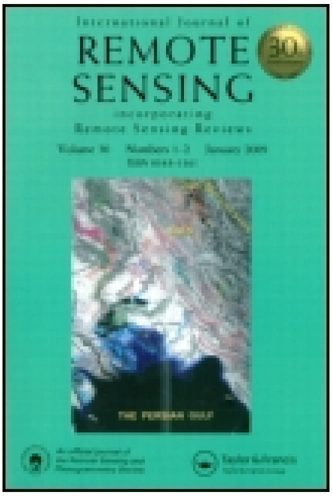

International Journal of Remote Sensing
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tres20

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Published online: 14 Jun 2008.

International Journal of Remote Sensing
Vol. 29, No. 14, 20 July 2008, 4237–4248

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(*Received 16 March 2007; in final form 12 December 2007*)

This paper presents the estimation of snow depth over north-western Indian Himalaya using the 18.7H and 36.5H GHz channels of Advanced Microwave Scanning Radiometer-EOS (AMSR-E). The Microwave Emission Model of Layered Snowpacks (MEMLS) was used along with AMSR-E to understand the difference in the snow pack emitted and sensor received signals due to the prevailing topography. The study shows that the brightness temperature of AMSR-E and MEMLS are comparable at 18.7 GHz with some differences in their values at 36.5 GHz showing the sensitivity of this channel to the prevailing topography.

Three years of AMSR-E data were used to modify the 1.59 algorithm to suit the terrain and snow conditions of the north-western Indian Himalayas. The retrieved snow depth is then compared with ground observations. Data from December to February 2003–2006 were used for the study of snow depths less than 1 m. The modified algorithm estimates the snow depth better than the old algorithm over the mountainous terrains of the north-western Himalayas.

1. Introduction

Snow is one of the most dynamic features on the Earth's surface and is important for global water and energy balance studies. Snow covers a large area over the earth during winter and is a substance undergoing continuous metamorphism within its pack owing to temperature, pressure, wind activity, radiation effects, etc. It is a major source of water storage and runoff and its high thermal capacity and albedo makes it an important contributor to global water, energy budgets and climate change studies (Cohen 1994, Kelly *et al.* 2003, Gong *et al.* 2004, Chang *et al.* 2005, Foster *et al.* 2005).

The all weather, day and night working capability of passive microwave remote sensors can be used to provide important information of global snow depth and water equivalent over a wide area (Foster *et al.* 2005, Tedesco and Kim 2006). This is especially important when the terrain considered is remote and not easily accessible like the Indian Himalayas and conventional techniques of measuring snow parameters over the entire region are not feasible.

The study of snow depth over the Indian Himalayas is important not only from the point of view of climate changes, and water and energy budgets but also to

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International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online © 2008 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/01431160701874595

monitor the frequent occurrence of avalanches. Snow avalanches over the Himalayas are a major threat to lives and property every winter (Sharma *et al.* 2004). Although representative observatories at approachable areas in valleys are used to record snow and meteorological parameters over these regions, these are point observations and there are wide differences in values when the entire spatial distribution of snow over the Himalayas are considered. Passive microwave remote sensors can be effectively used for daily monitoring of snow cover changes as they have high temporal resolution and improved spatial resolution.

In the present study, the Microwave Emission Model of Layered Snowpacks (MEMLS) has been used to compare the difference of the T_b (brightness temperature) obtained from the surface of the snow pack to that which is recorded by the satellite sensor to understand the changes in T_b owing to the complexity of the terrain. In this paper, Advanced Microwave Scanning Radiometer-EOS (AMSR-E) and ground observatory data for 4 years from 2003 to 2006 (December to February) have been taken into account. This paper presents a modification of the regression coefficients of the Chang *et al.* (1987) algorithm for estimation of snow depth using a passive microwave remote sensor. The regression coefficients have been modified to take into account the complexity of the terrain and also the difference of snow properties like density and grain sizes owing to the different climatic condition of the Himalayas. Recent findings show that the majority of the parameters involved in regression coefficients have scaling phenomena and exhibit long-memory effects (Grotan *et al.* 2005). Therefore the variability of the terrain, snow properties and climatic conditions can be considered to exhibit power law behaviour. Recent literature shows that the exponents of the power law can be achieved by employment of the detrended fluctuation analysis (DFA). DFA has been useful in several complex systems like air pollutants (Varotsos 2005), the aerosol index (Varotsos and Kirk-Davidoff 2006), etc.

2. MEMLS

MEMLS is a microwave emission model developed at the University of Bern, Switzerland and takes into account multiple volume scattering and absorption within a snow pack (Wiesmann and Matzler 1999). It is based on a six flux radiative transfer model, uses a correlation function approach and takes into account multiple scattering of radiation caused by stratification and snow grains, refraction and trapping of radiation, total internal reflection and coherent and incoherent superposition of radiation by layer interfaces (Matzler 2006). The advantage of using this model is that the snow characteristics can be studied at individual layers and this can give an important understanding of the penetration and attenuation of radiation for remote sensors. MEMLS has often been used to show the difference in the brightness temperatures using grain size and correlation lengths (Tedesco and Kim 2006). While grain size is different from correlation length, the relationship between them is complex and there are several methods available to connect one with the other. The correlation lengths of snow in this paper have been taken from the results based on Matzler (2002).

3. Datasets used in the study

AMSR-E data for 3 years 2004–2006 (both years inclusive) from December to February for snow depths less than 1 m have been used to recalibrate the Chang *et* *al.* (1987) algorithm to suit the Indian Himalayan conditions. AMSR-E data for 2003 and selected days of 2006 have been used to validate the algorithm. Snow Met Data (SMD 11) and stratigraphy data from our observatory sites for all 4 years have been used as ancillary data as well as an input to MEMLS.

4. Comparison of the brightness temperature of AMSR-E and MEMLS

As the region considered is very rugged, this implies interaction of the radiation emanating from the snow surface with the topography itself apart from all other natural causes like ongoing metamorphisms leading to layering and grain growth, MEMLS derived T_b was used to compare with the AMSR-E retrieved T_b. As MEMLS gives the T_b of the snow pack alone, comparing MEMLS T_b with AMSR-E T_b can help us understand the changes in space-retrieved brightness temperature owing to topographical effects like peaks, slopes, ridges, valleys, shadow and atmospheric effects.

However, comparison of AMSR-E with MEMLS may not strictly give the correct picture, as AMSR-E covers a spatial distance of 5 km for each pixel whereas MEMLS gives point representation. MEMLS is also capable of giving layer-wise distribution of brightness temperature but in this study MEMLS has been run for a single layer only (top layer) as satellite remote sensors see only the top layer.

Figure 1(*a*) and (*b*) shows the difference between MEMLS and AMSR E derived T_b for 18 GHz and 36 GHz channels, respectively. While T_b values of AMSR-E and MEMLS at 18 GHz are comparable (figure 1(*a*)), some differences are seen in the 36 GHz channels (figure 1(*b*)). In some cases the differences in T_b may also be due to errors in estimation of the correlation lengths of snow in addition to topographical influences. Also some differences can be attributed to the fact that MEMLS gives layer-wise distribution of T_b and may differ from the satellite received T_b as the snow type changes in the area covered by one pixel of AMSR-E. This problem can be partially solved if one considers a larger number of ground data points over the Himalayas.

5. Algorithm to estimate snow depth from passive microwave remote sensor

The algorithm in Chang *et al.* (1987), hereafter referred to as the 1.59 algorithm, has been used in the present study after suitable modifications of the regression coefficients using 3 years of AMSR-E data to account for the larger grain size and lesser density of the snow grains as well as the mountainous terrain of the Indian Himalayas.

Microwave emissions originating from a snow pack are a composite of those from snow and the underlying land surface (Foster *et al.* 2005). The snow crystals in a snow pack which is thicker than about 5 cm act as active scatterers of upwelling microwave radiation. The deeper the snowpack, the more scatterers are available for the scattering of radiation. A microwave radiometer can be used to detect the scattering of the upwelling radiation by using bands greater than 25 GHz while the emission of the underlying snowpack can be detected by using wavelengths less than 25 GHz. There is very little absorption of microwave radiation by the snowpack (Ulaby *et al.* 1981). The difference of signals recorded by bands greater than 25 GHz with those less than 25 GHz therefore gives an estimate of the snow depth, which is in general proportional to the difference between signals recorded by the two bands. This principle forms the basis of estimation of snow depth or water equivalent by

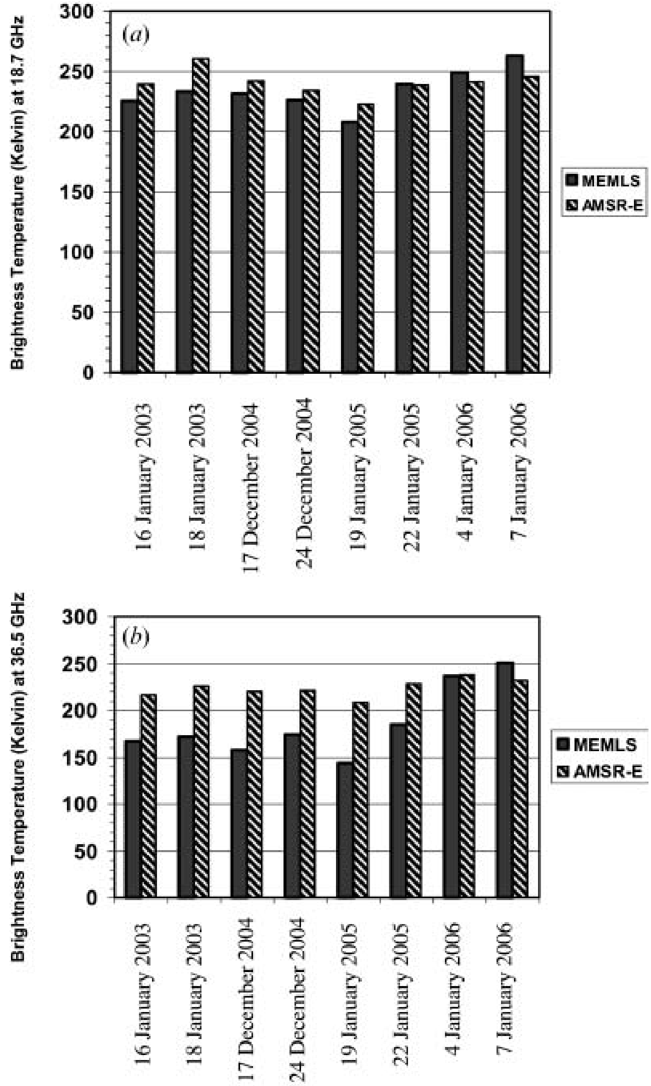

Figure 1. Comparison of MEMLS T_b with AMSR-E T_b at (*a*) 18.7H GHz and (*b*) 36.5H GHz.

passive microwave radiometers (Chang *et al.* 1976, Ulaby and Stiles., 1980, Tsang *et al.* 2000; Pulliainen and Hallikainen 2001, Kelly and Chang, 2003, Foster *et al.* 2005).

However, the snowpack history should be included in the estimation of snow depth (Kelly *et al.* 2003) as metamorphism inside a snowpack alters the microwave radiation. This is because there is appreciable growth of grains under the influence of melt–freeze cycles of a snowpack which can appreciably alter the microwave radiation. The snowpack grain size as well as the density is important for the microwave behaviour of the snow (Rosenfeld and Grody 2000).

An algorithm commonly used for snow depth estimation is the one developed by Chang *et al.* (1987) where the depth is retrieved from the brightness temperature difference of 19 and 37 GHz channels of SSM/I multiplied by a coefficient *a*, which is derived from radiative transfer model experiments of snow

$$D = a(T_{19} - T_{37}) + b \quad (1)$$

where D is the snow depth (in cm), a is 1.59, b is usually kept as zero, T_{19} is the brightness temperature at 19 GHz and T_{37} is the brightness temperature at 37 GHz channels of SSM/I. The average snow grain size is assumed to be 0.3 mm and the average density is 300 kg m^{-3}.

Equation 1, after modifying the regression coefficients to suit the grain size and density of the snow grains, has been used to calculate the snow depth from AMSR-E using the difference of its 18.7H and 36.5H GHz channels (Kelly and Chang 2003, Kelly *et al.* 2004). The same approach is used in this paper and the coefficients have been modified taking into account 3 years of data from 2003 to 2006 (both years inclusive) and using the least square method of regression fit. The average size and density of snow grains is 1.5 mm and 250 kg m^{-3}, respectively. The standard error of the predicted snow depth is 20.34 cm. The spread of points have been kept at three times the standard deviation of y upon x where y is the actual snow depth (in cm) and x is the difference of the T_b of 18.7 and 36.5 GHz of AMSR-E (figure 2). The coefficient of determination (R^2) value obtained is 0.2323. The maximum depth has been limited to 1 m to account for the approximate saturation limit of 37 GHz, which can saturate well below 1 m depending on the size of snow grains (Foster *et al.* 2005). Therefore the modified equation in the case of the Western Indian Himalayas turns out to be

$$D = 3.16(T_{18.7} - T_{36.5}) + 24.25. \quad (2)$$

Here $T_{18.7}$ is the T_b of 18.7 GHz and $T_{36.5}$ represents the same for 36.5 GHz channels of AMSR-E.

The above regression equation (equation (2)) is represented in figure 2. In this paper, equation (2) is hereafter known as the 3.16 algorithm. Horizontal polarization of both the frequency bands of the AMSR-E sensor has only been used in this study as it has been reported that the performance of the algorithm is the same for spaceborne sensors when either horizontal or vertical polarization is used (Rango *et al.* 1979, Foster *et al.* 2005).

The spread in the points has been (limited to three times the standard deviation of the values of the estimated snow depth y-axis upon the T_b difference of the above-mentioned channels of AMSR-E x-axis) allowed to facilitate a wider range of snow depth values. This figure shows that the ruggedness of the terrain, snowpack history and grain growth has to be taken into account to obtain an accurate estimation of snow depth. Although the value of b of 24.25 can be expected to overestimate the snow depth in certain cases, this algorithm does not work for shallow snow depths as well as for snow depths greater than ~70 cm.

For the snow depth retrieval, only clear days free of precipitation are taken into account and a positive difference ⩾4.0 between 18.6 and 36.5 GHz is considered as a snow pixel. This number has been agreed upon after taking into account statistics of 3 years of data.

6. Estimation of snow depth over the north-western Indian Himalayas using AMSR-E

Figure 3(a) shows the retrieval of snow depth over western Himalayas using equation (2). The AMSR-E retrieved aerial extent of snow cover has been used to

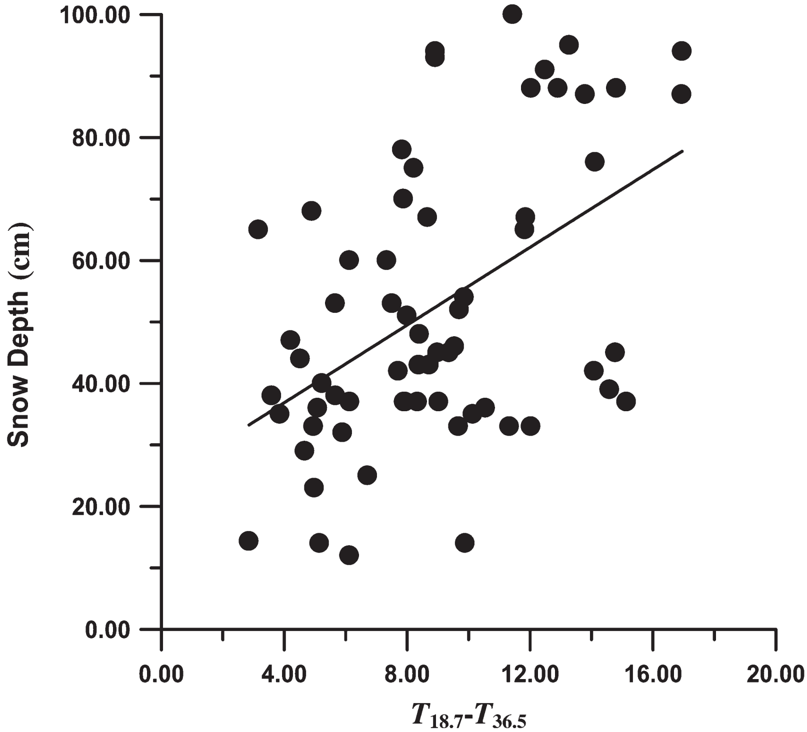

Figure 2. The regression curve used to derive the relation between brightness temperature and snow depth over the north-western Himalayas. The T_b difference for the 18.7 GHz and 36.5 GHz channels of AMSR-E is plotted on the *x*-axis.

compare with that of a Moderate Resolution Imaging Spectroradiometer (MODIS) image for the same day (figure 3(*b*)). Figure 3(*c*) shows the AMSR-E retrieved snow depth using the 1.59 algorithm. Comparison of figure 3(*a*), (*b*) and (*c*) shows that the 3.16 algorithm detects snow better than the 1.59 algorithm over the mountainous terrain of the north-western Himalayas. However, this technique is unreliable for shallow snowpacks as well as for snowpacks greater than ~60 cm for the prevailing conditions in the western Himalayas. As during peak winter, the snow depth over most parts of western Himalayas is well above 1 m, a different technique involving different bands and sensors will be developed.

6.1 *Validation of the AMSR-E retrieved snow depth with ground data and MODIS*

Clear days in December, January and February 2003 and 2006 were chosen for the validation of the AMSR-E data (figure 4). Ten observatory sites were chosen along the Indian Territory over the north-western Himalayas for the validation of the data. Figure 4 shows the comparison of AMSR-E retrieved snow depth with the ground-observed data.

Both 3.16 and 1.59 algorithms were used to estimate snow depth over north-western Himalayas and the values obtained were compared with *in situ* observations from 10 observatory sites. Figure 5(*a*) is snow depth estimation using the 3.16 algorithm and figure 5(*b*) shows the comparison with ground data. Figure 5(*c*) shows the snow depth estimation using the 1.59 algorithm. Comparison of figure 5(*a*), (*b*) and (*c*) shows that for mountainous regions, the 3.16 algorithm estimates snow

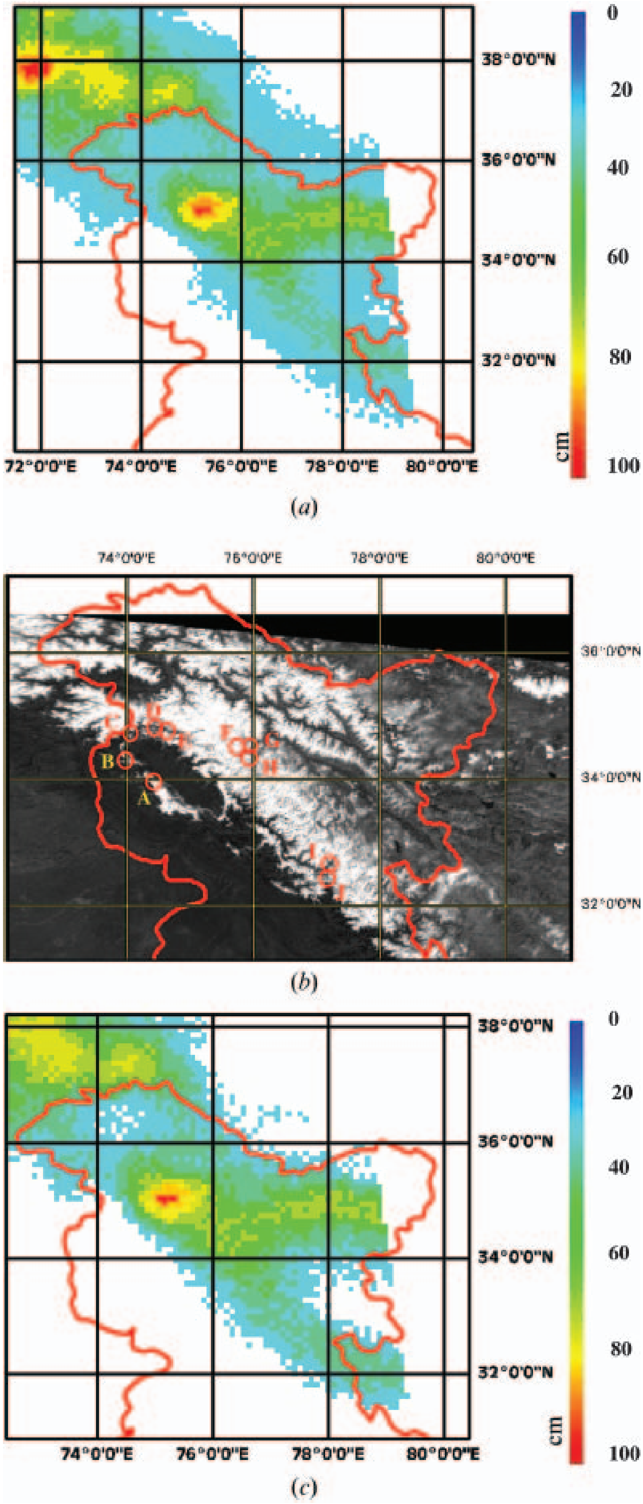

Figure 3. (*a*) AMSR-E retrieved aerial extent of snow on 31 January 2007 using the 3.16 algorithm. (*b*) Aerial extent of snow cover on 31 January 2007 using MODIS. The capital letters show the *in situ* sites where snow and meteorological data were collected. (*c*) AMSR-E retrieved aerial extent of snow on 31 January 2007 using the 1.59 algorithm.

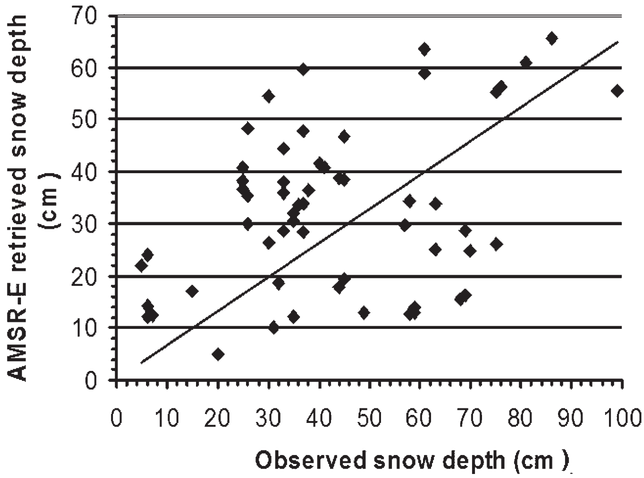

Figure 4. Estimation of snow depth using AMSR-E and comparison with observed snow depth.

depth better than the 1.59 algorithm. Figure 6(*a*)–(*c*) shows the same comparisons for another day. Both sets of figures clearly show that the 3.16 algorithm estimates snow depth with better accuracy compared to the 1.59 algorithm over the Himalayas.

7. Conclusions

The Chang *et al.* (1987) algorithm for the estimation of snow depth using passive microwave radiometer has been recalibrated and a new set of regression coefficients has been obtained based on 3 years of AMSR-E data (December to February, 2004–2006) using its 18.7H and 36.5H GHz channels for regions of western Indian Himalayas and for those days when the depth of snow is less than 1 m. The new set of coefficients has been found useful for the estimation of snow depth from 5 to approximately 60 cm of snow depth with average density and size of snow crystals being 250 kg m^{-3} and 1.5 mm, respectively. The standard error in the estimation of snow depth is 20.34 cm. This is mainly because of the coarse resolution of AMSR-E data as well as the fact that the Indian Himalayas, being in the tropical region, experience rapid changes in temperature leading to grain growth, which introduces errors in the estimation of snow depth.

The MEMLS model has been used to study the differences in the snowpack emitted and AMSR-E recorded T_b. It was found that while the T_b of 18.7H GHz of AMSR-E and MEMLS are comparable to each other, there are some differences in the 36.5H GHz channel, which is sensitive to the snowpack. The results show that brightness temperature is not as sensitive to the snow depth as compared to other factors like metamorphosis of snow, occurrence of fresh snow, complex terrain, etc., which play important roles in modifying the emission characteristics of snow.

Acknowledgements
The authors acknowledge Dr C. Matzler, University of Bern, Switzerland, for kindly providing us with the MEMLS model and for providing help with understanding the

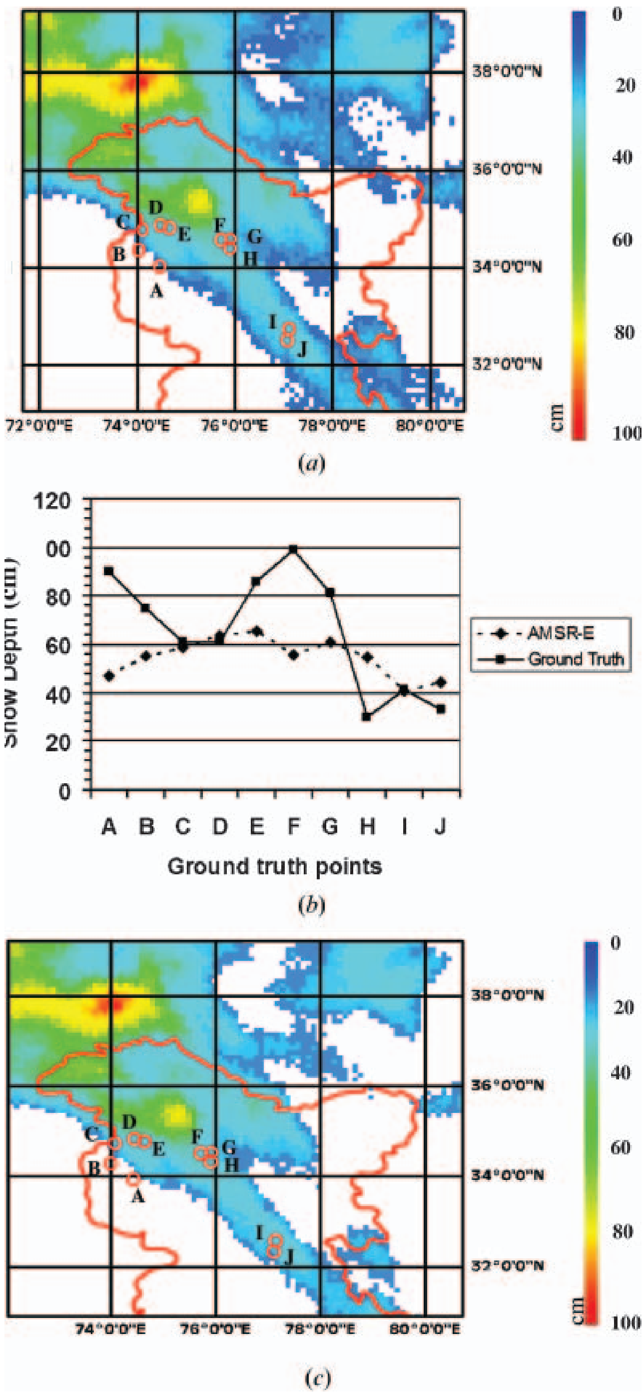

Figure 5. (*a*) Estimation of snow depth using the 3.16 algorithm on 9 January 2006. The capital letters are used to denote the different points where *in situ* data was collected (the values of which are given in (*b*)). (*b*) Comparison of the 3.16 algorithm with ground observations. The *x*-axis shows the different *in situ* sites where snow and meteorological data was collected. (*c*) Estimation of snow depth using the 1.59 algorithm on 9 January 2006. The technique shows an underestimation of snow depth over mountainous terrain.

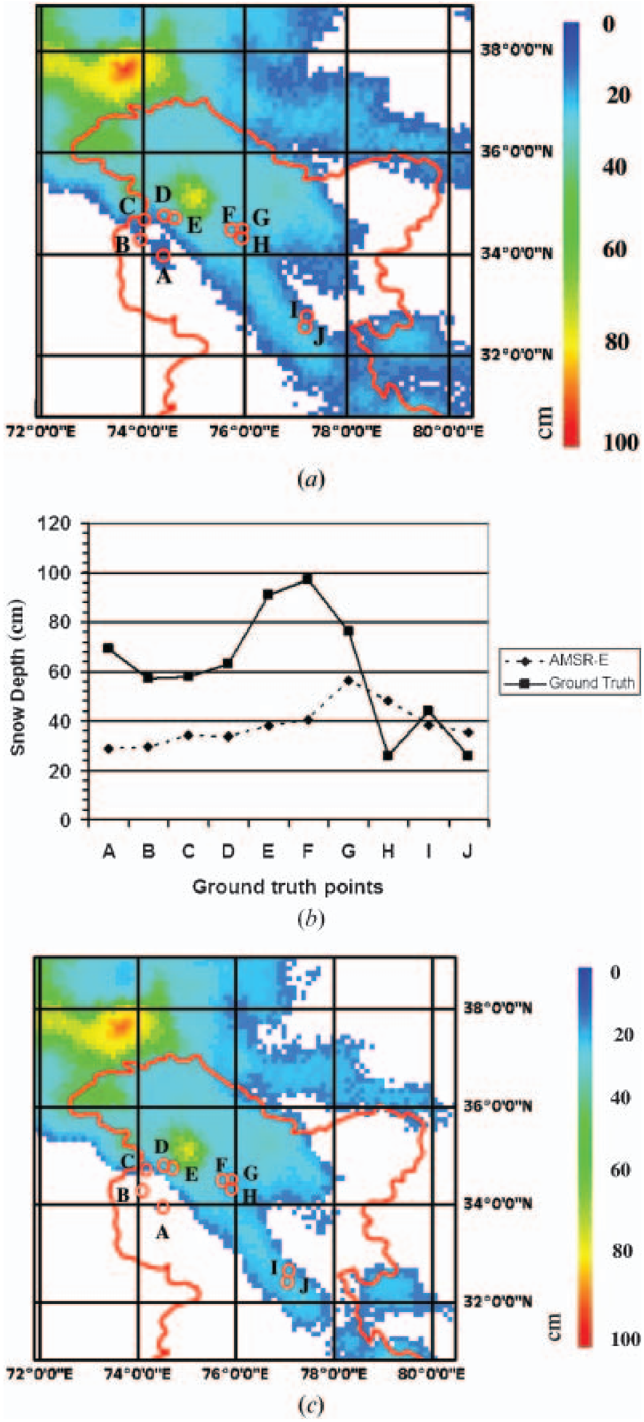

Figure 6. (*a*) Estimation of snow depth using the 3.16 algorithm on 14 January 2006. The capital letters are used to denote the different points where *in situ* data was collected (the values of which are given in (*b*)). (*b*) Comparison of the 3.16 algorithm with ground observations. The *x*-axis shows the different *in situ* sites where snow and meteorological data was collected. (*c*) Estimation of snow depth using the 1.59 algorithm on 14 January 2006. The technique shows an underestimation of snow depth over mountainous terrain.

model. Thanks are also due to Dr R. Kelly of Waterloo University, Canada, Dr M. Tedesco of GSFC, NASA and Mr N. K. Thakur, SASE, for the helpful discussions and suggestions.

References

CHANG, A.T.C., FOSTER, J.L. and HALL, D.K., 1987, Nimbus-7 derived global snow cover parameters. *Annals of Glaciology*, **9**, pp. 39–44.

CHANG, A.T.C., GLOERSEN, P., SCHMUGGE, T., WILHEIT, T.T. and ZWALLY, H.J., 1976, Microwave emission from snow and glacier ice. *Journal of Glaciology*, **16**, pp. 23–39.

CHANG, A.T.C., KELLY, R.E.J., JOSBERGER, E.G., ARMSTRONG, R.L., FOSTER, J.L. and MOGNARD, N.M., 2005, Analysis of ground-measured and passive-microwave-derived snow depth variations in midwinter across the Northern Great plains. *Journal of Hydrometeorology*, **6**, pp. 20–23.

COHEN, J., 1994, Snow cover and climate. *Weather*, **49**, pp. 150–155.

FOSTER, J.L., SUN, C., WALKER, J.P., KELLY, R., CHANG, A.T.C., DONG, J. and POWELL, H., 2005, Quantifying the uncertainity in passive microwave snow water equivalent observations. *Remote Sensing of the Environment*, **94**, pp. 187–203.

GROTAN, V., SAETHER, B.E. and ENGEN, S., 2005, Climate causes large-scale spatial synchrony in population fluctuations of a temperate herbivore. *Ecology*, **86**, pp. 1472–1482.

GONG, G., ENTEKHABI, D., COHEN, J. and ROBINSON, D., 2004, Sensitivity of atmospheric response to modeled snow anomaly characteristics. *Journal of Geophysical Research*, **109**, pp. D06107, DOI:10.1029/2003JD004160.

KELLY, R.E.J. and CHANG, A.T.C., 2003, Development of a passive microwave global snow depth retrieval algorithm for Special Sensor Microwave Imager (SSM/I) and Advanced Microwave Scanning Radiometer-EOS (AMSR-E) data. *Radio Science*, **38**, pp. 8076, DOI:10.1029/2002rs002648.

KELLY, R.E., CHANG, A.T., TSANG, L. and FOSTER, J.L., 2003, A prototype AMSR-E global snow area and snow depth algorithm. *IEEE Transactions on Geoscience and Remote Sensing*, **41**, pp. 230–242.

KELLY, RICHARD E.J., et al. 2004, Using Remote Sensing and Spatial Models to Monitor Snow Depth and Snow Water Equivalent. *Spatial Modelling of the Terrestrial Environment*. Edited by R. Kelly, N. Drake, and S. Barr. C 2004 John Wiley & Sons, Ltd, pp. 35–58.

MATZLER, C., 2002, Relation between grain size and correlation length of snow. *Journal of Glaciology*, **48**, pp. 461–466.

MATZLER, C. (Ed.), 2006, *Thermal Microwave Radiation: Applications for Remote Sensing*, pp. 241–250 (London: Institution of Engineering and Technology).

PULLIAINEN, J.T. and HALLIKAINEN, M., 2001, Retrieval of regional snow water equivalent from space borne passive microwave observations. *Remote Sensing of Environment*, **75**, pp. 76–85.

RANGO, A., CHANG, A. and FOSTER, J., 1979, The utilization of space-borne radiometers for monitoring snow pack properties. *Nordic Hydrology*, **10**, pp. 25–40.

ROSENFELD, S. and GRODY, N.C., 2000, Metamorphic signature of snow revealed in SSM/I measurements. *IEEE transactions on Geoscience and Remote Sensing*, **38**, pp. 53–63.

SHARMA, S.S., MATHUR, P. and SNEHMANI, 2004, Change detection analysis of avalanche snow in Himalayan region using near infrared and active microwave images. *Advances in Space Research*, **33**, pp. 259–267.

TEDESCO, M. and KIM, E.J., 2006, Retrieval of dry-snow parameters from microwave radiometric data using a dense-medium model and genetic algorithms. *IEEE Transactions on Geoscience and Remote Sensing*, **44**, pp. 2143–2151.

TSANG, L., CHEN, C., CHANG, A.T.C., GUO, J. and DING, K., 2000, Dense Media Radiative Transfer Theory based on quasicrystalline approximation with application to passive microwave remote sensing of snow. *Radio Science*, **35**, pp. 731–749.

ULABY, F.T. and STILES, W.H., 1980, The active and passive microwave response to snow parameters 2. Water equivalent of dry snow. *Journal of Geophysical Research*, **79**, pp. 1699–1708.

ULABY, F.T., MOORE, R.K. and FUNG, A., 1981, *Microwave Remote Sensing* (Reading, MA: Addison-Wesley-Longman).

VAROTSOS, C., 2005, Power-law correlations in column ozone over Antarctica. *International Journal of Remote Sensing*, **26**, pp. 3333–3342.

VAROTSOS, C. and KIRK-DAVIDOFF, D., 2006, Long-memory processes in ozone and temperature variations at the region 60°S–60°N. *Atmospheric Chemistry and Physics*, **6**, pp. 4093–4100.

WIESMANN, A. and MATZLER, C., 1999, Microwave emission model of layered snowpacks. *Remote Sensing of Environment*, **70**, pp. 307–316.