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EVALUATION OF ERTS IMAGERY FOR MAPPING AND DETECTION OF CHANGES OF SNOWCOVER ON LAND AND ON GLACIERS

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ABSTRACT

The percentage of snowcover area on specific drainage basins was measured from ERTS imagery by video density slicing with a repeatability of 4 percent of the snowcovered area. Data from ERTS images of the melt season snowcover in the Thunder Creek drainage basin in the North Cascades were combined with existing hydrologic and meteorologic observations to enable calculation of the time distribution of the water stored in this mountain snowpack. Similar data could be used for frequent updating of expected inflow to reservoirs. Equivalent snowline altitudes were determined from area measurements. Snowline altitudes were also determined by combining enlarged ERTS images with maps with an accuracy of about 60 m under favorable conditions. Ability to map snowcover or to determine snowline altitude depends primarily on cloud cover and vegetation and secondarily on slope, terrain roughness, sun angle, radiometric fidelity, and amount of spectral information available. ERTS imagery was also used to measure glacier accumulation area ratios, detect subtle flow structures on glaciers, identify surging glaciers and monitor changes in tidal glacier termini.

No operational method now exists for monitoring the varying extent of mountain snowcover. Satellite imagery has well documented potential to do this under certain conditions; in fact snow on land is one of the most striking features to be seen on satellite images. Since it is obvious that snow can be identified and measured on satellite images this paper will explore the usefulness of ERTS-type snowcover data to scientific and operational aspects of the management of water resources. Only a few selected examples can be presented. Some interesting applications of these data to the study of glaciers will also receive mention. The data and conclusions presented here are based on a limited sample of data for calibration, measurement, and analysis. Thus these data and conclusions are considered preliminary.

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1. MEASUREMENT OF SNOWCOVERED AREA

Routine measurement of snowcover on satellite imagery must be done by machine if it is to be of operational value; hand planimetering or dot-counting the highly intricate snowline is prodigiously time consuming. Also, measurement of the total snowcover shown on any certain image is of limited value; the hydrologist needs to know the snowcovered area in specific drainage basins. This requires precise registration of the imagery to a map.

We approached these problems through the use of the Stanford Research Institute electronic console ESIAC. Drainage and drainage basin outline maps of the North Cascades were superimposed and reduced to 70 mm positive transparencies. EPTS images were then registered to these maps, using the drainage pattern as a convenient guide for registration. The non-pertinent image area outside of the drainage basin was removed through use of an opaqued mask. Obvious shadows on snow were brightened with a cursor or measured separately. Image enhancement using several spectral bands to form a color presentation was used to refine the video brightness level coinciding most closely with the snow/no-snow boundary. The displayed region having a brightness higher than this level was then identified as the snowcover and a quantitative value of area of snowcover was simultaneously read out on another display. With only very general instructions operator variance was 8 percent, but after coordinating evaluation criteria operator variance reduced to 4 percent of the snowcovered area (less than 1 percent of most of the drainage basin areas).

Unfortunately, time has not allowed accurate calibration of brightness level in terms of known snow/no-snow boundaries. Thus the snow area data obtained with the ESIAC contain a small absolute error, and some slight discrepancies occur when comparing ERTS data with high-resolution aircraft data. This error will be reduced or eliminated in the next stage of the investigation when more attention will be given to calibration.

Through the study of many images, it appears that the ability to map snowcover depends primarily on cloud cover and vegetation, and secondarily on slope, terrain roughness, sun angle, radiometric fidelity of image, and amount of spectral information available. It is difficult for an experienced observer to distinguish some types of cloud or fog from snow even with all possible radiometric information, or to distinguish the snowline in forested terrain. In rough terrain, bare ground facing the sun may be lighter in tone than snow in shadow causing difficulty in identification, and this problem is intensified with low sun angle or longer wavelength sensors. Fully automatic mapping of snowcover in forested or mountainous terrain appears at this time to be impossible. Human eyes and brain control the analysis procedure, but this can be done quickly and efficiently with an interactive console such as the SRI ESIAC.

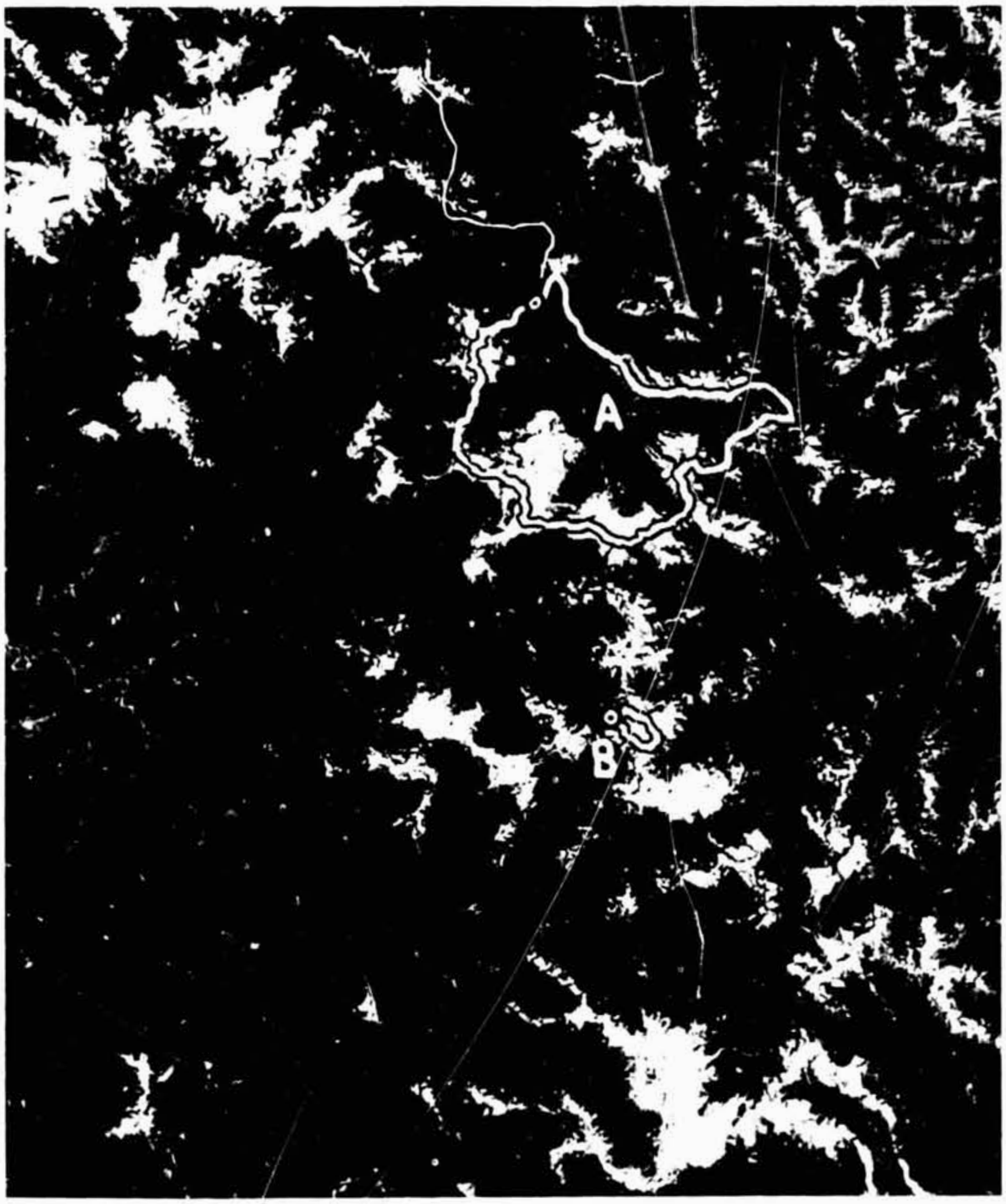

Figure 1.--2 September 1972 ERTS-1 image 1041-18253-4 of part of the North Cascades, Washington. The drainage basin Thunder Creek near Newhalem is indicated by A, *and the basin South Fork Cascade River at South Cascade Glacier is indicated by* B.

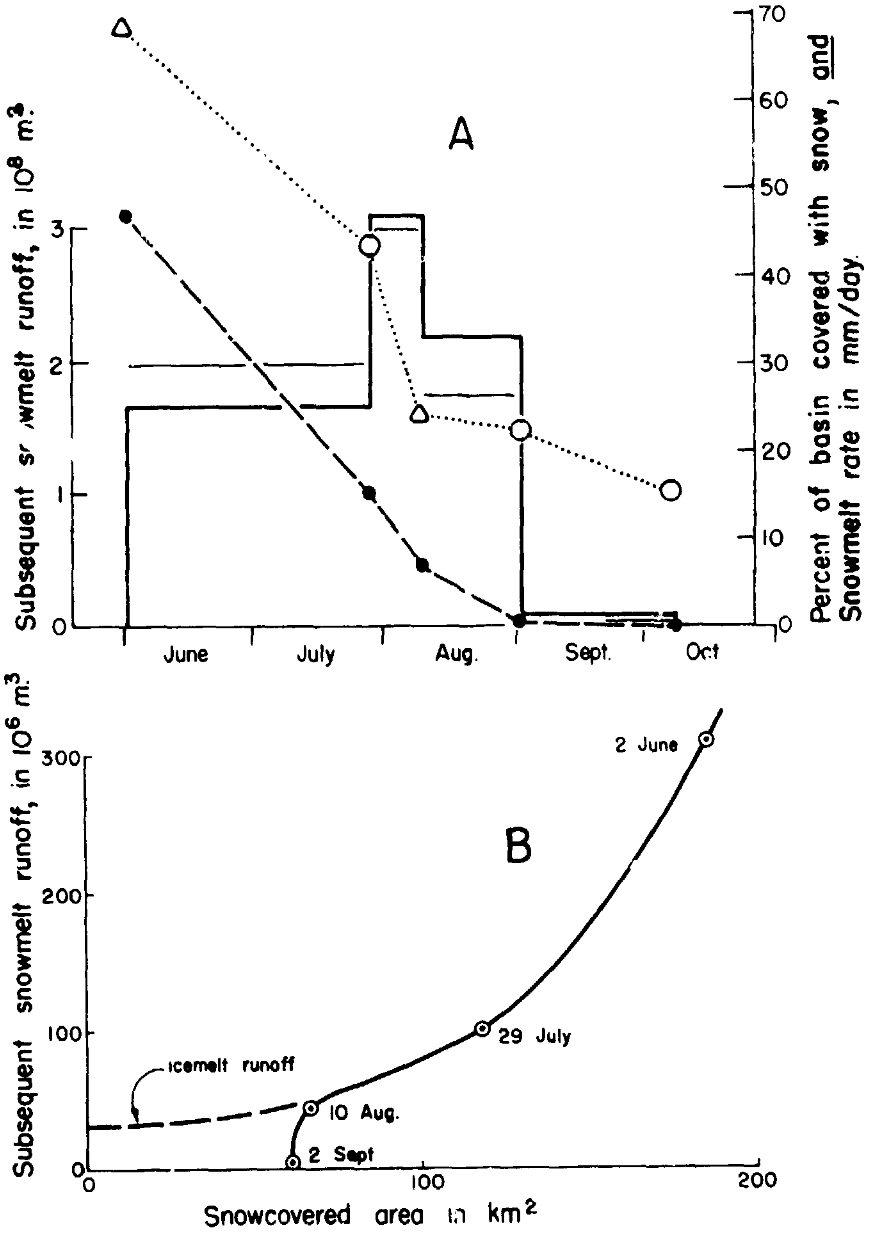

Figure 2A.--Snowcovered area (dotted line), subsequent snowmelt runoff volume (dashed line), and rate of snowmelt (heavy line) in the Thunder Creek drainage basin; thin line is average observed snowmelt rate. Triangles are data from 19.8 km altitude aerial photographs; circles are data from ERTS-1. B.--Subsequent snowmelt runoff as a function of snowcovered area, Thunder Creek drainage basin.

2. HYDROLOGIC ANALYSIS USING ERTS DATA

In the mountain west, most of the streamflow results from snowmelt. Therefore much effort has gone into the use of snow data in operational hydrologic procedures. Some of the newer procedures attempt to use snowcovered area as a variable or parameter. Empirical correlations between snowcover and runoff have been incorporated into computerized models for the continuous simulation of streamflow, such as the SSARR model (Rockwood, 1964; Schermerhorn and Kuehl, 1968). Snowcover data are also used to forecast subsequent runoff volumes (Parsons and Castle, 1959; Thoms and Wang, 1969; Leaf and Haeffner, 1971). These schemes, however, are strictly limited by the high cost of obtaining and analyzing aerial photographs at frequent intervals over large drainage basins. Can ERTS-type imagery fill this need?

In order to explore this problem, an analysis was made of three ERTS and two high altitude aircraft images of the drainage basin Thunder Creek near Newhalem, Washington (Fig. 1). Some results are presented in Figure 2. Snowmelt runoff from this 272 km^2 basin is utilized for the generation of electric power at Diablo and Gorge Dams on the Skagit River. Measurement of snowcovered area was done from ERTS images by SRI personnel on the ESIAC, and from high altitude aircraft photographs by USGS personnel. The snowmelt runoff and loss of snow mass were computed by a hydrologic balance procedure developed for the analysis of International Hydrological Decade glacier basins (Meier, Tangborn, Mayo, and Post, 1971; Tangborn, 1968) using hydrologic data gathered at the Thunder Creek gaging station and precipitation from nearby weather stations. These data were used with the ERTS and aircraft snowcover results to calculate the rate of snowmelt (in mm of water equivalent) in the Thunder Creek drainage basin. The calculated snowmelt rate is compared in Figure 2 with the actual melt rate observed at the index station P-1, altitude 1,890 m, on South Cascade Glacier which is 15 km south of Thunder Creek.

It is significant that the ERTS data can be used to compute other important hydrologic quantities, such as melt rate, and the results can be approximately verified by comparison with totally independent observations. Snowmelt rate is extremely difficult to measure at frequent time intervals (such as daily or weekly) at single points without very sophisticated and expensive instrumentation such as radioactive twin-probes. Snowmelt averaged over a large area is essentially impossible to measure directly with existing techniques. Yet a simple calculation using standard real-time hydrologic data combined with satellite imagery provides these results. In midsummer of 1972 the Thunder Creek snowpack changed area at a rate of about 1.6 percent per day; useful snowmelt data should be calculable for periods as short as 3-5 days if one assumes a 4 percent standard error in each area measurement.

Changes in snowcovered area in a specific drainage basin can be determined quickly with an electronic console, and Figure 2 shows that the resulting values are consistent with laboriously planimetered aircraft data. Thus a method now exists for frequent, routine, and confident measurement of area of snowcover. The plot of snowcovered area versus subsequent runoff volume might be directly useful to continuously update reservoir inflow forecasts. Past experience using aerial photographs to measure the depletion of snowcovered areas indicates that "Snow depletion rates are highly correlated with seasonal generated runoff volumes. Furthermore, the general shapes of the curves have been fairly uniform from year to year, even though the amount of snow and weather conditions which produced runoff were not the same" (Leaf, 1967). Thus when the form of this graph is established, quick measurements of snowcovered area can be immediately converted to snowpack storage and streamflow forecasts. ERTS-type satellite imagery combined with an interactive console such as ESIAC could thus yield data on expected reservoir inflows at low cost or could be combined with other simulation or numerical modelling procedures to improve forecast accuracy. This would result in more precise regulation of reservoirs, less waste of water, the sale of additional firm power, less need to put additional ground installations in wilderness watersheds, and less damage to the valley and river environment from excessively high or low streamflows.

3. ALTITUDE OF THE SNOWLINE

The locus of lowest altitudes of a mountain snowpack often approach a plane; thus a measure of the altitude of this plane defines the extent of the snow. Furthermore, this parameter may be more useful than the total area of snowcover when making comparisons between drainage basins or mountain massifs because it is less affected by lowland area or topography. However, actual snowlines are usually intricately convoluted with some bare ground at highest altitudes and some avalanche-deposited snow at altitudes much lower than the bulk of the snowcover. Measuring the mean altitude of the snowline is usually laboriously difficult.

To avoid this problem a new parameter is here defined: the equivalent snowline altitude (ESA) is that altitude above which the drainage basin area exactly equals the area of snowcover. (The area/altitude functions for most basins of hydrologic importance are known.) In Figure 3 are plotted values of ESA as determined from ERTS and aircraft photography for different times during the summer and fall of 1972. These data are from very different types of areas--two are in the North Cascades and one is in the Middle Cascades. One is a tiny basin (South Fork Cascade River, 6 km^2) with limited altitude span, one a large area (Mount Rainier, 1,228 km^2) with altitude differences exceeding 4,000 m. Yet the absolute values and the changes in ESA with time are reasonably consistent.* Although three areas is an insufficient sample for convincing results, ESA appears to be a useful parameter for extending snowcover data.

*The 2 June value for South Fork Cascade River is anomalously high because this basin has no area below 1,613 m, and the 8 October value is low because of limited area above 2,000 m.

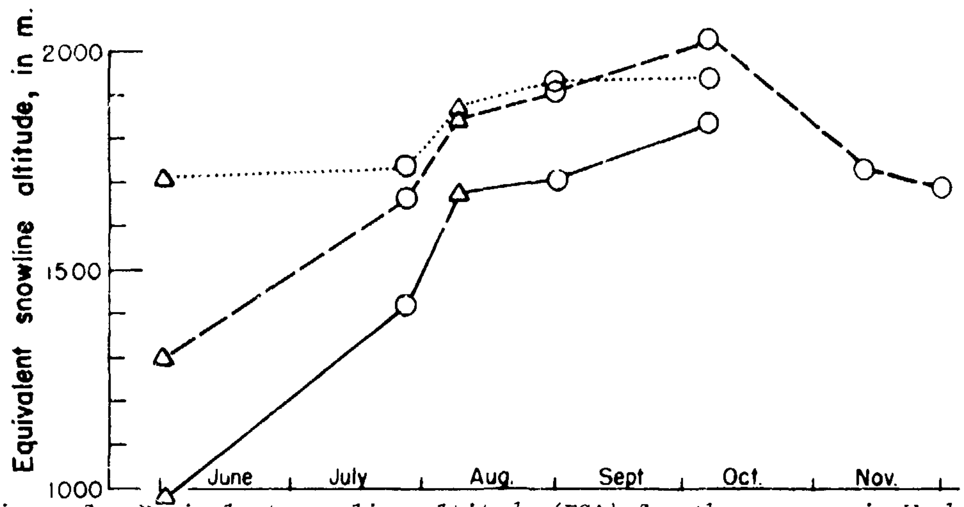

Figure 3.--Equivalent snowline altitude (ESA) for three areas in Washington: solid line, Thunder Creek drainage basin; dotted line, South Fork Cascade River at South Cascade Glacier; dashed line, Mount Rainier. Triangles are data from 19.8 km altitude aerial photographs; circles are data from ERTS-1.

Local snowline altitudes can also be obtained by superimposing a topographic map on ERTS imagery. An example of this is the following measurement of a 27 September image of the Anchorage, Alaska, vicinity, in which the snow margin is far more obvious than the snowline on the North Cascades image. This exceptionally sharp snowline was due to a storm the day before (18 mm of rain at Talkeetna) with the freezing level at 1,200 to 1,500 m above Anchorage. The snowline altitude is related to, but slightly lower than, the freezing level in the free atmosphere. Local snowline altitudes were measured by enlarging the ERTS image to 1:250,000 and using a transparent map overlay (Fig. 4). In this area the snowline altitude ranges from less than 400 m near Prince William Sound to highs of over 1,200 m west of Kenai Lake and in the higher parts of the Chugach Mountains. The freezing level was therefore lowest along the coast and highest further inland. Depressions of the freezing level parallel to the long valleys of Turnagain Arm, Port Wells, Nellie Juan River, and near Lake George are particularly striking.

Over most of the area shown in Figure 4, the altitude of the snowline could be determined with confidence to the nearest contour on the map (contour interval 200 ft = 61 m). In some local areas the snowline could not be mapped without considerable subjective decision and large variations were found between operators and between spectral bands; however, the snowline altitudes could invariably be determined to within 200 m.

Perhaps the greatest problem in understanding and monitoring mountain meteorology and hydrology is difficulty in obtaining mesoscale meteorologic information, because the mass and heat flux patterns are so complex and data gathering stations are so few in number. If mesoscale

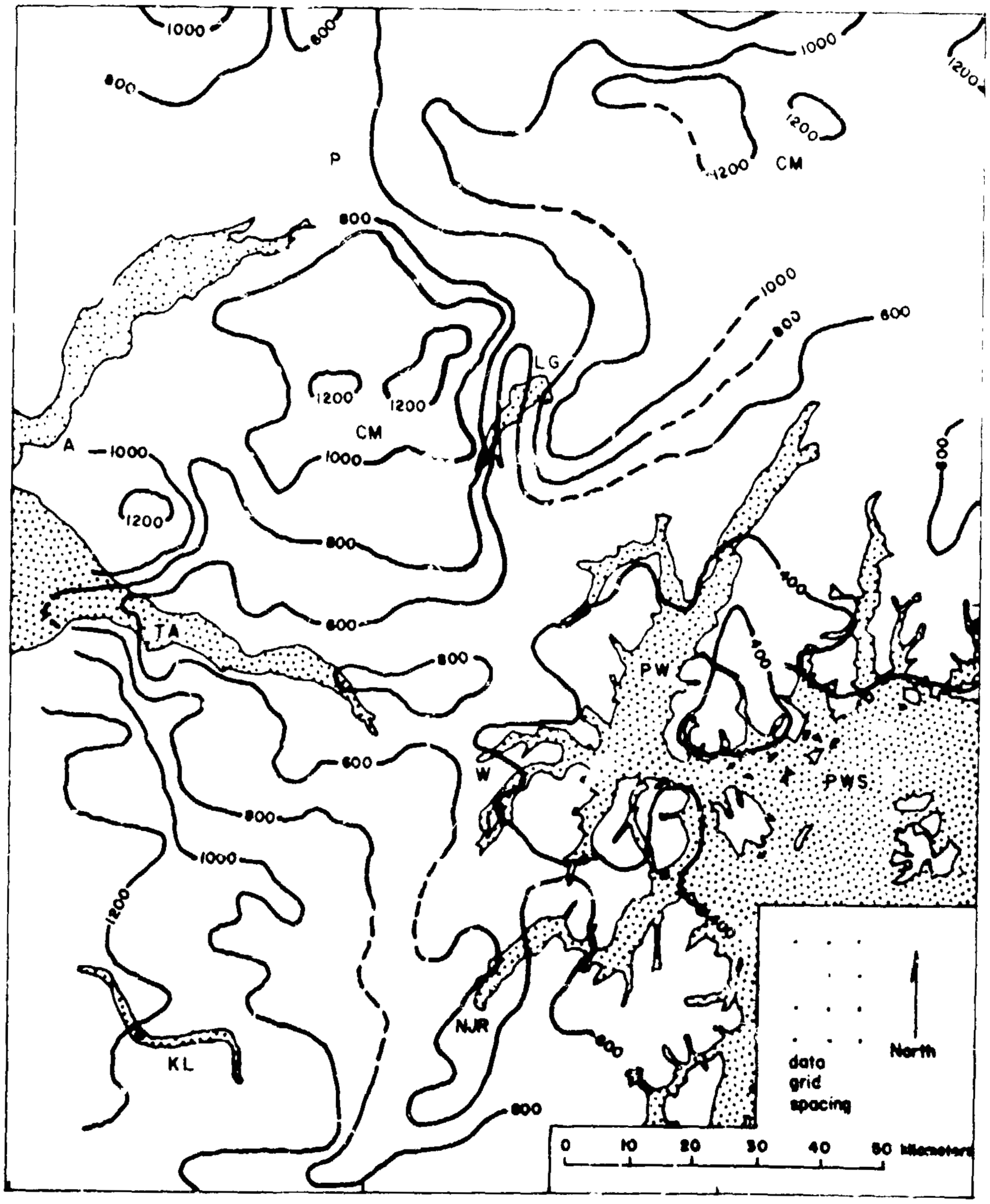

Figure 4.--Map showing the altitude of the snowline in the Anchorage area, Alaska, 27 September 1972. Data derived from ERTS images 1077-20451 and 1066-20453. Locations indicated as follows: A Anchorage, P Palmer, W Whittier, TA Turnagain Arm, CM Chugach Mountains, KL Kenai Lake, NJR Nellie Juan River, LG Lake George, PW Port Wells, PWS Prince William Sound.

variations of simple meteorological parameters could be measured, we could gain far better understanding of this problem. Thus the ability to derive synoptic mesoscale freezing level information from ERTS imagery such as Figure 4 is highly significant. A thorough analysis of the results shown in Figure 4 together with other meteorological data is now underway.

Knowledge of freezing level variations is of obvious direct importance to the utilization of the snow-water resource. In much of the mountain west, the quantity of snow produced and stored from a given precipitation event depends on the freezing level in the mountains. These data are not usually available from meteorological installations, which are generally located in lowland areas far removed from the mountains. Thus the ability to read freezing levels in the mountains from satellite imagery could be of immense operational value.

4. ACCUMULATION AREA RATIO

Snowlines on glaciers were found to be remarkably easy to identify, although alteration of the gray scale values on the bulk imagery was sometimes necessary. Thus it appears possible to rapidly determine the accumulation area ratio (AAR) from a large number of glaciers using ERTS imagery. This is important because the AAR has been proven to be a useful index to the mass balance of a glacier. By measuring the distribution of AARs at a given time in a given region and relating these to the data obtained at a glacier research station in the region, one can extend micrometeorological point measurements to meso- and even macroscale meteorological conditions. This is a necessary step in the complete understanding of glacier meteorology, a step which has been hitherto difficult to achieve.

A question arises, however, whether the resolution of ERTS imagery is sufficient to determine AARs from small glaciers (less than 10 km^2), which are most prevalent. In order to answer this problem, nine independent measurements were made for three different dates of the AAR of the small South Cascade Glacier basin (6.1 km^2) using enlarged ERTS images. The standard deviation of individual values from the means for that date was 3.4 percent. Although it has not yet been possible to check the error of the means with ground truth, AARs derived from high altitude aircraft photographs indicate that the error is less than 10 percent. Thus this powerful tool appears to be feasible even in areas where the glaciers are small.

5. OTHER GLACIER OBSERVATIONS

Other features on glacier surfaces appear in ERTS-1 imagery; some of these are surprising because they have not been observed on vertical or oblique aerial photography taken over a period of many years. One example is an interesting structure recognized for the first time on ERTS images of Bering Glacier. Just below the firn line the ice from the two main snowfields of the Bagley Icefield merges from east and west and then bifurcates, the Bering Glacier flowing southwest and the Tana Glacier northwest (Fig. 5). This situation results in a curious flow pattern

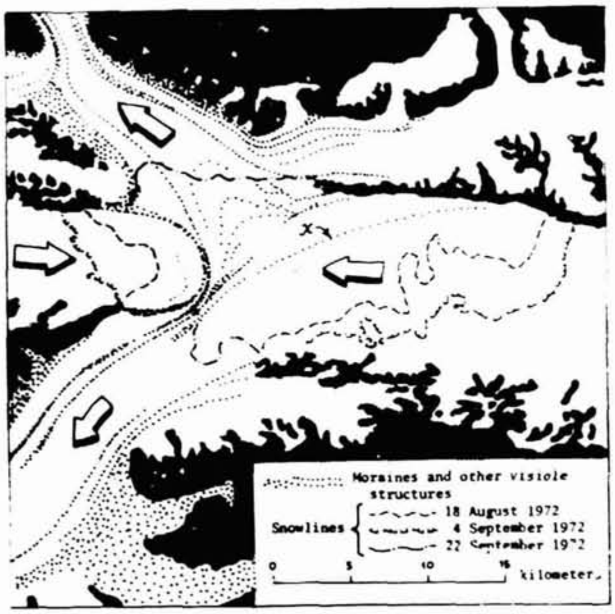

Figure 5.--Moraines, other structures, and snowlines at the juncture of the east (left) and west (right) arms of the Bagley Icefield, the Tana (upper left) and Bering (lower left) Glaciers. Arrows indicate ice flow direction. Structure labeled x is discussed in text.

which is further complicated by the fact that the Bering Glacier surges whereas the Tana evidently does not. During the surge phase additional ice must flow into the Bering lobe. The ERTS images show in remarkable detail what are probably very faint dust bands and medial moraines on the ice which, in turn, disclose directions of ice flow. A faint structure labeled x on Figure 5, probably inherited from the 1965-66 surge, suggests that during surges all of the ice from the western Bagley Icefield is channeled to Bering Glacier. When this lobe of ice begins moving into the Bering Glacier a rapid advance at the terminus, some 80 km distant, may be expected to occur three years later. Here is an example where space imagery has proven valuable to detect subtle features of such vast scale as to be unrecognizable from the ground or aircraft. There is practical importance to this: the forthcoming outburst of the large Berg Lake and other likely changes in drainage depend on the changing flow regimes of Bering Glacier, which can be understood through study of features such as this.

Surging type glaciers can be identified and large glacier surges can be monitored using ERTS imagery. For instance, the 1972 surge of the Yentna Glacier is plainly visible on ERTS imagery, and its folded moraines have been displaced more than 1,800 m down valley from their positions shown on recent maps and 1970 aerial photographs. Also visible on the ERTS image is a dark line where the rapidly flowing Yentna Glacier has sheared across the stagnant ice of the Lacuna Glacier. The causes of glacier surges--and why some glaciers surge while others do not--are questions of great scientific interest as this type of periodic sudden slippage is common to many other phenomena in nature, perhaps even to the mechanism of earthquakes. Surging glaciers may advance over large areas and cause devastating floods by blocking and suddenly releasing large quantities of meltwater; thus there is much practical interest in monitoring their behavior.

ERTS satellite images also show sequential changes in the termini of large Alaskan tidal glaciers. One particularly important example is the Hubbard Glacier. It has been advancing since first observed in 1890 and in recent years has threatened to close off Russell Fiord, which would then become a fresh-water lake and its outflow to the south would disrupt fish and game resources along the Situk River near Yakutat, Alaska. Previous to imagery from space, no scientific observations have been available in this remote area in winter. ERTS images (Fig. 6) show that a

Figure 6.--Changes in terminus of Hubbard Glacier from 20 September (left) to 8 October (right). Terminus is 11 km wide. Image 1059-20052-6 (left) and 1077-21020-4.

large embayment doubled in size in only 18 days. This represents a loss of approximately 3 km^2 of the area of the terminus during this period, a loss in area greater than ever before observed in an Alaskan glacier in so short a time. ERTS imagery, by allowing glaciologists to observe sequential changes in the Hubbard's terminus, will make possible more accurate predictions as to when the Russell Fiord closure will take place.

6. CONCLUSIONS

The potential ability to map snowcover from satellites has important practical and scientific ramifications. Much of the streamflow in the mountain west originates as snowmelt. The measurement of these snowpacks provides data on spring and summer streamflow into hydroelectric, flood control or irrigation reservoirs, and efficient regulation of these reservoirs requires accurate, real-time data. The monetary value of these data is appreciable: it has been reported that the electric power utility in a single city in the Northwest realized savings of about 1M$ the first year that data from four new snow courses were incorporated in the operational program. A report on the predicted usefulness of an earth resources satellite for water management in the Columbia Basin indicates multimillion dollar yearly savings through reduction of hedge by use of satellite snow data (Planning Research Corporation, 1969). Environmental savings are also appreciable: accurate forecasts of streamflow and reservoir inflow permits minimizing damage due to excessive or deficient outflow. At the present time, snow can be accurately measured at points, but no operational means exists to monitor its areal extent.

Another reason for urgency in developing operational remote sensing techniques in the western mountains is the Wilderness Act. Precipitation rates and snowpacks are highest in the high altitude alpine areas, and here water losses are minimal. Thus a large fraction of the total streamflow originates from these areas. Most of the high mountain area is also designated or *de facto* Wilderness, either in National Forests or National Parks. The Wilderness Act specifically prohibits installations; thus there can be no ground measurement of this important water resource.

These experiments with ERTS-1 imagery indicate that satellite monitoring of the areal extent of mountain snowcover, during late summer at least, may be feasible in certain limited situations. In cloud-free conditions with little vegetation hiding the snow, an ERTS-type system will provide data of immediate operational utility. On the other hand, vegetation and clouds are apt to seriously interfere with the information transmitted much of the time. Only a system using passive (or active?) microwave radiation has the potential to monitor the snow under all conditions. An ultimate snow monitoring satellite may well combine visible light sensors such as those on ERTS-1 with microwave radiometers, in order to add occasional high resolution images to the all-weather information flow from the lower resolution radiometers.

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