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THE ROLE OF SATELLITES IN SNOW AND ICE MEASUREMENTS

Donald R. Wiesnet

Environmental Sciences Group
Washington, D.C.
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Robert M. White, Administrator

National Environmental
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David S. Johnson, Director

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ABSTRACT. Earth-orbiting polar satellites are desirable platforms for the remote sensing of snow and ice. Geostationary satellites at a very high altitude (35,900 km) are also desirable platforms for many remote sensors, for communications relay, for flood warning systems, and for telemetry of data from unattended instrumentation in remote, inaccessible places such as the Arctic, Antarctic, or mountain tops. Optimum use of satellite platforms is achieved only after careful consideration of the temporal, spatial, and spectral requirements of the environmental mission. The National Environmental Satellite Service will maintain both types of environmental satellites as part of its mission.

1. INTRODUCTION

Today, a wide variety of environmental satellites equipped with various sensors are transmitting data on snow and ice to Earth at unprecedented rates. These data are, for all practical and operational purposes, virtually ignored by the hydrologic community. Our capability for collecting data on snow and ice far exceeds our ability to analyze the data. Why is this so? What can be done to alleviate the situation? What is already scheduled for future generations of satellites and sensors? Is fieldwork obsolete? What kind of satellite snow and ice data are available to the private sector and to the universities for research? These and other questions may be asked of NASA and NOAA/NESS, the agencies responsible for developing and maintaining, respectively, experimental and operational environmental satellites. The EROS staff of the Department of Interior is also deeply concerned, and properly so, in view of the spectacularly successful ERTS satellite and its hydrologic applications.

2. ORBITAL CONSIDERATIONS

Polar orbits--the NOAA 2 and NOAA 3 satellites represent the third generation of environmental satellites in the National Operational Environmental Satellite System. The satellites orbit at 1500 km; the orbit is near-polar and sun synchronous so that the satellite always crosses the equator at the same local solar time, in this case 0930 and 2130. This orbit is a typical improved TIROS operational satellite orbit, providing a twice-daily infrared (IR) image and a once daily visible band image of an area. Orbital characteristics of NOAA 2 are given in table 1.

This type of orbital coverage permits 12 hr change detection for dynamic snow and ice events. Cloudiness commonly reduces these observations, but in most of the United States it is possible to secure at least one cloudless view per week. The primary sensor for hydrologic use aboard NOAA 3 is the very high resolution radiometer (VHRR), a new, significantly improved dual channel scanner (visible, 0.6 to 0.7μm; infrared, 10.5 to 12.5μm).

Orbital characteristics of the Earth Resources Technology Satellite (ERTS 1) are shown in table 1. This unique satellite has orbital parameters different from NOAA 2 and NOAA 3; it provides an 18-day revisit cycle. Cloud cover may, at times, result in 36- or 54-day cycles of actual observation of the Earth's surface. For snow and ice studies in temperate zones, a data gap of 36 days is intolerable, but for Arctic regions it might be tolerated. The ERTS orbit, however, does not include areas poleward of 81°N or S. Winter sun angles in polar areas further restrict the areas and periods that can be imaged.

Geostationary orbits--NASA's Advanced Technology Satellite (ATS) has demonstrated the value of a 35,000-km geosynchronous orbit, in which the satellite appears to hover "motionless" over a point on the Equator. The advantages of this type of orbit are:

1. The viewing station is constant.
2. About 1/6 of the Earth may be observed almost synoptically.
3. Observations, limited temporally only by sensor performance, can be more frequent, e.g., as often as every 15 or 20 min.
4. Pointable "telescopic" observations can be made of those areas where high resolution is required for detailed observations.
5. Time-lapse imagery of storms, floods, snow cover, etc., can be prepared to study the genesis and dynamic aspects of important hydrologic events.
6. The satellite can collect and relay data in real time from instruments located at remote inaccessible sites, upon command, 24 hr a day. Data readouts also can be programmed to coincide with scheduled detailed imagery.
7. Processed data products can be retransmitted via satellite from central processing and analysis centers to local forecasting or warning centers in near real time.

SNOW MAPPING

Basin mapping of percent of snow cover is believed to be accurate to 5% in either mountainous terrain or flatland basins with areas greater than 5,000 km^2 when the VHRR visible channel is used on cloud-free days.

Unquestionably, snow-extent mapping of basins is feasible as an operational technique (Wiesnet and McGinnis 1973). To be of greatest value to the hydrologic community, snow-extent mapping must be done on some type of river basin map at a suitable scale. Because the NOAA 3 VHRR transmits an unrectified

Table 1.--Satellite orbital parameters

Parameters	NOAA 2*	NOAA 3	ERTS 1
Altitude (above Earth surface).................	1464 to 1510 km	1500 to 1509 km	908 to 929 km
Inclination.................	101.7°	102.0°	99.1°
Nodal Period..............	115.14 min	116.19 min	103.28 min
Precession of Nodes........	0.9857° per day	0.9911° per day	1.43° per day
Equatorial crossing time... (southbound)	0851 local solar time	0830 local solar time	0942 local solar time
Coverage frequency.........	IR: 12 hr VIS: 24 hr	IR: 12 hr VIS: 24 hr	18 days

* From Schwalb (1972)
From A. Butera, NESS, personal communication
From General Electric (1972)

image, it must be rectified prior to mapping. A Bausch and Lomb Zoom Transfer Scope (ZTS) is an acceptable optical method of rectification, and the SRI console appears to be an acceptable electronic-optical method (Evans and Serebrey 1973). Sophisticated computer programs for automated production of snow-extent basin maps are possible and desirable, but none is known to be in use at this time.

The 1000-m resolution or "spot size" of the VHRR system tends to eliminate the problem of distinguishing the "true" snowline from intermittent patches of snow interspersed with bare ground (figs. 1 and 2). The shadow effect, in which a low sun angle can cause shadows that decrease the reflectivity of the snow in a steep-sided valley, and the vastly better resolution of ERTS are probably the reasons for VHRR snow-extent measurements being consistently smaller in area than ERTS 1 measurements (fig. 3). This effect will be more severe at higher latitudes. A third problem, and probably the most vexing, is the dificulty of detecting snow in heavily wooded areas, particularly in the coniferous forests.

The ERTS 1 satellite provides superb, sharp (80-m ground resolution) multispectral images for snow extent mapping (fig. 4). With these ERTS 1 images of unsurpassed cargographic accuracy one can quickly and easily map snow extent in basins as small as 272 km^2 (Meier 1973). Basins larger than 34,000 km^2 would exceed the size of one ERTS frame and present some mapping problems. For example, the first ERTS overpass over a basin might secure part of the desired imagery on a cloudless day. The following day might be overcast, so the ERTS would obtain no data on snow.

Other factors limiting the usefulness of ERTS imagery for snow studies are the 18-day revisit time and the long wait (30 to 60 days) from collection of data to receipt by the investigator. A quick-look capability, such as developed by the Canadians at their ERTS data collection site, would eliminate the second problem.

NASA's Nimbus 5 satellite, launched in December 1972, carries an Electrically Scanning Microwave Radiometer (ESMR) that is capable of measuring the Earth's brightness temperature--hence its snow cover--through almost any cloud cover. Ground resolution of the instrument ranges from 25 x 25 km to 45 x 160 km, thereby limiting the usefulness of this instrument--at least for snow mapping--to large-area studies.

In summary, plans for operational snow-extent mapping by satellite of certain selected river basins were implemented for the 1973-74 snow season at NOAA/NESS. The ZTS and the improved resolution of the VHRR made this possible. ERTS 1 has been and is extremely useful as a calibration tool. It has by far the best resolution of any environmental satellite. Snow extent mapping by satellite is today a viable technique for monitoring snow packs. As this is increasingly appreciated by hydrologists, we may expect to see a great deal of activity directed toward developing improved and automated techniques.

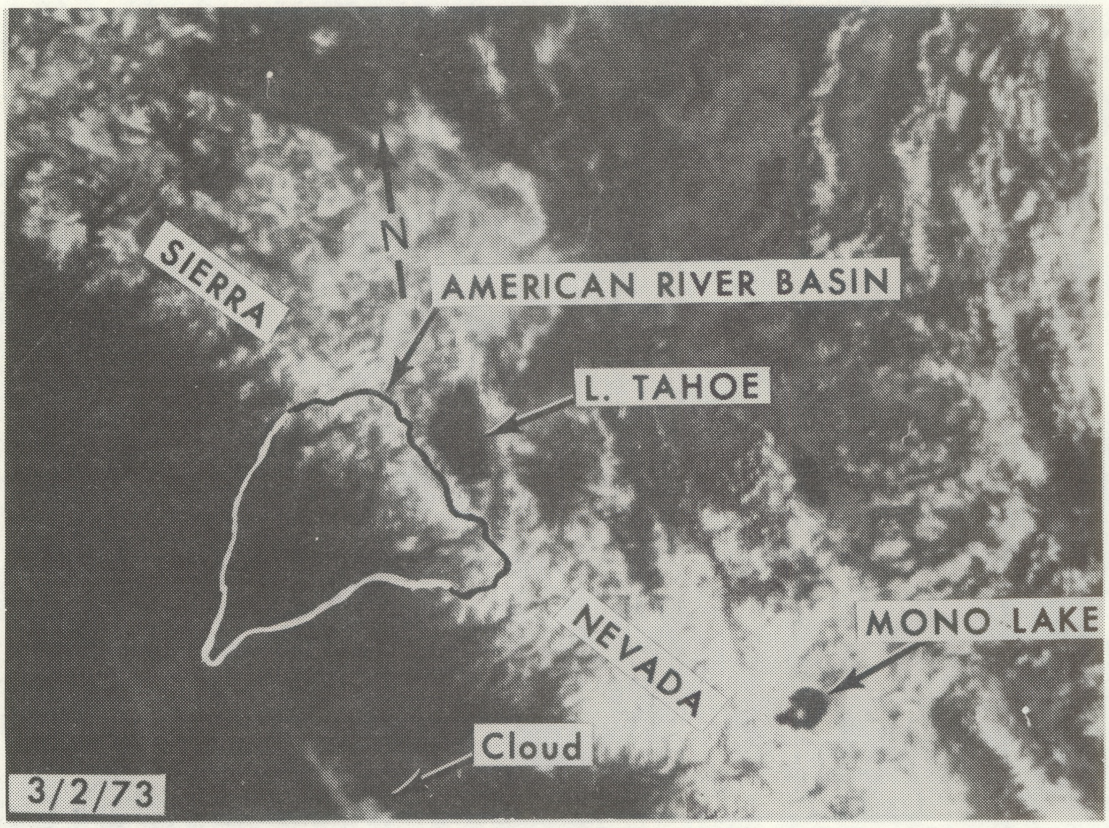

Figure 1.--Enlarged NOAA 2 VHRR-VIS image of the central Sierra Nevada, 1713 GMT, Mar. 2, 1973, orbit 1728 (recorded data). Figure 2 was prepared from this image, which is slightly distorted. Scale is about 1:4,000,000.

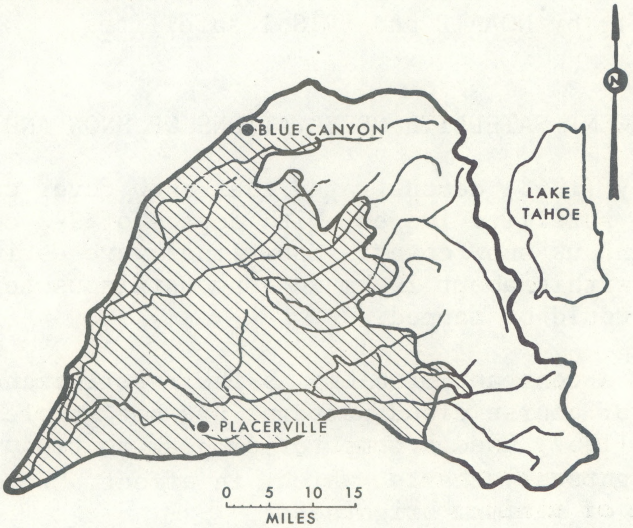

Figure 2.--Snow-extent map for the American River basin, Calif., prepared from NOAA 2 VHRR imagery shown in figure 1. Hatched area is snow free.

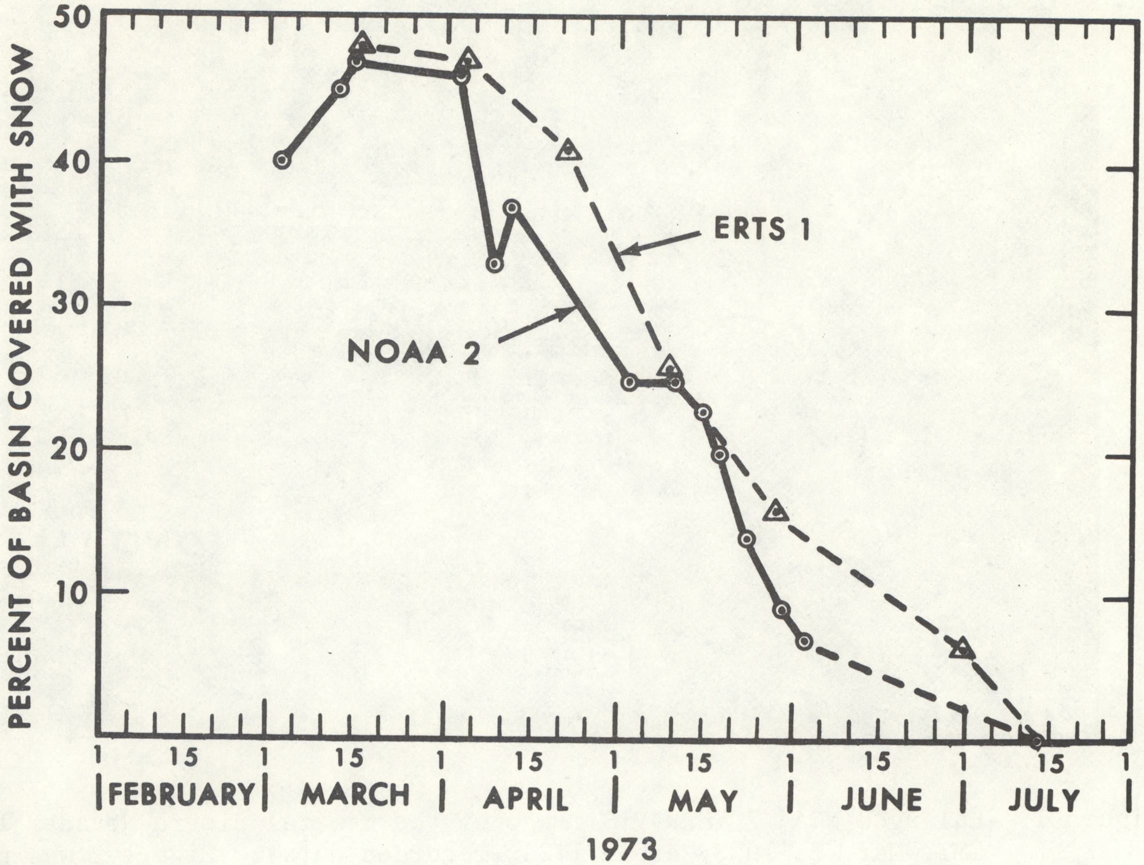

Figure 3.--Comparison of snow-extent mapping of the American River basin, Calif., by NOAA 2 and ERTS 1 satellites.

RECENT SATELLITE OBSERVATIONS OF SNOW AND ICE

Barnes and Bowley (1968) demonstrated that snow cover can be reliably identified from (ESSA) satellite images, with depths of 2-3 cm or more commonly appearing as continuous snow cover. Snow lines were estimated to be accurately located to within about 20 km in nonmountainous terrain. Basins as small as 1400 km^2 could be mapped.

Clouds have been a constant problem, as their reflectance commonly matches that of snow; but of course cloud patterns are not stable from image to image. McClain and Baker (1967) used a computer program to produce 5-day CMB (Composite Minimum Brightness) charts, which, in effect, "removed the clouds" by computer selection of minimum brightness.

Figure 4.--Mosaic of ERTS 1 images of Lake Erie showing ice coverage on Feb. 17-18, 1973. Air temperatures are below freezing everywhere. Ice cracks have occurred during the 24 hr prior to first pictures.

McClain (1973) in a comprehensive summary of satellite snow survey methods points out the chief problem is very often the location of the entire area to be mapped (the basin) rather than the extent of the snowline.

The NOAA 2 and NOAA 3 VHRR images have vastly improved our capability for mapping snow. These new operational environmental satellites have a 1-km resolution, i.e., 4 times better in the visible band and 10 times better in the IR than the previous series of satellites. By use of the Zoom Transfer Scope and the VHRR imagery (fig. 2), snow cover was mapped within several river basins (Wiesnet and McGinnis 1973) as a pilot study of snow-extent mapping in the American River basin of California in cooperation with the National Weather Service Office of Hydrology.

The plan was to prepare a map as soon as possible after the imagery was received using the ZTS, then measure areal extent of the snow, and finally, using the NWS telecommunication network, send the percent of basin covered by snow to the cognizant River Forecast Center (RFC). In this way, the RFC usually would get the data within 30 hr after the satellite passed over the basin. Our goal was to furnish data no more than 36 hr after satellite transit of the basin. Fourteen VHRR snow cover maps (fig. 2) and snow-extent measurements (fig. 3) of the American River basin were made in the spring of 1973.

About two man-hours were required to map snow extent in the American River basin (5,601 km^2). The same amount of time was required to map the Red River of the North, which is a 104,120-km^2 basin. In mapping the Red River of the North basin, the coniferous forest canopy problem slightly affected the snow-extent maps, although the problem is more acute in the Adirondack Mountains--which lie partly in the Lake Ontario basin--and in Canada. By carefully mapping the forested areas, which are mainly at the eastern edge of the basin, it was possible to extrapolate the snow extent into the forest. Conversely, determining whether the snow persists under the canopy subsequent to melting in the open fields is conjectural. Research directed toward devising methods of determining snow extent in regions of heavy forest canopy would be welcomed by all investigators.

COST COMPARISON OF SATELLITE SNOW MAPPING

At the request of the Director of the National Environmental Satellite Service, a comparison figure was calculated between the cost of satellite (NOAA 2) measurement of Sierra Nevada snow cover and the cost of conventional aircraft measurements. Assuming that 20 basins were of interest and that a simple altimeter survey would be done by a light plane, at least 40 hr of flying at a total cost of at least $20,000 would be required. Using satellite data, the entire Sierra block could be mapped in two man-days for a direct cost of about $200. This is a cost comparison ratio of 100:1.

ICE STUDIES OF THE GREAT LAKES

The ambitious International Field Year for the Great Lakes (IFYGL) has caused many hydrologists to realize that the use of satellite data is perhaps the only means to gather synoptic environmental data over a body of water as large as Lake Ontario. The VHRR thermal scanner aboard NOAA 2 could provide a thermal map of the lake every 12 hr. Cloud cover reduces the amount of useful data, but once-a-week cloud-free views are common. Upwelling water is easily detectable, snow extent can be mapped, and ice can be observed and measured. By using VHRR digital data and known water surface temperatures at a few locations, thermal maps can be prepared for use in evaporation calculations over the lake surface. Ice extent also may be measured to determine the lake's contribution to snow storm effects on the lee side of the lake. Ice conditions are also of great economic importance to Great Lakes shipping interests.

The mosaic of ERTS 1 images in figure 4 shows the ice on Lake Erie near Cleveland on Feb. 18, 1973, and near Buffalo on Feb. 17, 1973, in MSS band 7 (0.8 to 1.1μm). Air temperatures are below freezing but a moderate 5-mps (10 kt) wind has begun to break up the ice cover by moving it to the east.

MELTING SNOW AND ICE

Satellite detection of melting snow and melting lake ice, using visible and near-IR (0.8 to 1.1μm) data together, has been achieved; ERTS 1 and Nimbus 3 data were used (Strong et al. 1971, Wiesnet 1973). Although these multispectral techniques have permitted identification of melting snow, the relation of spectral reflectance of snow to type, age, and water equivalent of snow is not well known in general and is rarely studied. Recent (not yet published) work by H. W. O'Brien and Richard Munis, performed at the U. S. Army Cold Region Research and Engineering Laboratory under contract to NOAA/NESS, confirms these satellite observations. The need for basic studies of snow and ice reflectance and emission in various bands of the electromagnetic spectrum cannot be overstressed. Mistakes in interpretation and analysis of snow scenes cannot be avoided unless we know the emission and reflection characteristics of snow and ice under varying conditions.

There is considerable interest in developing a capability of measuring the percent of the snowpack that is melting at the surface. Whether this technique can be made operational and whether a sensor should be developed specifically for this application remain speculative questions.

SNOW THICKNESS

Brightness or reflectivity of snow has been related to snow thickness (Barnes and Bowley 1968, McGinnis and Wiesnet 1973) but this technique has limitations. Vegetation canopy, variable photographic processing, urban effects of buildings, age and condition of snow, refreezing, etc. are factors that influence reflectivity determinations and render most correlations speculative at best. Ground- or aircraft-based research on the "behavior" of snow reflectivity as snow accumulates, ages, and melts is minimal and further research should be encouraged.

WATER EQUIVALENT OF SNOW

A very dynamic parameter of ripening snowpacks is the water equivalent of the snow. It is also one of the most meaningful measurements that the operational hydrologist can have. Despite some encouraging progress in passive microwave experiments (Meier and Edgerton 1971), no satellite technique for determining water equivalent is yet available. Peck, et al. (1971), however, using aircraft flying at low altitudes (90 m) have made areal surveys using sensitive scintillometers to measure water equivalent values. Bissell and Peck (1973) described a ground station instrument that could measure water equivalents and telemeter that measurement to a receiving station via a geostationary satellite (GOES) upon command. Ten such instruments in the Sierra Nevada would go a long way toward ameliorating the lack of data from remote sites.

CONCLUDING REMARKS

Earth-orbiting polar satellites are desirable platforms for remote sensing of snow and ice, for use as relay stations for telemetering commands and data, and for collection of data on spectral reflectivity and infrared and microwave emissions. Hydrologists, in general, are unfamiliar with satellite data, and are waiting to be convinced of the utility and reliability of satellite data. Yet, satellites have a demonstrated capability for mapping snow extent in small-scale (1,000 km^2) basins and in mesoscale (10,000km^2) basins. During the melt season, weekly snow-extent measurements by VHRR are feasible in many areas. ERTS data have been related to meltwater runoff curves (Meier, 1973); VHRR data ultimately will be so related. Knowledge of this relation can benefit all water users as well as flood forecasters. The ERTS and NOAA 2 satellites truly present a golden opportunity to the hydrologic community to plan and carry out an improved program of satellite snow and ice observations. The capability for snow mapping exists; only the commitment is lacking.

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