Avalanche Phenomena in Northwest Himalaya: A Review

M.S. Shekhar[1] and A. Ganju[2]
[1]Defence Geoinformatics Research Establishment, Sector 37A, Chandigarh
[2]Retired Director, Snow & Avalanche Study Establishment, Sector 37A, Chandigarh
Email: raja6043@yahoo.com

ABSTRACT

Snow avalanches impact pedestrian and vehicular movement during winter in Indian Himalaya. For prediction of snow avalanches, the nation has covered a long distance in developing tools and techniques for prediction of snow avalanches. The challenges posed by the changing climatic conditions, which has in turn affected the avalanche phenomena, have been addressed to a large extent though a lot remains yet to be done. This review paper discusses avalanche phenomenon with its characteristics particularly in Western Himalaya followed by forecasting techniques developed and used so far. The effect of changing climatic pattern on avalanche phenomenon has been discussed.

Keywords: *Avalanche, Western Himalaya, Snowfall and Pir Panjal Range.*

1. Introduction

The Himalaya has always been an attraction for scientists from all over the world for its hidden wealth of geological information, water resource, high altitude atmosphere besides rich fauna and flora. It is also an attraction for adventurist, pilgrims all over the country and abroad. During winter, many parts of Indian Himalaya get inaccessible due to its severe cold weather conditions and copious amount of snow and rain as a result of the movement of synoptic systems known as Western Disturbances (WDs). Heavy snowfall and associated gale winds with these WDs produce snow avalanches, which cause road blockages, landslides, forest damage etc. in the snow bound areas of Himalaya. The typical orographic features of the high Himalayan ranges are also very sensitive to record global climate change in glaciers, lake sediments and other landforms. The changing climate, in recent past, has affected the pattern and frequency of the avalanching in Himalaya over a period in some regions of Himalaya.

Recent studies have shown that global mean surface temperature over Himalaya has increased by 0.6°C over last 100 years (Jhajharia and Singh, 2011). All India mean annual surface temperature has increased by 0.5 °C during the period 1901-2003 (Kothawale and Rupakumar, 2005). Long term trends in the maximum, minimum and mean temperatures over Northwest Himalaya (Bhutiyani et al., 2007) show significant rise in mean air temperature in the northwest Himalaya with significant rate of increase recorded during winter period. In another study (Bhutiyani et al., 2009) concluded an increasing but statistically insignificant trend in winter precipitation and statistically significant decreasing trend in monsoon and overall annual precipitation in North Western Himalaya (NWH) during the period 1866–2006. Shekhar et al., 2010 further corroborated the findings by reporting increase in winter maximum, minimum and mean temperature over Western Himalaya (WH) by 2.8°C, 1°C and 2°C respectively. In another observational study (Shekhar et al., 2018) have shown that an increasing trend for mean temperature for all the mountain and altitudes ranges of Western Himalaya for the period from 1991 to 2015. This study also confirms that global warming has affected the Himalaya range on regional scale.

The avalanche affected area in Indian Himalaya is spread over a distance of 2500km covering 26°N to 37°N and 72°E to 96°E (Sharma and Ganju, 2000). The Western Himalaya covers the states of UT of Jammu & Kashmir (J&K) and Himachal Pradesh extending from 31°N to 36°N and 73°E to 80°E with altitudes 2000m to 7000m. Depending on year-to-year variations in snowfall distribution and prevalent weather conditions, different types of avalanches occur in the Pir-Panjal range of the Western Himalaya though dominated by direct action avalanches. In this region, snow avalanches often block critical transport corridors (Ganju and Dimri, 2004; Singh et al., 2005) and cause human, property, livestock, and/or infrastructure losses (Rheinberger et al., 2009; Leone, et al., 2014). This paper discusses briefly the avalanche phenomena in Western Himalaya with special emphasis on the Pir Panjal range. Section 2 describes details about various characteristics of avalanche phenomena over the Western Himalaya. Avalanche forecasting over Western Himalaya has been described in Section 3. A few recent findings on avalanche pattern with respect to changing climate has been described in Section 4. A brief of the futuristic view of avalanche forecasting has been given in Section 5 and conclusions are given in the last Section 6.

2. Characteristics of Avalanche Phenomena in Western Himalaya

2.1 Classification of avalanche activity

McClung and Schaerer (1993) have grouped avalanche areas into two categories i.e., Maritime and Continental depending upon the prevalent weather pattern in the area. Relatively heavy snowfall and mild temperatures characterize the maritime snow climate. In this climate, avalanche occurs during or immediately following the storms making the prediction of such types of avalanches fairly easy. On the other hand, continental snow climate is characterized by relatively less snowfall, cold temperatures and the locations are considerably inland from the coastal areas. Prediction of such avalanches is rather complex and requires continuous monitoring and evaluation. Based on the prevalent climate pattern that affects Himalaya, Sharma and Ganju (1999) have classified the avalanche areas of Western Himalaya in three broad zones such as the Lower Himalayan Snow Climatic Zone or Subtropical Zone, Middle Himalayan Snow Climatic Zone or Mid Latitudinal Zone and Upper Himalayan Snow Climatic Zone or High Latitudinal Zone (Figure 1). The details of terrain and meteorology of these zones have been summarized in Table 1 below.

Lower Himalayan Zone is the zone of warm temperature, high precipitation and short winter periods. The avalanche activity is quite high, with most of the avalanches triggering during snowfall as direct-action avalanches. The mountainous areas falling in this category are the Pir Panjal range in the UT of Jammu and Kashmir and lower altitudes on the windward side of the same range in Himachal Pradesh.

The Middle Himalayan Zone is characterized by the high mountain peaks encompassing numerous glaciers. This range receives good amount of total snowfall during winter. Severe avalanche activity is reported in this range throughout the winter. The areas falling in this zone are windward side of the Great Himalayan Range in Jammu and Kashmir and upper reaches of Pir Panjal range in Himachal Pradesh.

The Upper Himalayan Zone houses some of the longest glaciers of the world. The areas falling in this region are leeward side of the Great Himalayan Range (Jammu and Kashmir and Himachal Pradesh), Zanskar range and Karakoram range. Snowfall in this zone is generally scanty but it is extended almost throughout the year. Avalanches from this glaciated region start with as little as 30-40 cm of fresh snow.

2.2 Factors iinfluencing avalanche activity in the Western Himalaya

Avalanche activity in Western Himalaya Region, as in any other snow avalanche regions of the world, is influenced by the factors such as terrain, weather, snowfall and changes inside the snowpack. The shape and size, orientation and elevation of the slope of the terrain contribute to type and magnitude of an avalanche phenomenon. Weather parameters such as the temperature and wind speed and its direction influence the avalanche frequency and severity. Generally, during snowfall, wind stays calm within the valleys. This is the period when generally deep depression sets in the foot hill regions of Himalaya. Subsequent to snowfall spell, that may last maximum up to 4-5 days, heavy wind blows over the avalanche terrain contributing in the excessive accumulation of snow on some lee slopes, which helps in releasing avalanches from

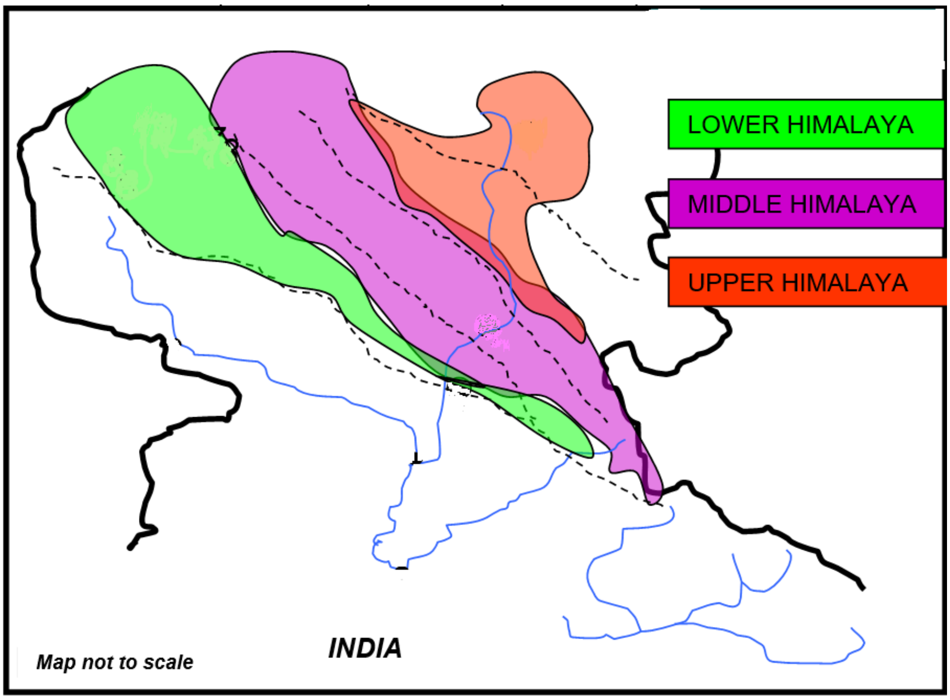

Figure 1: Snow-avalanche climatic zones (Sharma and Ganju, 1999) in Western Himalayan region.

Table 1. Terrain and Meteorology of Indian Himalaya (Sharma and Ganju, 1999).

Factors	Lower Himalayan Zone	Middle Hiimalayan Zone	Upper Himalayan Zone
Terrain			
Altitude	3200- 4100m (76%)	3500- 5300m (100%)	5000- 5600m (100%)
Slope	30-38 (64%)	32-40 (75%)	28-32 (67%)
Ground	Tall grassy cover	Scree and Boulders	Rocky, scree and glacial
Meteorology			
Snowfall in a storm	20-80cm (56%)	20-80cm (81%)	10-20cm (51%)
Average total yearly snowfall	15-18m	12-15m	7-8m
Temperature (^{o}C)			
Highest max	20.2	14.5	9.0
Mean max	6.8	0.96	-8.1
Mean min	-1.6	-11.3	-27.7
Lowest min	-12	-25.4	-41

such slopes. This is the period when cyclonic circulation moves further eastwards with the weakening of winter depression in northwest Himalaya. Most of the avalanche slopes in the Western Himalaya accumulate by about 60 cm of standing snow in the very first major snow spell, which is sufficient to cover all ground irregularities. Further buildup of snow slowly adds to the overburden pressure and consequent snow cover instability. Average snowfall intensities of about 3 cm or more per hour with more than 40 to 60 cm of snowfall in 24 h can create conditions favorable for avalanching in Western Himalaya. Similarly, negative temperature gradient in a snow cover plays a major role in influencing the release of delayed action avalanches in any particular winter. Such temperature gradients within a snow pack become steep enough during subsequent continuous clear days for a week to fortnight under very low ambient temperature conditions. This sets the process of Temperature Gradient (TG) metamorphism within a snowpack, which is responsible for the formation of a weak and fragile depth hoar layer within a snowpack that favors for the release of delayed action snow avalanches.

3. Avalanche Forecasting

Among the various methods of avalanche hazard mitigation and management, the indirect or passive method is the prediction / forecast of avalanches whereas the active or direct methods are structural control, artificial triggering of avalanches etc. For undertaking avalanche forecast in any area, mapping and registration of avalanche sites along various routes / road axes in avalanche prone areas are required. It is done by routine ground and aerial reconnaissance of the area and nowadays remote sensing and GIS technology is more frequently used for the purpose. Snow-meteorological parameters from select points in avalanche prone area are used in running various prediction models such as snow cover simulation model (Ganju et al., 1994), Expert System (Naresh and Pant, 1999) and coupled Nearest Neighborhood (NN) model (Singh and Ganju, 2004). Now-a-days more advanced snow simulation models like Snowpack (Bartelt and Lehning, 2002) are used for the purpose. At Snow and Avalanche Study Establishment (SASE) (now Defence Geoinformatics Research Establishment: DGRE) an advanced version of avalanche prediction model developed by (Singh and Ganju, 2004) is used for regular snow avalanche forecast during winter by DGRE.

The task of integrating snow pack simulation model with mesoscale weather forecast model MM5 (Dudhia, 1993; Grell and Dudhia, 1994) and snow avalanche prediction models like Nearest-Neighbours (NN) model was first attempted in Indian Himalaya by (Singh et al., 2005). The motivation for such integration was taken from the works of Buser (1983), McClung and Tweedy (1994), and Kristensen and Larsson (1994) for the development of semi-automatic prediction of snow avalanches in Indian Himalaya. Lately many new versions and features were introduced by Gassner et al. (2000), Brabec and Meister (2001), Purves et al. (2003), McCollister et al. (2003), and Singh and Ganju (2004). These models are generally used in now-casting mode with effective forecast period from 12h to 24h in the future. An advanced NN based avalanche forecast model is operational at DGRE for prediction of avalanches for the current day (day of observation of input data). The variables used in this model are chosen as suggested in previous studies (Perla, 1970; Fo¨hn et al., 1977; Obled and Good, 1980; Buser, 1983; McClung and Tweedy, 1993). The parameters required from NWP model to provide input to NN model are air temperature, snow surface temperature, snow depth, and wind parameters. Now the NN Model has been integrated with the mesoscale weather forecast model WRF for avalanche forecasting up to day-3 in western Himalaya. The input variables required for the NN model are generated from the WRF weather forecast for day-2 and 3.

Avalanche forecasting is the most economically viable, effective and practically suitable methods to assess avalanche danger as it can be applied in a large area and requires much less investments as compared to direct or active methods. Avalanche forecasting may be practiced on various spatial scale levels as per the requirement of users. Mountain weather prediction and prediction of snowfall amount is an integral part of the avalanche forecasting. With the advancement in computing technologies, database management tools and decision marking algorithms, avalanche forecasting has improved significantly over a period in Indian Himalayan region.

4. Climate Change and Snow Avalanche over Western Himalaya

Changing climatic conditions have also modified the pattern of avalanche activity world over the land cover changes, such as afforestation and deforestation, have too played a role (García-Hernández et al., 2017) in changing avalanching phenomenon. In recent decades, several studies have demonstrated decreasing trends in snowfall and snow cover duration in lower and middle-elevation mountainous regions of both North

America and Europe (Falarz, 2002; Laternser and Schneebeli, 2002; Marty, 2008; Durand et al., 2009). These changes have led to an upslope retreat of the areas affected by large avalanches (Eckert et al., 2010) and to the occurrence of wet snow avalanches at places where avalanches were mostly dry earlier (Naaim et al., 2016). The ongoing climate change and global warming has also impacted the cryosphere of Indian Himalaya (Shekhar et al., 2010), with substantial consequences on the risk of natural disasters, human well-being, and terrestrial ecosystems. The warming observed in recent decades has been accompanied by increased snow avalanche frequency in the Western Indian Himalaya (Ballesteros-Cánovasa et al., 2018). This study shows that warming air temperatures in winter and early spring have favored the wetting of snow and the formation of wet snow avalanches. They have reconstructed a snow avalanche history for the Indian Himalayas and investigated whether ongoing climate warming has had an impact on the frequency and magnitude of snow avalanching in the recent past. The use of tree rings has a long tradition in snow avalanche reconstructions in North America and Europe according to Stoffel (2013), Butler and Sawyer (2008), but the information is yet not available for the Indian Himalayan range (Sharma and Ganju, 2000). A GLARMA model was used to investigate relationships between monthly climate covariates (Schläppy et al., 2016) and the occurrence of snow avalanches since the beginning of the 20th century. This tree-ring–based snow avalanche reconstruction in the Indian Himalayas shows an increase in avalanche occurrence and runout distances in recent decades. Statistical modeling suggests that this increase in avalanche activity is linked to the concurrent climate warming. The increased avalanching in the Western Indian Himalayas is thus likely to result from the preservation of a sufficiently thick snow cover in high-elevation avalanche release areas combined with more frequent crossing of the melting point of snow, which, in turn, results in more frequent, mostly wet, snow avalanches. This conclusion for the Western Himalayas is in line with observed changes in the typology and timing of avalanche activity in the European Alps (Naaim et al., 2016). However, their findings contradict the theory that warming results in less snow, and thus lower avalanche activity which remains a topic of research.

5. Avalanche Forecasting: A Futuristic View

The complex orography and diverse climatic conditions make it difficult for an avalanche forecaster to apply a unified code to predict avalanches in the Western Himalayan region. The conditions prevailing in different Himalayan Snow Climatic Zones are diverse and caution a forecaster to remain on continuous watch for forecasting avalanches during snow storms and thereafter in different snow climatic zones of Indian Himalaya. Lower Himalayan Zone demands a very accurate continuous avalanche forecast. The Middle Himalayan Zone warrants a very accurate monitoring of meteorological parameters in accessible as well as in inaccessible areas. Similarly, Upper Himalayan Zone warrants continuous study of snow not only during the winter periods but also throughout the year. Complete control of avalanches is possible only through active methods comprising essentially erection of structures in the formation zone of avalanches, afforestation and artificial triggering of avalanches. These methods besides being expensive are difficult to execute in certain areas. However, the passive method of avalanche forecasting has to be very effective so that the inhabitants in the snowbound avalanche prone areas develop faith in the system. While data sparse Himalayan region and inaccessibility in these areas makes avalanche forecast a great challenge, various tools can be used to assist forecasters in being fairly accurate in predictions since technologies like Information, Communication, and Satellite have taken a giant leap in various frontiers of science. Avalanche forecasting involves study of terrain, snow, weather and its interaction with mankind. The study of terrain has been made quite easy with the use of GIS and satellite-based information. However, the technology has yet not been usefully utilized in understanding the avalanche terrain. Some of the snow parameters like albedo, outgoing longwave radiation (OLR) that have direct relation on avalanche occurrences have yet to be integrated with the avalanche forecasting scheme through the study of satellite imageries. Weather forecast, which was once totally based on surface observations, has now made significant advances with the advancement in Numerical Weather Prediction models at very high resolution and availability of satellite pictures. Timely dissemination of avalanche forecast with robust communication network till last mile is very important for the mitigation of avalanche accidents. The geomatic solution can be integrated in all aspects of avalanche forecasting that starts with the terrain studies and ends with the dissemination of information and finally carrying out of rescue operations. The latest GIS techniques based monitoring and spatial analysis can become an indispensable tool in the prediction of avalanches. A digital elevation model (DEM) of the terrain can delineate the slope zones accurately and assist a forecaster in identifying potential fracture zones of avalanche slopes. Similarly, information pertaining to different aspects of avalanche slopes when viewed using DEM and GIS can identify slopes where instability is likely to persist for long time. The ground cover details can be easily obtained from high-resolution IRS series of satellites and stored permanently with the terrain information. With slope aspect, slope angle, and elevation information, a topographic representation and analysis of any avalanche path can be undertaken with greater precision.

Using a combination of imageries and data of optical (IRS, LANDSAT, SPOT) and microwave sensors (RADARSAT, ERS), it is possible to delineate information related to snow pack characteristics. The extent to which avalanches can reach the valleys and damage facilities can to a certain extent be calculated using the GIS technology. The movement of personnel through the avalanche terrain can be properly marked by using GPS. GPS can also be used effectively to pin point the dangerous zones on maps and avoid mishaps. At the time of rescue operations also, by communicating exact coordinates of the location of the accident, rescue can be attempted in poor visibility conditions. Avalanche forecaster would be able to provide better forecasts, if communication of the exact sites that have triggered earlier with dimension of the avalanche debris using all above mentioned technologies are made available in real time.

6. Conclusions

Predicting accurately any natural phenomenon has always been a challenge for scientists and snow avalanche is no exception. Snow avalanche is a fairly well understood phenomenon now and its mitigation techniques are also in place. However, the available advanced technologies have yet to be fully operationalized to further fine tune the prediction models and other mitigation techniques. The effect of climate change on avalanching phenomenon has already been explained with certain variations in different mountain ranges all over the world. The infrastructure coming up in the snow bound mountainous region, which is in avalanche prone area, demands a structural solution and all-weather connectivity ab initio. The technological breakthrough in last decade or so has made it now possible to provide reasonable engineering solutions for the development of infrastructure in avalanche prone areas with more accurate avalanche warning maps at an update rate of 12h. The prediction of avalanches in Indian Himalaya is likely to improve in future as many tools are in the development stage as on date and some technologies have yet to find its application in avalanche mitigation.

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