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AN ALL DIGITAL APPROACH TO SNOW AREAL MAPPING AND SNOW MODELING

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ABSTRACT

A study has been undertaken to incorporate remote sensing data into a spatially distributed model of snowpack evolution. Preliminary results are presented on the estimation of primary parameters needed in such a model.

INTRODUCTION

In many areas of the world, as well as in California, it is necessary for the management of water resources to evaluate and predict snowmelt, an important input to hydrologic systems and models. We note that the physical basis and the mechanisms of snow ablation have been understood and modeled for a number of years [1,2]. These physically based models have been verified experimentally on a local scale using a snow lysimeter installed in the Andes Mountains in Chile by Amorocho and Espildora. They obtained good agreement between model prediction and experimental data. The same physical elements are used in the spatially lumped snow submodels of watershed hydrologic models such as the Sacramento RFC model, developed by Burnash and his associates [3,4]. However, information about the snowpack is sparse and difficult to obtain. Since the important physical parameters which determine the evolution of the snowpack vary substantially across a watershed, there are difficulties in the development, calibration and operational use of a spatially distributed, physically meaningful snow ablation model.

A number of studies on the areal mapping of snow using remote sensing have been undertaken in the last few years [5,6,7,8] which have evolved into a NASA sponsored handbook of techniques for satellite snow mapping [9]. Most of this work is directed to the estimation of the areal extent of the snowpack and attempts are now being made to incorporate such data into empirical ("rational") snowmelt runoff models.

In our work we have undertaken the incorporation of satellite into a physically based, distributed model of snowmelt to be used eventually for runoff prediction. We approached this work by the determination of the physical quantities which are of prime interest in the modeling of basin wide snowmelt. Precipitation, temperature, albedo, wind speed, relative humidity and cloud cover

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are the physical parameters which determine the evolution of the snowpack. We have obtained some partial results on the determination of some of these parameters by remote sensing. Thus this paper takes the form of a progress report and outline of our work.

Because of the time scale of the dynamics of the snow ablation process we are using NOAA-3 and NOAA-4 data, which is available every day, as well as Landsat data. A very large part of our time has been spent gathering a snowmelt season, April 1975 to July 1975, of NOAA data for California and coming to grip with a number of important auxiliary data handling problems such as radiometric correction and calibration and geometric correction. Since these problems are at the heart of the quantitative use of satellite data, we discuss briefly, in the next section, their importance in this work and the results and techniques available for their solution.

DATA GATHERING AND CORRECTION

Since the snowpack evolves quite rapidly it appeared to us from the start that we needed in our work the frequency of coverage provided by the NOAA-3 and -4 satellites. Further, at this time, only the NOAA satellites provide data in a thermal IR band as well as in a visible band. We thus proceeded to gather all usable data collected by the NOAA-3 or NOAA-4 satellites over California, both in the visible and in the thermal infrared, from April 1, 1975 to July 8, 1975. More than 20 dates are available, corresponding to more than 40 digital tapes, recorded by NOAA at 1600 bits per inch (BPI). The data had to be converted to 800 BPI before we could make use of it. The volume of data to be handled and the reformatting needed are serious limitations at this time in the quantitative use of the data from NOAA satellites. Still, the data was available very rapidly at the NOAA-NESS satellite field receiving station in Redwood City and thus rapid access to the data for operational uses is possible.

Radiometric Calibration and Correction

Very few people, up to now, have made quantitative use of NOAA data and thus the information available on the calibration procedure and on the correction of deterministic errors in the data is fragmented and inadequate.

We have to mention first the difficulties in the calibration procedure, that is to say in the conversion of the numerical value or counts, provided on digital tape into temperature or brightness values, as recorded by the satellite. This calibration procedure contains still some uncertainties and inconsistencies which will require elucidation. Although formally calibration could be different for each scan line of the data, we have found that for an area of the size of California, the data correction is essentially constant for the whole area for any single pass of the satellite.

The limb darkening correction is a deterministic data correction for atmospheric effects. As the nadir angle of the satellite sensors varies during a scan line, the effects of the atmosphere will also change. In the thermal band the correction needed is discussed by Smith et al [10] and we used a semiempirical formula also used by Merrit and Stevenson [11]

$$\Delta T = (-26.81 + 0.107T)e^{0.00012\phi^2}$$

in which ΔT is the correction to the recorded temperature T(°K) and ϕ is the nadir angle (°arc). For nadir angles of less than 30°, the angular correction is of second order. Random radiometer errors and banding or stripping errors are also present in the data. We have developed a two dimensional filtering program which substantially reduce these errors. These errors are severe only for thermal infrared data acquired by NOAA-4.

Geometric Correction

Because of the highly distorted view of the earth provided by the NOAA and to a lesser extent by the Landsat satellites, geometric correction of the data is mandatory. This geometric correction is needed for one of two purposes. The first one is in order to obtain satellite data for a ground truth station. The second one is needed to transform satellite data into map compatible data. For both purposes we have made use of a least square fitting program using biquadratic fitting polynomials. At least six ground control points are needed for this geometric correction. Because of the difficulty of locating land features on NOAA-3 or NOAA-4 images one has to use an area at least as large as the State of California in the correction procedure. At this time we have residual geometric errors of the order of 2 pixels. These residual errors result in a fundamental limitation on the fininess of the distributed model which can be developed.

ESTIMATION OF THE SNOWPACK ALBEDO

The albedo is a very important parameter to the dynamics of snowmelt. The albedo is generally quite high for new fallen snow and decreases fairly rapidly after a snow storm. The snow albedo depends primarily on the surface conditions of the snowpack. Based on an analysis of the physics of snowmelt, or on empirical observations, models have been proposed for the evolution of the albedo with time. We shall mention the albedo curves based on a study made at the Central Sierra Snow Laboratory by the Corps of Engineers [1]. These curves are shown in Figure 1. We also show in Figure 1 experimental values obtained at the Central Sierra Snow Laboratory during January 1975. The trend of the experimental curve matches well the standard curve proposed but the absolute values are significantly in error.

Several questions are of interest in the use of remote sensing for the estimation of albedo. First, we note that the albedo is the fraction of incident energy reflected by the snow.

Since satellite sensors measure the energy reflected in narrow spectral bands, it is not clear that any single band in the visible wavelength range or in the near-infrared is a good indicator of albedo. Some experimental results have been presented by O'Brien and Munis on the Red and Near-Infrared Spectral reflectance of snow [12]. Their results indicate that the spectral reflectance scales down in a fairly uniform way across the wavelength range in the near infrared but that this may not hold in the visible spectrum.

To proceed with a study of brightness values recorded by a satellite and their correlation with albedo values, we need ground truth on the albedo measured at ground stations.

To our knowledge, the only location in the Sierra Nevada where albedo is recorded is at the Central Sierra Snow Laboratory (CSSL) in Norden, California. The laboratory is in a clearing a few hundred feet wide in a forested area. Thus, the CSSL can be fairly precisely located on Landsat data but not on NOAA-3 and NOAA-4 images which have a resolution of 0.9km. A preliminary comparison of known albedo with the digital values recorded in the visible band by the NOAA-3 satellite indicate a very low correlation, if any, between the albedo and the recorded brightness. This lack of correlation may be due to the specifics of the location of the Central Sierra Snow Laboratory mentioned, with additional errors in obtaining the proper remote sensing data for the laboratory since geometric correction of the data is required. At this time, Landsat data is not available at suitable dates to allow the observation of curves such as shown in Figure 1. We are planning to use the infrequent Landsat data in a statistical correlation with albedo ground truth at CSSL. On the basis of the results of O'Brien and Munis [12], we expect that Landsat spectral band 7 may be a good indicator of albedo. We shall pursue studies with NOAA-3 data in the visible range.

Another possible use of remote sensing data in the study of albedo is to consider the spatial variation of reflectance across the snowpack as an indicator of variation in albedo. By analyzing the brightness values recorded by the NOAA-3 satellite in the visible spectrum we find in all cases that brightness covers a broad range of values across the snowpack. Since the reflectance of snow is similar for source-detector angles ranging from 0 to 30° [12], it seems that the variation in brightness in nonforested areas must be attributed mainly to differences in the evolution of snowpack with elevation, temperature, etc.

We shall proceed with our investigation by combining remote sensing data during the snow season with other data on relief and vegetation cover. Additional ground truth information on albedo is needed for continuation of our work.

ESTIMATION OF TEMPERATURE FIELDS BY REMOTE SENSING

Another important parameter which determines the evaluation of the snowpack, is the temperature. The temperature varies during the day at any specific location and also with geographic location at any given time. One can hope to obtain by remote sensing a snapshot of the temperature field across the snowpack at the time of overflight by the satellite. Under the best of conditions, one would obtain a detailed absolute temperature field. At the least, one would like to obtain relative temperature information for portions of the watershed with different elevations and aspects. We have made use of NOAA-3 and NOAA-4 thermal infrared data which have a time of overflight of approximately 11:30 a.m. over California. On the basis of hourly temperature data obtained at the Central Sierra Snow Laboratory for January through May 1975, the daily temperature profile follows definite patterns during clear days and overcast days. Thus the knowledge of the temperature at one specific time should be adequate for a fairly accurate determination of the temperature history of the snowpack.

To assess the accuracy of the temperature recorded in the thermal IR by the NOAA-3 and NOAA-4 satellites we have used temperature data from the National Weather Service, National Climatic Center, at a number of high quality, first order stations in California and also at the station in Reno, Nevada. The data that we were able to use in our geographic area of interest was obtained at Red Bluff, Sacramento, Fresno, Reno, and Bishop. None of these stations is in a mountainous snow covered region. Data is also available at the Central Sierra Snow Laboratory but we have not made use of it up to now and we expect difficulties comparable to the ones we encountered in using the albedo data at the CSSL, because of the limited resolution of the sensors.

Using the temperature data of these first order climatic stations we have done a preliminary determination of the correlation of satellite recorded temperatures with ground truth.

The following steps are needed to carry out this work:

1. Determination of the geometric correction needed for each date. This requires ground coordinates and satellite data coordinates of seven control points and this step is a time consuming operation.
2. Transforming of climatic station coordinates into satellite data coordinates.
3. Extraction of satellite data pertinent to each climatic station.
4. Follow, for each station, the calibration procedure provided by NOAA to transform numerical values into temperatures recorded by the satellite.
5. Use the limb darkening correction outlined earlier to correct for atmospheric effects.

This procedure has been used to generate the 12 data points shown in Figure 2. The data was obtained at a total of 6 climatic stations (Mt. Shasta could be used on one date, in addition to the 5 stations mentioned earlier).

The results shown in Figure 2 call for several comments. First, two data points are not shown. They would be on the left side of the figure and give a large discrepancy between ground temperature and satellite recorded temperature, the satellite recorded temperature being very much lower. We believe that this difference is due to the fact that the satellite was recording the temperature of the top of clouds above the station rather than the ground temperature. In one case, corresponding to Sacramento, we ascertained that clouds were actually present. Thus, these 2 data points have been discarded.

The remainder of the data points were kept and show a fair correlation between satellite recorded temperature and ground temperature (correlation coefficient = 0.67). Note however that the numerical values are significantly different for ground and satellite temperatures. It is possible that systematic errors have been made in the calibration of the data. Since empirical factors appear in the limb darkening correction, it is possible that a tuning of the calibration procedure from the range of geographic locations and temperatures of interest in this study will have to be performed. We intend to pursue the systematics of this problem by using considerably more data that we have done to date and by performing correction of the data for banding and random errors. By and large, we are encouraged by these preliminary results and believe that a usable ground temperature can be inferred from satellite data in the thermal IR.

We have also generated a number of pseudocolor images of the thermal IR data to determine whether a range of temperature could be perceived across the snowpack and whether isothermal line could be distinguished. Several such images will be shown at the workshop. Isothermal lines can be perceived readily. Variations of numerical values corresponding to approximately five degrees centigrades of temperature can also be distinguished. Thus, by the use of ground truth at one or two stations on the snowpack a usable temperature field across the snowpack could be obtained.

MONITORING THE AREAL EXTENT OF THE SNOW

Within the context of our interest in developing data for a distributed model of snowpack evolution, this specific task is not of prime importance. We anticipate that instead of being a prime input to a model, the variation of areal extent with time will be used to check that the model is working satisfactorily. We have undertaken two investigations on areal extend determination. The first one is to compare the areal extent as determined from Landsat data to the same values obtained from NOAA satellites visible data. Results showing fairly close agreement between the values obtained from the two sources of data have been reported by Wiesnet and McGinnis [6]. We are using classification algorithms and digital data rather than outlining the snowline images. We do not have yet enough comparable data from both satellite systems to derive definite conclusions.

Another related question is the determination of the snow areal extent on a daily basis (when possible) from NOAA satellite data. Since a number of data correction steps are needed in such a procedure we shall generate a "noisy" time series for snow areal extent. Since we expect, on physical grounds, a smooth variation of snow areal extent with time we can use data filtering techniques to improve the estimate on any given date.

DISCUSSION AND CONCLUSIONS

In view of the fragmentary results presented here it is obvious that much remains to be done to develop the procedure for mapping albedo and temperature fields of the snowpack. We expect substantially more definite results on both these parameters in the coming few weeks. An interesting possibility which emerged in the course of our study is the discrimination of clouds from snow on the basis of temperature. This is a separation which is impossible to do using the visible or near infrared spectral bands. Since the information on present cloud cover is another prime parameter which determines the evolution of the snowpack, any progress on remote detection of cloud cover over snowfields would be most germaine to our overall study.

Some of the problems of data correction and calibration that we have encountered are necessary to a quantitative use of remote sensing data. Some others, concerned with data gathering and conversion, should be readily amenable to solution in an operational situation. To mention a specific example the amount of NOAA satellite data needed on any watershed is quite small, a few thousand data values. At this time we have to handle and convert more than 10 million data points in order to extract the limited useful information.

With reference to the development of a distributed model of snowpack evolution we are fortunate to benefit from the cooperation of Dr. J. Amorocho of the Department of Water Science and Engineering at UC Davis. Dr. Amorocho and his associates are currently testing a local model of snowpack evolution with data acquired at the CSSL. The extension of this work to a distributed model for a watershed is a step which becomes possible with the advent of remote sensing data. Thus, significant progress on both fundamental conceptual grounds and possibly on practical grounds, runoff prediction, seem feasible.

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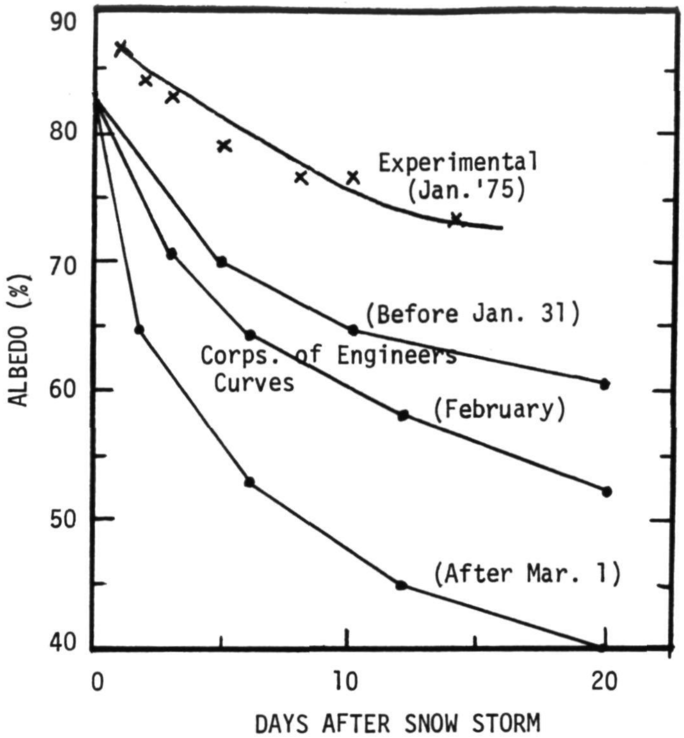

Figure 1: Evolution of Albedo

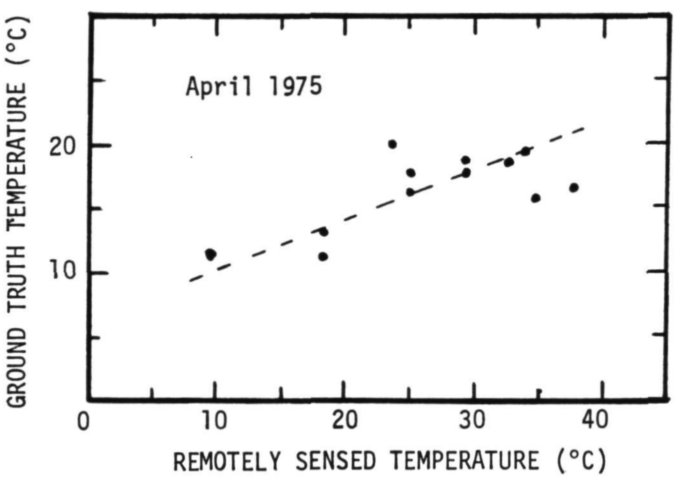

Figure 2: Correlation of Remotely Sensed and Ground Truth Temperature