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ABSTRACT

Research work in the United States from 1975-1978 in the field of remote sensing of snow and ice is reviewed. Topics covered include snowcover mapping, snowmelt runoff forecasting, demonstration projects, snow water equivalent and free water content determination, glaciers, river and lake ice, and sea ice. A bibliography of 200 references is included.

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REMOTE SENSING OF SNOW AND ICE: A REVIEW OF RESEARCH IN THE UNITED STATES 1975-1978

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Remote sensing has become a valuable tool in snow and ice studies because of its unique capability for acquiring measurements of glaciological conditions over large areas (Rango, 1977). Two major objectives are to develop techniques for improved monitoring of existing conditions and to incorporate the new data into various forecasting or management systems.

Since 1974 various investigators have gained experience with and developed techniques for snowcover interpretation from visible and infrared data from satellites such as Landsat and NOAA. Numerous techniques are available for analysing the data ranging from simple photointerpretation to automated digital methods (Schneider, et al., 1976; Meier and Evans, 1975; Meier, 1975; Rango and Itten, 1976; Barnes and Smallwood, 1975; Dallam and Foster, 1975; Katibah, 1975; Luther, et al., 1975; and Algazi and Suk, 1975). In addition, the use of Skylab data for snow-mapping has been investigated (Barnes, et al., 1975; 1977) with most significant results pertaining to the use of the 1.55 μm - 1.75 μm band for discriminating clouds from snow (Bartolucci, et al., 1975; Barnes and Bowley, 1977; and Valovcin, 1976).

Radiative transfer modeling has been used to calculate the solar reflectance of snow and to estimate the effect of snow aging on reflectance (Choudhury and Chang, 1978a; and Choudhury and Chang, 1978b). O'Brien and Munis (1975a) have examined the reflectance of snow at discrete visible and near infrared wavelengths with emphasis on effects due to aging and melting.

As a result of the extensive experience with satellite snowcover data several applications have developed. NOAA has established techniques for using satellite imagery to detect, measure

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and map mean monthly snowcover over the Northern Hemisphere (Wiesnet and Matson, 1975; and Matson, 1977). Regression analysis using nine years of data yielded several equations with correlation coefficients significant enough to have possible applications for 30, 60, and 90 day forecasting of seasonal, hemispheric, and continental snowcover (Wiesnet and Matson, 1976).

Rango, et al. (1977b) used meteorological satellite snow extent data to derive a regression relationship between early April snowcovered area and April-June seasonal yield on the Indus River in Pakistan. In these large data-sparse regions the satellite snowcover data period of record actually exceeds the conventional data base.

Thompson (1975) in Wyoming found that the snowcovered area on a particular date was better related to the accumulated runoff/total seasonal runoff ratio than to just the seasonal runoff in a statistically significant expression. A long-term data base was obtained by compositing aircraft and Landsat snowcover data with resulting analysis indicating that snow extent was useful in reducing seasonal runoff forecast error when incorporated into procedures to update water supply forecasts in California on a 15-day basis as the melt season progressed (Rango, et al., 1977a). Several runoff models including the Streamflow Synthesis and Reservoir Regulation (SSARR) model (Speers, et al., 1979) have options permitting the use of snowcover input data and variable elevation zones for calculating snowmelt. In addition, several hydrologic models, although not originally requiring snowcover input, have been modified to accept satellite snow extent data for the generation of daily discharge values (Leaf, 1975; and Hannaford, 1977).

Based on promising results in snow mapping, seven federal and three state agencies have conducted a program to test the usefulness of the satellite data in operational snowmelt-runoff forecasting (Rango, 1978). Both empirical and modeling approaches have been evaluated in connection with the satellite snowcover data in four regions of the western U.S., namely, Arizona

(Schumann, 1975; Warskow, et al., 1975; and Kirdar, et al., 1977), California (Brown and Hannaford, 1975), Colorado (Washichek and Mikesell, 1975), and the northwest states (Limpert, 1975). Preliminary results were documented (Rango, 1975c) and a final workshop will conclude the project in April 1979.

Investigations into the use of remote sensing techniques for the measurement of more fundamental snow properties are also being carried out. The use of visible and near-infrared wavelengths for inferring snow properties such as depth (McGinnis, et al., 1975a), water equivalent (Sharp and Thomas, 1975; Merry, et al., 1977), and density (McMillan and Smith, 1975) has been tested with limited success and development of gamma ray techniques for measurement of snow water equivalent has continued (Bissell, 1975a; Fritzsche and Feimster, 1975).

Microwave monitoring of snowpack properties has received considerable attention because this portion of the electromagnetic spectrum has the capability for penetrating snow allowing for inference of internal characteristics. Satellite snowcovered area measurements have been made using Nimbus 5 (Kunzi and Staelin, 1975; Kunzi, et al., 1976) and Nimbus 6 (Rango, et al., 1979) radiometers. Several other passive microwave studies have covered the modeling of microwave emission from snow (Chang and Gloersen, 1975; Chang, et al., 1976; Zwally, 1977), comparison of model calculations and satellite observed brightness temperatures from polar firm (Chang and Choudhury, 1978; and Chang, et al., 1978), development of a method to determine snowfield temperature profile and mean crystal size by using multifrequency microwave radiometer measurements (Chang, 1978) and correlation of microwave emission to water equivalent, depth, and free water content (Hall, et al., 1978; and Shiue, et al., 1978). For dry snow conditions on the high plains significant relationships between snow depth or water equivalent and microwave brightness temperature were developed (Rango, et al., 1979). Associated active

microwave and snow studies have included modeling of the electromagnetic reflection from snow (Linlor and Jiracek, 1975; and Linlor, 1976) and analysis of experimental ground-based measurement programs (Angelakos, 1977; Ellerbruch, et al., 1977; Linlor, et al., 1977; Angelakos, 1978; Ulaby, 1976; Ulaby and Stiles, 1977; and Ulaby, et al., 1978).

Landsat images have proved to be very useful for collecting certain basic data from glaciers, for example, long term surface velocities are readily determined by comparison of displacement on images taken at different times (Krimmel and Meier, 1975). Surging glaciers are easily identified and their associated short term high flow rates have been measured in various locations (Krimmel, et al., 1976; Post, et al., 1976; and Meier, 1976). Large glaciers and icecaps have also been monitored (Williams, 1976). The location of the snowline on a glacier can easily be mapped with Landsat, and when observed at the end of the melt season can be related to the annual net mass balance (Braslau and Bussom, 1979). Under direction of the U.S. Geological Survey Landsat is being used currently to compile a worldwide glacier atlas.

Formation and dissipation of river ice on the Ottawa River was monitored daily using visible imagery from NOAA satellites. The break up of 14 ice-covered reaches was observed during the melt period in April 1976 (McGinnis and Schneider, 1978). Radar monitoring of river ice provides an all weather capability during cloudy periods and was tested on the St. Lawrence River. A contour map showing the accumulation pattern of frazil and brash ice was obtained (Dean, 1977).

Visible and near infrared observations over the Great Lakes have been used with reasonable success for mapping ice cover and type (Sydor, 1976; and McMillan and Forsyth, 1976). However, for operational purposes cloud cover is a significant problem, and, as a result, side-looking airborne radar (SLAR) has been used successfully for ice monitoring purposes (Schertler, et al.,

1975). Additional studies were conducted to determine radar capability for determining ice type and condition (Bryan and Larson, 1975) and properties of frozen northern lakes (Weeks, et al., 1977). Radar studies on Alaskan lakes indicate that discrimination between lakes frozen completely to the bottom versus lakes with fresh water beneath the ice is possible, thus providing additional information on lake depth (Sellman, et al., 1975; and Elachi, et al., 1976). The measurement of lake ice thickness was accomplished using a short-pulse radar system which can be ground-based or airborne (Cooper, et al., 1976). Monitoring of lake ice using passive microwaves has also been investigated (Bryan and Hall, 1976), and it appears that ice thickness variations can be distinguished (Hall and Bryan, 1977; and Hall, et al., 1978).

The use of remote sensing in sea ice studies is directed toward answering fundamental questions regarding amount of ice covered ocean, ice movement, and ice formation and ablation. Data generated by remote sensing is used in determining the influence of sea ice on atmospheric and oceanic processes. It seems fortunate that the current increase in scientific interest about sea ice coincides with a time of rapid evolution of both remote sensing platforms and sensors. Campbell, et al. (1975) present an overview of mesoscale and macroscale studies of floating ice in three sensor categories: visual, passive microwave, and active microwave.

Using visible satellite imagery the primary advances have been in tracking ice floe movement using sequential imagery (Campbell, 1976a; Hibler, et al., 1975; Shapiro and Burns, 1975; and Campbell, 1977), ice lead and polynya dynamics (Campbell, 1976b), seasonal sea ice metamorphosis (Campbell, 1976c), and dynamics of ice shear zones (Campbell, 1976d). A statistical method for discriminating sea ice from clouds with 90% or greater accuracy has been developed (Gerson and Rosenfeld, 1975). Visible imagery has been used to compile statistics on ice conditions for applications such as off-shore oil and gas exploration (Barnes, et al., 1978). In addition

visible and thermal imagery have been used for estimations of sea ice thickness, although the presence of snowcover may cause a limitation to relative amounts only (Poulin, 1975; Hall, 1975; Kuhn, et al., 1975; LeSchack, 1975; and Rothrock, 1975).

The advantage of microwave observations of sea ice rests in the capabilities to penetrate clouds and to make observations during the polar night. In the Beaufort Sea five ice zones were discriminated using aircraft multispectral passive microwave observations (Campbell, et al., 1976). Brightness temperature levels and relative fluctuations are used to distinguish between shorefast sea ice, shear zone, mixed first-year and multi-year sea ice, mixed first-year ice and medium to large multi-year floes, and the polar ice zone. The radiometric signatures are most pronounced at 0.8 and 1.5 cm wavelength (Campbell, et al., 1976). The time variation of sea ice concentration and multi-year ice fraction within pack ice in the Arctic Basin was examined using the 1.55 cm radiometer on the Nimbus-5 spacecraft (Gloersen, et al., 1978) with significant variations between seasons being observed. Previously unobserved areas, several hundred kilometers in extent, of sea ice concentrations as low as 50% were discovered deep in the interior of the Arctic polar sea ice pack. Sea ice observations by Nimbus 5 in the polar regions are reviewed by Zwally and Gloersen (1977).

Active microwave studies of sea ice have shown the capability of synthetic aperature radar for displaying the orientation of leads in the ice and the percentage of open water in the entire sea ice scene (Bryan, et al., 1977). Experiments with radar scatterometers indicate that various types of sea ice categories can be distinguished with about a 87% correct identification accuracy at the 13.3 GHz frequency (Parashar, et al., 1977). The profiling of sea ice thickness has also been attempted using an impluse radar (Morey, 1975). A large variety of active and passive microwave measurements of sea ice were made as part of the Main Arctic Ice Dynamics Joint Experiment 1975-1976 (Campbell, et al., 1978).

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