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Evaluation of Snow Parameters using Passive Microwave Remote Sensing

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ABSTRACT

The study of snow characteristics using conventional techniques for vast, rugged and remote snow covered areas of Himalayas is very difficult. In the present study, the satellite data of SSM/I sensor has been used. Changes in snow accumulation result in related variations in passive microwave brightness temperature. This study attempts to develop new algorithms using brightness temperature for snow water equivalent (SWE) and snow depth that will suit the Indian Himalayan conditions. The snow and meteorological data recorded in the field is used to determine the empirical coefficients, which have been further used in the algorithm development. The parameters evaluated can be used as the input for the avalanche risk analysis, as one can estimate average snow depth and SWE of the area which are main input for avalanche forecasting. Algorithms are further used for the prediction of snow depth and SWE for subsequent winters using the brightness temperature. A good correlation was found between the predicted and the observed values from the ground observatory data.

Keywords: SSM/I, snow water equivalent, snow depth, brightness temperature, avalanche risk analysis, avalanche forecasting, algorithm, avalanche monitoring, remote sensing, sensors, special sensor microwave/imager

NOMENCLATURE

A_1 to A_{14}	Geographical constants
SSM/I	Special sensor microwave/imager
T_B	Brightness temperature
H	Horizontal polarisation
NW	Northwest
V	Vertical polarisation
T_0	*273.16 °K*
$T_B(H)$	Brightness temperature at horizontal polarisation
$T_B(V)$	Brightness temperature at vertical polarisation
t	Atmospheric transmittance

1. INTRODUCTION

Snow in the Himalayas is a vital renewable natural resource for India, but also a hazard in the form of avalanches, which in turn strongly affects the safety of human lives and many other developmental activities, contributing to national economy. The vast snow covered areas are generally located at high altitudes in remote and inaccessible areas. Thus, avalanche monitoring and mitigation is severely hampered by the factors such as limited or nonexistence

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of communication. Remote sensing techniques offer a way to augment conventional measurement techniques by providing repetitive observations with a high spatial density. One major problem with the application of visible wavelength data is the need for clear sky conditions. Persistent cloud cover in winter may, in some instances, limit data to only a few days per month. In addition, visible band data do not provide the opportunity to extract snow water equivalent (SWE) or snow depth (SD) information.

Space-borne microwave radiometers are promising tools for global monitoring with high temporal repetition rate, because of the potential of the microwave to observe the earth surface through clouds and to provide information on the internal properties of the snowpack. Microwave remote sensing is being successfully used for monitoring numerous parameters of the earth, ocean, and snow surface. An objective of passive remote sensing of snow is the identification of snowcover extent and precipitation, and retrieval of useful parameters, such as SNE, emissivity and SD, etc.

The first SSM/I to become operational was launched aboard Defense Meteorological Satellite Program (DMSP) F8 in June 1987. Recently, an SSM/I was carried on DMSP F10 launched in December 1990, and F11 in November 1991. SSM/I is carried on a spacecraft, which is in a circular sun synchronous, near-polar orbit at an altitude of 833 km with an inclination of 98.8° and an orbital period of 102 min. The above results in 14.1 full orbit revolutions per day. With a swath width of almost 1400 km, the SSM/I provides near-global coverage every day. SSM/I scans the earth surface at 19.3 GHz, 37.0 GHz, and 85.5 GHz in vertical and horizontal polarisations, and at 22.2 GHz in the vertical polarisation. The incidence angle at the surface is 53.3° and the effective fields of view ranges from 69 km x 43 km (19 GHz) to 15 km × 13 km (85 GHz).

Microwave emission from a layer of snow over a ground medium consists of emission by the snow volume and the underlying ground. The intensity of the microwave radiation emitted from a snowpack depends on the physical temperature, grain size, the density and the underlying surface conditions of the snowpack. Snow parameters significantly affecting microwave sensor response are liquid water content, crystal size, SD, SWE, snow surface roughness, density, and temperature.

Most of the research regarding the SD and the SWE was carried out at relatively homogeneous flat areas such as the Canadian high plains and the Russian steppes and significant regression relationships between SD, SWE and brightness temperature have been developed. Chang and Foster[1] have used satellite microwave data to derive SWE in flat homogeneous areas with some success. A relationship between the difference in microwave brightness temperature at two different frequencies (37 GHz and 18 GHz horizontal polarisation), and the basin-wide average SWE was obtained. The SWE values derived from the model were consistent with the values generated by a reliable snowmelt run-off model using snowover extent data. Further, using vertically polarised brightness temperatures from SSM/I, a statistically oriented discriminant function has been developed and used to separate snow areas from non-snow areas.

Due to rugged mountainous region of northwest Himalayas, the study area represents the specific terrain properties, which are not the same as of the plains of Canada and Russia. Thus, one cannot directly use the geophysical constants of regression equations suggested for the above said areas. Therefore, an attempt has been made for developing a modified regression equation for the study area using SSM/I and field snow profile data.

2. STUDY AREA

Study area Patseo (77° 15′ 43″ E longitude and 32° 45′ 18″ N latitude) is located in Greater Himalayan range, at about 3800 m above mean sea level, on a flat ground where three valleys meet. The area experiences high wind, relatively lesser snowfall, and low temperatures in comparison to that of Pir Panjal range, which lies in lower Himalayan region southward of the Great Himalayan range.

In the early winter due to steep temperature gradient that sets in the shallow snowpack, depth hoar/cup crystal formation takes place in this region. In the present study, SSM/I data used is in the form of the brightness temperature at four

SSM/I channels. (19 GHz, 22 GHz, 37 GHz, and 85 GHz). Winter data (November to April) of five year from 1997-2001 of snow stratigraphy and brightness temperature have also been used.

3. METHODOLOGY

Snow is a scattering material. Surface and volume scattering of microwave radiation are both responsible for the variations in the brightness temperature. Scattering by ice particles attenuates radiation as it propagates through the snowcover. Scattering reduces the high frequency brightness temperature relative to the lower frequency measurements. To differentiate snow-bound areas and snow-free areas, the value of scattering index (SI) was calculated using the following Equation (Ferraro *et al.*, 1996):

$$SI = \text{Max}\ (22V\text{-}85V,\ 19V\text{-}37V) \quad (1)$$

The application of passive microwave is currently limited to dry snow. Once liquid water is present on the ice grains, the snow surface becomes a strong emitter, and thus may be indistinguishable from the bare ground.

Regression analysis was applied on previous year's brightness temperature (T_B) data and field observatory data. Empirical relations were developed and have been used for forecasting SWE and SD. Regression equation may be linear or nonlinear, depending upon the approximations. The simplest relation is the linear regression, where it is assumed that the variables are related linearly. The coefficients of regression equation are calculated by weekly averaged brightness temperature from the SSM/I sensor and the SD, SWE of ground, of the winters of 1997-2001. For the calculation of these geophysical constants, the Gaussian elimination method was used, which reduces the system of equations to an equivalent triangular system that can be solved by back substitution. This procedure was used for the development of algorithm. Stepwise analysis has been done. First the linear regression equation was drawn using 19 GHz and 37 GHz frequencies at the vertical polarisation. Correlation coefficient between the data derived from the algorithm and the stratigraphy data was calculated. Using all the frequencies of SSM/I, the similar calculation have been done.

To achieve better correlation between the ground data and satellite data, power regression equations were drawn. In this overall analysis, the geophysical constants were calculated and were further used in the regression equations. At the same time, the standard error corresponding to each geophysical constant was calculated. This standard error is the criteria for the selection of any frequency. If by the inclusion of any frequency the standard error, *i.e.* the difference between the observed and the predicted values, is increasing than that particular frequency is discarded from the algorithm.

Using the above method, the final algorithm for the SD and SWE as the function of various parameters, was developed as below.

$$\begin{aligned} \text{SD and SWE} = {} & A_1 + A_2 * [T_B(19H)-T_0] \\ & + A_3 *[T_B(19V)-T_0] - A_4 * [T_B(22V)-T_0] \\ & - A_5 * [T_B(37H)-T_0] + A_6 * [T_B(37V)-T_0] \\ & - A_7 * [T_B(85H)-T_0] + A_8 * [T_B(85V)-T_0] \\ & + A_9 * [T_B(19H)-T_0]^2 + A_{10} * [T_B(19V)-T_0]^2 \\ & - A_{11} * [T_B(22V)-T_0]^2 - A_{12} * [T_B(37H)-T_0]^2 \\ & + A_{13} *[T_B(37V)-T_0]^2 - A_{14} * [T_B(85H)-T_0]^2 \end{aligned} \quad (2)$$

4. RESULTS AND DISCUSSIONS

Figure 1 shows the variations of weekly averaged T_B for 2002-03 for all four SSM/I channels. The T_B at lower frequency shows higher values compared to higher frequency. For higher frequency, an interesting phenomenon of volume scattering is observed, in this, the individual ice grain reduces the T_B by scattering some of the radiations out of the sensors field of view. Thus, the values of the brightness temperature are lower at higher frequency. The curve (Fig. 1) also shows that T_B is high in October and decreases from November to March end. After that, T_B starts increasing.

The value of T_B increases from April onwards because of the onset of snow melting, which produces liquid water in the snowpack; radically altering the

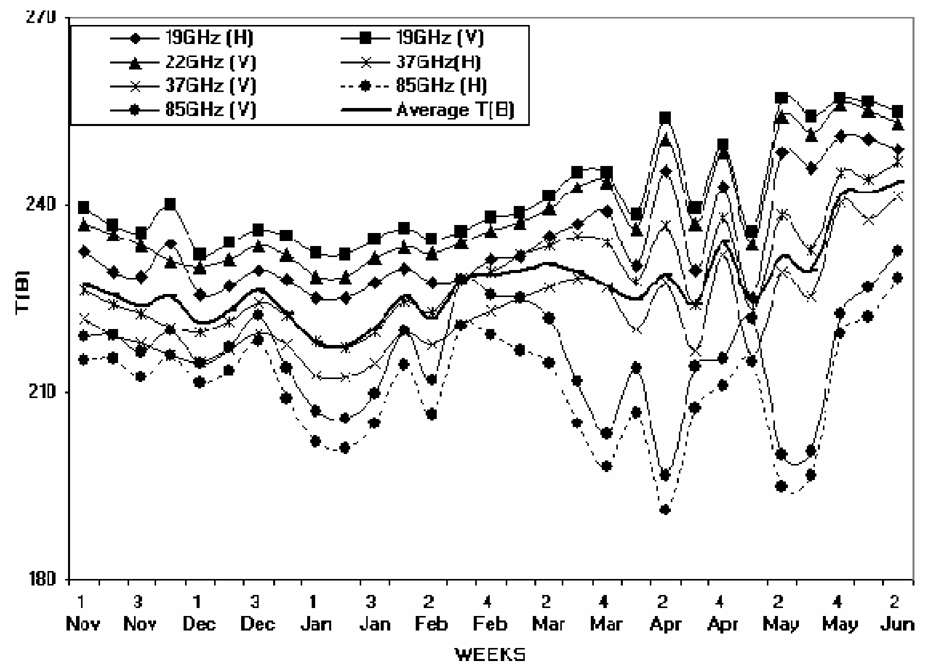

Figure 1. Variation of T_B for 2002-03.

snow emissivity. The water coats the snow grains and causes a significant increase in internal absorption of the microwave radiation and a decrease in volume scattering and results in an increase in the snow emissivity. The microwave signals emitted from the underlying ground surface propagate through the snow and are scattered by the randomly spaced snow grains into all directions. The snow present absorbs very little microwave energy, and thus contributes very little in the form of self-emission. The attenuation generally increases as the frequency becomes higher, grain size increases or the snow depth increases. Pronounced increase of the standard deviation of T_B (*H*) from 19 GHz to 85 GHz for the snowcover is due to increase of atmospheric transmittance *t* with frequency causing larger temporal and spatial variations of atmospheric transmittance at 85 GHz than at lower frequencies.

In Fig. 2, using the formula for scattering index given by Ferraro, *et al*. The scattering index has been modified. To differentiate the snow-free areas from the snow-bound areas based on scattering index, it was found that if SI is < 15 and T_B(19V) > 245K, T_B(37V) > 235K, T_B(85V) > 225K, the area is snow-free, otherwise it is snow-covered area.

From Figs 3 and 4, stratigraphy data is the actual SD observed on the ground and the

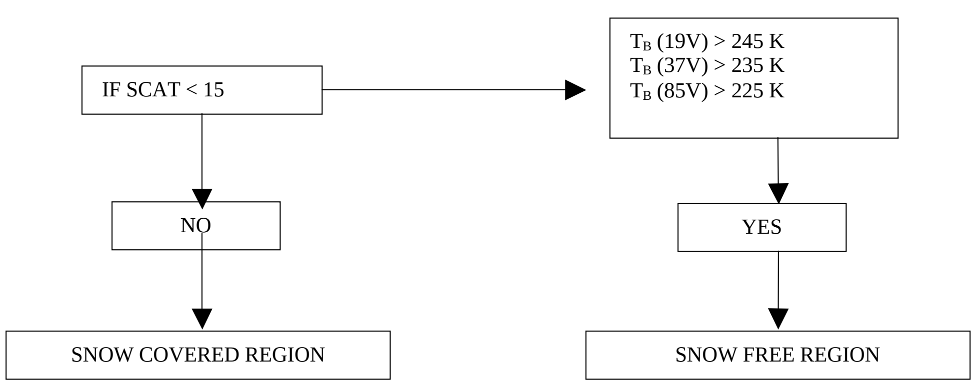

Figure 2. Decision tree for snow identification.

SSM/I data is showing the snow depth computed after fitting curve with the help of SSM/I data. Considering T_B at 19 GHz(V) and 37 GHz(V) frequencies as two variables, a linear regression equation for the SD and SWE is established. After calculating geophysical constants, derived SWE and SD were compared with the ground observatory data. The satellite-derived and ground observatory data do not show a good correlation.

From Figs 5 and 6 of SD and SWE, it is found that the values at the ground and by the satellite are correlated much better than the earlier one. In this, the T_B was used at all the frequencies.

A comparison of SD and SWE has been made using Figs 7 and 8. It has been observed that when power regression equation is used (Figs 9 and 10) in place of linear regression equation (Figs 5 and 6), the difference in the observed values and the predicted values reduces significantly.

Finally, from Figs 9 and 10, it was found that the power regression equation of second degree is best suited for Indian conditions. Thus, using the geophysical constants in this second-degree equation, the predicted values are found to be very close to the observed values. From the comparison of Figs 3 and 4 with Figs 9 and 10, it is clear that the power regression equation gives better results or in other words, using power regression equation, difference between the satellite-derived SD/SWE and the ground SD/SWE can be minimised.

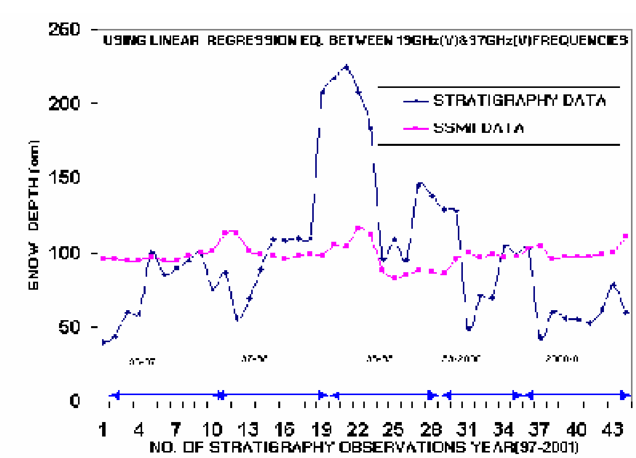

Figure 3. Comparison of snow depth between stratigraphy and SSM/I data at Patseo.

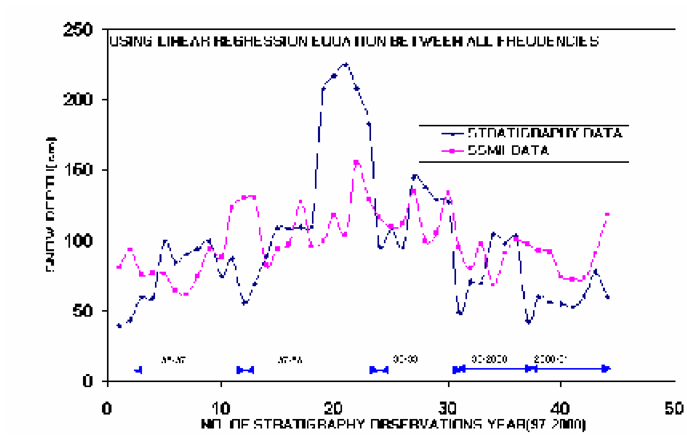

Figure 5. Comparison of snow depth between SSM/I and stratigraphy data at Patseo.

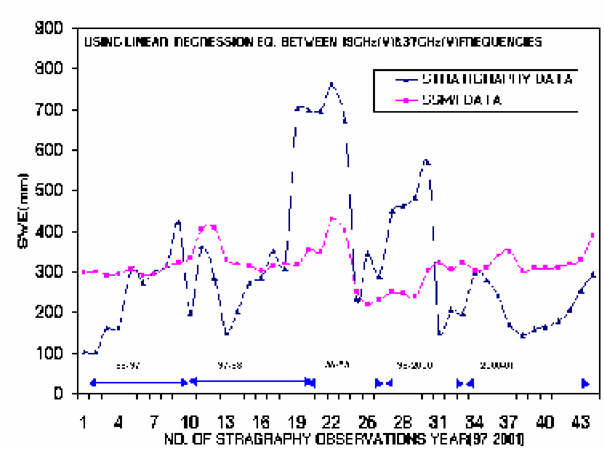

Figure 4. Comparison of SWE between SSM/I and stratigraphy data at Patseo.

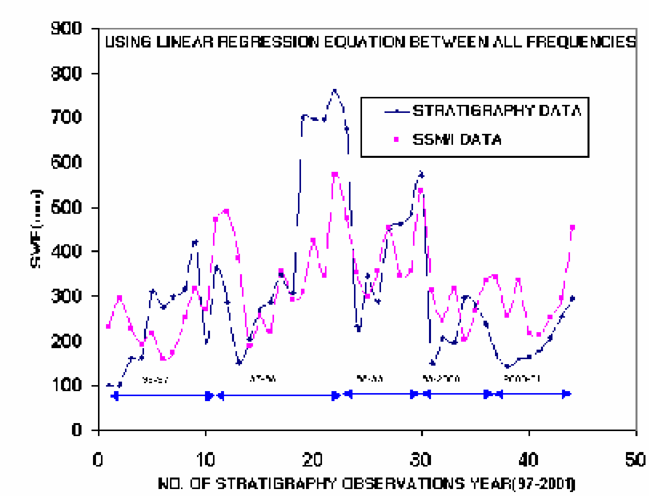

Figure 6. Comparison of SWE between stratigraphy and SSM/I data at Patseo.

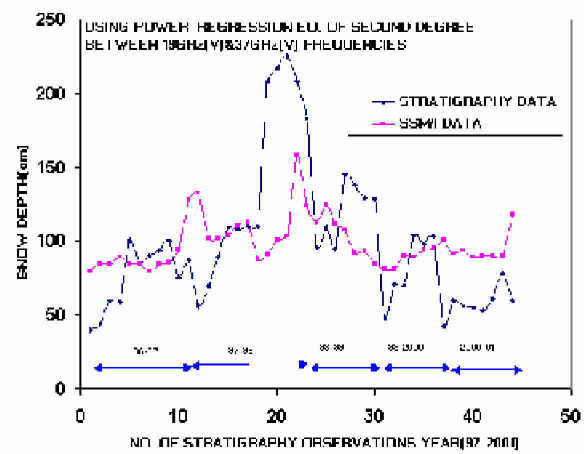

Figure 7. Comparison of snow depth between stratigraphy and SSM/I data at Patseo.

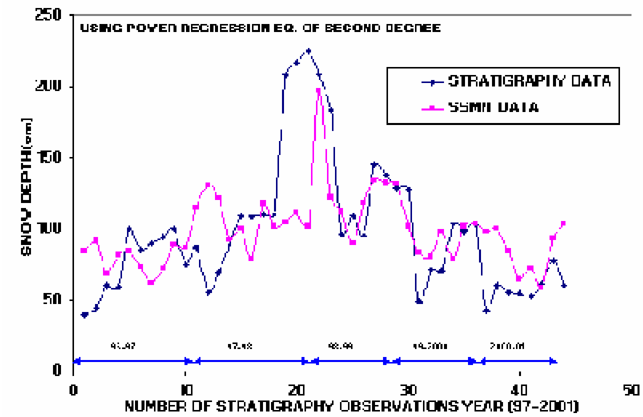

Figure 9. Comparison of snow depth between stratigraphy and SSM/I data at Patseo.

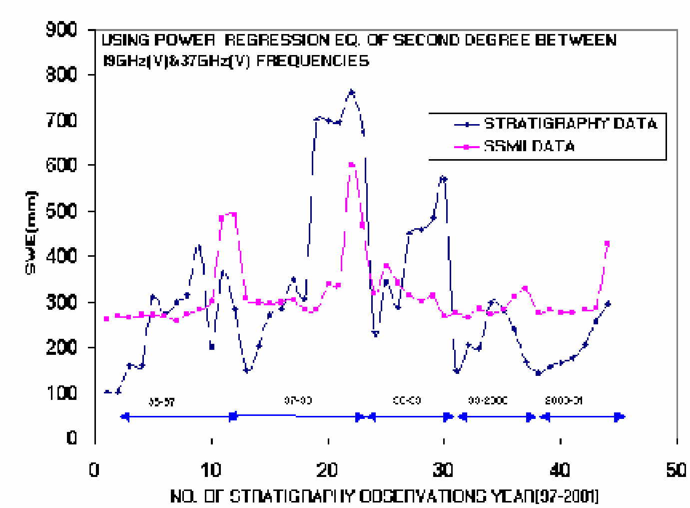

Figure 8. Comparison of SWE between stratigraphy and SSM/I data at Patseo.

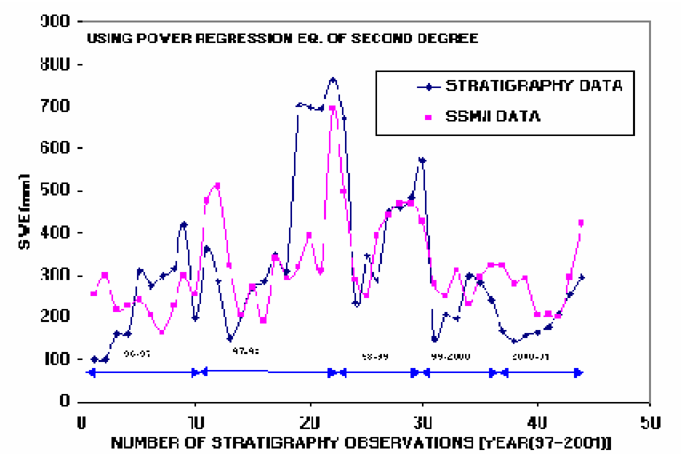

Figure 10. Comparison of SWE between stratigraphy data and SSM/I data at Patseo.

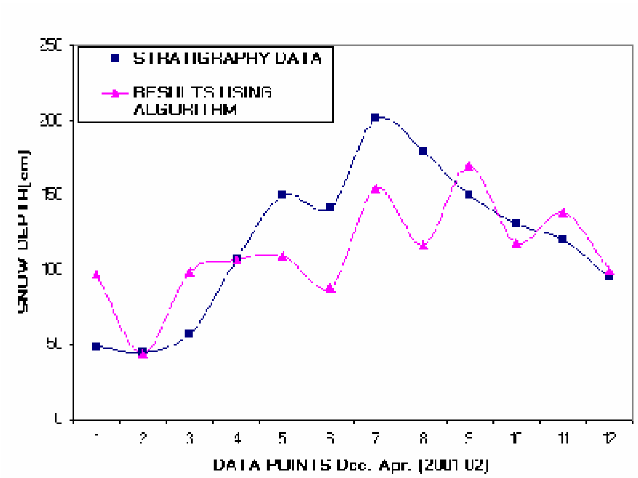

Figure 11. Comparison of snow depth based on algorithm and stratigraphy data.

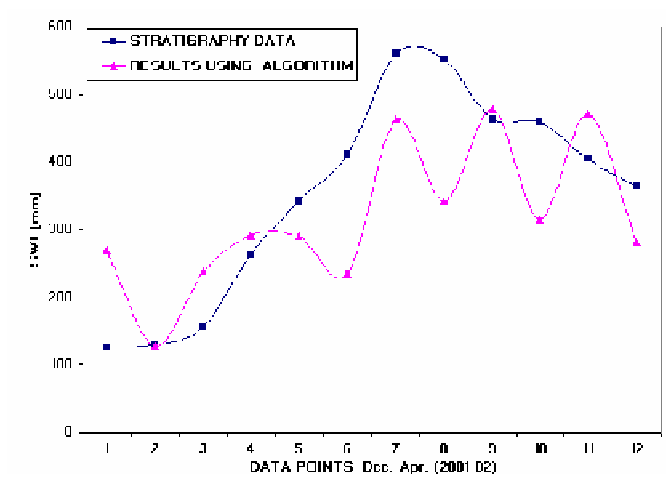

Figure 12. Comparison of SWE based on algorithm and stratigraphy data at Patseo.

Now, algorithm are generated for SD and SWE using the SSM/I and snow profile data from 1996-2001. In Figs 11 and 12, efforts were made to use these equations to predict the values for 2001-2002. It has been found that the values predicted by these equations using the brightness temperature are very close to the values observed at the ground.

5. CONCLUSION

It has been observed that only brightness temperature is not sufficient to identify snow covered areas, but the combination of brightness temperature and scattering index or snow results in identifying the snow covered regions with precise accuracy. It also has been observed that the brightness temperature of snow-covered areas decreases as the snow depth increases and vice versa. Knowledge of the conditions of the ground underlying the snow is important for the interpretation of observed brightness temperature. Ground temperature is subtracted from the satellite brightness temperature, to get the brightness temperature only from the snowpack. Snow depth and SWE algorithm are developed (based on the statistical analysis), which have further been utilised for the prediction of SWE and SD for the consequent years' data.

Algorithm generated over one area are not suitable for other areas. Therefore, algorithm should be developed for individual areas, which could be useful to improve the assessment of snowpack conditions.

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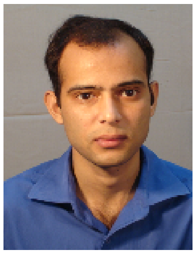
Contributors



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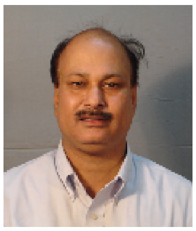

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