MAPPING SNOW SURFACE TEMPERATURE FROM THERMAL SATELLITE DATA IN THE SOUTHERN SIERRA NEVADA

By

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Introduction

For an accurate assessment of the surface energy exchange over snow, each aspect of energy input and output must be evaluated. At a point this can be done by direct measurement or, for a homogeneous area, by an appropriate empirical or theoretical model of the parameters of interest. However, over a very large area of rugged snow-covered terrain, such as the southern Sierra Nevada, direct measurement of energy exchange parameters is not possible, and the data necessary to drive most appropriate models are difficult to obtain. Satellite determination of the surface temperature of the snow cover over an area of extreme relief can be used to monitor these energy fluxes if the satellite data can be geometrically corrected and properly calibrated.

In this paper we show the potential utility of using thermal satellite data to derive net longwave radiation over a rugged snow covered area. This work is part of a larger effort to extend an energy balance snowmelt model over a large mountainous region utilizing satellite radiometry. Models of incoming solar and thermal radiation which account for atmospheric and terrain effects have been developed and tested (Dozier, in press; Marks and Dozier, 1979), and a technique for determination of surface reflectance over snow from satellite data has been derived (Frew, 1980). The work presented herein is intended to provide detailed information on the utility of thermal satellite radiometry in energy balance snowmelt studies.

Background

The net longwave radiation at the surface is

$$I_n = I\downarrow - (1-\varepsilon_s)I\downarrow - \varepsilon_s \sigma T_s^4 = \varepsilon_s(I\downarrow - \sigma T_s^4) \qquad (1)$$

where:
I_n = net longwave radiation ($W\ m^{-2}$)
$I\downarrow$ = incoming longwave radiation ($W\ m^{-2}$)
T_s = surface temperature (°K)
ε_s = surface emissivity
σ = Stefan-Boltzman constant ($5.6697*10^{-8}\ J\ m^{-2}\ °K^{-4}\ sec^{-1}$)

Spectrally, longwave radiation occurs in wavelengths greater than 4μm, and the sources are primarily the atmosphere and the earth surface. Solar radiation in this spectral region is very small (13 Wm^{-2} at the top of the atmosphere) due to the earth sun distance. Determining the net radiation in the longwave region is simpler than for the solar region because the spectral albedo and emissivity is more constant for most earth materials at wavelengths larger than 4μm. For snow, O'Brien and Munis, (1975) showed that reflectance is nearly zero above 2.5μm, so that in the wavelength band where most terrestrial and atmospheric radiation occurs (8-12μm) a snow surface may be assumed to be a near perfect blackbody.

In general, given a surface emmissivity, the temperature of a snow surface can be determined by measuring its radiant flux and inverting the Stefan-Boltzman Equation.

$$T_s = [I\uparrow/(\varepsilon_s T)]^{1/4} \qquad (2)$$

where: $I\uparrow$ = outgoing longwave radiation ($W\ m^{-2}$)

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From this principal, surface temperature can be determined from the measured radiant flux. Spaceborne thermal sensors usually sense only a narrow band (typically 10 to 12μm) to take advantage of transmission through atmospheric 'windows'. Satellite determined temperatures are calculated from a more specific form of equation (2) which is corrected for radiant flux from a specified spectral band. Shafer and Super (1971), intent upon determining snow surface temperature from aircraft borne radiometers, showed the emissivity of snow to vary from .966 to .990.

Spaceborne radiometric measurements are complicated by atmospheric degradation, and a difficult geometric registration problem. The spatial resolution of most thermal satellites is around 1 km^2, so unless the snowcover is total some temperature averaging occurs at the subpixel level. This is especially problematic in areas of high relief or when the snowcover is discontinous. Atmospheric degradation is simplified by the lack of scattering in the thermal region (4-50μm) (Paltridge and Platt, 1976). The atmosphere is a mixed gas made up of nitrogen and oxygen along with several trace gases. A few of these trace gases, (water vapor, carbon dioxide, and ozone), are responsible for most of atmospheric thermal interaction. At lower elevations aersols can also affect thermal satellite data (Stowe, 1971; Jacobowitz and Coulson, 1973), but this is generally not a problem in higher alpine areas.

ΔT is defined as the difference between the actual surface temperature and the satellite estimate of the surface temperature.

$$\Delta T = T_s - T_e \qquad (3)$$

where: T_e = satellite measured surface temperature (°K)

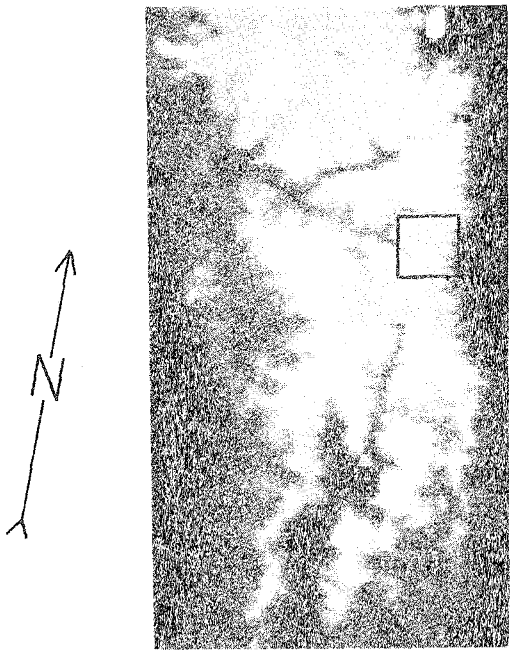
Water vapor absorption, termed e-type interaction, may commonly cause a ΔT of +1 to +2 °K (Anding and Kauth, 1970; Maul and Sidran, 1973; Prabhkara et. al., 1974; Kunde et. al., 1974).

The problems associated with atmospheric interaction and the large spatical resolution cell of the satellite sensor are compounded by the need for geometric rectification and registration of the satellite data to a geographic coordinate system. Establishing the exact UTM coordinates of each pixel is difficult. Detailed surface features are not readily apparent upon visual inspection of the imagery. A regression technique similar to that described by Algazi and Suk (1976) allowed for the accurate location of ground control sites on the thermal imagery. A lack of information in the data header prohibited geometric rectification which would have accounted for pixel skew and allowed for exact registration with a digital terrain grid.

Because of the problems discussed above most snow investigators have used thermal satellite data primarily for snow detection and snow extent mapping (Wiesnet, 1974; Barnes and Bowley, 1974; McGinnis et. al., 1975). In these studies absolute surface temperature determination was not necessary or possible. With a complete snowcover, and with a minimum of atmospheric interference, Siefert et. al., (1976) reported an accuracy from NOAA thermal data of ±1.0 °K over snow. The potential for accurate snow surface temperature determination exists, but the data must be properly corrected and calibrated. The results presented here show that this is possible in an area of high relief with a minimum of field data.

Study Area

The upper portions of the Kings and San Joaquin drainage basins in the southern Sierra Nevada were used as the test areas. These areas range in elevation from 2000 m to 4300 m and provide a major snow catchment area for the mountina range. Snow accumulation is highly variable. Seventy-five percent of the annual runoff occurs during the April thru July snowmelt period.



<u>TIROS-N</u> <u>Satellite</u> <u>Image</u>

Band 4; April 21, 1979

White areas are snow or clouds.

(Glen Pass Test Area is indicated)

Figure 1. The Southern Sierra Nevada Study Area as seen from a satellite.

The area used for illustration in this paper is the Glen Pass area, which is represented as a digitized grid of elevations taken from the NCIC Digital Terrain Tapes (see figure #2).

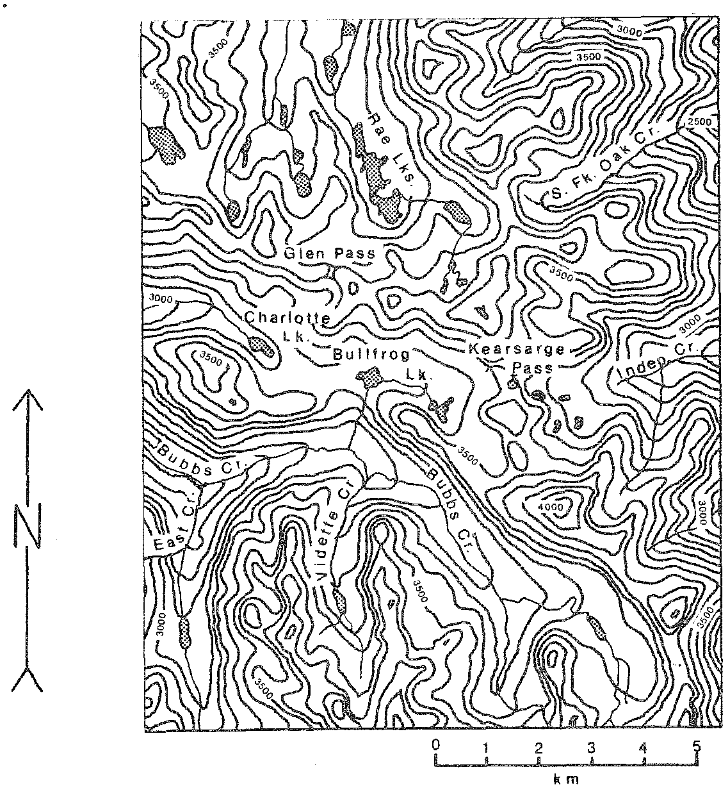


Figure 2. Topographic map of the Glen Pass test area drawn from a digital elevation grid at a 100 m spacing. Contour interval is 100 m. Elevations over this area range from 2400 m to 4200 m.

This grid of elevations is used as the reference grid for the computation of terrain effects and net longwave radiation. Satellite temperature data has been roughly "registered" to this grid so that there is a surface temperature for each grid point.

Data Collection

During the 1978-1979 snow season Tiros-N thermal satellite imagery of the study area for several dates were acquired. For dates corresponding to the satellite overpasses, ground truth was collected in remote parts of the southern Sierra Nevada. Of these, three dates (April 6, April 21, May 6) have been selected for analysis and one, April 21, is used for illustration purposes.

Data from band 4 of the Tiros-N satellite were used for this study. The spectral resolution of band 4 was 10.5 to 11.5μm and the spatial resolution at the nadir point was approximately 1 km^2. Temporal coverage was twice daily (1500 hrs. and 0300 hrs.). Only the daytime coverage was used in this study. The spectral interval of band 4 minimizes atmospheric interference because it occurs in the 8-12μm 'atmospheric window' (Paltridge and Platt, 1976). Though a 1 km^2 resolution is fairly course, it provides many more samples than could be collected by manuel techniques in remote alpine areas. While cloud cover is a problem during winter, adequate cloudfree coverage of the study area was available during most of the 1978-1979 snow season.

The greatest problem with the Tiros-N satellite data was the format in which it was available. During the 1978-1979 season West coast coverage was available only in 'field station format'. In this format the radiometric resolution is reduced from 10 to 8 bits reducing the precision of the data from .1°K to .5°K. Moreover, the data header does not contain sensor calibration data or the latitude and longitude tick marks necessary for image rectification. This left some question as to the actual quality of the data, and rendered an accurate geometric rectification of the data essentially impossible. However, Tiros-N was replaced in 1979 by NOAA-6 which carries essentially the same thermal sensors. Beginning in Fall 1979 NOAA-6 data will be available in Local Area Coverage/High Resolution Picture Transmission (LAC/HRPT) format which includes complete calibration data, and latitude and longitude tick marks every 40 pixels (Kidwell, 1979).

Use of the Tiros-N data for this study is intended only to illustrate the potential applications of satellite determined surface temperatures over alpine snowfields. With the assumption that Tiros-N was reasonably calibrated, the NOAA specified 'noise equivalent temperature difference' (NEΔT) for band 4 was 0.12°K. Disregarding atmospheric interference, the combination of the NEΔT and the reduction to 8 bit resolution should give a reliability of data in field station format, or an estimated NEΔT, of 0.75 to 1.0°K. This study, with only an approximate geometric correction, verifies this accuracy level.

Field Data

Extensive ground truth data were collected during the winter of 1978-1979 within the study area. This investigation attempted to remedy the severe shortage of ground truth upon which previous investigators based their findings (Siefert, et. al., 1975; Algazi and Suk, 1976). Measurements of surface temperature, air temperature, wet bulb temperature, and incoming and outgoing longwave radiation were taken at numerous locations over a large (10-15 km^2) area on the date of satellite overpass. Additional surface temperature measurements were made from high vantage points at the time of the overpass. Measurements of surface temperature were made with a radiant thermometer (Teletemp, Model 44) modified so that its maximum accuracy was around 273.16°K.

Results

Of the eleven dates for which field data was collected during the 1978-1979 snow season, three dates were selected for extensive analysis. Selection critiera included consideration of cloud cover, field data quantity and quality, and the relative ease in locating ground control and ground truth sites on the imagery. Table #1 shows that the ΔT values for these three areas are only slightly larger than the estimated NEΔT of the sensor. Ground truth for the Dusty Basin and the Humpries Basin test area show the satellite data as warmer than the field data (negative ΔT). In the Dusy Basin snow

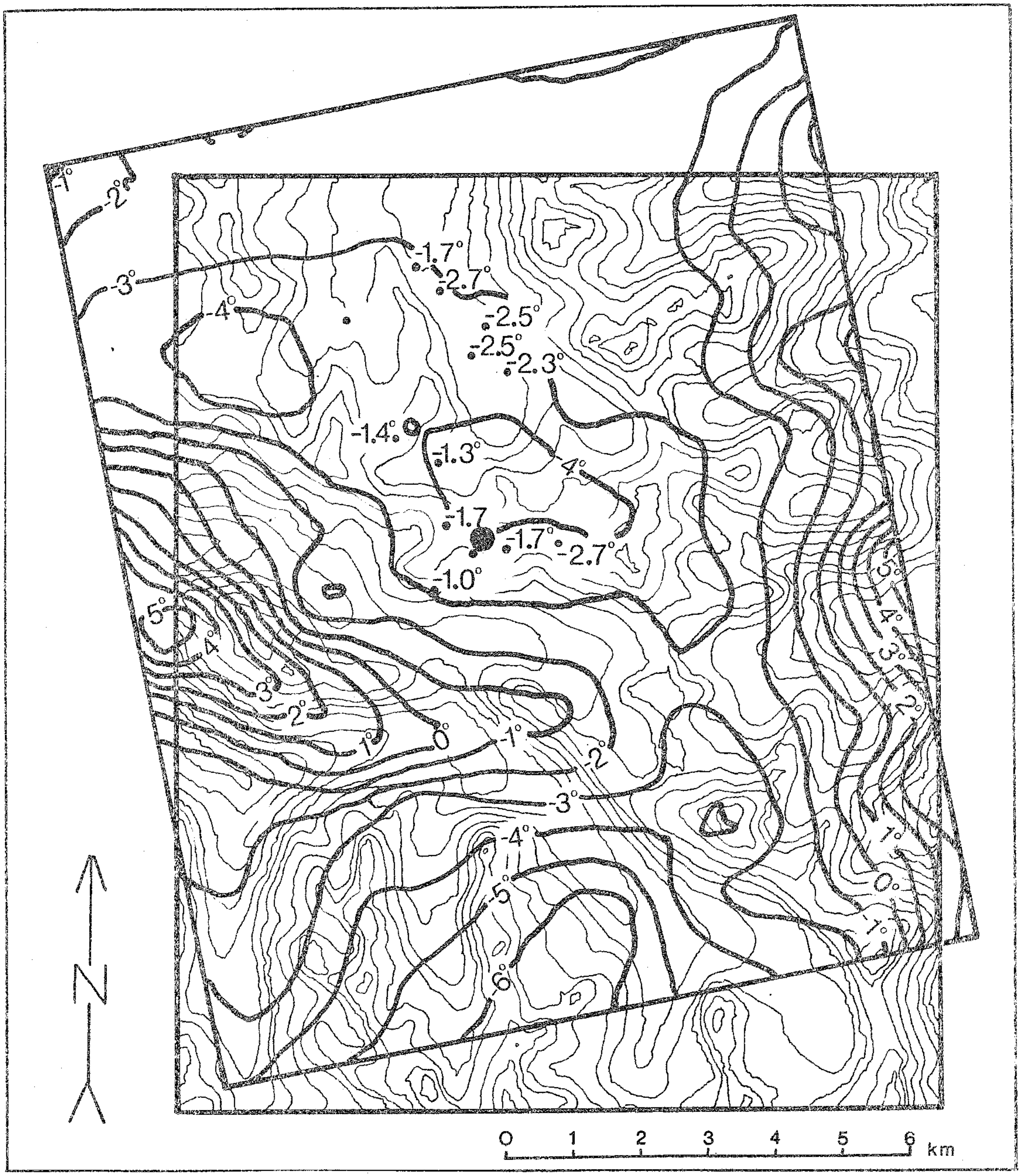


Figure 3. Map of satellite determined surface temperatures overlayed in approximately the correct geometric aspect, on an elevation grid of the Glen Pass test area. Underlying contour map is identical to that shown in Figure #2, but is left unlabeled. Temperature contours are indicated with bold lines. Temperature map has been resampled to a 100m grid spacing, and a contour interval of 1°K. (Note: Centigrade temperatures are indicated on the map for clarification purposes.) Field measurement locations and values are indicated on map.

temperature varied from 269 to 262°K on the day of the overpass. Many of the measured surface temperatures were in areas of mixed rocks and snow. Rock temperatures over the same period varied from 272 to 280°K. For selected samples from areas of nearly total snow cover, the average ΔT was -1.28°K. This was also true in the Humpries Basin where for selected areas of total snow cover, such as large snow covered lakes, the ΔT was very small (-.05 to 0.0°K). The larger values of ΔT in areas of mixed rock, trees, and snow is caused by the spatial averaging inherent in the satellite data.

Table 1: Accuracy of Measured vs. Satellite Determined Surface Temperatures for Three Test Areas in The Southern Sierra Nevada

Date	Location	Samples	Mean ΔT (°K)	Std. Error
April 6	Dusy Basin	13	-3.59	2.38
April 21	Glen Pass Area	12	+0.99	0.45
May 6	Humpries Basin	17	-1.28	2.07

The best overall test results were in the Glen Pass area. The average ΔT was within the estimated NEΔT of the sensor (+.99°K), and the standard error was also very small (0.45). Ground truth was collected in areas of total snow cover where no rocks or trees were emerging thru the snowpack. Of all the areas sampled this site represented the most continuous total snow cover over a large area. Above the snow covered area were rock peaks and divides but on this date the rock temperatures were very close to that of the surrounding snow fields. The excellent results for this date reflect the total snow cover and uniform snow and rock temperature.

Manual geometric correction was done by the tedious method of repeatedly displaying the satellite image data over a terrain image until the field area can be located to the satisfaction of the investigators. Figure #3 illustrates the results of this for the Glen Pass test area. The terrain grid is represented as an unlabeled contour map identical to the labeled map in figure #2. The temperature surface is shown as a smoothed version of the original satellite data overlayed in its approximate orientation. Measurement sites are marked on the figure.

The results of these tests are very encouraging. Though the geometric correction of the satellite data was only approximate, the T values are small, and within the tolerance allowable for large scale energy exchange calculations. With better calibration data, and more accurate geometric information, such as is now available through the LAC/HRPT format, reliable lite data over remote alpine areas.

Potential Applications

Though there are numerous applications for mapping surface temperature in alpine areas, for energy balance considerations computing net longwave radiation is the most straight forward. In an alpine area of high relief, incoming longwave radiation can be modeled from air temperature, vapor pressure, and terrain information (Marks and Dozier, 1979). Thermal satellite data are used to more accurately determine the influence of surrounding terrain. Net longwave radiation is then calculated from surface temperatures using equation (1). This was done for the Glen Pass test area. Digital images of surface temperature, incoming longwave radiation, and net longwave radiation are shown in figure #4.

The surface temperature image was created from the temperature map shown in figure three. The satellite data was resampled to a 100 m grid spacing and artifically 'registered' to the topographic grid for illustration purposes. Air temperature and vapor pressure are computed for each terrain grid point from reference values collected on the overpass date (274°K and 5.35 mb at a 3170 m reference elevation). Lapse rates of -.007°K m^{-1} for air temperature and -.0015 mb m^{-1} for vapor pressure were selected as being characteristic of the area under typical winter conditions. Terrain view factors were computed using a technique developed by Dozier, Bruno and Downey, (1979). Incoming longwave radiation was then computed for each terrain grid point by

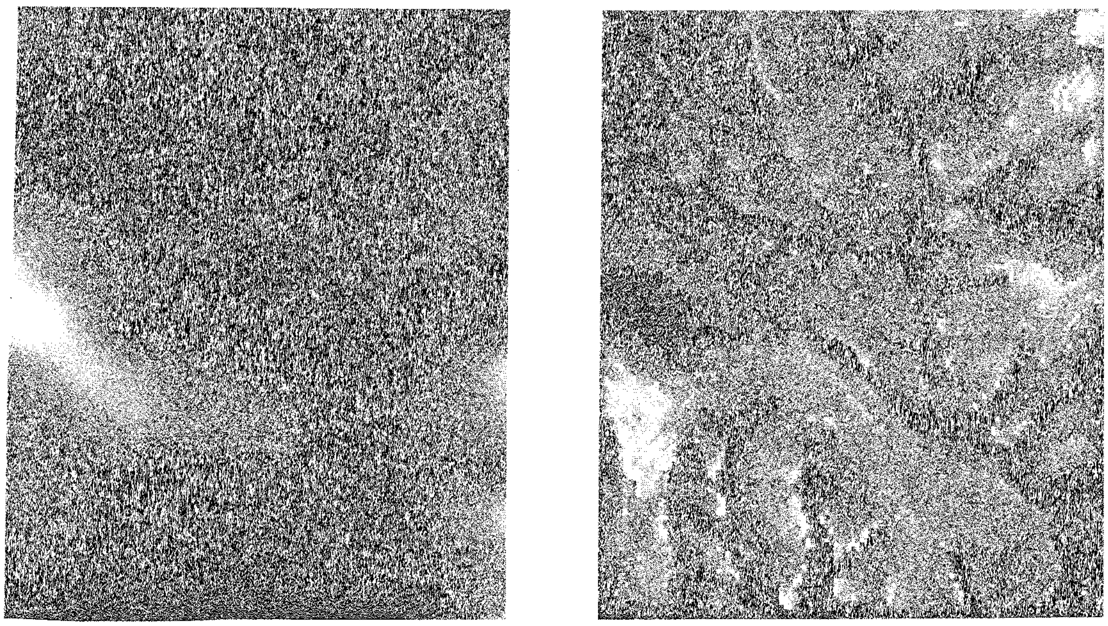
$$I\downarrow = (\varepsilon_a \sigma T_a^4)Vf + (\varepsilon_s \sigma T_s^4)(1-Vf) \qquad (4)$$

where: ε_a = effective atmospheric emissivity

T_a = air temperature (°K)

Vf = terrain view factor

In the original test of this model no reliable surface temperature data existed and the temperature of the terrain within thermal view of a grid point was approximated by the mean daily air temperature. In this study, this estimate was replaced by a satellite measurement of the surface temperature. Net radiation was then computed, using equation (1), from the grids of incoming longwave radiation values and satellite derived surface temperatures.



SURFACE TEMPERATURE (Light indicates warmer temperatures)

NET LONGWAVE RADIATION (Dark indicates more negative values)

Figure 4. Digital images of surface temperature and net longwave radiation over the Glen Pass test area. Brightness contrast is a linear streach over the range of values in each image (see Table #2). The lack of contrast in the temperature image results from the limited range of temperatures over the area.

Table 2: Distribution of the values over the digital images of Surface Temperature, Incoming Longwave Radiation, and Net Radiation shown in Figure 4. (Note: For radiation values, a negative sign indicates a flux away from the surface.)

Image	Mean Value	Max. Value	Min. Value
Surface Temp.	271.75°K	278.83°K	266.28°K
Incoming Long-wave Radiation	212 Wm^{-2}	270 Wm^{-2}	160 Wm^{-2}
Net Longwave Radiation	-93 Wm^{-2}	-42 Wm^{-2}	-160 Wm^{-2}

Table #2 presents the distribution of values over the digital images shown in figure #4. The accuracy of the temperature values is good, as was discussed earlier. The incoming longwave radiation values are reasonable and within the range found by Marks and Dozier in the Southern Sierra Nevada during the 1977 and 1978 snow seasons. Net radiation values are acceptable given the geometry of the surface temperature data.

Conclusion

The results achieved in this investigation are reasonable approximations of the surface longwave energy exchange over a large complex area. With the improvements made in the NOAA-6 data format, very accurate geometric rectification and registration will be possible. With the more accurately located surface temperature values net longwave radiation may be accurately modeled, thus representing another step toward the area simulation of the energy balance of an alpine snow cover using modeling techniques and satellite radiometry.

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