

Usefulness of mesoscale weather forecast for avalanche forecasting

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Avalanche occurrence is a result of the structural collapse of snow cover in the upper reaches of mountainous regions. The collapse may occur either by internal factors related to snow metamorphism or external factors like excessive loading of the snow cover due to snow precipitation, falling of boulders and snow lumps, cornice collapse, explosive waves or seismic activities. Thus to predict an avalanche accurately, an avalanche forecaster is required to keep a continuous record of the weather elements prevailing in the higher reaches which contributes to metamorphism and also the excessive loading of the snow cover due to snow precipitation, cornice formation and its collapse, wind transportation, etc. The information available of the above factors on the synoptic scale, though sufficient for assessment of avalanche danger on a larger scale for a period specific forecast for a general area, is however not sufficient for site-specific and time-specific forecast of an avalanche. This, to a certain extent, can be achieved through mesoscale modelling of various weather parameters using a high-end workstation. This paper describes the genesis of avalanche formation, and the conventional techniques of avalanche forecast in vogue in most of the countries experiencing snow precipitation and avalanches. The paper also brings out how mesoscale modelling of weather parameters can assist in site- and time-specific forecast of an avalanche.

AN avalanche is the downward descent of a large mass of snow on a slope with a high velocity and force. The downward motion may be in the form of gliding or sliding along the slope like a rock fall, flowing along the slope like a fluid or whirling through air like a hurricane.

A typical avalanche site can be divided into three zones, viz. (a) formation zone, with a slope angle of 30–50 degree, (b) middle zone, with a slope angle of 15–30 degree and (c) run out zone, with a slope angle of less than 15 degree. Generally, an avalanche starts at formation zone, attains a maximum speed at middle zone and comes to halt at run out zone by depositing the snow mass, which came down along with the avalanche. There are several methods to mitigate the avalanche hazard. Some of them are active and a few of them are passive. Erecting steel structures at various zones of an avalanche, constructing mounds along the avalanche path, afforestation, etc. are some of the active methods in

controlling avalanches. Avalanche forecasting is a passive method by which the likely release of an avalanche can be predicted and thus the movement of personnel can be restricted along the path of an avalanche. Economically, in comparison to active methods, avalanche forecasting is much cheaper.

The avalanche forecasting is done basically by finding out the current snow pack stability and assessing the same on subjecting it to the weather forecast. Snow pack stability analysis and weather forecast play a key role in prediction of avalanches. The present work focuses on the importance of fine resolution accurate weather forecast, which is possible through mesoscale meteorological modelling for avalanche forecasting.

A brief outline about different types of avalanches, genesis of an avalanche, avalanche-prone areas and various methods used for avalanche forecasting are given in succeeding sections. The necessity and usefulness of mesoscale weather forecast for avalanche forecasting is summarized in the last section.

Types of avalanches

Formation of an avalanche largely depends on the type of snow, terrain and the prevailing weather conditions. Avalanches can be broadly classified into two categories, viz. (a) Loose snow avalanche and (b) Slab avalanche.

Loose snow avalanches start at or near the surface and they usually involve only surface or near-surface snow. These start at a single point and spread out as they move down along the slope of a mountain in a triangular pattern as more snow is pushed down the slope. The two most important pre-requisites for the formation of loose snow avalanches are (a) the snow is in weak cohesion, and (b) it is lying on a steep slope. When the above two conditions are prevailing, a small crystal/grain of snow loses contact with its neighbouring counterpart due to lack of cohesion and gathers mass and momentum. As the particle descends with increased mass, it disturbs other crystals/grains which also start moving down with the already moving snow mass. The motion continues as long as the movement is on steep slopes. The avalanche comes to a halt once it reaches flat ground where its kinetic energy is absorbed into frictional energy. Loose snow avalanches trigger when a force, sufficient to overcome the internal cohesion and frictional resistance, is applied. This may be due to falling of stones in the formation

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zone, falling of lumps of snow from the tress in the formation zone, shock waves due to explosives or otherwise, movement of skiers, etc. Snow of loose cohesion may be either dry or wet, but the important point with respect to water content is that wet loose snow avalanches can be much more massive than the dry ones. For either dry or wet loose avalanches the basic mechanism is the same.

The failure or separation of a snow slab lying on a slope and its downward descent with high momentum is known as slab avalanche. Snow slab is a cohesive layer of snow with a thinner, weaker failure layer beneath it. A snow slab becomes a slab avalanche once it is cut out around all boundaries by fracture. It is initiated by a failure at depth in snow cover, ultimately resulting in the movement of a block of snow. The zone demarcating the ruptured snow and the unruptured snow on the slope takes the form of a zig-zag line. The three pre-requisites for the formation of slab avalanches are: (a) the snow has had time to gain cohesion, (b) it has gained some strength, and (c) it is lying on a steep slope.

Slab avalanches occur when either there is increase in stress and there is decrease in strength or there is simultaneous increase in stress and decrease in strength. Slab avalanches could be dry or wet slab avalanches. Dry slab avalanches occur in the early part of winter and during peak winter when fallen snow crystal undergoes equi-temperature (ET) metamorphism or temperature gradient (TG) metamorphism under sustained sub-zero temperature. Wet snow avalanches generally occur in the later part of the winter when slab is subject to above zero degree celcius temperature which causes formation of thin water film around the crystal, thereby making the snow slab wet.

Avalanche areas in India

Snow avalanches occur during winter months in the snow-bound belt of Western and Central Himalaya and to some extent in Eastern Himalaya. Indian Himalaya stretches from east to west for about 2500 km across 72°E to 96°E long, and 26°N to 37°N lat. From the main Himalayan belt, the main mountain system is divided into three principle zones which have marked orographic features. These are the Great Himalaya, Lesser Himalaya and the Outer Himalaya. The Himalaya have about 43,000 km² of permanent ice bound area¹.

In India, Jammu and Kashmir (J&K), Himachal Pradesh (HP), Uttaranchal and part of Sikkim are the avalanche-prone states. Snow and Avalanche Study Establishment (SASE) is concentrated only in J&K, HP and to some extent in Uttaranchal. 109 villages in HP, 91 in J&K and 16 in Uttaranchal get affected due to constant threat of avalanches throughout the winter season². In addition to this, Army deployed in the border areas of J&K and Siachen are also under the threat of avalanches.

Nine major road axes in J&K and two road axes in HP are being covered by SASE to forewarn the troops and civil population of the impending avalanche danger.

Avalanche forecasting techniques in vogue

Avalanche forecasting is by far the best and cheapest method available for avalanche hazard mitigation. However, the methodology suffers from objectivity and above all, requires comparison of the antecedent conditions with the present one, thus subject to continuous revision. It has the advantage of covering large area.

Conventionally avalanche forecasting is being done by assessing the snow pack stability using contributory factors approach. These factors are terrain, snow pack and weather. The terrain factor is a fixed parameter for any given location whereas snow and weather factors are varying, which have to be analysed in detail. Some of the snow pack factors considered are snow depth, nature of snow surface, existence of weakness within snow pack, bond between new and old snow pack, etc. Some of the meteorological factors considered are temperature, snow surface temperature, wind speed and direction, precipitation amount, density and crystal type at current time and at future time (through weather forecast).

The current snow pack stability is also being analysed quantitatively using the stratigraphy data of snow pack by physically digging a pit on snow pack and measuring various parameters periodically on weekly basis in the observatory site and at different aspect of the slope.

Also the current snow pack stability is qualitatively evaluated through some field tests such as Rutschblock test, shovel test, shear frame test, ski test, etc. These tests are simple and handy and take only a few minutes but at the same time provide first hand information about snow pack stability. However, it is not feasible to conduct these tests at all sites because of the problem of accessibility. For different sites, current snow pack stability is extrapolated from where field tests have been carried out.

Indirectly, current snow pack stability is assessed by analysis of snow and meteorological factors of snow pack. The technique requires building up of snow cover from day 1 qualitatively as well as quantitatively. Qualitative analysis, though helpful, is highly subjective. Quantitative assessment of snow pack stability is achieved by snow cover model. This model and the related models like Digital Terrain Model (DTM), constitutive relationship, snow cover distribution model and failure criterion model would provide complete information on the current status of snow pack stability.

Importance of weather forecast in avalanche forecasting

For operational avalanche forecasting, presently conventional and process-oriented methods are applied for the whole of J&K including Siachen area, HP and part of Uttaranchal area. For selected areas, statistical methods are also being applied for avalanche forecasting. A snow cover model, giving snow pack structure is employed to find the current stability of the snow pack. For selected road axes, avalanche

forecasting is also attempted through expert systems. One of the major inputs for all the above-mentioned models is the quantitative weather forecast information. Also, an integrated avalanche forecast model is being developed at SASE using various inputs of snow cover model, statistical model and quantitative weather forecast parameters. This model too requires an accurate numerical weather forecast to predict avalanches accurately.

The observed meteorological parameters are available at observatory locations, which are mostly located in the valleys, i.e. run out zones of an avalanche. However, for the prediction of avalanches, the relevant snow and meteorological parameters of formation zones and middle zones of avalanche slopes are required. Though the global and regional weather forecast models give a quantitative weather forecast, the information is not adequate to predict avalanches since one grid point of weather forecast models covers one or few road axes. Hence, there is a necessity to predict weather in a fine resolution, preferably 2 km for the purpose of avalanche forecasting.

Initially, SASE attempted to predict temperature and wind pattern over a valley using a dry, hydrostatic mesoscale model with a single radiosonde (RS)/rawinsonde (RW) data of valley. Numerical simulations were performed for Kashmir valley in J&K by initializing the model with RS/RW data of Srinagar and for Manali region in HP with RS/RW data of Manali. The fine resolution topography derived from US Geological Survey (USGS) 30 arc second data and the region considered for numerical simulation are shown in Figure 1. The model could simulate appropriately the day time up-slope flows and the night time down-slope flows and subsequently the valley wind.

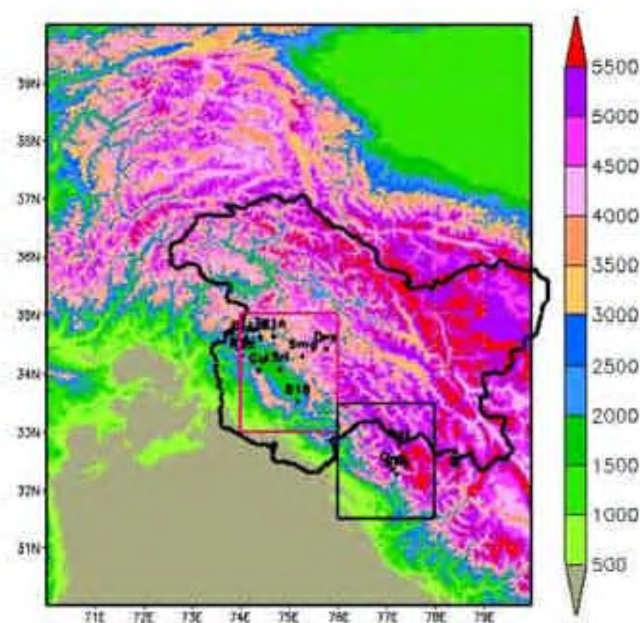


Figure 1. Shaded topography image of J&K and part of HP. Domain considered for Kashmir valley and Manali valley are marked by rectangles.

From the avalanche forecasting point of view, wind is an important parameter as it is responsible for drifting snow from one side of the slope and depositing it on the other side along the ridgeline of mountain. This mainly leads to formation of cornice along the ridgeline. Due to over-deposition of snow or any disturbance, the cornice may break and can trigger an avalanche. A schematic diagram of a structure of a cornice is shown in Figure 2 (ref. 3). In this the prevailing wind along the ridge line is from west to east direction. With the help of a mesoscale model, it will be possible to identify the regions of formation of potential cornices.

A test run of the model with Srinagar and Manali data has demonstrated that wind profiles can give the required information about the possible cornice formation along the ridge line. The test results of the model of simulated horizontal wind pattern in horizontal (x - z) cross section along Srinagar for Kashmir valley and along Manali for Manali valley for afternoon hours are shown in Figures 3 and 4 respectively. The mesoscale model output helps in knowing vital information about the wind along the ridgeline of avalanche prone mountains.

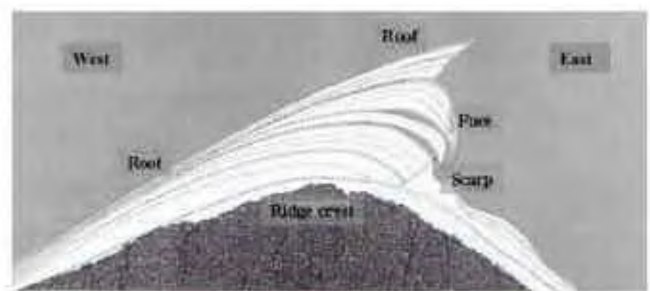


Figure 2. A schematic diagram of structure of a cornice along ridge line. The prevailing wind is from west to east³.

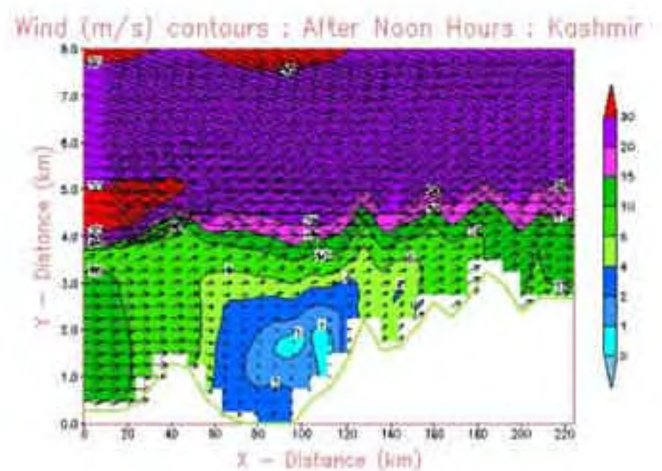


Figure 3. Simulated horizontal wind (u , v) pattern for afternoon hours along the horizontal cross section (x - z) passing through Srinagar (Kashmir valley).

The air temperature pattern of the valley and the surface temperature at different locations of the valley will help in calculating heat and mass flux between snow and atmosphere, which will help in knowing the metamorphic changes of the snow crystal. It is also possible to ascertain qualitative crystal structure of the falling snow from the atmospheric profile data and deduce its metamorphic state on subjecting it to energy exchange processes. In the model, the surface temperature is computed by solving energy balance equation. The results of the test run of the model simulated temperature pattern along x - z cross section of Kashmir valley and Manali valley for afternoon hours are shown in Figures 5 and 6 respectively. This result will help in predicting crystal structures, which are directly temperature dependent and has direct relevance in prediction of avalanches. The dry hydrostatic model simulates the wind and temperature pattern over a small area with the available limited data, however, it does

not have the capacity to simulate precipitation. The model simulates wind and temperature pattern fairly well during synoptically calm days. Keeping in view the limitations of the model, another versatile mesoscale model was employed to predict various weather parameters in the western Himalayan region.

A versatile mesoscale model, developed jointly by National Centre for Atmospheric Research (NCAR) of Pennsylvania State University (PSU), commonly known as 'MM5', was employed to simulate various weather parameters over western Himalayan region. As a case study, a western disturbance which hit the Jammu and Kashmir (J&K) and its adjoining areas on 13–15 March 2001 was taken up for the simulation. The initial fields were taken from the National Centre for Medium Range Weather Forecasting (NCMRWF) global analysis of 13 March 2001 (00 UTC). The surface data of SASE observatories were also incorporated in the analysis. Simulations were performed for 24 h.

In this a coarse domain with a horizontal grid spacing of 30 km keeping the centre point at 75°E longitude and 35°N latitude was considered. Also, a nest domain of 10 km horizontal grid spacing was considered covering the J&K and parts of HP (Western Himalayan Region). The model simulated precipitation contours of mother domain and nest domain after 12 h of simulation, i.e. valid for 13 March 2001 (12 UTC) are shown in Figures 7 and 8 respectively. Similarly the 24 h forecast values of precipitation are shown in Figures 9 and 10 respectively. From the 12 h forecast, it is clearly seen that the weather system lies in the west side of J&K, whereas 24 h forecast shows that the weather system has moved well inside J&K. Using the forecast of quantitative precipitation values along with the wind pattern, it was possible to estimate roughly the additional load coming on the existing snow pack in different avalanche-prone zones due to direct precipitation and due to transportation of wind. This precise fine resolution forecast of weather parameters has helped in assessing the snow pack

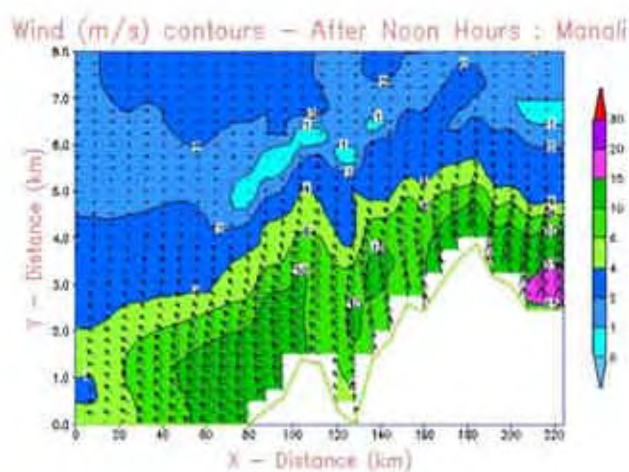


Figure 4. Simulated horizontal wind (u , v) pattern for afternoon hours along the horizontal cross section (x - z) passing through Manali (Manali valley).

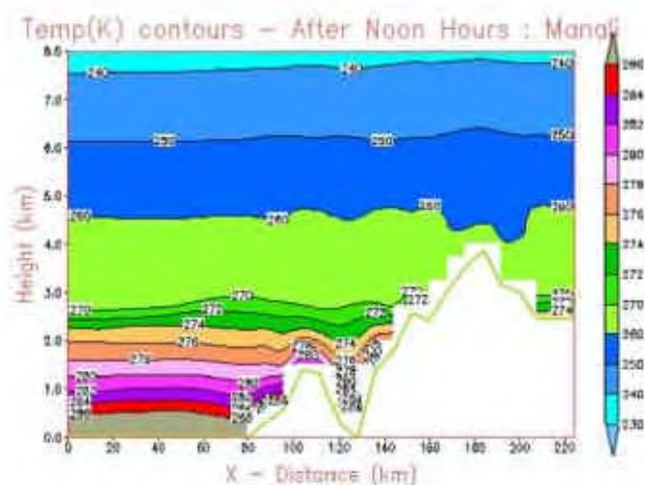


Figure 5. Simulated temperature pattern for afternoon hours along the horizontal cross section (x - z) passing through Srinagar (Kashmir valley).

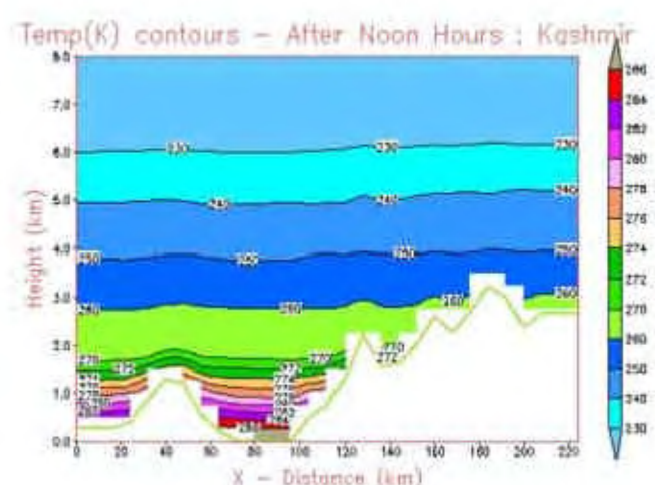


Figure 6. Simulated temperature pattern for afternoon hours along the horizontal cross section (x - z) passing through Manali (Manali valley).

Table 1. Model predicted meteorological parameters over different stations in J&K

Model predicted meteorological parameters	Valid for 13 March 2001 (12 UTC)			Valid for 14 March 2001 (00 UTC)		
	Station 1 (74.11E, 34.62N)	Station 2 (74.00E, 34.44N)	Station 3 (74.33E, 34.08N)	Station 1 (74.11E, 34.62N)	Station 2 (74.00E, 34.44N)	Station 3 (74.33E, 34.08N)
Precipitation (mm) (water equivalent in past 12 h)	13.5	04.6	0.4	16.7	17.8	18.0
Ground temperature (K)	276.5	277.5	281.3	273.3	273.0	274.3
Temperature (K) at 2 m level	276.9	277.4	281.4	274.5	274.3	276.5
Sp. humidity (g kg^{-1}) at 2 m level	5.11	5.83	5.39	4.32	4.36	3.64
East-west wind u (ms^{-1}) at 10 m	-1.2	-2.3	3.5	-4.4	-4.9	4.6
North-south wind v (ms^{-1}) at 10 m	1.7	3.0	4.1	6.4	-0.8	7.9

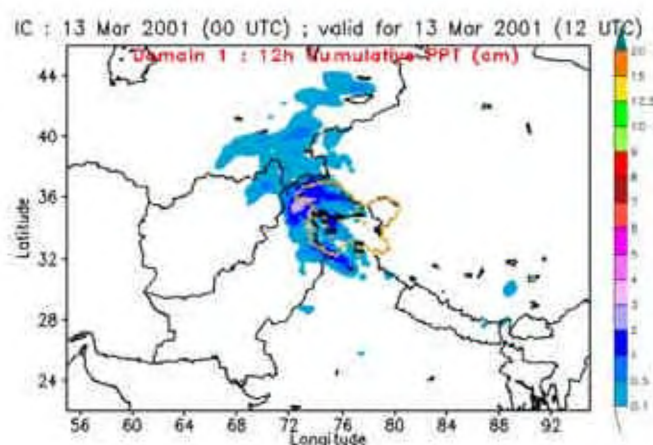
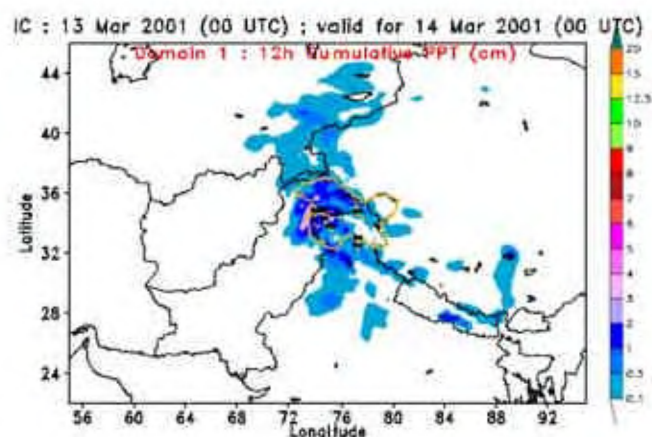
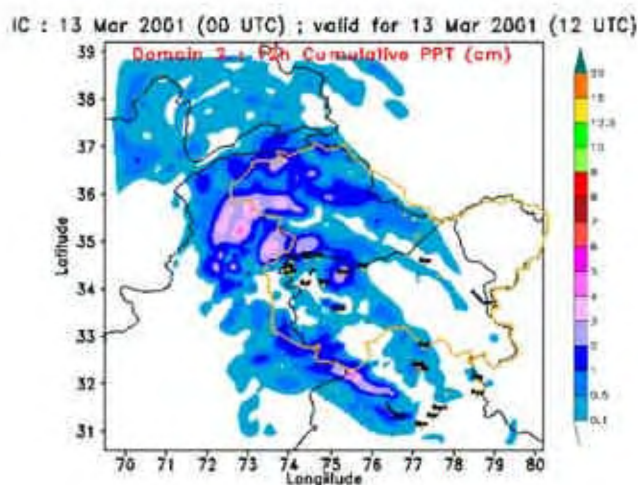
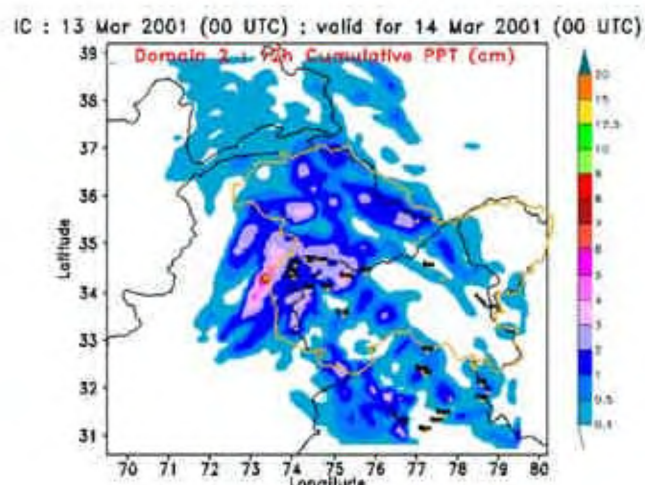
**Figure 7.** Model simulated cumulative precipitation of past 12 h for mother domain (30 km resolution) valid for 13 March 2001 (12 UTC hours).**Figure 9.** Model simulated cumulative precipitation of past 12 h for mother domain (30 km resolution) valid for 14 March 2001 (00 UTC hours).**Figure 8.** Model simulated cumulative precipitation of past 12 h for nest domain (10 km resolution) valid for 13 March 2001 (12 UTC hours).**Figure 10.** Model simulated cumulative precipitation of past 12 h for nest domain (10 km resolution) valid for 14 March 2001 (00 UTC hours).

Table 2. Model predicted precipitation (mm) values along with the observations over different stations in J&K for Day 1 to Day 4, when the MM5 model was run with initial data of 13 Jan 2002 and 16 Feb 2003 (00 UTC hours)

Model predicted/ observed 24 hour cumulative precipi- tation (mm) (water equivalent in past 24 hours)	13–17 January 2002 case			16–20 February 2003 case		
	Station 1 (74.11E, 34.62N)*	Station 2 (74.00E, 34.44N)*	Station 3 (74.33E, 34.08N)*	Station 1 (74.11E, 34.62N)*	Station 2 (74.00E, 34.44N)*	Station 3 (74.33E, 34.08N)*
	Pre/Obs	Pre/Obs	Pre/Obs	Pre/Obs	Pre/Obs	Pre/Obs
Day 1	65/70	47/51	10/29	52/54	26/64	28/41
Day 2	65/82	84/99	39/45	69/98	54/102	94/39
Day 3	06/50	05/75	03/46	33/79	22/79	45/63
Day 4	05/03	03/13	01/53	26/32	16/45	07/18

*Pre, Predicted values; Obs, Observed values.

stability precisely at different places, thus enabling site-wise prediction of avalanches.

In the foregoing paragraph, typically one example was given to illustrate the usefulness of mesoscale model forecast in avalanche forecasting. A few meteorological parameters predicted through the MM5 model over Station 1 in Keran sector, Station 2 in Chowkibal Tangdhar sector (CT sector) and Station 3 in Gulmarg sector are given in Table 1 along with the lat./long. of the stations.

The above information was used in statistical avalanche forecast models developed at SASE. From the avalanche forecast models, the probability of occurrence of avalanches along Keran sector, CT sector and Gulmarg sector over J&K were found to be high. The ground observations recorded at these stations also revealed that many avalanches have taken place along Keran, CT, and Gulmarg sectors during 13–14 March 2001 (ref. 4).

Presently SASE is using the MM5 model for Western Himalayan region to get quantitative weather forecast 4–5 days in advance. There are many other cases in record where the mesoscale model forecast has been used in avalanche forecast models for predicting avalanches more accurately. 13–17 January 2002 and 16–20 February 2003 cases are two typical examples, where the MM5 model forecast was found more useful in avalanche prediction.

During 13–17 January 2002 and 16–20 February 2003, a severe snow storm affected Western Himalayan region. The MM5 mesoscale model predicted widespread precipitation for subsequent 4 days over the western Himalayan region when the model was initialized with the 13 January 2002 and 16 February 2003 (00 UTC hours) data. The model-predicted precipitation values for the above two cases over the three stations mentioned above are given along with the observations in Table 2.

On application of the model-predicted meteorological parameters in avalanche prediction models, the chances of occurrence of an avalanche along Keran Sector (Station 1), CT sector (Station 2) and Gulmarg sector (Station 3) were found high. The avalanche occurrences report from these sectors of 13–17 January 2002 and 16–20 February 2003 matched with our predictions⁵. Had the mesoscale model predicted parameters not been used in the statistical ava-

lanche prediction models, the avalanche prediction models would not have predicted high avalanche occurrence in the above three sectors. Thus, the mesoscale model outputs have been found quite useful in prediction of avalanches.

Conclusion

Qualitative and site-wise prediction of avalanches as well as integrated avalanche forecast models require precise weather forecast. Ideally speaking, the numerical forecast of the following weather elements up to 7 km altitude at least 24 h in advance, preferably 3 days in advance, is required for the purpose of avalanche forecasting or for the use of avalanche forecast models.

The important weather elements are:

- Precipitation amount and type
- Wind speed and direction
- Temperature
- Radiation
- Relative humidity (RH) and pressure.

The numerical forecast of the above parameters is possible through nested modelling approach of mesoscale modelling. Though presently aiming at a resolution of 10 or 20 km scale, avalanche forecasting demands weather forecast at a much finer resolution, preferably on a better than 2 km grid scale.

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