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An Approach to Measure Snow Depth of Winter Accumulation at Basin Scale Using Satellite Data

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Abstract**—**Snow depth estimation and monitoring studies have been carried out for decades using empirical relationship or extrapolation of point measurements carried out in field. With the development of advanced satellite based remote sensing techniques, a modified approach is proposed in the present study to estimate the winter accumulated snow depth at basin scale. Assessment of snow depth by differencing Digital Elevation Model (DEM) generated at the beginning and end of winter season can be experimented for the region of interest (Himalayan and polar regions) accounting for winter accumulation (solid precipitation). The proposed approach is based on existing geodetic method that is being used for glacier mass balance estimation. Considering the satellite datasets purely acquired during beginning and end of winter season, it is possible to estimate the change in depth or thickness for the snow that is accumulated during the winter as it takes one year for the snow to get transformed into firn (snow that has survived one summer or one-year old snow).

Keywords**—**Digital elevation model, snow depth, geodetic method, snow cover.

I. Introduction

ABOUT one third of the Earth's land surface may be covered seasonally by snow. Up to 50% of the Northern Hemisphere land surface has snow cover during the winter. Snow has high albedo thereby reflecting the sun's radiation back to atmosphere maintaining energy balance. Melting of snow and glaciers in polar regions impacts sea level rise and is an important indicator of global warming. The snow accumulated in winter melts during summer and serves as source of many perennial rivers in Himalayan basins. The snow and glaciers nourish rivers originating from Himalayan region which serves millions of people living at higher latitudes especially for domestic, industrial, agriculture, and hydroelectric power generation. Snow depth measurements help in estimating the amount of fresh water stored in the form of snow that melts during summer and feed the rivers. During winter, the snowfall is very intense and field measurements are not logistically feasible all the time for snow depth estimations. During winter, the entire Himalayan basins/sub-basins are covered with snow and the field visit for measurements becomes impossible sometimes due to harsh terrain environment. Usually, the point measurements of snow depth are carried out using instruments like snow fork, snow gauge, etc., for a smaller area which are later interpolated for larger areas. This process of interpolation may introduce many errors in the measurements affecting the accuracy of the measurement. With the use of remotely sensed data, it is possible to estimate snow depth for larger areas with space-based inputs. The use of satellite data processing helps in estimating snow depth for large areas without physically visiting the field for ground-based measurements. However, there is a need for validating the remotely sensed data with ground truth data.

In literature, various empirical equations and models are available for estimation of snow depth which depends on point observations of snow water equivalent and snow density. In remote sensing-based approaches there are very few researches reported related to snow depth estimation which makes use of satellite data [1]. In this paper authors propose an approach based on geodetic method used for glacier mass balance estimation using DEM differencing. The mass balance of a glacier is a measure of amount of mass gained during the winter and amount of mass lost during summer for a given year (change in mass of a glacier over a stated period) [2]. Geodetic method adopted for mass balance estimation is also applicable for estimation of snow depth by using satellite images of appropriate time period targeting the start and end of winter accumulation of snow.

II. Geodetic Method for Mass Balance (Change in Thickness)

Geodetic methods are an indirect approach used for the determination of the mass balance of a glacier. Maps of a glacier made at two different times can be compared and the difference in surface elevation observed can be used to determine the changes in mass balance with time.

The geodetic mass balance is calculated from the volume change derived from topographic data. This alone is not sufficient since estimates of the densities of the lost or gained volumes are also necessary. In this process, two DEMs are acquired at different dates, t1 and t2, usually at the end of the ablation period. The length of the experimental time period $\Delta t = t2 - t1$ can vary from as little as one year to many decades. The volume change ΔV in the period Δt is then calculated for the entire glacier either from the contour lines of elevation [3] or with a raster method [4]. The multiplication of the volume change ΔV with the mean density ρ results in the mass balance within this period. Classical geodetic work of the highest (mm) precision was demonstrated in the 1970s for purposes of measuring horizontal crustal strain over regional scales [5].

III. Snow Depth Estimation

Snow depth maps derived from satellite images are based

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on either extrapolation of field measurements or using empirical relationship existing between snow density and snow water equivalent ([SWE] ÷ [Density] = Snow Depth).

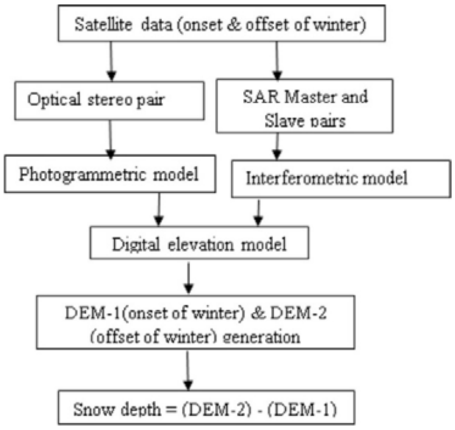

Fig. 1 Methodology suggested for estimating snow depth

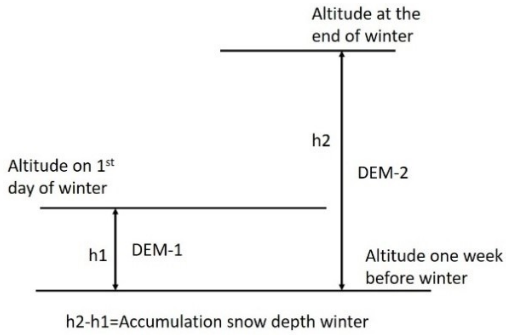

Fig. 2 Illustration of snow depth estimation

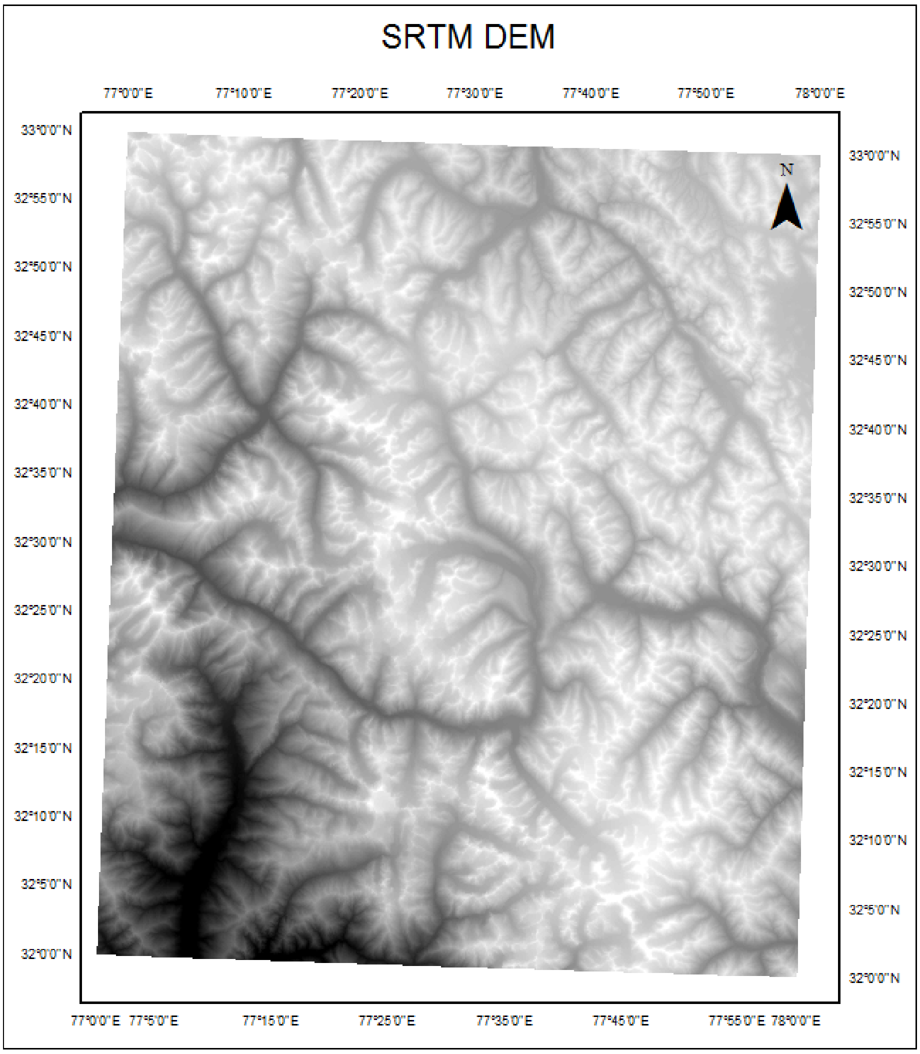

Fig. 3 SRTM DEM - February 2000

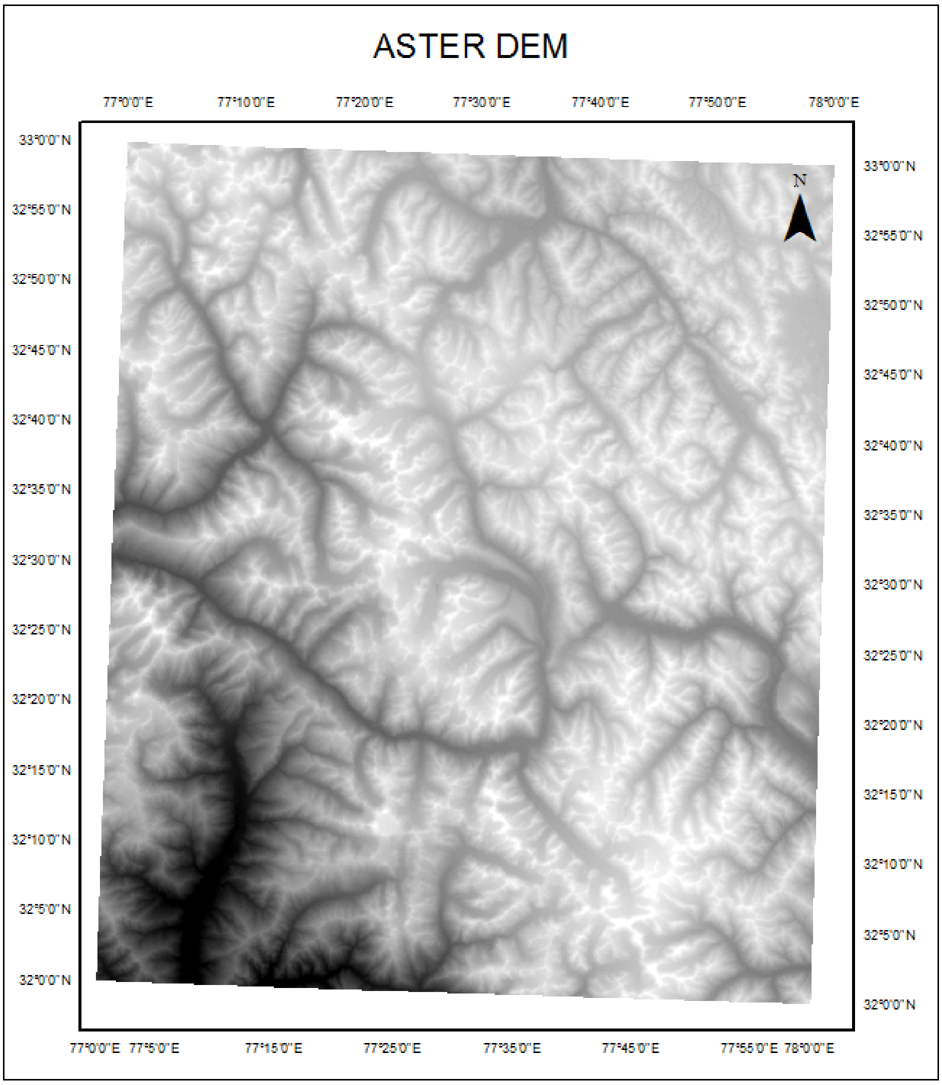

Fig. 4 ASTER DEM - October 2011

In this paper, we propose a modified approach to measure winter accumulated snow depth at basin scale using geodetic method with space-based inputs. The basic idea is to use DEM differencing for snow depth estimation. During winter, there is snowfall that is accumulated at basin scale (at glaciated and non-glaciated area). If the satellite based optical stereo pair datasets or Synthetic Aperture Radar (SAR) datasets are available during onset and offset of winter, it is possible to generate two DEMs of onset and offset of winter. The elevation difference between these two generated DEMs will provide an estimation of snow depth accumulated during the winter period at basin scale including glaciated and non-glaciated regions. The estimation is purely for the snow accumulated during winter, as the snow takes at least one year to get transformed in to firn. The DEMs can be generated (Fig. 1) either with optical stereo pair data using photogrammetric techniques or alternatively with SAR datasets using SAR Interferometry (INSAR) technique which are frequently being used for geodetic estimation of glacier mass balance in literature [6]-[11]. At glacier scale, the same method with the prescribed duration of datasets, also contributes to estimate the winter mass balance of the glaciers. The DEMs generated using SAR INSAR technique may have issues related to penetration capabilities of microwave signals due to large wavelength sometimes (example-C band has an average penetration of approximately 2.4 m) [12]. The SAR sensors with large frequency bands and small wavelengths are preferred for this kind of studies due to negligible amount of penetration.

When optical data stereo pair data set is used, acquisition of first data set (for DEM-1) is on 1st day/1st week/beginning or onset of winter based on data availability. Second set of data (for DEM-2) is obtained during last day/last week/end or offset of winter based on data availability. If the SAR data are used instead, 3 sets of data are required to generate DEM-1 and DEM-2. Acquisition of first set of SAR data is done either one week before the onset of winter/one day before onset of winter based on data availability. Second set of SAR data is taken on 1st day/1st week of beginning or onset of winter based on data availability. Acquisition of third SAR data set is done during last day/last week/end or offset of winter based on data availability. DEM-1 is generated by using first & second data sets and DEM-2 is obtained from first and third data sets for SAR databased DEM generation. The difference between DEM-1 and DEM-2 would give thickness/depth of the snow accumulated during winter. This method of measurement of snow depth is illustrated in Figs. 1 and 2.

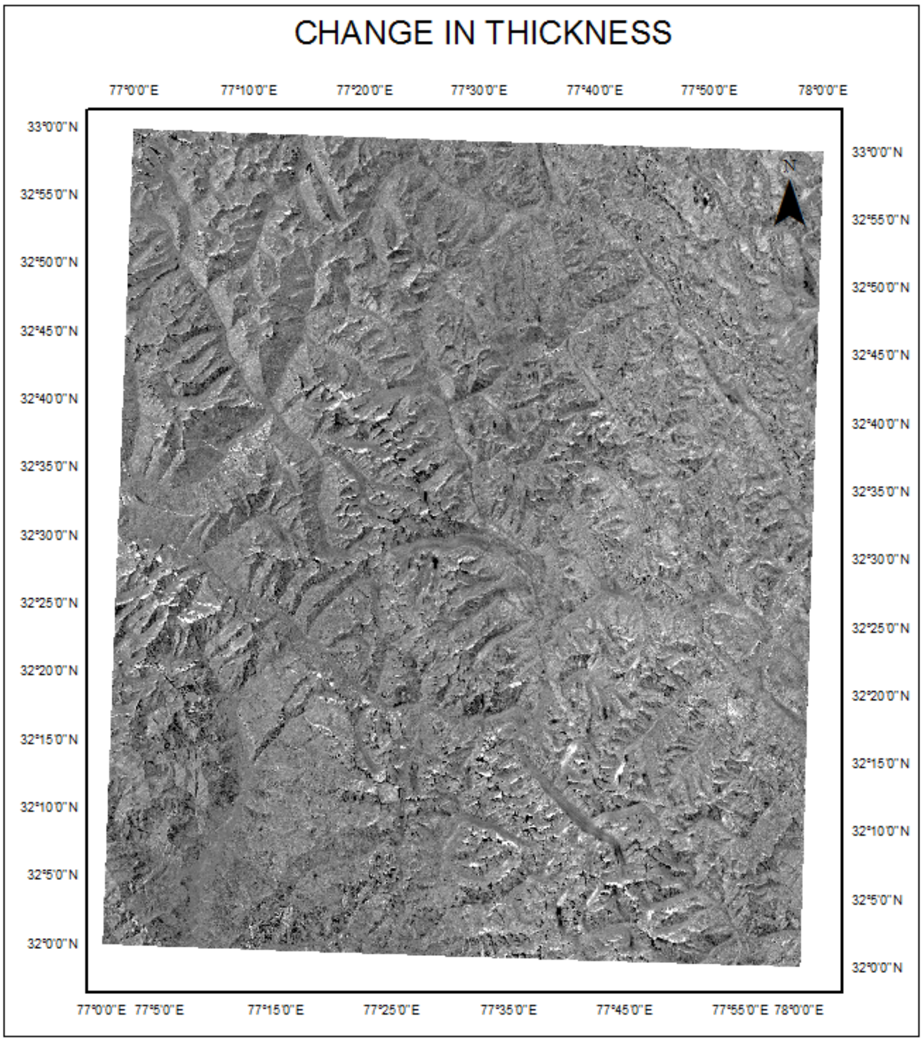

Fig. 5 Change in thickness for 11 years (2000-2011)

TABLE I
TIME OF ACQUISITION OF DATASETS

Optical data (we need 2 data sets)		**SAR data (we need 3 data sets)**	
Data for DEM-1		Data for DEM-1	
1^{st}Data (Stereo pair)	1^{st} day of winter or 1^{st} week of winter or at the beginning or onset of winter	1^{st} data	One week before winter or one day before winter
		2^{nd} data	1^{st} day of winter or 1^{st} week of winter or at the beginning or onset of winter
Data for DEM-2		Data for DEM-2	
2^{nd}Data (Stereo pair)	Last day of winter or last week of winter or End or offset of winter	1^{st} data	One week before winter or one day before winter
		3^{rd} data	Last day of winter or last week of winter or End or offset of winter
Data sets are taken based on data availability			

When DEMs are generated using the proposed data sets, and difference is taken, it actually gives the estimation of thickness/depth of snow accumulated during that winter. The change in depth or thickness is purely for the snow that is accumulated during the winter as it takes one year for the snow to get transformed into firn. This snow depth measured at glacial and non-glacial area in a basin scale could be used to estimate the seasonal runoff for that basin. Figs. 3 and 4 represent Shuttle Radar Topography Mission (SRTM) DEM generated using SAR interferometry model and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEM using stereo photogrammetry model respectively representing (location) a part of Chandra basin, Lahaul & Spiti district of Himachal Pradesh (Western Himlayas), India. Fig. 5 shows the change in thickness obtained by DEM differencing (ASTER-SRTM) for a period of 11 years (2000-2011). In case of using two DEMs generated from 2 different models for the study of change in thickness, the bias corrections suggested by Nuth and Kääb [13] have to be incorporated.

IV. Conclusion

This paper demonstrates a modified approach for snow depth estimation during winter accumulation at basin scale suitable for polar and Himalayan regions. Same approach could also be used to estimate glacier winter mass balance at glacier scale. This approach provides an estimate for snow depth using space based inputs during winter where the field study is not logistically feasible especially at rough terrains like Himalayas. Snow depth estimation is useful in assessing the stored fresh water potential in the form of snow using snow density parameter for Himalayan region and for sea level rise studies for polar regions.

V.Future Work

Snow can be classified as dry and wet snow based on the snow water equivalent (SWE). In SAR data, the backscattering coefficient sigma naught for dry snow is mainly from the surface below the snow cover. Using this correlation, we propose to derive an empirical relationship based model for deriving snow depth for dry snow based on backscattering sigma naught values as our future work.

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