Operational Airborne and Satellite Snow Cover Products of the National Operational Hydrologic Remote Sensing Center

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ABSTRACT

The Office of Hydrology of the National Weather Service maintains a cooperative National Operational Hydrologic Remote Sensing Center, based in Minneapolis, to generate remotely sensed hydrology products. Terrestrial gamma radiation data sensed from low-flying aircraft provide information to infer snow water equivalent over a network of more than 1500 flight lines covering portions of 25 states and 7 Canadian provinces. Additionally, hydrologists use Advanced Very High Resolution Radiometer (AVHRR) data and Geostationary Operational Environmental Satellite (GOES) data to map digitally areal extent of snow cover over regions covering two-thirds of the U.S. and southern Canada where snow cover is a significant hydrologic variable. This paper reviews the techniques: (1) to make airborne snow water equivalent measurements using terrestrial gamma radiation data, (2) to make satellite areal extent of snow cover measurements, and (3) to reduce and to distribute, in near real-time, both alphanumeric and graphic products to end-users in the U.S. and Canada.

1 INTRODUCTION

The National Weather Service maintains a cooperative National Operational Hydrologic Remote Sensing Center, based in Minneapolis, to generate remotely sensed hydrology products. The National Weather Service, the U.S. Army Corps of Engineers and other Federal, state, and private agencies use the real-time, airborne snow water equivalent data and satellite areal extent of snow cover data operationally when issuing spring flood outlooks, water supply outlooks, river and flood forecasts, and reservoir inflow forecasts. Hydrologists in the Minneapolis office ingest and process the airborne and satellite data and distribute products electronically, in near real-time, to NWS and non-NWS end-users in both alphanumeric and graphic format.

2 AIRBORNE GAMMA RADIATION SNOW MEASUREMENT TECHNIQUE

The potassium, uranium, and thorium radioisotopes in the upper 20 cm of soil emit natural terrestrial gamma radiation. A detection system on-board an aircraft flying 150 m above the ground senses the terrestrial radiation. The water mass in the snow cover attenuates, or blocks, the terrestrial radiation signal. Consequently, the difference between airborne radiation measurements made over bare ground and snow covered ground provides sufficient information to calculate a mean areal snow water equivalent value with a root mean square error of less than one cm. Each flight line is typically 16 km long and 300 m wide covering an area of approximately 5 sq km. Consequently, each airborne snow water equivalent measurement is a mean areal measure integrated over the 5 sq km area of the flight line. Figure 1 is a map of the 1990 airborne snow survey flight line network.

Carroll and Carroll (1989A, 1989B, 1990) have reported, in detail, on the techniques used to make airborne snow water equivalent measurements in a prairie, forest, and mountain snowpack environment. Fritzsche (1982) has reported on the physics and calibration of the airborne gamma radiation spectrometer developed under contract by EG&G, Inc. Fritzsche discusses the details of the system hardware and the radiation spectral data collection and analysis procedures that will not be discussed here.

Equation (1) gives the relationship used to make airborne snow water equivalent measurements:

$$SWE = \frac{1}{A}\left[\ln\frac{C_o}{C} - \ln\left(\frac{100 + 1.11\,M}{100 + 1.11\,M_o}\right)\right] g\ cm^2 \qquad (1)$$

where:

C and C_o = Uncollided terrestrial gamma count rates over snow and bare ground,

M and M_o = Percent soil moisture over snow and bare ground,

A = Radiation attenuation coefficient in water, cm^2/g

Compton tails associated with the peaks of higher energy, the cosmic radiation component, the aircraft and fuel, the pilots, and the detection system itself contribute extraneous radiation to the spectra. The raw radiation count rates for various photopeaks must be "stripped" of the extraneous radiation to give the pure, uncollided radiation count rates (Fritzsche, 1982). Air mass between the airborne sensors and the terrestrial radiation source also attenuates the radiation signal. Consequently, the detection system continuously records air temperature, air pressure, and radar altitude necessary to calculate and to compensate for the intervening air mass. Software strips the appropriate photopeaks of extraneous radiation and normalizes them to a standard air mass of 17 g/cm^2.

2.1 Airborne Measurement Error and Simulation

The principal sources of error in airborne snow water equivalent calculation using the relationship given in equation (1) are: (1) errors in the normalized count rates (C, C_o), (2) errors in the estimate of mean areal soil moisture over the flight line (M, M_o), and (3) errors in the radiation attenuation coefficient (A) derived from calibration data. Carroll and Carroll (1989B) simulated the principal sources of error for airborne measurements made over forested watersheds with as much as 60 cm of snow water equivalent. Airborne snow water equivalent measurements can be made in forest environments with 60 cm of water equivalent with an error of approximately 12 percent. The simulated results agree closely with the empirical errors derived from ground snow survey data collected in a forest environment with 48 cm of snow water equivalent (Carroll and Vose, 1984). In addition, the simulation technique can be used to assess the effect of the principal sources of error on airborne measurements made over agricultural environments with 2.0 to 15.0 cm of snow water equivalent. The error of the airborne snow measurement is, in part, a function of snow water equivalent and ranges from 4 to 10 percent. Again, the errors derived from the simulation agree closely with the errors derived using airborne and ground-based snow survey data collected over an agricultural environment (Carroll, et al., 1983).

3 SATELLITE AREAL EXTENT OF SNOW COVER MEASUREMENTS

In the operational satellite snow cover mapping program, AVHRR data are ingested, radiometrically calibrated, and geographically registered to one of 17 windows (Figure 2). Analysts use a digital image processing system to generate a snow/no-snow/cloud cover byte plane image classification from the satellite data. Hydrologists process the snow cover image classification using a geographic information system where digital elevation model (DEM) and digital, hydrologic basin boundary data sets reside. Six windows in the West, approximately 1000 km by 1000 km, contain DEM and basin boundary data sets. The geographic information system generates percent areal extent of snow cover statistics for each of approximately 5 elevation zones in each of approximately 400 major river basins in the western U.S. Ten additional windows contain basin boundary data sets to map snow cover for the Upper Midwest, the Great Lakes, New England, and southern Canada.

During the 1990 snow mapping season, the Center mapped 2,113 river basins in North America on multiple occasions using AVHRR and GOES satellite data (Figure 3). During the period January 31 through May 7, 1990, analysts mapped 65 windows (Figure 2) and generated 9,123 snow cover analyses using the NWS basin boundary data set (Figure 3).

Baglio and Holroyd (1989) recently completed research to evaluate different snow cover mapping techniques using GOES, AVHRR, and Landsat Thematic Mapper (TM) data over the San Juan Mountains in southwestern Colorado. They developed change detection and multispectral space classification techniques to evaluate snow cover mapping techniques using GOES and AVHRR data. The research developed procedures to screen cloud cover and to map snow cover under forest canopy using AVHRR data in the West. Landsat TM data sets provided a base with which to compare the GOES and AVHRR snow cover mapping techniques. Szeliga, et al. (1990) developed techniques to use digital elevation model (DEM) data to ensure temporal and spatial solar normalization for the multiple 1987 and 1988 satellite image data sets.

3.1 Refinements in Snow Cover Assessment

Holroyd and Carroll (1990) and Holroyd, et al. (1989) describe techniques and refinements used to map areal extent of snow cover using AVHRR data that will not be reviewed here. The Center has incorporated the refinements into the NWS operational snow mapping procedures. The major refinements include: (1) scaling of AVHRR data in bands 1, 2, and synthetic band 6, (2) terrain corrections, and (3) change detection.

Data scaling of bands 1 and 2 within the 0-255 byte data range was originally giving an albedo resolution of 0.5 percent. The comparatively low resolution represented only a 5-bit data range and did not take advantage of the full byte range available for electronic transmission or the 10-bit resolution of the spacecraft data stream. Consequently, we now rescale bands 1 and 2 to an albedo resolution of 0.25 percent.

The original data scaling of band 6 (i.e., band 3 minus band 4) within the 0-255 byte data range produced a saturation of band 3 and occasionally band 4 at radiative temperatures of 46 degrees Celsius or higher. To correct for the image saturation, the classification algorithm arbitrarily classifies all pixels that have a band 3 value greater than 245 (40 degrees Celsius or higher) as snow-free.

Classified images from the early morning NOAA-10 satellite accentuate the snow on the east-facing slopes and under represent snow on the west-facing slopes. Similarly, images from NOAA-11 in the early afternoon and NOAA-9 in the late afternoon have snow cover apparently enhanced on the sunlit slopes and diminished on the shaded slopes.

To correct the images made over rugged terrain, we use 30 arcsecond digital terrain data and: (1) resample to the 901 m pixel size and projection of the AVHRR imagery, (2) calculate the slope and aspect of the terrain, and (3) calculate the solar incidence angle, i, by equation (2).

$$\cos(i) = \cos(z)\cos(s) + \sin(z)\sin(s)\cos(A-a) \quad (2)$$

where z is the solar zenith angle, s is the terrain slope angle, a is the terrain aspect angle, and A is the solar azimuth angle. The band 1 values divided by cos(i) give the brightness values appropriate to flat terrain and a vertical sun. These terrain corrections reduce the solar azimuth bias associated with the areal extent of snow cover. Of course, the corrections are not perfect because terrain variability introduces substantial variability of solar incidence angle within each pixel.

4 AIRBORNE AND SATELLITE SNOW COVER END-USER PRODUCTS

The NWS typically conducts airborne snow surveys from January through March each year using two aircraft simultaneously to support spring snowmelt flood outlooks and water supply forecasts. Maps and a User's Guide are available that give the current airborne flight line network, the details of the airborne snow water equivalent measurement technique, and the procedures to access electronically the snow water equivalent data in real-time.

Hydrologists distribute the alphanumeric and graphic airborne and satellite snow cover data over both the National Weather Service computer network and the commercial MCI Mail electronic mail network. Real-time messages transmit the airborne and satellite data 4 hours after the snow survey aircraft land anywhere in the country and 36 hours after the satellite overpass. The Center endeavors to map areal extent of snow cover for all 17 windows approximately once a week, the effect of cloud contamination notwithstanding. Figure 3 shows the NWS basins where snow cover was mapped in 1990. New basins in the West and southern Canada will provide greater coverage for satellite snow cover mapping in the future.

This paper describes, in some detail, the content and procedure to access the real-time, alphanumeric and graphics products available to U.S. and Canadian end-users. Each snow cover mapping season, we:

1. Map areal extent of snow cover in the U.S. using the National Weather Service basin boundary data sets. We no longer use the USGS hydrologic unit code basin boundaries as we have in the past,

2. Distribute real-time fax maps of the areal extent of snow cover with the basin boundaries, snow cover, and cloud cover for all the basins we map,

3. Provide real-time, electronic, IBM-PC compatible maps (in PCX format) of areal extent of snow cover, with basin boundaries (and color-coded by elevation zone in the West), for all the basins we map, and

4. Provide real-time raster images, in a lat/long geographic projection, of snow/no-snow/cloud cover for use in image processing or geographic information systems for all the basins we map.

Each snow season we distribute the alphanumeric products over AFOS (the NWS communications network) and MCI Mail as described in the current User's Guide (version 3.0; 1988 November 1).

4.1 Regions for Airborne and Satellite Snow Cover Data Collection

Figure 1 is a map of the 1990 Airborne Snow Survey Program national flight line network. The snow survey aircraft make airborne snow water equivalent measurements over selected basins, requested by NWS field offices, where snow water equivalent information is critical to spring flood outlooks, river and flood forecasts, or water supply forecasts.

Figure 2 is a map of the 17 windows for which we collect AVHRR and GOES satellite data to map areal extent of snow cover. Figure 3 is a map of the 2,113 NWS basin boundaries used in 1990 to calculate percent areal extent of snow cover. In the western U.S. (windows 1, 2, 3, 4, 12, and 17), we mapped areal extent of snow cover in 1990 for 494 total basins and for 298 basins by elevation zone. Each of the 298 basins contains 2 to 5 elevation zones. We have the capability to ingest the satellite data as far north as 55 degrees. We do not, however, have a complete basin boundary data set for southern Canada and no digital elevation data set for Canada. We plan to obtain the Canadian basin boundary data set for Alberta, Saskatchewan, Manitoba, southern Ontario, and Nova Scotia from the Environment Canada Water Resources Branch in Hull. Consequently, in 1991 we hope to map areal extent of snow cover south of 55 degrees north (windows 12-16) using Canadian basin boundaries.

4.2 Basin Boundary Maps and Database

Large-scale maps are available that show the NWS basins given in Figure 3. Two maps describe each window: one map contains the NWS basin boundaries, the associated SHEF ID for each basin, and state boundaries; the second map contains the NWS basin boundaries, flight line locations, and state boundaries. Additionally, the NWS basin boundary databases and the airborne flight line databases (that provide the salient characteristics including SHEF IDs, basin name, and elevation zones) are available in hardcopy, IBM-PC ASCII, and Lotus file formats.

4.3 Real-Time Snow Cover Products

4.3.1 Airborne Snow Water Equivalent by Line and Basin (MCI/AFOS-ASCII)

The real-time, alphanumeric, airborne snow water equivalent data, by flight line and basin, are available on AFOS and MCI Mail. AFOS product MSPRRMASP gives the airborne snow water equivalent data by flight line; AFOS product MSPRRMASB gives the mean areal airborne snow water equivalent data by basin. We post both AFOS products to MCI Mail (bulletin board NWS AIRBORNE SNOW). We calculate and distribute the mean areal airborne snow water equivalent estimates, by basin, for airborne data collected only in the Upper Midwest and in the East. The User's Guide gives the data format.

4.3.2 Satellite Areal Extent of Snow Cover by Basin/Zone (MCI/AFOS-ASCII)

Alphanumeric, percent areal extent of snow cover data, by basin (and by elevation zone in the western U.S.), are available in real-time on MCI Mail (bulletin board NWS SATELLITE SNOW) as described in the User's Guide. We added a number of basins and elevation zones in the West in 1990. As a result, the satellite snow cover messages tend to be long and to overwhelm AFOS. Some AFOS messages can exceed ten AFOS pages and consequently complicate AFOS data transmission and storage. To minimize this complication, we send out a one page AFOS message (MSPRRMASC) giving the mapping date and window number (Figure 2) each time we generate a snow cover map. In this way, it is possible for all NWS field offices and all non-NWS end-users to access the MCI Mail bulletin board (NWS SATELLITE SNOW) using a PC and the procedures given in Appendix 2 of the User's Guide and download the current satellite snow cover data.

4.3.3 Satellite Areal Extent of Snow Cover by Basin (FAX-Map)

We fax satellite areal extent of snow cover maps for each of the 17 windows (Figure 2), in real-time, upon request. The faxed maps include the areal extent of snow cover, cloud cover, and state and NWS basin boundaries. Elevation zone snow data are not included on the faxed maps. We send the faxed maps at night; consequently, to receive the faxed snow cover maps, you need to provide us with the telephone number of your fax machine that must be capable of receiving unattended fax messages.

4.3.4 Satellite Areal Extent of Snow Cover by Basin/Zone (MCI/PCX-Map)

In addition to the faxed snow cover maps, we distribute, in real-time using MCI Mail, maps of the satellite areal extent of snow cover, by basin, for each of the mapping windows upon request. The maps include state and NWS basin boundaries, snow cover, and cloud cover for all 17 windows. For the West windows (1, 2, 3, 4, and 17), the maps are also color-coded by elevation zone. The IBM-PC compatible images are in PCX format (by Z-Soft Corporation) that can be viewed and edited by a number of PC programs including PC Paintbrush and MS Paintbrush. Additionally, we provide the software necessary to display the PCX files in a time-series fashion on an IBM-PC VGA system with a screen resolution of 640 by 480. In this way it is possible for end-users to receive and display, in real-time, a time-series of satellite areal extent of snow cover maps for specific basins of interest during the snow season. The MCI Mail subject line for each PCX map file contains the window number and the date of the satellite image (e.g., W12-900314).

4.3.5 Satellite Areal Extent of Snow Cover by Window (Raster Map)

The PCX image files of areal extent of snow cover are not suitable for digital image processing. Consequently, we can provide a digital image of snow/no-snow/cloud cover in a geographic projection (i.e., longitude/latitude format) suitable for use in any geographic information system or digital image processing system upon request. The raster image does not have the basin boundaries imbedded in the image. The digital basin boundaries, however, are available upon request.

4.3.6 IBM-PC Demonstration Diskette

As an example of the PCX snow cover maps available over MCI Mail, an IBM-PC demonstration diskette is available upon request. The demonstration diskette contains snow cover images from the 1990 snow mapping season and a program that allows you to view a time-series of the snow cover maps on an IBM-PC compatible system with a VGA monitor and graphics board (resolution 640 by 480).

4.4 MCI Mail Electronic Mail System

MCI Mail is a commercial electronic bulletin board system. MCI Mail users typically set up their own MCI account with a specific user name. All MCI Mail subscribers (as well as subscribers from other commercial electronic bulletin board systems) can exchange electronic ASCII mail using any PC communications package. Additionally, it is possible for any MCI Mail user to set up a bulletin board system and post ASCII files to the bulletin board for other subscribers to download at their convenience.

We have created three bulletin boards to which we post ASCII files containing airborne snow water equivalent data, satellite snow cover data, and schedule and program information. Additionally, we have set up a general NWS MCI Mail account that will allow any end-user to access the bulletin boards and download the ASCII files described below, at no cost, using a PC and any standard communications package. Appendix 2 of the program User's Guide gives the instructions necessary to access the MCI Mail bulletin boards.

4.4.1 NWS/MCI Mail Bulletin Boards

We maintain three MCI Mail bulletin boards:

1. NWS AIRBORNE SNOW contains alphanumeric airborne snow water equivalent data. The subject line contains the states and dates for which data are collected (e.g., MNWIMI900215/18).

2. NWS SATELLITE SNOW contains alphanumeric satellite areal extent of snow cover data. The subject line contains the window number and the date of the satellite image (e.g., W12-900314) used to generate the data set.

3. NWS SNOW SCHEDULE contains general information including airborne and satellite data collection schedules (to the extent that our crystal ball will permit).

We purge data sets from each of the three bulletin boards two weeks after posting; old data sets can be reposted upon request.

4.4.2 Required End-User MCI Mail Account Number

And now the bad news. There ain't no way to post and retrieve a binary file (i.e., a PCX snow cover map file) to the MCI Mail bulletin board system. It is possible only to transfer a binary file directly to another MCI Mail account. Consequently, it is necessary for each user who wants to receive the real-time, color coded, satellite snow cover PCX map to subscribe to MCI Mail ($25 per year) and provide us with their MCI Mail user name.

And now for more bad news---binary files can be downloaded from MCI Mail accounts only by using Lotus Express or Norton Commander (version 3.0) commercial PC software. Unfortunately, standard PC communications packages do not have the capability to download binary files from MCI Mail---only ASCII files. If you intend to download the snow cover maps, you will need a copy of Lotus Express or Norton Commander (version 3.0) to download the binary PCX image/map files from your specific MCI Mailbox to your PC. The Norton Commander software is a DOS shell that will allow you to download MCI Mail binary and ASCII files, in background, and view the PCX map files among many other things. Norton Commander lists for $149 and is available for $89 from PC Connection at (800) 243-8088.

NOTE: It is not necessary for you to have your own MCI Mail account or Nort on Commander to download the ASCII files posted to the MCI Mail bulletin board system---only to receive the binary, PCX map files.

4.4.3 US and Canadian Access to MCI Mail

MCI Mail has recently changed all of their telephone access numbers in the U.S. Consequently, the MCI Mail telephone access numbers given in Appendix 2 of the User's Guide are obsolete. MCI Mail can be accessed from anywhere in the U.S. at 300 or 1200 baud by calling (800) 234-6245. User's can access the NWS/MCI Mail bulletin boards by: (1) using their own MCI Mail account and user name, or (2) using the NWS account, user name, and procedure described in Appendix 2 of the User's Guide. Canadian access to MCI Mail remains unchanged. We can provide instructions for those in Canada who want to access our MCI Mail account (user name NWSSNOW) as described in Appendix 2 of the User's Guide.

4.4.4 Setting Up an MCI Mail Account

You can set up your own MCI Mail account at a cost of $25 per year by calling MCI at (800) 444-6245 or (202) 833-8484. Once you set up an MCI Mail account to receive the PCX binary map files, give us your MCI Mail user name so we can routinely send you the PCX binary map files for your area of interest.

4.5 Airborne And Satellite Data Collection Schedule

We conduct airborne snow surveys at times and in regions of the country where snow water equivalent information is critical for use in spring flood outlooks, water supply outlooks, and river and flood forecasts. Snow cover conditions and the NWS field offices' requirements for airborne snow data dictate the airborne snow survey schedules during the snow season. We post the airborne data collection schedule to the MCI Mail bulletin board.

In 1991, we plan to begin satellite snow cover mapping on January 2. Our goal is to map snow cover for each window once a week; cloud cover, however, gets in the way. Consequently, if we are unable to map each window once a week, we endeavor to map each window as frequently as possible when cloud cover permits.

4.6 End-User Requests

Interested users can receive more information on any of the aforementioned snow cover products, maps, or data sets by contacting:

Mr. Milan Allen
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6301 - 34th Avenue South
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FTS 725-3232
FAX 725-3338

If you have any questions, suggestions, or require any additional information, please give Milan a call.

5 SUMMARY

We are developing techniques to incorporate DEM data and forest canopy cover data into the snow cover classification procedures to better estimate snow cover in areas where the snow surface is obscured from view by: (1) cloud cover, or (2) dense forest canopy. Research is also continuing toward improvement of normalization procedures to include corrections for within image effects of terrain and for effects of atmospheric scattering and absorption. Additionally, we are working on techniques and procedures to generate, in near real-time, a raster (or grid-cell) snow water equivalent data set using: (1) ground-based point snow water equivalent data, (2) airborne line snow water equivalent data, (3) satellite areal extent of snow cover data, (4) digital elevation data, and (5) forest canopy cover data sets.

6 REFERENCES

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Airborne Snow Survey Flight Line Network

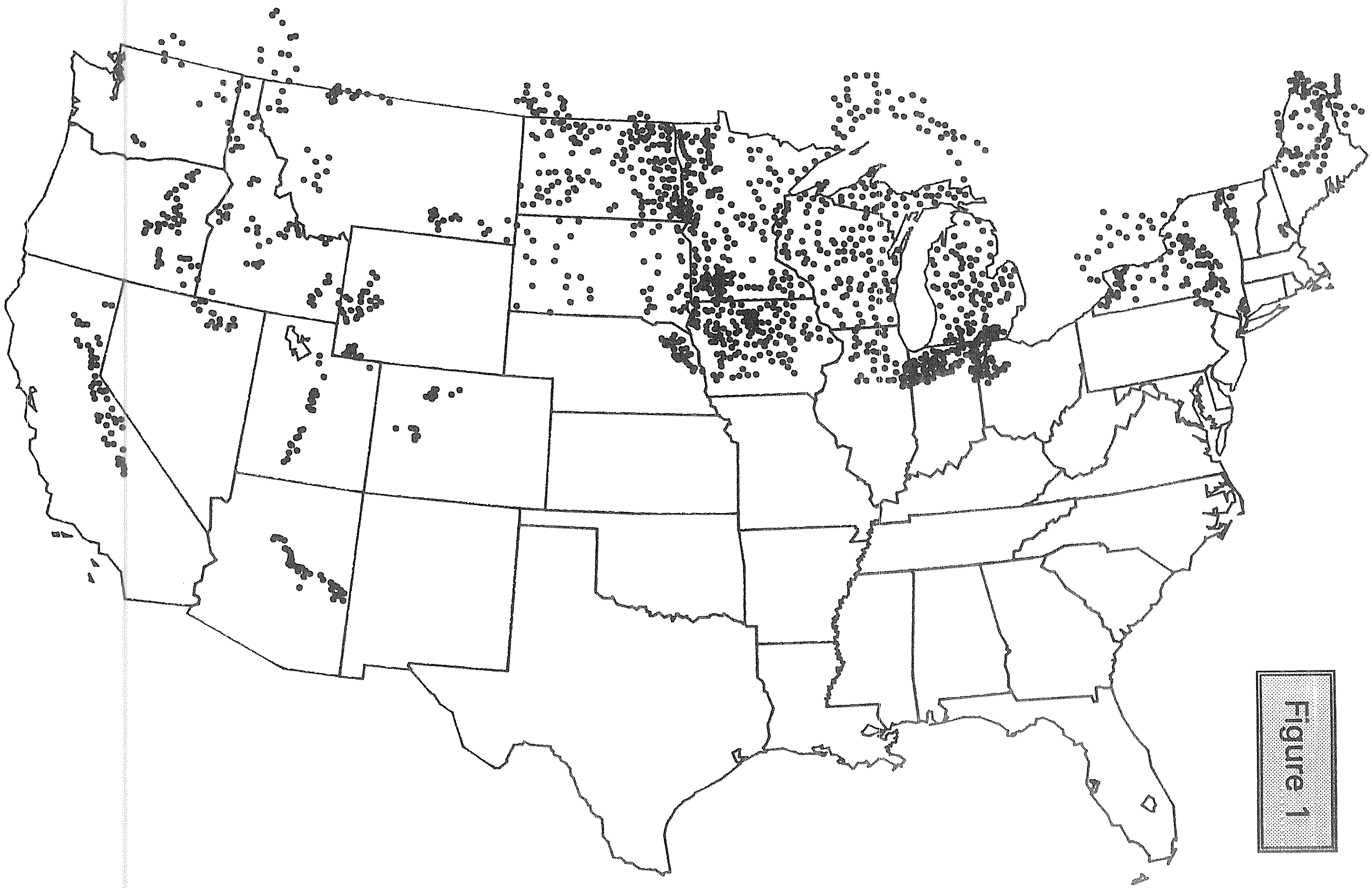

Figure 1

Figure 2

1990 Snow Mapping Windows

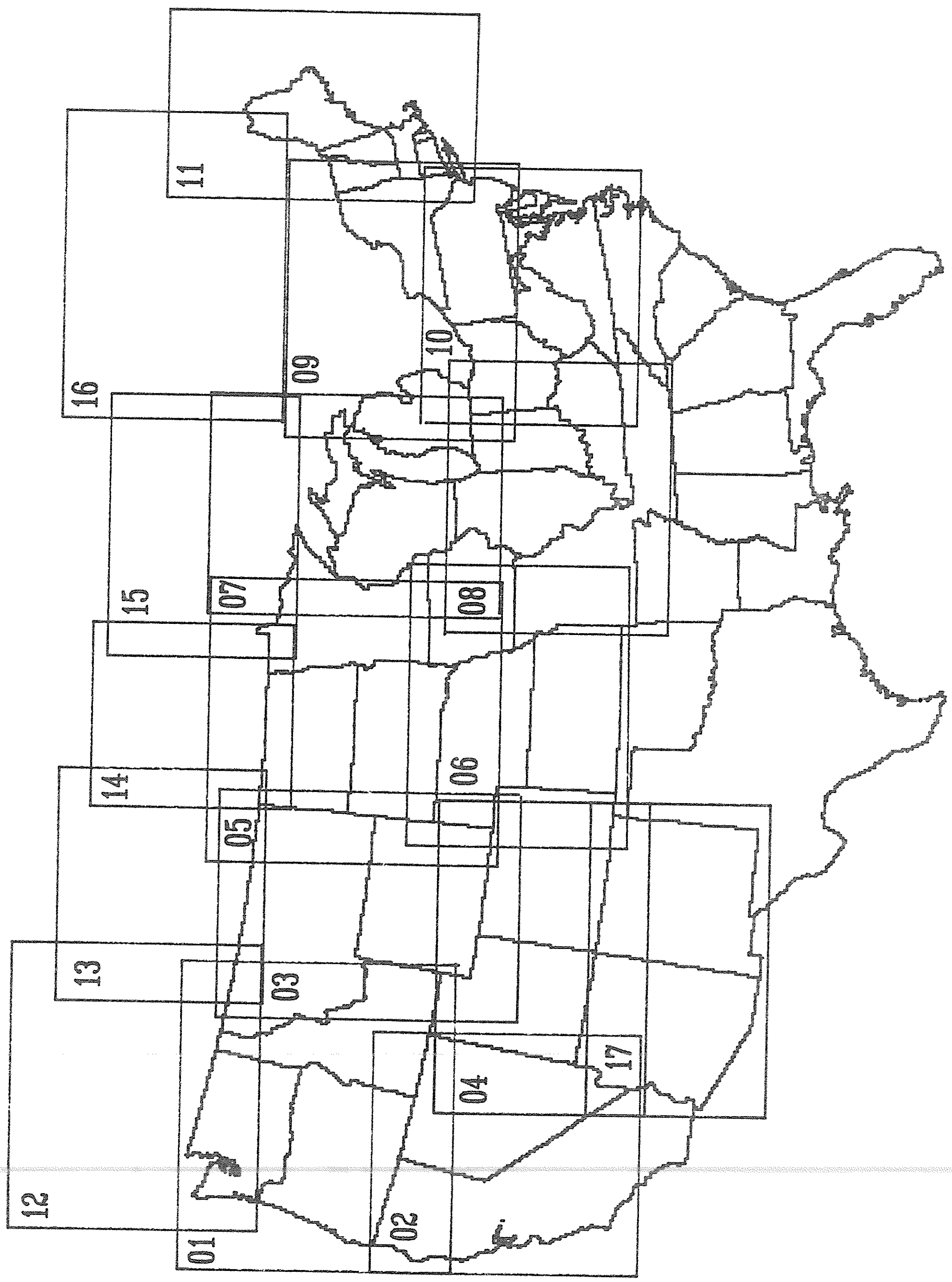

Figure 3

1990 Snow Mapping Basins