Preliminary Evaluation of Thermal Infrared Aircraft Data for Mapping Snow Cover in the Sierra Nevada Mountains

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ABSTRACT

Moderate Resolution Imaging Spectroradiometer (MODIS) Airborne Simulator (MAS) data are examined to determine the utility of the thermal infrared channels for mapping snow. In preparation for the first MODIS to be launched as part of the Earth Observing System (EOS), algorithms to map snow using MODIS data are currently being developed, in part, using MAS data. Data from visible and near-infrared channels of the MAS acquired over the Sierra Nevada Mountains, California have been studied. Separate snow maps were produced using visible and thermal-infrared data. Results did not agree in terms of the amount of snow-covered area mapped. The map derived using the thermal-infrared channel showed that 42 percent of the scene was snow- covered, while the map derived using the visible data showed that about 53 percent of the scene was snow covered. Many forested areas and areas of patchy snow were not classified as being snow covered using the thermal infrared data. Temperatures computed using the thermal infrared data (without atmospheric correction), showed that snow temperature was variable, with the coldest snow corresponding to the highest elevations. It is concluded that thermal-infrared data from MODIS sensors may be useful in refining measurements of snow-covered area in the future when used in conjunction with data from visible and near-infrared sensors.

INTRODUCTION

Accurate mapping of snow extent and reflectance and determination of timing of snowmelt is important because many areas of the world rely on snowmelt for their water supply. The extent and duration of snow cover are indicators of climate change if measured in a decadal time scale, in addition, snow cover has a major effect on global energy balance.

Future instruments will permit both improved snow mapping and snow reflectance measurements to be obtained at regional and global scales. One such instrument is the Earth Observing System (EOS) Moderate Resolution Imaging Spectroradiometer (MODIS), a 36-band spectroradiometer that will have a spatial resolution ranging from 250 m to 1 km. The first MODIS will be launched in 1998 and will have an overpass at about 10:30 A.M. A second and identical MODIS instrument will be launched later and will have an afternoon overpass at about 1:30 P.M. The morning overpass will be in the descending mode and the afternoon overpass will be in the ascending mode. There will be complete coverage of the Earth every one to two days (Salomonson et al., 1992). The MODIS bands will span much of the reflective part of the electromagnetic spectrum, thus enabling the calculation of integrated reflectance. Data will also be available in the thermal infrared parts of the spectrum, and along with ancillary data on atmospheric conditions, will permit the computation of snow surface temperature.

Techniques are under development (e.g.. see Riggs et al., 1992) to map snow in an automated way using an algorithm that will employ multiple MODIS bands. Until MODIS is launched, aircraft MODIS Airborne Simulator (MAS) data will be used to aid in the development of an algorithm designed for global snow mapping. After MODIS is launched, MAS data will be useful for verification of the accuracy of the snow mapping algorithms. Some work has been done on the use of thermal-infrared data for snow mapping, however this needs to be explored further. The MAS is suitable for this because it has channels in the thermal infrared as well as in the visible and near-infrared parts of the spectrum.

On 31 October 1991 during a test flight, MAS data were acquired from the NASA ER-2 aircraft over snow-covered mountains and some non-snow-covered valleys and lakes. The study area is in the Eldorado and Toiyabe National Forests which are located south of Lake Tahoe and east of Sacramento, California and is centered at approximately 38°30'N, 120°W. In this paper, results from a preliminary analysis of a visible and a thermal-infrared channel are presented to analyze the applicability of the thermal-infrared channels for mapping snow.

BACKGROUND

Since 1966, the National Oceanic and Atmospheric Administration (NOAA) has produced maps of Northern Hemisphere snow extent. This data set contains invaluable information regarding the extent and decadal-scale variability of snow cover in the Northern Hemisphere (Matson et al., 1986; Matson, 1991; Robinson and Dewey, 1990), though some difficulties have been identified in the data set (Robinson and Dewey, 1990). Since the Northern Hemisphere snow cover is delineated manually by a very labor-intensive process, it is often difficult to discriminate clouds from snow and to map the snow in dense forests. These problems result in errors that are difficult to quantify.

While other satellite sensors have also been used to map snow, difficulties remain. The satellite-borne passive microwave sensors can map snow through darkness and clouds, and can even be used to obtain an estimate of snow water equivalent, but the resulting image resolution is coarse. The resolution is on the order of tens of kilometers (Chang et al., 1987). Despite this low resolution, compared with data from visible sensors, the accuracy of the passive microwave-derived global snow maps is within about 10 percent of the NOAA maps (Chang et al., 1987).

The Landsat Thematic Mapper (TM) data can provide excellent results for mapping snow at the river basin scale (Rango and Peterson, 1980; Rango and Martinec, 1982; Dozier and Marks, 1987) along with good snow/cloud discrimination using the middle (1.55-1.75 μm) and thermal infrared (10.4-12.5 μm) regions of the electromagnetic spectrum. Additionally, using the TM, snow reflectance at near-nadir view angles may be calculated (Dozier and Marks, 1987; Hall et al., 1989) and snow grain size may be estimated (Dozier, 1984). However, while the high (30 m) spatial resolution of the TM makes it suitable for mapping snow at the river basin scale, it is not suitable for mapping snow globally because of the fact that snow over large regions cannot be mapped simultaneously, and the repeat cycle of the Landsat-4 and -5 satellites is 16 days.

Remote sensing of the surface temperature of snow requires knowledge of the emissivity of snow as well as of the atmospheric transmittance during data acquisition. Shafer (1971) measured the emissivity of various types of snow and found that an average emissivity for freshly fallen snow is 0.975. The mean emissivity for all snow surface types was 0.978, thus substantiating the hypothesis that snow has approximately blackbody characteristics in the 8 to 14 μm spectral interval.

Because ice absorbs strongly in the infrared region, snow is effectively of infinite thickness even at shallow depths as far as emission and absorption of infrared radiation are concerned. Thus the underlying surface does not contribute to thermal emission, even from snow that is only a few millimeters thick (Dozier and Warren, 1982; Foster et al., 1987). In addition, knowledge of surface (snow) emissivity, atmospheric attenuation, and particularly the amount of atmospheric water vapor must be considered in order to determine surface temperature from remotely-sensed data accurately (Foster et al., 1987).

Thermal-infrared data may be useful for identifying areas of melting snow. The delineation of a snow boundary may depend on the detection of relatively small radiative temperature differences; variations of only a few degrees in the temperature across a snow surface may be significant in terms of the snowpack condition (Foster et al., 1987).

Previous work has demonstrated that thermal-infrared data are useful for the study of snow and ice-covered terrain. Lougeay (1974) found strong thermal contrasts in glaciated terrain near the Donjek Glacier in the St. Elias Mountains, Yukon Territory, Canada. He found a maximum of about a 25°C difference between thin (5-15 cm in thickness) ablation moraine that had ice underneath and moraine that did not have ice underneath. He also studied Landsat-3 thermal data of the Wrangell Mountains, Alaska and found thermal contrasts due to topographic exposure and material type (Lougeay, 1982).

A snow cover, even a very thin one, strongly influences the conducted heat flux and surface temperature (Poulin, 1974). The energy that penetrates snow is either absorbed or reflected at the snow/soil interface. However, on a snow-covered frozen lake, a significant portion of the energy is transmitted in or through the lake ice. Thus, snow on land is warmed faster than is snow on a frozen lake. Snow melts sooner over land as compared to over an adjacent frozen lake. This is because the energy is not available to melt the overlying snow if it is absorbed into or through the ice in a lake (Poulin, 1974). Thus, snow surface temperature can often reveal information about the underlying medium.

Barnes et al. (1974) studied thermal-infrared satellite data from an early Nimbus satellite and found that the snow temperatures were 5-10°C lower than the temperatures of the surrounding non-snow-covered terrain. They also found that the coldest temperatures were located at the highest elevations in either snow or non-snow-covered areas. In addition, they observed that temperatures of pixels comprised of snow, sensed remotely, may exceed 273 K, the melting point of water. If the snow pixel is not pure, the other features within a pixel may have a temperature greater than 273 K, especially if it is located on a south-facing slope. Thus the average temperature within a pixel could easily be greater than 273 K even if snow comprises more than 50 percent of the pixel.

Thermal-infrared satellite data from the Heat Capacity Mapping Mission (HCMM) satellite, flown in 1978, were useful for identifying some thermal characteristics of snow. Barnes et al. (1981) found that the thermal-infrared data could be used to map snow as readily as could visible data during the daytime when the contrast between snow and non-snow-covered terrain was greatest. Their ability to map snow using nighttime thermal-infrared data was hampered by the reduced contrast between the temperature of snow and the temperature of the surrounding terrain.

Characteristics of the MAS

The MAS, as configured in the fall of 1991, consisted of 11 channels ranging from 0.675 to 12.20 μm with varying band widths (Table 1). The MAS is flown on the NASA ER-2 aircraft which has a maximum altitude range of 21.4 km and a maximum air speed of 410 knots. Modifications are currently being performed on the MAS. Upon completion, in 1992, the MAS will have 52 channels, a swath width of +/- 43° and a footprint size of 2.5 mrad, and a spectral range of 0.47-14.2 μm. The resolution of the MAS data is dependent upon the altitude of the aircraft. For example, at an aircraft altitude of 18 km, the spatial resolution is 45 m.

Table 1. Center wavelengths and bandwidths of the MAS as configured on 31 October 1991.

Channel #	Center Wavelength (μm)	Bandwidths (μm)
2	0.68	0.05
3	1.64	0.05
4	1.98	0.05
5	2.13	0.05
6	2.18	0.15
7	3.75	0.15
8	4.65	0.15
9	4.50	0.4
10	8.80	0.5
11	10.95	0.5
12	11.95	0.5

RESULTS

A 31 October 1991 MAS scene of part of the Sierra Nevada Mountains in California is shown in Figure 1. While there were no coincident ground observations, the high contrast between snow covered and non-snow-covered terrain permitted us to map snow-covered areas, visually, as well as to distinguish between areas of "pure" snow and snow-covered forests, and to compute radiances using the channel 2 visible data. Atmospheric correction has not been applied to any of the data in this scene, though this will be necessary in order to obtain physically-meaningful radiances and surface temperatures from the MAS in future work. Thus the radiances and temperatures reported in this paper are considered to be "at-sensor" values.

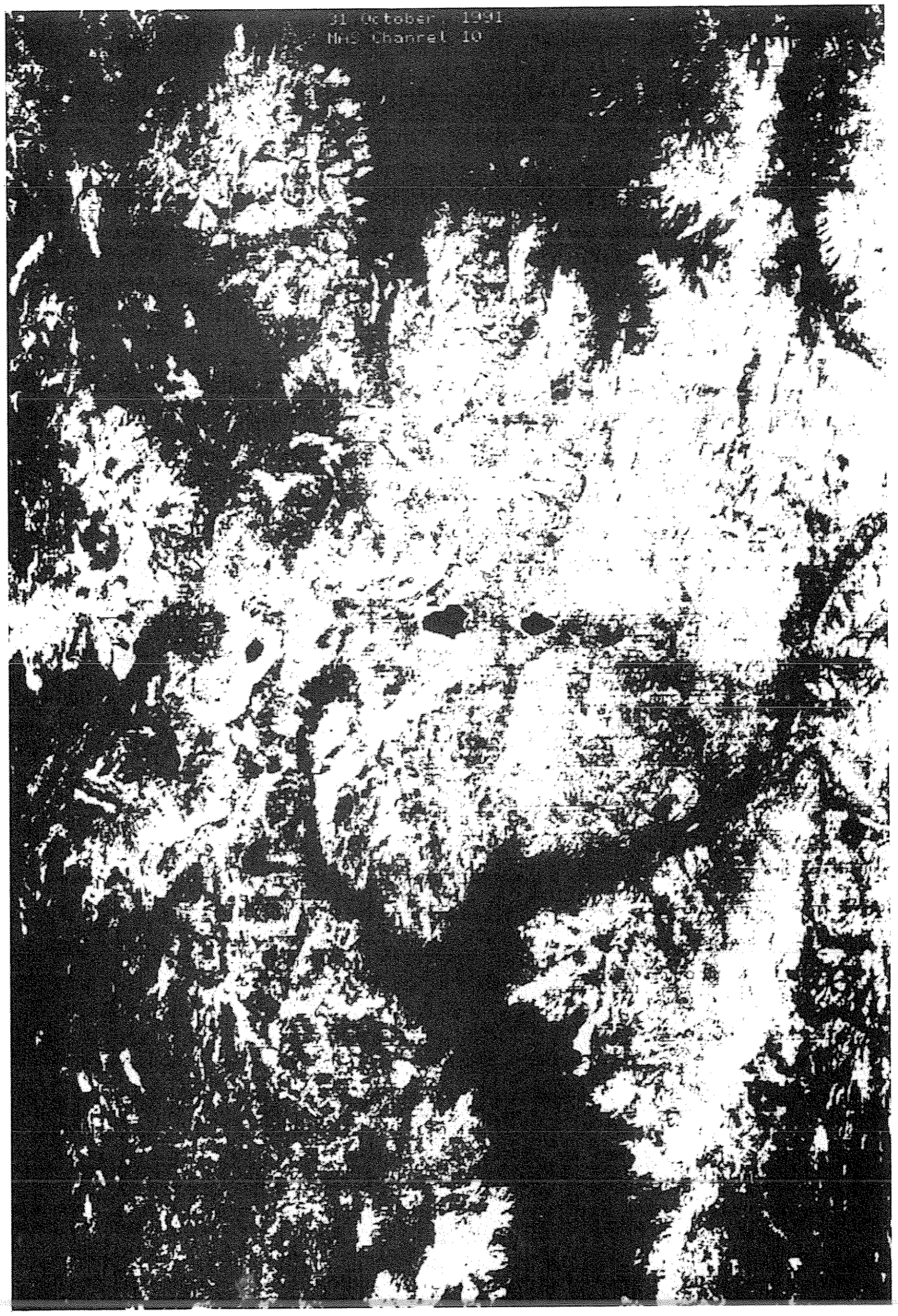
Using channel 10 (one of the MAS thermal-infrared channels), we were able to map snow-covered area and to compute "at-sensor" snow temperatures.

The areas that appear to be pure snow exhibited the highest radiances as computed from MAS channel 2 digital numbers (21.78-23.43 mW cm-2 sr-1 μm-1). These radiances correspond quite well to the highest radiances measured using Advanced Solid-State Airborne Spectroradiometer (ASAS) data (Hall et al., in press) in northern Montana in March 1991. ASAS channel 18 (center wavelength 0.69 μm) radiances (acquired at nadir) for pure snow over lake ice were approximately 21 mW cm-2 sr-1 μm-1.

Snow covers approximately 53 percent of the entire scene as delineated visually using visible data from MAS channel 2 (Figure 2) in the Sierra

1. Study area in the Sierra Nevada Mountains, California, as shown using channel 2 (center wavelength 0.68 μm) MODIS airborne simulator (MAS) data obtained on 31 October 1991.

2. Snow covered area as determined from MAS channel 2 (center wavelength 0.68 μm*) data obtained on 31 October 1991 in the Sierra Nevada Mountains, California. According to this classification, the snow-covered area comprises 53 percent of the entire scene.*



3. Snow-covered area as determined from MAS channel 10 (center wavelength 8.8 μm) data obtained on 31 October 1991 in the Sierra Nevada Mountains, California. According to this classification, the snow-covered area comprises 42 percent of the entire scene.

Nevada. Only 42 percent of the entire scene (Figure 3) was considered snow covered using the thermal-infrared channel 10 data. For this analysis, pixels with surface temperatures equal to or less than 273 K were considered snow covered since even melting snow should have a temperature no higher than 273 K. Within the snow-covered areas, at-sensor temperatures ranged from 263 K to 273 K. Mixed pixels may result in higher temperatures in snow-covered vegetated areas because the non-snow material adjacent to, or protruding through, the snow may have a surface temperature greater than 273 K (Barnes et al., 1974). The visible and thermal-infrared data showed only a 31 percent agreement in terms of snow cover mapped.

Within the snow-covered areas, there was some correspondence between the pure snow, as defined by the channel 2 (visible) data, and the coldest snow surface temperatures obtained from the channel 10 (thermal infrared) data (Figure 3). The areas that were coldest and displayed the highest radiances tended to be at high elevations.

MAS channel 10-derived temperatures in the range 263-268 K are found at elevations greater than about 2580 m (8500 feet). Because the slope and aspect are also important in determining surface temperature, a south-facing slope will have more direct solar radiation resulting in warmer snow temperatures. The use of a digital elevation map of the area will permit us, in the future, to study the relationship between slope, aspect and thermal infrared snow surface temperature in more detail (Robert E. Davis/CRREL, Hanover, NH, personal communication, June 1992).

DISCUSSION AND CONCLUSION

Based on this preliminary analysis, the MAS thermal-infrared data are useful for delineating snow-covered area, however, the use of MAS thermal-infrared data resulted in measurement of a smaller snow-covered area in the 31 October 1991 MAS scene of the Sierra Nevada than did use of visible data. Results from the visible data resulted in assignment of about 11 percent more area as snow covered than did results from the use of the thermal-infrared data. Because of mixed pixel effects, many snow-covered pixels displayed thermal-infrared temperatures greater than 273 K. (For this purpose, only pixels having temperatures <273 K were considered to be definitely snow covered.) A more in-depth study in which visible, near-infrared and thermal-infrared data are employed should help us to map the snow in this scene more accurately using a combination of several channels.

Snow temperatures, as measured using the MAS thermal-infrared data, varied with elevation and, most probably, with orientation of the mountain slopes with respect to the Sun. Digital elevation model data, in conjunction with MAS data, will help us in the future to quantify the influence of slope and aspect on snow surface temperature.

Analysis of diurnal change of snow surface temperature may be a viable method for improving snow-covered area measurement. The diurnal variation change in temperature of a dark surface is likely to be greater than the diurnal change in the temperature of a bright or white surface like snow, thus not as much diurnal variation in surface temperature would be expected over snow as compared to over adjacent non-snow-covered terrain (Barnes et al., 1974). Morning and afternoon MODIS thermal-infrared data, when available, could be useful for analysis of diurnal temperature variations within a scene and thus improved delineation of snow-covered area.

The thermal infrared data may prove useful for delineating snow in forests and for refining the measurement of the date of snowmelt. These and other applications of thermal-infrared data for the study of snow will be explored with additional MAS data, combined with digital elevation models of this region.

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