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Operational algorithm for generation of snow depth maps from discrete data in Indian Western Himalaya

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ABSTRACT

In this paper, an algorithm is proposed for generation of snow depth maps. The efficacy of the algorithm has been established through a case study in lower and middle Himalayas, India. The algorithm is a modified version of the spatial interpolation method proposed earlier in Swiss Alps. The method uses discrete point data supplemented with remotely sensed derived information data to create snow depth maps at spatial resolution of 0.5 km. *In situ* snow depth observations from 14 locations, automatic weather station (AWS) recorded snow depth from 9 locations, moderate-resolution imaging spectroradiometer (MODIS) images and shuttle radar topographic mission (SRTM) DEM form the database. The algorithm is based on the dependency of snow depth on elevation above mean sea level, which is later adjusted through the *in situ* snow depth observations to represent the local and regional characteristics of the snow distribution. The algorithm has been validated for different days of the winter season 2012–2013 using leave-one-out station cross-validation method. The mean absolute error (MAE) and root mean square error (RMSE) in estimation of snow depth have been observed as ~34 cm and ~42 cm respectively during the season. The snow depth maps generated from the proposed algorithm may be useful in assessment of snow avalanche hazards as well as in various hydrological and glaciological studies in the inaccessible cryospheric region of the Western Himalaya.

1. Introduction

Indian Western Himalaya consists of many parallel mountain ranges from south to north, e.g., Pir Panjal range, Great Himalayan range, Zanskar range, Laddakh range, and Karakoram range (Gusain et al., 2009). These ranges receive snowfall during the winter season. During this time, most part of the land gets snow covered. Lower and middle Himalayas receive the highest snowfall and are severely affected by snow avalanches. During the last decade and a half, more than two hundred fatalities have been reported due to snow avalanches in this region. Therefore, knowledge of snow depth information along with other snow-meteorological parameters is vital for snow avalanche prediction in this region. *In situ* observations of snow depth are very sparse in this region. Therefore, remote sensing data supplemented with *in situ* observations are preferred to provide variation in snow depth at spatial level.

Snow depth has been studied widely using *in situ* observations as well as remote sensing observations in different cryospheric regions by various researchers, e.g., Shi and Dozier (2000), Brown et al. (2003), Kelly et al. (2003), Romanov and Tarpley (2007), Che et al. (2008), Das and Sarwade (2008), Marty (2008), Dai et al. (2012), Bühler et al. (2014, 2015), and Grünewald et al. (2014). Various approaches have been adopted for mapping the snow depth. These include interpolation of *in situ* based measurements (Foppa et al., 2007), algorithms for space-borne passive and active microwave observations (Das and Sarwade, 2008; Kelly et al., 2003; Shi and Dozier, 2000), assimilation of space-borne observations with *in situ* based measurements (Dai et al., 2012), snow depth estimation using LIDAR data processing before and after the snowfall, generation of digital surface models (DSMs) of winter and summer terrain using photogrammetric image correlation technique (Bühler et al., 2014, 2015), etc.

Very few studies have been carried out to map snow depth in Indian Western Himalaya (Das and Sarwade, 2008; Singh et al., 2007). Singh et al. (2007) developed a regression equation to estimate snow depth in Patseo region of Great Himalaya using passive microwave SSM/I data along with *in situ* recorded snow depth. They estimated snow depth at spatial resolution coarser than 13 km and observed an RMSE of 37.5 cm. However, the regression equation obtained is region specific and can be used for only Patseo region of H.P (Himachal Pradesh) Himalaya, as high errors were obtained for other regions. Das and Sarwade (2008) used AMSR-E data to estimate snow depth in Indian Western Himalaya at a coarse spatial resolution of 5 km. They used microwave emission model of layered snowpacks (MEMLS) along with AMSR-E to understand the difference in the snowpack emitted and

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sensor received signals and modified algorithm proposed by Chang et al. (1987) for mountainous terrain of Indian Western Himalaya. They found algorithm to be useful for estimation of snow depth from 5 cm to approximately 60 cm with absolute error of 20.34 cm. The main limitation of the algorithm was estimation of snow depth only up to 1 m. However, a major part of the Indian Western Himalaya has snow depth more than 1 m during winter season (Gusain et al., 2004, 2009).

These limitations of models in Indian Western Himalaya provide an opportunity to explore for alternate techniques to map snow depth with larger acceptance. In the present paper, a modified version of the spatial interpolation method proposed by Foppa et al. (2007) has been developed to generate maps of snow depth for its operational use in the lower and middle Himalayas.

2. Study area and data

The study area belongs to lower and middle Himalayas of Jammu and Kashmir from 33.48°N to 34.83°N latitude and 73.68°E to 76.12°E longitude. It comprises of Kashmir valley, Pir Panjal, Shamshabari, and Great Himalayan ranges in India (Fig. 1). Kashmir valley is located between Pir Panjal and Great Himalayan ranges and is around 135 km long and 32 km wide. The elevation ranges between 1600 m to 1900 m a.s.l. approximately. Srinagar is the meteorological station of Snow and Avalanche Study Establishment (SASE) in Kashmir Valley at an altitude of 1652 m a.s.l. In the south of the valley lies Pir Panjal range. This range is generally thickly forested below 2800 m a.s.l. and tree line exists up to 3300 m elevation. Beyond this elevation, the area is generally barren or rocky with few patches of seasonal grasses. Banihal and Gulmarg are the meteorological stations of SASE in this range at an elevation of 2830 m and 2800 m a.s.l, respectively. Shamshabari range is an arc shape mountain range in the northwest of the Kashmir valley. This range is thickly forested in the lower elevation below 3000 m a.s.l and is generally barren or rocky above 3300 m a.s.l. Haddan-Taj (3080 m), Stage 2 (2650 m), Ragini (3160 m), Z-Gali (3100 m), and Pharkiyan (2960 m) are meteorological stations in this range. Great Himalayan range lies in the north of the Kashmir Valley and shows a large spatial variability in the terrain. In this range, area is largely barren or rocky, strewn with boulders, glaciated in the higher reaches, and vegetated in some valleys. Kanzalwan (2453 m), Sonamarg (2745 m), Drass (3092 m), Pathar (4250 m), Firmbase (4760 m), and Kilnala (3620 m) are the meteorological stations in this range. Pir Panjal and Shamshabari ranges receive higher snowfall amount during winter compared to Great Himalayan range. However, temperatures are lower in Great Himalayan range compared to other two ranges.

Elevation of snow covered region varies from 1800 m to 6900 m a.s.l. during winter in these ranges. SASE has 14 manned snow-meteorological observation stations in the study area (shown as circles in Fig. 1). Elevation range of the meteorological stations and AWS varies from 1652 m a.s.l in Kashmir Valley region to 4760 m a.s.l. in Great Himalayan range. Most of the stations are installed on a small plain area (approximately 10 m × 10 m) on a mountain slope. Srinagar station is located in a large plain area of Kashmir valley. Banihal station is located at the mountain top and high wind is recorded at this station compared to other stations. Cornice formations are frequent during winter around Banihal station due to heavy wind drift. Ragini station in Shamshabari range is near the top of the mountain and high snow depths are recorded at this station compared to nearby stations due to heavy wind drift deposition. Drass station is located in the valley of the Great Himalayan range and comparatively shallow snow pack observed at this station during peak winter compared to other stations at higher elevation in the same range. Snow-meteorological data including snow depth are recorded daily at the observation stations manually. Snow depth data has also been collected using ultrasonic sensors mounted on 9 AWSs at remote locations in the study area (shown as triangles in Fig. 1). The elevation range of AWS varies from 2344 m a.s.l. to 4212 m a.s.l. One AWS is located in Pir Panjal range at an altitude of 2615 m a.s.l., two AWSs are in Shamshabari range at an altitude of 2344 m and 2736 m a.s.l and six AWSs are in Great Himalayan range at an altitude of 2739 m, 2941 m, 3006 m, 3283 m, 3850 m, and 4212 m a.s.l.

Moderate-resolution imaging spectroradiometer (MODIS) sensor (Salomonson et al., 1989) data have been used for generation of snow cover maps at spatial resolution of 0.5 km in the study area by the method proposed by earlier researchers (Gusain et al., 2014; Hall et al., 1995; Kulkarni et al., 2006; Mishra et al., 2012; Negi et al., 2009; Sharma et al., 2014). These snow cover maps have been used to determine the snow line in the region. The snow line locations have been used as additional data points having zero snow depth (Foppa et al., 2007) to supplement the *in situ* data base for spatial interpolation. The elevation information at all the locations (pixels) of the study area has been obtained from processed SRTM DEM freely available at http://srtm.csi.cgiar.org/. The SRTM DEM was compiled by Consultative Group for International Agriculture Research Consortium for Spatial Information (CGIAR-CSI) and made freely available to the public via Internet. The vertical accuracy of the CGIAR-CSI processed SRTM DEM is better than a standard SRTM DEM accuracy of 16 m (Gorokhovich and Voustianiouk, 2006). The downloaded SRTM DEM was re-sampled at 0.5 km spatial resolution to match the spatial resolution of MODIS derived snow cover maps. The re-sampled DEM was used for spatial interpolation of *in situ* snow depth data.

The daily snow depth data collected at manual observation stations, snow depth data recorded by AWSs, SRTM DEM, and MODIS sensor images forms the data base for the present study to generate snow depth maps using spatial interpolation.

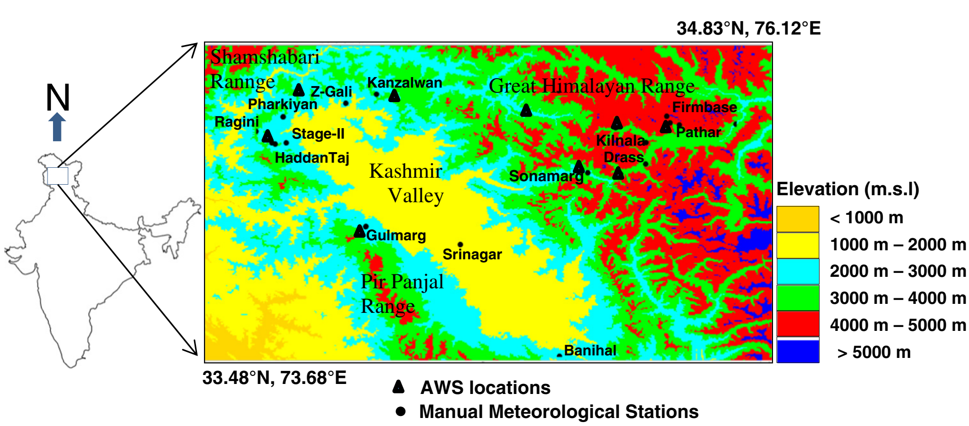

Fig. 1. Study area and variation in elevation. Circles in the map show manual observation stations and triangles show AWS observations of snow depth.