MONITORING SNOWPACK CONDITIONS WITH AN INTERACTIVE GEOSTATIONARY SATELLITE SYSTEM

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INTRODUCTION

Traditionally, water resources forecasters have relied upon point measurements of snow water equivalent, temperature, and precipitation collected from manual snow courses, cooperative observers, climatological stations, and remotely sensed platforms for snowpack monitoring. These point measurements are extrapolated to derive mean areal values for individual hydrologic units (river basins). Regression analyses, lapse rates and empirically derived curves are also applied to these data sets to account for the effects of large topographic and physical features such as mountains and lakes.

Spatial data sets became available with the launch of the first meteorological satellites. Snow cover maps derived from satellite imagery provided forecasters with information on snowpack location and extent. During the last five years there have been two important development phases in the transition from manual photointerpretation techniques to digital techniques. The original digitally derived maps were alphanumeric computer printouts utilizing relatively coarse 4 km GOES visible data sets. Processing required a batch processing system to access the National Environmental Satellite Data and Information Services (NESDIS) data bases on the IBM 360/195 computers in Washington, D.C. Currently, snowmapping operations utilize real-time full resolution 1 km GOES data on the Interactive Centralized Storm Information System (CSIS) at the National Severe Storms Forecast Center (NSSFC) in Kansas City. CSIS processing capabilities have enabled the NSSFC satellite hydrologist to begin developing more diversified products and services to monitor snowpack conditions in addition to expanding areal coverage with the more detailed snowcover maps.

Visual Snowcover Mapping Techniques

Prior to 1978, NESDIS employed photointerpretation techniques to produce operational snowcover maps. The technique utilized a Zoom Transfer Scope (ZTS) to register a rectified and enlarged visible image from NOAA polar orbiting satellites to a basin outline by aligning landmarks (lakes, rivers, etc.). The snowline was traced onto the basin map and percent snowcover was calculated using a planimeter or electronic density slicer. These visually derived analyses were labor intensive and accuracy was directly related to the analyst's familiarity with each basin's topography,

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canopy, and skills interpreting the effects of varying illumination angles on features (forests, etc.) within each basin.

Snowcover Mapping with Digital Data

From 1978 to 1981, NESDIS began conducting snowmapping tests utilizing digital GOES data on interactive and batch processing systems to increase the timeliness, effectiveness, accuracy and expand the areal coverage to meet user requests.

Results of tests conducted on interactive systems using GOES imagery and basin boundary overlays displayed on video terminals were somewhat mixed. This visual technique enhanced the analyst's ability to eliminate clouds and measure snowcovered area by pixel counting. However, complex snowlines and discontinuous snowcover required superior eye-hand coordination by the analyst. Limitations with existing hardware and software resulted in emphasis being placed on the digital snowmapping technique being concurrently developed on the NOAA main computers.

This batch processing all digital procedure was tested operationally during the spring of 1981. This procedure developed snowfree/cloudfree data sets (masks) for each basin. The darkest (lowest count value) pixel within each basin was chosen as the "threshold value" used to reference every pixel in each basin. During the snowmapping season a new threshold value was selected to brighten or darken the mask to account for varying solar illumination angles.

On cloudfree days the program was submitted through a Remote Job Entry (RJE) terminal to the NOAA main computers in Suitland, MD. Repetitive submissions are required to exactly align the mask and the visible data and then produce a series of snowcover maps. The initial threshold value was added to each pixel in the mask and compared to each pixel retrieved from the GOES data set. If the mask plus threshold value is less than the GOES value, the pixel is assumed to be snowcovered. The number of snowcovered pixels was divided by the total number of pixels in the basin to derive percent snowcover.

Between December, 1981 and July, 1984, the SFSS generated and distributed 691 snowcover analyses covering 16 basins in the western United States. Because the procedure required visible data from a GOES satellite at 135°W, the program was significantly affected by the failure of three GOES satellites beginning in November, 1982. The failure of GOES-5 and the decision to move GOES-6 to a more central location threatened to leave the SFSS without the ability to generate digital snowcover analyses. After months of reviewing the digital snowcover mapping software it was decided the manhours required to modify existing software and write new software for the reduced resolution data would not be worth the effort.

CURRENT SNOWMAPPING OPERATION

Centralized Storm Information System (CSIS)

CSIS is a developmental system which exists in an operational environment and supports the operational mission at the National Severe Storms Forecast Center (NSSFC). CSIS is a spin-off of the University of Wisconsin's Space Science and Engineering Center's (SSEC) Man computer Interactive Data Access System (McIDAS). While the ultimate goal of CSIS is to improve NSSFC's ability to forecast severe weather, it also represents another phase in the NWS effort to develop a system to ingest, analyze, integrate and display real time data from all available sources.

The CSIS system consists of a GOES receiving antenna system, four Harris slash-6 computers, five interactive video terminals, conventional surface and upper air data, dial-up radar inputs, 1600 bpi magnetic tape drives used for data archiving and four 300 mb hard disks, an interface to other NSSFC computers and a phone link with the SSEC McIDAS for Visible Infrared Spin Scan Radiometer (VISSR) Atmospheric Sounder (VAS) data access.

System flexibility gives the analyst a diverse menu of options and capabilities including: real-time stretched data from the GOES VISSR; color enhancement of satellite imagery; the ability to superimpose data and analyses on satellite imagery; locating of points on the imagery using earth, satellite, and screen coordinates; a macro language facility for defining a sequence of commands; color graphics; the capability to overlay a variety of maps over satellite data, to change the gray scale of imagery and remap data to different map projections; a statistical analysis of data; data archival on magnetic tape; and black and white hardcopy of graphics and/or imagery.

CSIS Snowcover Mapping

The CSIS snowcover mapping technique is based on the fact that snowcover increases the brightness of a land area. The following are the procedures used in the CSIS snowcover mapping technique:

- Identify areas to be mapped and select data sectors.
- Develop an automated system to collect full resolution data.
- Set up seven day rotating files to archive the data.
- Input United States Geological Survey (USGS) catalog units for basin delineation over areas to be mapped.
- Prepare snowfree/cloudfree reference data bases (masks).
- Remap GOES data into mask projection.
- Exactly align the mask and GOES data.
- Adjust the brightness of the mask to reflect the difference in solar illumination angle of the GOES data.
- Composite two images to eliminate clouds.
- Compare each pixel in the mask and image to produce a snow/no snow image.
- Sub-divide each sector into mapping scenes.
- Eliminate cloud contamination manually with the cursor.
- Overlay basin boundaries and digitally compute percent snowcover.
- Overlay percent snowcover tables for each basin.
- Hardcopy the snow/no snow image with basin boundaries and tables.
- Archive GOES data used for mapping on magnetic tape.
- Disseminate maps via first class mail and rapifax.

Real time full resolution GOES data are received directly from satellite and stored on the CSIS Data Base Manager (DBM). A clock controlled scheduler then "sectorizes" these data and sends them to another CPU where they are stored for real time or future display on an interactive terminal. Snowcover mapping data are stored in two seven-day rotating files, one for each time period. During the winter and early spring, data are archived at 1700Z and 1800Z (GMT). From early Spring through July, data are archived earlier at 1600Z and 1700Z to reduce the possibility of small cloud contamination. Software was written to allow the analyst to manipulate file parameters and display the files with one line keyins.

The USGS basin boundary tape has 27,000 sectors representing regions, sub-regions, accounting units, and catalog units for the contiguous 48 states. The highly detailed boundaries are defined by latitude/longitude pairs of points that are line segments between individual basins. Software developed by the NWS Office of Hydrology (OH) was modified to read the data into CSIS. Additional software was written to convert the data to CSIS geographical format, and display various configurations of regions, sub-regions, accounting units, and catalog units in addition to the snowmapping basins.

Full resolution GOES-5 visible data for September 24 and 25, 1983 were aligned and composited to create snowfree/cloudfree images. These images were then remapped into a projection of the satellite at its winter longitude (108°W). Navigation coordinate data were then exactly aligned with the imagery using landmark coordinates derived from 1:1000000 Lambert Conformal Operational Navigation Charts.

The satellite visible images need to be corrected for brightness changes due to the daily and seasonal change of the sun angle. It has been assumed that the land and snow reflect sunlight in an isotropic manner. This is a good first order approximation to these surfaces as long as extreme sun angles are avoided. The visible brightness counts on the GOES satellite have been digitized with a square root digitization technique.The solar zenith angles θ were calculated for the center of the basin of interest for the reference image and the current image and the entire satellite image was then multiplied by the correction factor

$$\sqrt{\frac{\cos \theta_1}{\cos \theta_2}}.$$

To reduce the amount of time required to manually align the GOES-imagery a reference mask software was developed to align the imagery with the mask resulting in the alignment of the digital data bases. The entire operation requires one command and two single letter keyins. GOES data and the reference mask are loaded on "opposite frames" of a terminal. This allows the analyst to flicker between the two images using a one letter keyin as the toggle switch to check their alignment and look for landmarks visible on both images. A cursor is placed directly over the landmark in the GOES imagery by moving a pen over a data tablet connected to the terminal. The one letter keyin is entered and the reference mask is displayed. The operation is repeated on the reference mask. The GOES data are repositioned and all pixels are now given the navigation, satellite, and earth coordinates of the reference mask. The repositioned image is loaded and alignment is checked by flickering between the realigned image and the mask.

Compositing two images to eliminate clouds is a combination of the two previous steps. Brightness levels of one image are scaled to match the illumination angle of the other. Pixels on each image contaminated by cloud shadows are set to zero using a cursor data function. The two images are aligned and every pixel in each image is compared. The darkest pixel value is then selected to produce the composited image.

Snowcover sectors are produced by comparing every pixel in the sector with every pixel in the scaled mask. If the sector pixel is brighter than the mask pixel, the sector pixel is classified as being snowcovered and its count value is used to build the snowcover sector. If the sector pixel is less than or equal to the mask value, the pixel in the snowcover sector is given a count value equal to zero.

Each snowcover map in a sector is then displayed and checked again for cloud contamination. If contamination exists, it is removed interactively using a cursor data function which sets the contaminated values to zero or the threshold stripping program can be rerun with the background increased by a small delta to determine the snow/no snow threshold. Each catalog unit boundary is overlayed over the snowmap and a statistical discrimination function is used to derive percent snowcover by dividing the number of non-zero pixels by the total number of pixels inside each boundary. Percentages are then entered into a macro, written to overlay a table of percent snowcover values on each map. An interactive enhancement function is used to convert all non-zero pixels to white and change catalog boundaries to gray. Hard copies are made using a Honeywell VGR 4000 Video Graphics Recorder. Snowcover maps are disseminated via first class mail and rapifax. GOES image sectors used to derive snowcover maps are archived on magnetic tape.

During 1985, the 16 basins mapped using reduced resolution NESDIS data were subdivided into 68 USGS hydrologic catalog units and service was expanded to include 17 additional catalog units in Idaho. The catalog units range in size from 800 to 12,000 sq. km. and cover 350,000 sq. km. From late February through June 1985, the SFSS derived and disseminated 773 snowcover analyses for 85 catalog units in the western U.S.

CSIS Snowcover Mapping in Perspective

Many factors affect the accuracy of satellite areal snowcover measurements, including data resolution, methodology, exactness of basin boundaries, precision of registration of boundaries to imagery, measuring techniques, and the skill of the analyst applying the tools and procedures. There are four critical time components that affect the operational utilization of these data: frequency of observation, the time between data collection and availability for analysis, time required to do the analysis, and the time required to deliver the product to the users. The principal costs of the product are data acquisition, data processing and product delivery.

In terms of accuracy, the GOES interactive digital snowcover mapping technique has many distinct advantages over manual photointerpretation procedures except in the area of data resolution. LANDSAT's 30 m resolution is clearly superior to the NOAA polar orbiting data (1000 m at Nadir) and GOES (1000 m at the Equator). The digital technique has the ability to overcome the complexity of reflected light on various types of terrain from constantly changing solar illumination angles. Navigation and geographic data bases in CSIS enable the analyst to register imagery and basin boundaries more accurately (±1 km) than a ZTS, and pixel counting is far more reliable than a planimeter or density slicer. The digital technique is not affected by complex, broken, or spotty snow fields. The digital technique also has considerably shorter processing times per basin than planimeter techniques. All other factors can be considered equal.

"Finding the clear spots" between cloud cover is one of the greatest advantages of using GOES data, because visible imagery is collected every 1/2 hour during daylight hours and is available for analysis within five minutes time. The wide range of possible collection times allows more frequent and reliable data collection. Analyses for 29 basins can be completed within 40 minutes of the data collection time. Maps can be disseminated within one hour of data collection time using a rapifax and within 24 hours using overnight express mail service.

While the CSIS technique has many advantages over other procedures, its' accuracy in heavily forested areas must be verified and documented through a cooperative program with OH and the users.

SERVICE REQUIREMENTS

Background

During the 1970's, the National Aeronautics and Space Administration (NASA) sponsored the Applications Systems Verification and Transfer (ASVT) snowmapping program. This five year user cooperative effort used four test sites in Arizona, California, Colorado and the northwestern United States to perform operational evaluations of the effects of technological capabilities (in existence at that time) on water resources forecasting.

Study results show that sixtyeight percent (68%) of the surface water in the 11 western states is derived from snowmelt runoff. The total value of snowmelt runoff water is subdivided into the following categories:

Irrigation & hydrodelec energy	- 87%
Municipal & Industrial	- 9%
Flood Damage	- 4%
Other Uses	- <1%

Test results show that a minimum 6% improvement in forecast accuracy was achieved using satellite derived snowcover maps. This six percent improvement in forecasting snowmelt runoff would result in a total annual benefit of $36.5 million (1981) dollars for irrigated agriculture and hydroelectric energy for the 11 western states. Estimated annual cost for the 2,195,250 km^2 area impacted by snowmelt forecasting was $0.23/$km^2$. These costs were derived from the Colorado ASTV and are based upon acquiring eight sets of Landsat imagery ($400), 16 man-days to interpret the imagery ($800), eight man-days to implement the data ($600) and the cost of a zoom transfer scope (ZTS) ($10,000) with 25% utilization and amortized over 10 years. CSIS snowmapping costs during 1985 were $0.14/$km^2$ of area mapped.

User Survey

The user community for snowcover maps is diverse in mission and, therefore, product utilization varies. Field and research offices of the National Weather Service (NWS), Corps of Engineers (COE), Bureau of Reclamation (BOR), Soil Conservation Service (SCS), Agricultural Research Service (ARS), and the Forest Service can utilize these data for real-time, medium range and seasonal streamflow forecasting, reservoir regulation and a variety of other water resources and agricultural services at regional and local levels. Additionally, many agencies will utilize these data to develop, expand and calibrate hydrologic models.

During the summer of 1985, the SFSS surveyed existing and potential satellite hydrology users to prioritize expansion and development work on CSIS. Products and services listed for operational testing and development were percent snowcover per basin, percent snowcover per elevation zone per basin, solar insolation and precipitation, skin temperature over snowcovered area, atmospheric data (temperature, wind speed and direction), and historic data sets of all these products.

Additional information was also solicited for user requirements for product format, resolution, frequency of observations, seasonal coverage, and timely dissemination.

Survey Results - Non-Weather Service Users

Surveys were distributed to existing snowcover users and new agencies that had requested coverage during the 1986 snowmelt season. Therefore, the results cannot be interpreted as being representative of the entire hydrologic community. In fact, the results stated here will only cover non-NWS users.

In general, percent snowcover was requested by operational users plus historic data sets, while nonoperational users engaged in model development and calibration requested all or parts of the products surveyed. New areal snowcover mapping service was requested for 561,000 sq. km in the Western United States, 516,000 sq. km in the Great Lakes Basin and 176,000 sq. km in the Appalachian mountain range from Pennsylvania to Alabama. Elevation zone snowmapping services were generally confined to basins above 6,000 ft.

Solar insolation was the most requested product in terms of total areal coverage and regional diversity. Data was requested for 2,823,000 sq. km, including large areas such as the Great Lakes Basin, Great Plains, and Appalachians, in addition to requests on the sub-regional and basin levels from West Virginia to California.

Skin temperature data was requested for 979,000 sq. km in the Great Lakes, Missouri headwaters, Appalachians, Rio Grande headwater, Salmon River, Death Valley, and Salt River Project. Half of the interest in the data is to see if it will help identify those portions of the snowpack where melt has begun.

The other half is for year-round monitoring of skin temperatures for vegetative and soil moisture stress on a real-time basis.

Upper air data was requested for 753,000 sq. km in the Great Lakes, Missouri headwaters, Sierras and Death Valley areas. These data will be used to develop, calibrate and drive operational models year-round. These data are needed on a real-time basis.

One of the most significant results of the survey has been requests by at least one office from the ARS, BOR, COE, USFS and USGS for all or most of the products surveyed. These data sets will be utilized to develop, calibrate and test a variety of hydrologic models. Output from these models will enable us to assess the value of these data sets and the validity of the scientific principles and techniques used to derive these data. These studies will play an integral role in prioritizing and implementing the data operationally.

CURRENT SERVICE OBJECTIVES

Areal Snowcover Mapping

During the 1986 snowmelt season, snowcover mapping services will be expanded to include an additional 561,000 sq. km in the Western United States and 128,000 sq. km for Lake Superior drainage. These new areas are almost double the 350,000 sq. km mapped during 1985. This expansion of service area is made possible by new software that will enable the hydrologist to display, combine and analyze imagery and geographical data bases more efficiently. Selected basins will be analyzed under snowfree and snowcovered conditions to assess the combined effects of various solar illumination angles, slope orientations, and terrain on visible brightness levels.

Snowcover Mapping by Elevation Zones

The Rio Grande River above Del Norte, Colorado, Salmon River above Whitebird, Idaho and possibly the Boise River above Lucky Peak Dam will be mapped by elevation zones. Digital elevation data sets will be remapped into the satellite projection of the snowfree/cloudfree mask. Each pixel in the mask which has a corresponding pixel in the elevation data set will then be level discriminated with the elevation pixel to produce a gray scaled elevation image. The derived snowcover image, elevation range and the hydrologic boundary data set will be combined to produce images of snowcover area and the percent of snowcover by elevation zone per hydrologic unit. These maps will only require one additional step and one minute of time to the existing procedure.

Solar Insolation

The metamorphosis of a snowpack can be modeled by monitoring the energy balance of incoming solar radiation, escaping longwave radiation, sensible heat advection, and precipitation. Techniques developed by Gauthier *et al.* (1980), and Gauthier (1982) have shown the feasibility of measuring solar insolation from geostationary satellite data and detecting mesoscale variability in energy balance. One of the primary influences on the radiation balance is cloud cover, and one of the techniques used to determine snowcover was developed to identify cloud cover. Elevation data sets will also be utilized to account for terrain orientation (snow lasts longer on the north slope of a mountain than on the south slope) and to adjust the data sets to more accurately estimate these parameters. We plan to investigate the possibility of monitoring the conditions on CSIS.

CONCLUSIONS

Interactive digital snowcover mapping with 1 km visible GOES data is an accurate, timely, and cost effective means of acquiring basin snowcover area to assess, allocate and forecast water resources from snowmelt runoff because:

- It can overcome the complexities of reflected light on various types of terrain from constantly changing solar illumination angles.
- Imagery and basin boundaries can be accurately registered (± km).
- Pixel counting is a fast, accurate and reliable measuring technique.
- Data collection is more frequent and reliable.
- Cloud contamination can be minimized more effectively.
- Up to 30 snowcover analyses can be completed within 40 minutes of the data collection time.
- Digital data can be archived easily and inexpensively.
- Analyses only cost $140 per 1000 sq. km. per year during 1985.

Today's long and short range snowmelt runoff forecasting systems are dependent upon a variety of point hydrometeorological observations which are then statistically weighted and/or extrapolated to derive areally distributed data sets. Escalating costs for data collection have made snowpack monitoring with an interactive geostationary satellite system the most cost-effective means of acquiring temporally and spatially complete data sets to enhance the value of all other data.

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