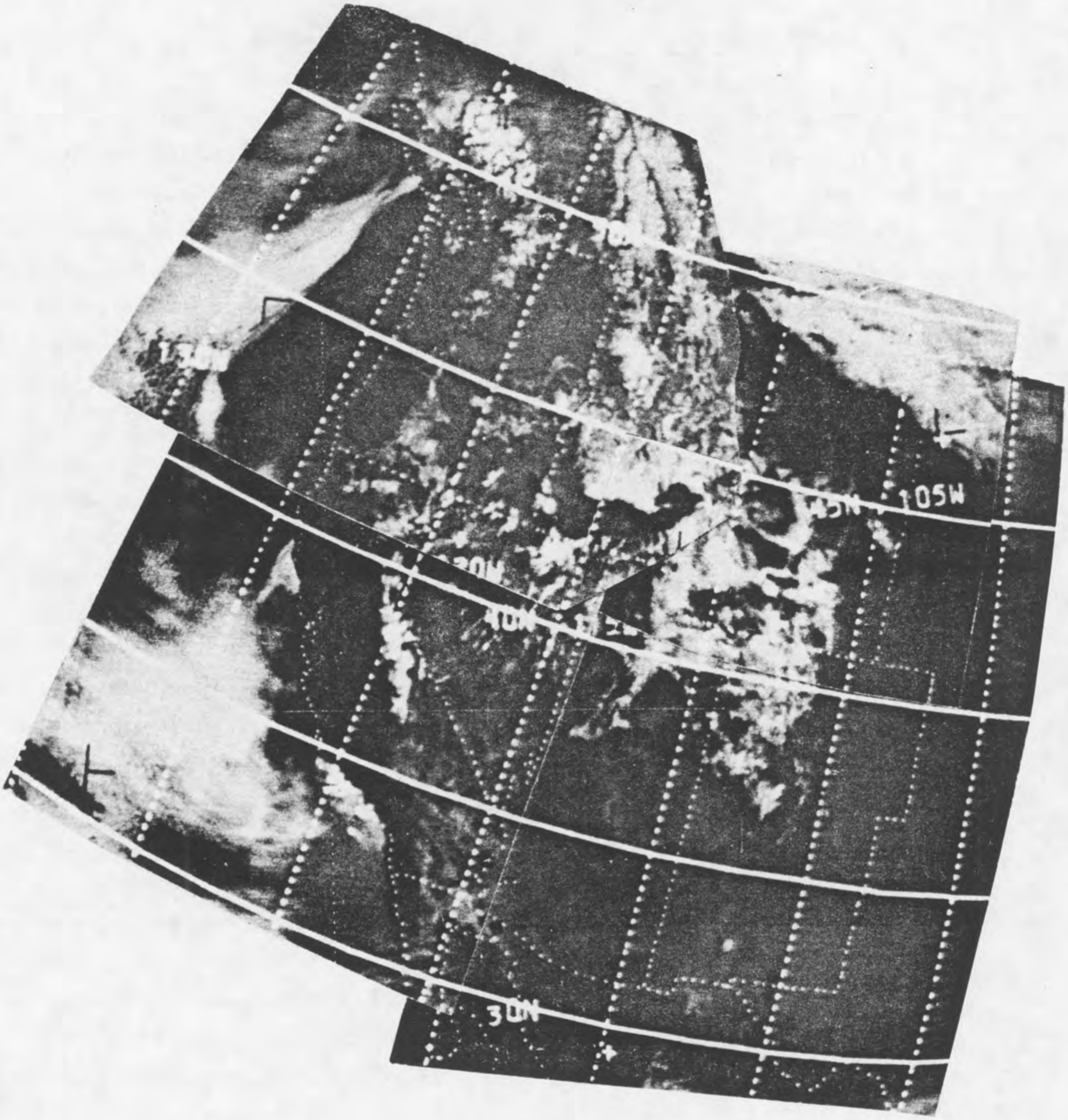

Figure 6 Cloud-free mosaic of the Western United States compiled from ESSA-3 photographs taken in February and March 1967. The snow cover distribution is typical of winter conditions. Many ranges and individual mountains can be identified.

The Outlook for Satellite Snow Surveillance

The ESSA system of operational satellites is now providing reliable twice per day global coverage, with one of the satellites having direct read-out APT capability. In addition to data in the analog form, such as that used in the studies described in this paper, the satellites equipped with AVCS camera systems provide data in the form of digitized brightness values. Automatic identification and mapping of snow may be possible from these data, enabling more quantitative results to be obtained than from analysis of analog photographs. However, camera resolution, and hence mapping accuracy, would not be improved.

Data from future earth-synchronous satellites, such as ATS-3, currently in position over the equator south of the United States, may be useful for assisting in snow identification. In addition, changes in snow brightness at various sun angles can be studied, with respect to obtaining more reliable estimates of snow depth. However, with such a satellite positioned over the equator at an altitude of 22,300 miles, the angle of view over polar and subpolar regions is rather large and the resolution not as good as desired. An excellent ATS-3 photograph is shown in Fig. 7.

Improved detail in snow cover mapping would result from cameras with higher resolutions and with greater dynamic ranges of gray scale. The resolution of the Nimbus II AVCS camera was about 0.5 miles, but this camera operated only during the summer season (the Nimbus II APT system operated through the winter). A future Nimbus satellite may carry a Dielectric Tape Camera which would provide a resolution of 0.1 to 0.2 miles.[10] Camera systems proposed for the Earth Resources Technology Satellite (ERTS) will be capable of 200 ft. ground resolution, which is comparable to that of the photographs obtained from manned space flights (Fig. 8).

Higher resolution photography without an increase in the number of raster lines per picture can be achieved only through a decrease in the area covered in each picture. Development of TV cameras with greater numbers of raster lines is being undertaken. Nevertheless, a future system might be comprised of two cameras, one of lower resolution to identify cloudiness and one of very high resolution to photograph only the cloud-free areas. The mapping accuracy of present satellite photography is also

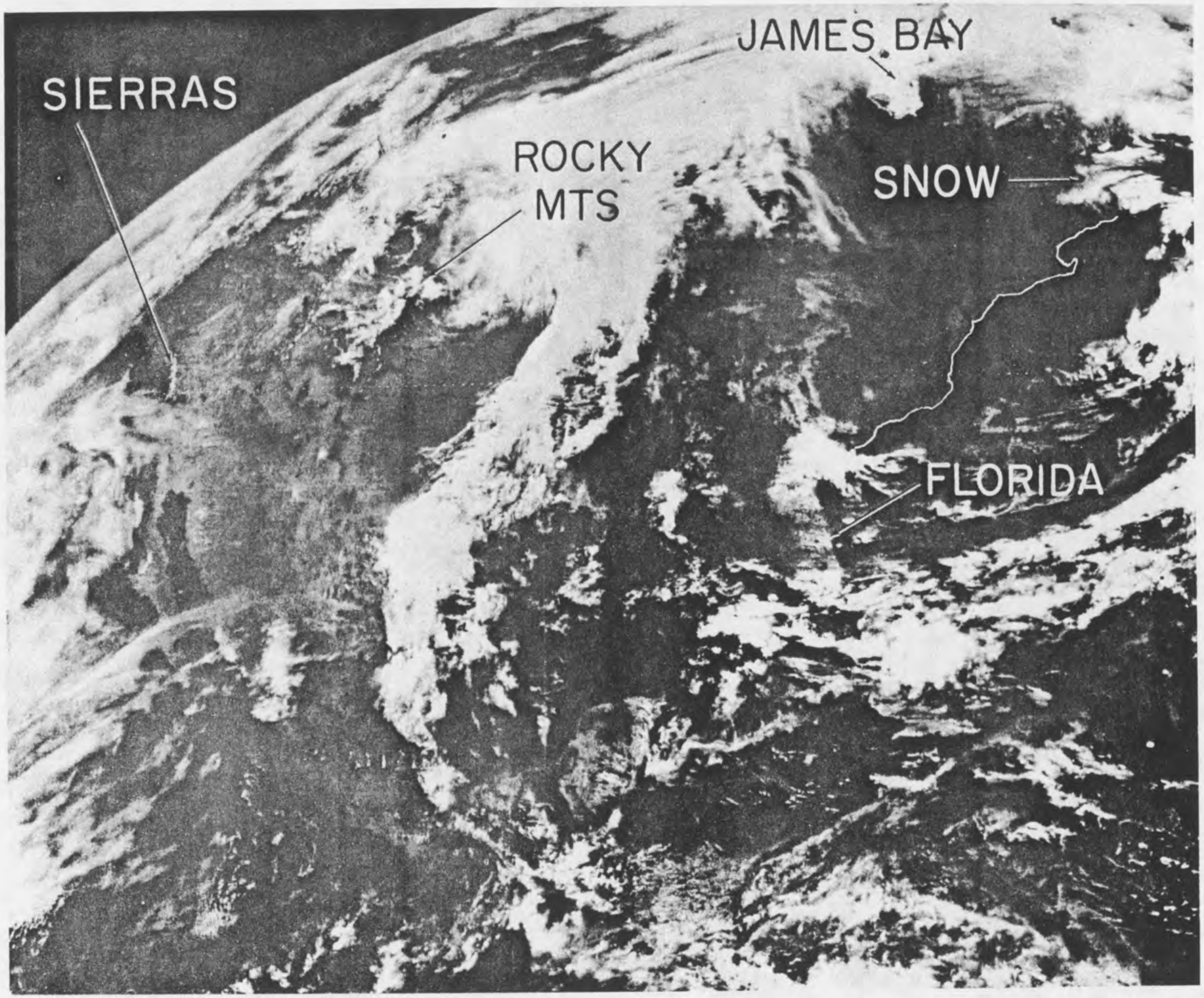

Figure 7 Enlarged portion of an ATS-3 photograph (7 May 1968) showing the United States and Southern Canada. Snow can be seen in western mountain areas, such as the Sierras. Snow that fell the previous day over northern Main and the Maritime Provinces can also be indentified (Photograph courtesy of NASA and Hughes Aircraft Corporation).

Figure 8 Gemini V photograph (26 August 1965) showing mountain snow cover in the Himalayan Region. The ground resolution in this photograph is of the order of that proposed for future Earth Resources Satellite Systems. (Photograph courtesy of NASA).

limited as much by the accuracy with which satellite attitude can be determined, and the pictures can be geographically gridded, as by camera resolution. Future satellite systems with improved resolutions can achieve their full potential only if accompanied by more accurate techniques for attitude determination.

Regardless of the type of camera systems developed, cloud interference and estimation of snow depths greater than a few inches will remain major problems in the operational use of satellite photography. The development of systems that can view the earth in other than the visual part of the spectrum may alleviate this problem, at least to some degree. Differentiation between snow and cloud may be easier in the infrared, since even in winter,most clouds would be colder than snow. An infrared sensing system can also complement a video system with nighttime observations, and can measure the surface temperature of the snow cover, a significant parameter for predicting snow melt.

The sensor with perhaps the greatest promise for improving satellite snow surveillance (when used jointly with an appropriate camera system) is the microwave radiometer.[11] Cloud cover interference occurring with visual and infrared observations would be greatly reduced, and some measure of snow depth may be attainable. Some attenuation can, however, be expected from precipitating clouds, and the required resolutions may be difficult to obtain from satellite altitudes.

In summary, satellite photography can already provide the hydrologist with useful information concerning snow cover distributions. From existing data, the horizontal distribution of snow can be mapped as accurately as, or more accurately than, from a typical ground station network. Future mapping, based on higher resolution camera systems, can be expected to be considerably more accurate than from ground stations, especially in remote or mountainous areas where the reporting network is sparse. With more sophisticated earth-viewing geophysical satellites planned for the coming years, the outlook for operational snow mapping from satellite data is promising.

Acknowledgement

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