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A PROGRESS REPORT ON ESTIMATING SNOW DEPTH USING VHRR DATA FROM NOAA ENVIRONMENTAL SATELLITES

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ABSTRACT

The NOAA environmental satellites provide daily coverage of the Earth in the visible (0.6-0.7μm) and thermal (10.5-12.5μm) spectral bands. The ground resolution of the Very High Resolution Radiometer (VHRR) is 1 km at nadir. This improved resolution in the visible permits more detailed observations of snow features than was possible with previous operational satellites. A densitometer examination of a visible-band image from Feb. 11, 1973, which shows heavy snow cover in considerable detail over areas extending from Alabama to North Carolina, indicates that, in general, there is direct correlation between increasing brightness and increasing snow depths. A power regression analysis of greatest satellite brightness versus greatest snow depth for 201 data pairs produced a correlation coefficient of 0.86. Similar analysis of five late winter and early spring cases resulted in much lower correlations.

INTRODUCTION

The brightness of snow received as reflected radiation by visible-band sensors aboard meteorological satellites has been mentioned as a possible indicator of snow depth (Barnes and Bowley 1968, McClain 1973). Because of the much improved resolution of the Very High Resolution Radiometer (VHRR) data from the NOAA-2 environmental satellite, compared with the data available to previous investigators, a decision was made to test this hypothesis. The first opportunity for such a study occurred on Feb. 11, 1973, immediately following a heavy snow storm that struck the southeastern part of the United States.

SOUTHEAST SNOW STORM OF FEBRUARY 9-10, 1973

The winter of 1973 will be remembered well in the southeastern United States for the storm of February 9 and 10. This storm, the result of the interaction of two sharply contrasting air masses, produced record snow depths. An outbreak of very cold Arctic air entered the Northern Plains on Monday, Feb. 5, 1973. This large air mass plunged rapidly southward into Texas but made only slow progress eastward. By 1800 GMT (1300 LT) on Thursday, February 9, the leading edge of the cold air mass lay along the eastern slope of the Appalachian Mountains. Rain began falling in a broad band 350 km wide in the area of frontal convergence. Temperatures remained mild along the Atlantic seaboard until a developing cyclone drew in the very cold air just west of the Appalachians. The precipitation in Alabama and Georgia subsequently changed to freezing rain and sleet and then to snow during the morning and early afternoon of Friday, February 9. This snow spread into North Carolina and South Carolina as the deepening cyclonic disturbance moved northeastward into the Atlantic Ocean. Snow continued falling during most of Saturday in Georgia and the Carolinas, ending along most Carolina coastal sections after midnight. On Sunday morning, record snow depths were found on the ground at many locations in Alabama, Georgia, and the Carolinas. Figure 1 shows the total snowfall in Alabama, Georgia, and South Carolina as analyzed by the individual State climatologists from scattered point observations taken largely by untrained cooperative observers. Data and isopleths, originally in inches, were obtained from individual State climatological summaries for February 1973 (Environmental Data Service 1973). Despite inconsistent values from State to State, particularly along the Georgia-South Carolina border (where the 2.5 cm isopleth in northeastern Georgia matches the 15-cm isopleth in northwestern South Carolina) values in excess of 30 cm were reported throughout an extensive band from east-central Alabama through northeastern South Carolina. The dashed line represents the author's interpretation of the 2.5-cm isopleth in Alabama. Storm totals, because of the warm ground and settling of the snow, were somewhat greater than observations taken Sunday morning at 1200 GMT after the storm's ending. Rapid clearing followed the storm; and at approximately 1545 GMT (1045 LT) on orbit 1489, Feb. 11, 1973, the NOAA-2 satellite viewed the cloud-free but snow-covered landscape (fig. 2).

NOAA ENVIRONMENTAL SATELLITES

The NOAA Environmental satellites scan Earth in about 25 orbits every 2 days at an altitude of approximately 1500 km in a sun synchronous near-polar orbit.[1] Essentially the same area of Earth is viewed every other day, although the orbit of the satellite progresses eastward about 1° of longitude every 25 orbits. Aboard the spacecraft are various sensors (Schwalb 1972), each with its own identical backup system.

Most important of the sensors for hydrological use is the VHRR. This instrument scans Earth in both the visible (0.6-0.7μm) and the thermal (10.5-12.5μm) regions of the spectrum. The VHRR system generates analog signals that, after transmission to the readout station, are transformed into a photographic format. VHRR

[1]NOAA 4, launched on Nov. 15, 1974, has been the operational satellite since Dec. 17, 1974.

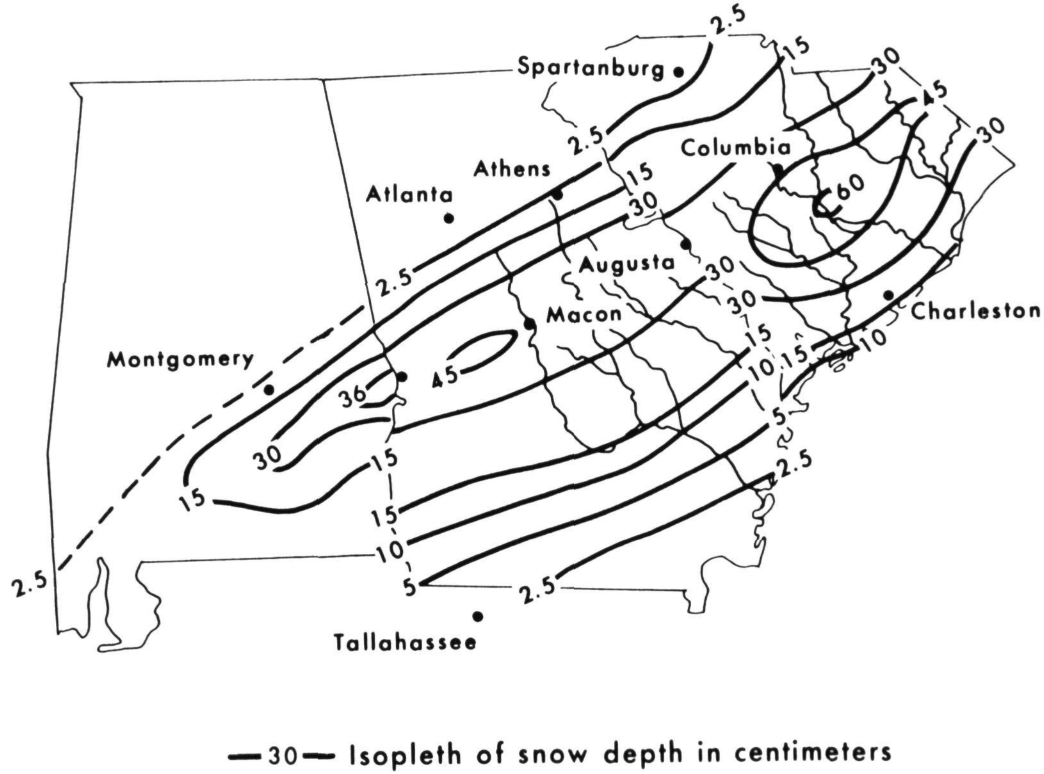

Figure 1. Total snowfall, snow storm of Feb. 9-10, 1973.

data are also available on digital tapes. With a resolution of approximately 1 km at nadir, the VHRR imagery is 4 times better in the visible and 10 times better in the thermal regions than data taken by instruments aboard NOAA 1 and earlier satellites.

One of the drawbacks of VHRR images is that panoramic distortion increases with increasing distance from the center line of the image. The image is built up through a combination of the satellite's forward motion in orbit and its VHRR scanning perpendicular to this motion. This distortion is caused, in part, by the curvature of Earth's surface and produces foreshortening of the image toward the horizon.

IMAGERY ANALYSIS

Figure 2 shows the snow-covered area as seen in the visible range by the VHRR. State boundaries have been added to point out the distortion in the image and to provide reference points for location. These boundaries were added to figure 2 by using a Zoom Transfer Scope (ZTS), an optical device used to transfer information from unrectified satellite images to base maps, and vice versa. The distortion is greatest in the eastern portion of the image. A distinct western limit of the snow is evident, as well as a highly reflective (bright) strip in the center of the snow area, corresponding generally to the deepest snows shown in figure 1. Some land features in the snow belt, such as the swampy or heavily forested areas adjacent to many rivers, contrast sharply with adjacent areas in the snow-whitened land. The more heavily forested Piedmont Plateau in the western section of the snow area is mottled in appearance and is less bright than elsewhere. The 1-km resolution of the VHRR permits easy identification of many small rivers and also enables the analyst to determine the location of the western snow edge to within 8 km when drainage features are used as local reference points.

Analysis of the recorded brightnesses takes into account the system's limitations. Each pixel (picture element) of the VHRR image covers an area of approximately 1 km^2 (at nadir) on the ground. The brightness value of each pixel thus represents an average response that may include dark, forested regions as well as highly reflective open fields, even when both are snow covered. Also, the VHRR visible-band sensor is not a perfect detector. Figure 3 shows that the relative response of the detector falls short of perfect (1.0) throughout the design range of 0.6 to 0.7μm and also senses some energy outside these limits.

The enhancement of land features by the differing reflectance of snow cover has been described. While this factor is useful for identifying and locating specific landmarks, it tends to mask the relation of snow brightness to snow depth. The aging of a snow pack is manifested in a reduction of the surface brightness--another factor to consider when attempting to relate snow brightness to snow depth. In the study of this relationship, the image was enhanced using a color densitometer. Various color schemes were tried, but none could discriminate more than three

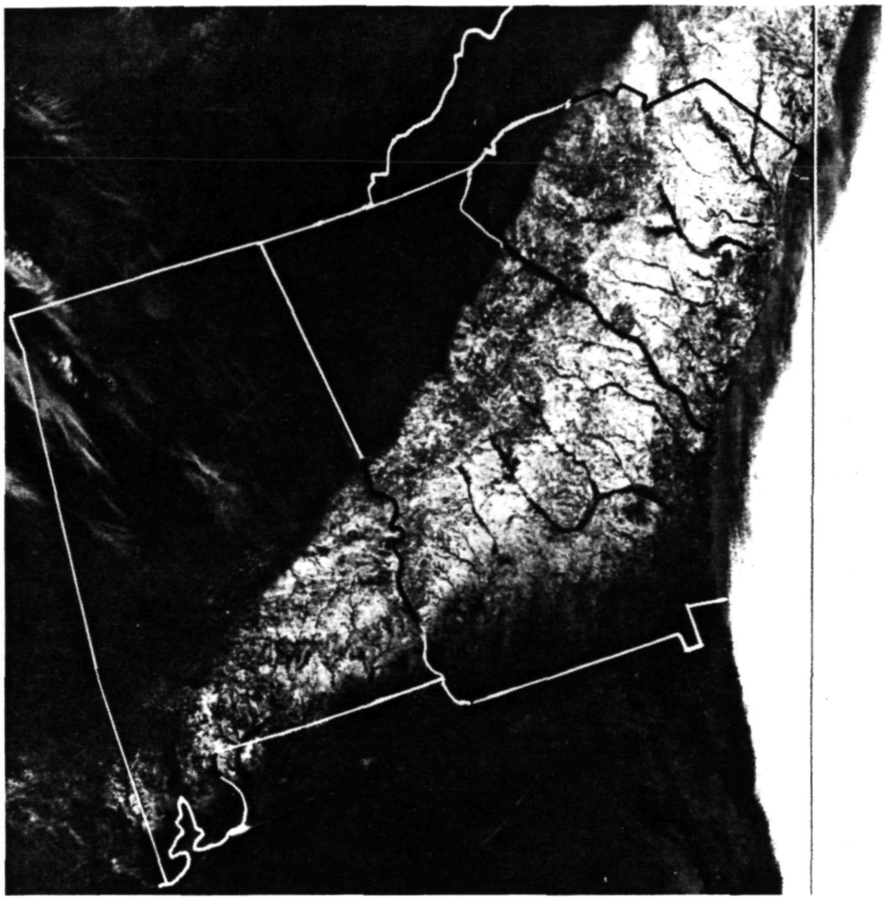

Figure 2. Portion of the NOAA-2 VHRR visible (0.6-0.7μm) image taken at 1545 GMT on Sunday, Feb. 11, 1973.

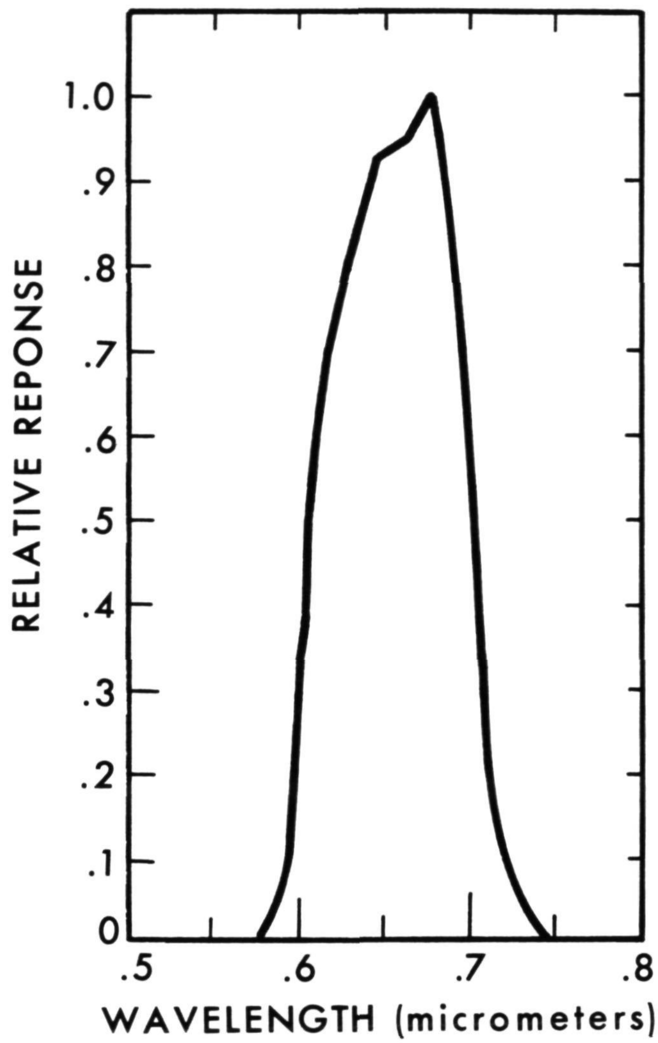

Figure 3. NOAA-2 VHRR visible relative spectral response curve (prelaunch).

ranges of depth, 0 – 8 cm, 8-30 cm, and >30 cm, which are entirely qualitative and show little improvement over earlier estimates by Barnes and Bowley (1968) using lower resolution satellite imagery. They distinguished three levels of brightness in snow-covered areas of the Great Plains: trace-2.5 cm, 2.5-10 cm, and >10 cm.

In figure 4, a north-south densitometric trace through the snow area is shown on the left; the white strip through the image is the cross section that the trace represents. The densitometer trace is a quantitative measure of changes in photographic gray scales; it was produced from a black and white photograph using a color densitometer. Brightness values are represented along the horizontal axis, with increasing values to the left. Outside the snow area, brightness values are uniformly low. Within the snow-covered area, values are higher but show several fluctuations, which are a function of varying land use. The abrupt termination of the snow along the northwest boundary of the snow area is associated with a rapid decrease in brightness. The southern boundary of the snow area is more diffuse; thus, the decrease in brightness is gradual.

DIGITAL TAPE ANALYSIS

Digital computer printouts analogous to the pictorial display were produced from the VHRR analog tapes. The analog tapes were converted into nine-track digital tapes containing every scan line generated by the VHRR. Each scan line consists of individual, partially overlapping samples, two of which cover a 1-km^2 field of view. These elemental pieces of information can be averaged or combined in various schemes to meet the needs of the investigator.

A computer program was adapted to accept VHRR digital data and produce, at 1-km or 4-km resolution, histograms of brightness values at preset class intervals and provide the smallest and greatest brightness values for each 32 x 32 element area. The program also contours each area using the preset class intervals, thus providing an isopleth map. The 1,024 brightness values and annotations for location are included in the program.

Using the 1-km resolution option (32 x 32 km squares), a grid of 201 VHRR squares was fitted to figure 1. Owing to the scarcity of detailed snow-depth measurements on the morning of Feb. 11, 1973, comparison of the snow brightness with ground truth necessitated substitution of snowfall totals [as provided in Environmental Data Service (1973] for snow depth values. The greatest snow depth for each square (from fig. 1) was matched with the greatest brightness value. Various mathematical best fits were calculated for the data pairs with brightness as the dependent variable. Figure 5 shows the 201 data points and the best fitting power curve. The correlation coefficient was 0.86.

The power curve fit of the data appears more consistent with the apparent relationship of brightness to snow depth. Rather small increases in depth when the snow is only several centimeters

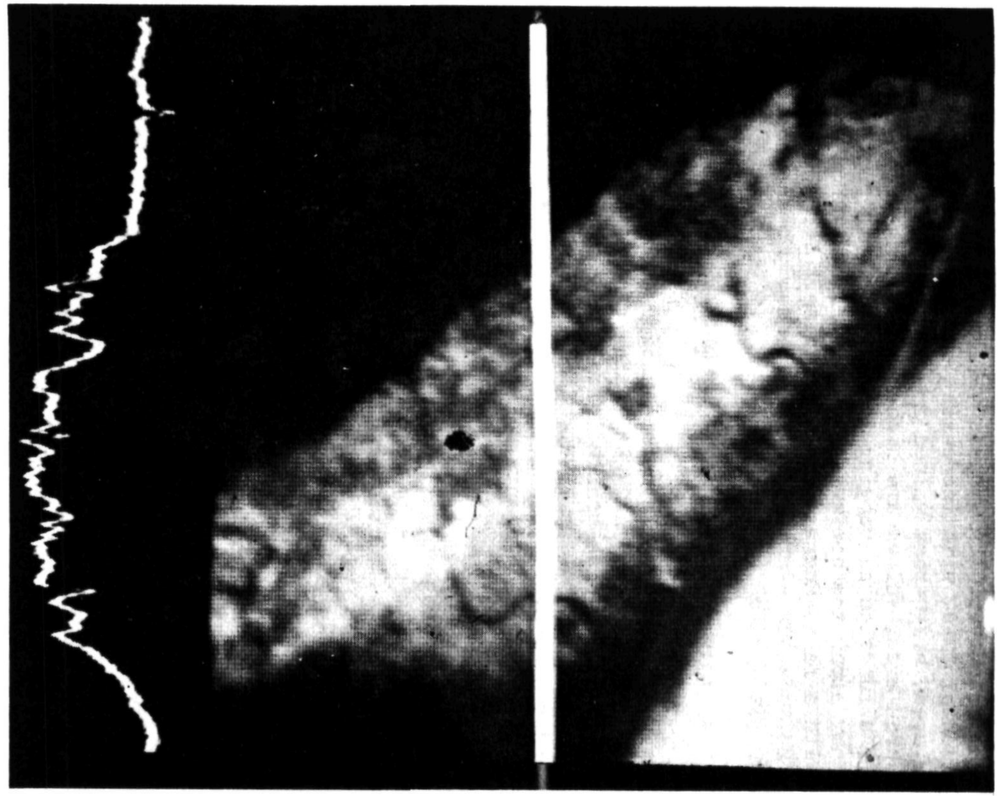

Figure 4. Densitometric trace through portion of snow-covered area in South Carolina and Georgia.

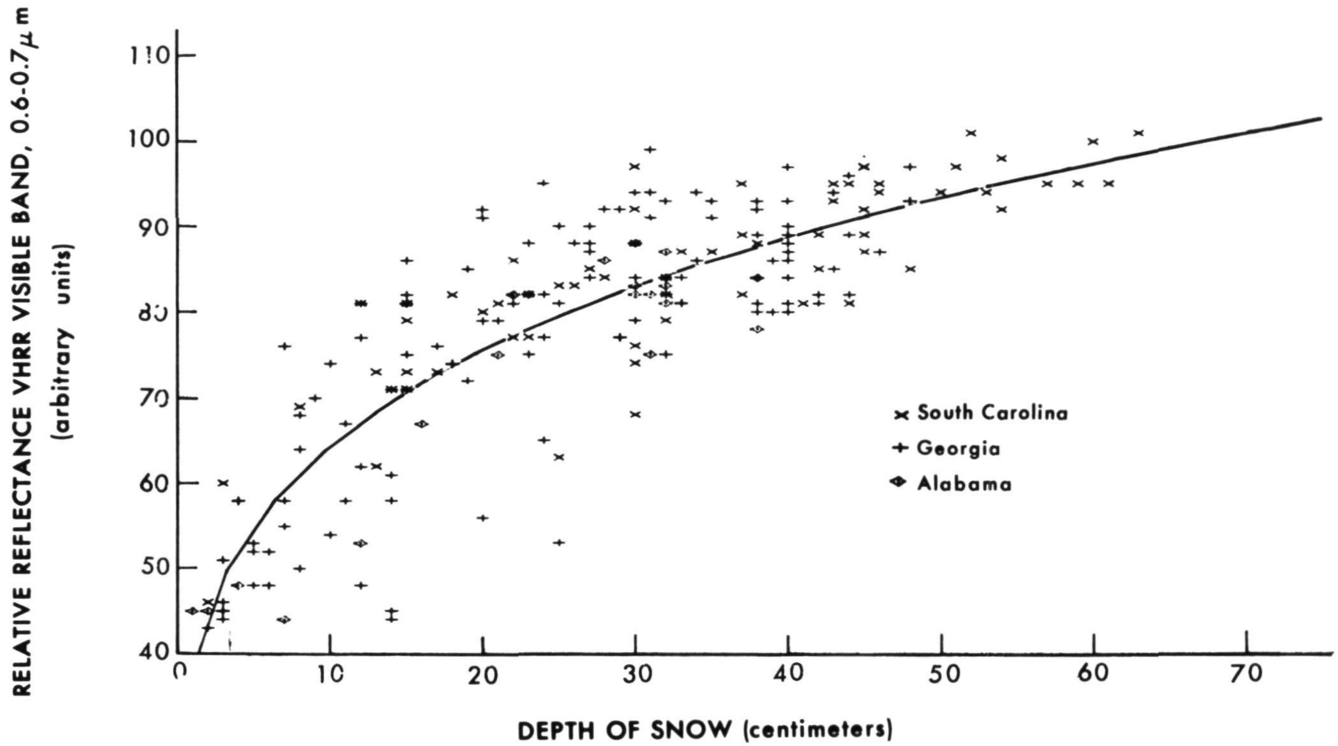

Figure 5. Relation of relative VHRR visible reflectance to depth of snow.

deep produce large increases in brightness. In this case, the snow covers more and more objects on the ground as it deepens, first individual blades of dormant grass, then small shrubs, then larger objects. Once the snow accumulates to about 25 cm, most small plants are covered, only the larger shrubs and plants (corn stalks to trees) remain visible and in most cases will remain uncovered except in some mountainous areas where extremely heavy snows occur.

Some radiation penetrating into a snow pack, if not absorbed by underlying vegetation and soil, eventually returns to the surface and contributes to the albedo. Giddings and LaChapelle (1961) demonstrated that absorption from an underlying black surface greatly reduced the albedo of aged snow until snow depths exceeded 20 cm. Thus small increases in satellite-observed brightness may be observed even when tops of vegetation are being covered with 10 to 20 cm of snow.

Regarding data discontinuities in the snow isopleths at State boundaries, the following procedure was used. When a 32-km square fell across a State boundary, the greatest depth was determined using data from the State having the greater portion of the square. Also, some error in snow-depth estimates could occur because of the misalignment of distortion of the squares fitted to figure 1. Further, most of the snow-covered area in Alabama received some sunshine late in the day on Saturday, February 10 1973, which probably melted a small amount of snow. The amount of snow remaining at the time of the satellite observation on Sunday morning, therefore, is believed to be slightly less than that indicated in figure 1. The scarcity of ground observations precluded a re-evaluation of snow depths. The effect of the Sun on the reflectivity of the snow and, thus, on the brightness recorded by the satellite also is not considered. Both of these effects caused by the Sun, however, trend in the some direction (i.e., toward decreasing values).

The curves derived from the data are for the NOAA-2 VHRR visible-sensor 1. Equivalent curves may be different for either NOAA-3 or NOAA-4 visible sensors or the other NOAA-2 VHRR visible sensor. The general relationship likely would remain, but with perhaps differing brightness limits. For this case, the lower limit of brightness (bare ground) is between 40 and 43; the upper limit of snow brightness is 101.

Five additional examples of snow cover were analyzed comparing the greatest satellite brightness with snow depth. The data examined were collected on 3/18/74, 3/24/74, 3/26/74, 4/10/74 and 4/11/74, and the locations ranged from the Midwest area eastward through New York. Correlation coefficients for various mathematical best fits ranged from 0.01 to 0.79, but principally fell between 0.40 and 0.60, with the power curve fit providing the higher correlation more frequently than the other mathematical fits as well as the highest correlation coefficient (0.79). These coefficients were much lower than those observed in the Southeast case. Temperatures remained below freezing following the first two snowfalls until after passage of the satellite on 3/18/74 and

3/24/74, while melting was occurring during the satellite overpasses, 3/26/74, 4/10/74, 4/11/74, on the later snowfalls. Since the correlation coefficients varied little for all cases analyzed, the effect of melting snow surfaces on the snow depth-snow brightness relation is not apparent.

Most critical to the analyses was the lack of snow depth measurements. The sole source of snow depths was the individual State Climatological Data summaries (NOAA 1974). The scarcity of ground observations became apparent when preparing isopleth maps of snow depths. In New York's mountainous regions much interpolation was required to produce a contoured map for comparison with satellite brightness. Snow, present in the higher elevations (as seen in satellite images), would be less or non-existent in the valleys where most observations are made. Only small variations in snow depth were noted in the Midwest. Unlike the Southeast case, no sharp gradient in snow depth existed, the satellite data being clustered at a few observed depths, for example, 2.5 cm, 5.0 cm, and 7.5 cm.

RESULTS

The improved resolution of the VHRR over previous sensors on operational satellites permits mapping of snow limits to better than a 10-km resolution, which is an improvement over the 20- to 40-km resolution reported with earlier satellites (McClain 1973). Although the radiance data received from the satellite are unrectified, the enhancement of identifiable land features by the snow permits the precise location of snow boundaries of mesoscale resolution. Color renditions of the black and white imagery by means of a color densitometer, although subjective, do permit coarse estimates of snow depths, but the improvement over estimates made from earlier, lower resolution satellite sensors is minor.

For the Southeast case a significant correlation of 0.86 was achieved when the greatest brightness value in a given 32 x 32 km square was paired with the greatest snow depth for the same square. Using the greatest brightness within a particular region is, in effect, searching for the clearings and open areas that are free of trees and other nonsnow-covered objects that lower the average brightness of the 1-km element. The same procedure, however, used on five later cases produced substantially lower correlation coefficients (0.40 to 0.60).

CONCLUSIONS

The VHRR provides a synoptic picture of snow extent not possible from point observations on the ground. The 1-km resolution of the VHRR sensors permits positioning of snow limits to within 10 km, some two to four times better than that possible with data from earlier operational satellites.

For one case, freshly fallen deep snow over an area of widely varied land use in the Southeast, snow-depth estimates correlate well with snow brightness. The power curve relationship indicates that a rapid increase in brightness corresponds to increases in snow depths when depths are less than 25 cm; for depths exceeding 25 cm, much smaller brightness increases are encountered as depths increase.

The usefulness of satellite brightness data to estimate snow depths is apparently limited by insufficient ground observations of snow depths and limited to areas where strong gradients in snow depths occur over relatively short distances (50 km). Eighteen new cases for 1975 are presently being analyzed and it is hoped that this large sampling will enable one to define under what conditions, e.g., particular type of snow and terrain as well as necessary density of ground observations, satellite brightness can be a reliable indicator of snow depths.

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