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Continuous Snow and Rain Data at 500 to 4400 m Altitude near Annapurna, Nepal, 1999–2001

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Abstract

Knowledge of spatial and altitudinal variations in precipitation in high mountains is integral to quantifying alpine climates and to calibrating interactions between climate and surface processes. To date, however, few meteorological networks exist in alpine settings. A network of 14 meteorological stations was installed across the Annapurna Range in central Nepal in 1999 and expanded in subsequent years to 19 stations. In order to measure snow depths and water equivalents in high-altitude sites, a combination of look-down distance rangers and gamma-ray loggers was installed at 5 sites. The data from this network delineate a strong south-to-north gradient in monsoonal precipitation. Precipitation peaks at 5032 mm yr^{-1} at about 3000 m altitude on the southern side, which is also approximately the lowest altitude of winter snow in the area. Annual precipitation decreases to $\sim$1100 mm yr^{-1} in the rain shadow to the north of the Himalayan crest. Although snow depth and snow water equivalent content are strongly dependent on station altitude, snow depth shows little spatial variation at a given altitude, partly due to the surprisingly low local wind speeds. Based on extrapolation of mean monthly summer lapse rate of air temperature, only snow precipitates above 5883 m.

Introduction

The spatial distribution of precipitation over the landscape is a key input to studies of climate and surface processes. Orographic precipitation models and weather observations in valleys suggest that the precipitation generally decreases in the lee side of major mountain barriers (Smith, 1979; Barry, 1992; Houze, 1993; Barros and Lettenmaier, 1994). The current interest in the coupling between the climate and topography (Koons, 1989; Willett, 1999; Beaumont et al., 2001; Lave and Avouac, 2001; Burbank, 2002; Pratt et al., 2002; Roe et al., 2002;) has highlighted the need to accurately describe precipitation as a function of both altitude and position in the landscape and to expand meteorological networks to ridges and hillsides to assess mesoscale topographic effects.

High-altitude precipitation has been a subject of long-standing debate and controversy (Barry, 1992) and still remains less studied due to the general paucity of high-altitude stations. Published time series from the Nepalese Himalaya of snow properties (depth, density, snow water equivalent) are mainly from Mt. Everest region (Yasunari and Inoue, 1978; Seko, 1987) and are characteristically short in duration and are scattered irregularly through the year, although most records are from the summer months. The few existant long and continuous precipitation time series either come from automated rain gauges (Bollasina et al., 2002) that are known to both grossly underestimate the amount of snow and delay recording snowfall amounts due to slow snow melt in the gauge bucket, or are based on modeled extrapolation of low-altitude observations (Tangborn and Rana, 2000). No snow data exist in the literature from Annapurna Range of central Nepal, which receives considerably more precipitation than Mt. Everest and Khumbu region.

Here I present rare data from a network of 16 automated weather stations on the flanks of the Annapurna Range that were installed as part of efforts to calibrate precipitation radar flown as part of NASA's Tropical Rainfall Monitoring Mission and to delineate potential coupling between climate, erosion, and tectonics under the aegis of the National Science Foundation (NSF). These are the first continuous high-altitude precipitation data published from the Nepalese Himalaya. These data span 2 yr and clearly illustrate how precipitation varies spatially and as a function of altitude.

Field Area

The field area (Fig. 1) is located in the Annapurna Range in the Nepal Himalaya (centerpoint N28°25′, E84°20′). Two of the world's highest mountains are adjacent to the field area (to the east, Manaslu rises to 8156 m and to the west, Annapurna reaches 8091 m). The area is characterized by a strong summer monsoon that generally lasts from mid-June until mid-September and by a dry winter, when precipitation falls as snow primarily at altitudes above 3000 m. The study area is $\sim$30 km by 60 km, and the distance between neighboring stations is of the order of 10 km (Fig. 1). The floors of valleys lie at 500 to 2000 m elevation, whereas the highest peaks within the network area range from 5000 to 7000 m. The upper limit of rhododendron forest lies at $\sim$3700 m, above which only shrubs and grasses grow. Man-made terraces that cover large portions of the slopes below about 2000 m are heavily cultivated. The upper parts of the field area (up to 4500 m) are utilized in the summer for free-range grazing of domestic livestock.

Instrumentation

The instrumentation used in this meteorological project includes the following: Sonic snow-depth rangers (Judd communications nominal accuracy $\pm$1 cm or 0.4 % of the distance), gamma-ray snow water-equivalent logger (Canberra snow monitor, repeatability of a measurement is typically $\pm$15 mm snow water equivalent [SWE] on a daily basis, determined in this study when snow was absent. When daily measurements are averaged over 5 d, the repeatability is $\pm$8 mm SWE). In addition, other meteorological instruments (thermometers, hygrometers, anemometers, rain gauges, etc.) were deployed at many stations.

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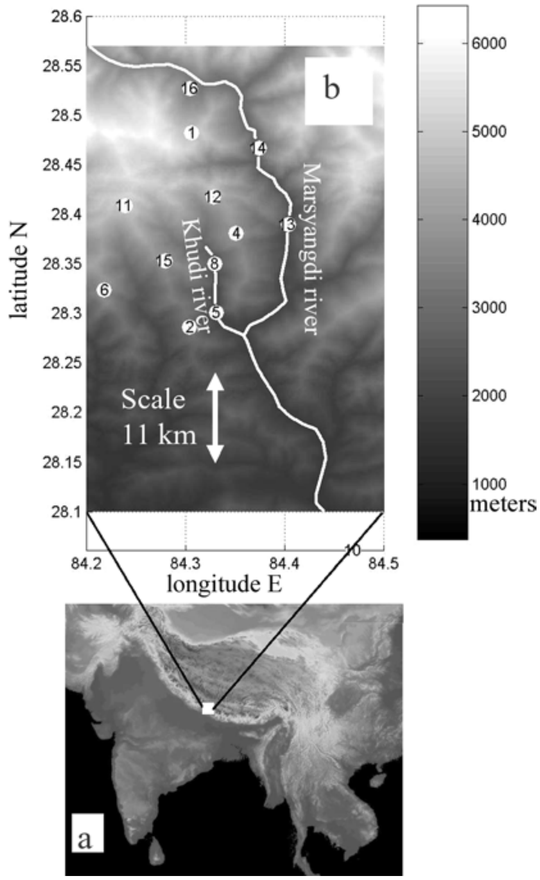

FIGURE 1. (a) Approximate location of the field site in Nepal marked with white rectangle. (b) Topography and major rivers of the field area in Annapurna Range, Nepal. Weather stations are marked by black numbers on white background (note station number 10 below the shaded map). For more details on stations see Table 1.

Precipitation Measurements

The snow water equivalent (SWE) content was measured daily with the Canberra gamma-ray snow detector. The measurement technique is predicated on the fact that gamma-ray radiation from space is attenuated by water molecules (solid or liquid) in the snowpack. The difference between the intensity of the incident gamma-ray radiation above the snowpack and the attenuated radiation below the snowpack allows calculation of the SWE content. The repeatability of the processed daily SWE measurement is typically ±8 mm. For further details see (Osterhuber et al., 1998) or Canberra Inc. gamma-ray snow-logger manual.

All the measurements are timed at three minutes past midnight local Nepal time (GMT +5:45 h). The snow depth measurement takes 4 s. The gamma-ray logger measures radiation for 1 to 3 h depending on the location and year of measurement. Longer measurement intervals are required at lower altitudes in order to acquire comparable amount of gamma ray radiation that is attenuated by the additional moisture in the atmosphere. The longer measurement intervals also reduce the noise induced by short-term spurious variations in the radiation and therefore yield more accurate measurements.

Rain was measured in 30-min intervals by standard tipping-bucket rain gauges. All instruments were connected to digital data loggers from which the data were manually retrieved six to eight times per year.

Results

The annual precipitation record is dominated by the summer Asian monsoon, which typically spans ~3 mo beginning in mid-June.

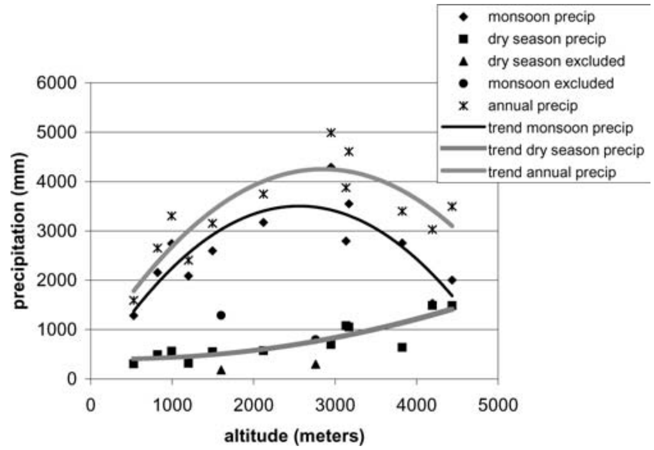

FIGURE 2. Monsoon (June–September) precipitation has a clear maximum at about 3000 m altitude, whereas dry season (October–May) precipitation increases monotonically with altitude. The stations that are located on the north side of the Himalayan crest (Tal and Temang) do not follow this trend due to the considerably drier weather and are excluded from the determination of the trend lines.

Moisture derived from the Bay of Bengal sweeps northwestward until it impinges of the southern flank of the Himalaya in the vicinity of the Annapurna Range. There is a strong correlation between topographic elevation and monsoonal precipitation along the southern flank of the range. As the topography climbs above 1500 to 2000 m, the monsoonal precipitation more than doubles (Fig. 2). The amount of rainfall on ridges is persistently greater than that recorded in the valley bottoms at the same latitudinal position within the range (Fig. 3). In general, the valleys receive less rainfall than do adjacent ridges. Valley precipitation during monsoon (June–September) is 62% and winter precipitation (October–May) is 37% of the ridge precipitation. Overall, measured annual rainfall displays a maximum of ~5000 mm water/yr at an altitude of ~3000 m and tapers northward to <1100 mm water/yr at the most northerly station reported here.

The total annual precipitation in the study area ranges from 5032 mm (2950 m altitude) in the rainy southern side of the range to 1099 mm (2760 m altitude) in the northern rain shadow (Fig. 3).

The monsoon (June–September) precipitation as a function of altitude has a markedly different pattern from the dry season (October–May) precipitation. The monsoon precipitation peaks at about 3000 m altitude. The dry season precipitation that amounts to only 12 to 49% of the total annual precipitation increases monotonically with altitude.

Unlike summer storms in which both rainfall intensity and amount is highly localized, in the winter of 1999–2000, the major snowstorms can be traced simultaneously at all high-altitude stations (Fig. 4). Each of the vertical jumps in the snow water equivalent (as calculated from the gamma-ray loggers) represents a 24-h increment of snowfall and water accumulation. The contrast with the summertime precipitation patterns suggests that the strong convective monsoonal storms are replaced by more stratiform precipitation during winter storms. Despite the synchrony of snowfall events, the absolute SWE increases with altitude (Fig. 5). The anecdotal evidence in the field suggests that the snow depth in the winter 1999–2000 was much larger than long-term average. Snow accumulated at all stations above 3000 m until the end of March, at which point the snow began to melt at lower altitudes, while the snow depth continued to increase about an additional 400 mm at highest station. Significant melting at Rambrong (4400 m) did not occur until May, about 1.5 mo later than at the stations below 4000 m. During the subsequent 20 d at Rambrong, melting removed an average of 40 mm of SWE daily.

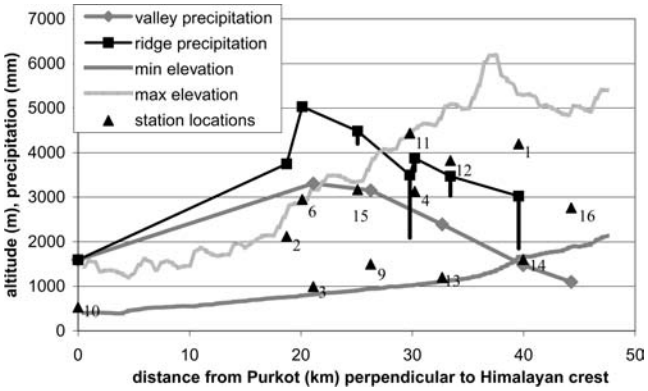

FIGURE 3. The total annual precipitation 1 September 2000–31 August 2001. The precipitation between stations is linearly interpolated and does not reflect possible orographic effects. The total annual precipitation at ridge and valley stations generally decrease towards the north. The maximum precipitation occurs at altitude of about 3000 m on the southern, rainy side of the mountains. The black vertical bars show the amount of precipitation that falls as snow. The trend of the Himalayan crest in the field area is approximately 288°. The maximum and minimum landscape elevations are derived along a 40-km-wide north-south strip over the field area (shown in Fig. 1b) and projected on to a line (18°) that is perpendicular to the crest trend. The numbers next to station locations refer to Table 1.

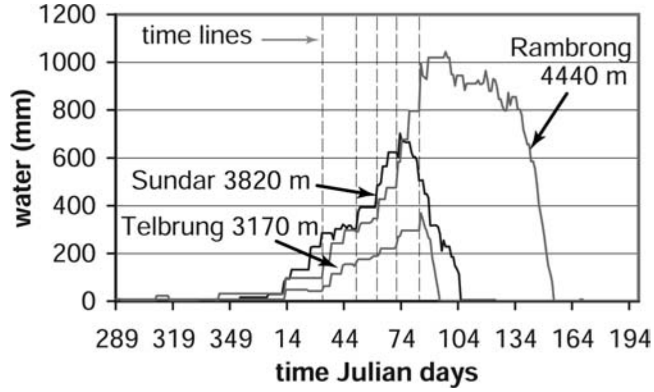

FIGURE 4. Snow water equivalent depth for three stations over the winter 1999–2000. The dashed vertical lines highlight the synchronicity of the major precipitation events over the area.

In the succeeding winter (2000–2001), absolute snow depths were considerably less, averaging only about 50% of the maximum depths of the previous winter. However, the maximum SWE at Rambrong station equaled the maximum water content of the previous year (Fig. 5). For other stations that received snow the maximum SWE was lower for winter 2000–2001 than the previous winter. The snow depths at all altitudes again increased in concert through the season until the end of March.

Typically the wind redistributes the snow in the high mountains (Gray and Male, 1981; Meister, 1989), however, in the Annapurna Range, the redistribution appears to be very limited, and thus identical time series of snow depths can be obtained 8 km apart at same altitude. The wind speed is measured at the top of 10-m tower as total number of anemometer revolutions/30 min. These 30-min mean velocities are averaged for the period of 1 January 2001–1 May 2001 to get an average wind speed for the time of the year when snow falls. The mean wind speed at Rambrong (4440 m) above tree line is 2.1 m s^{-1} and Koprung (3130 m) below treeline is 1.1 m s^{-1}. The mean annual wind speeds for year 2000 are at Rambrong 1.7 m s^{-1}, Telbrung 0.3 m s^{-1}, and Koprung 0.9 m s^{-1}. Wind speeds in the summer tend to be lower than in the winter.

In both winters the maximum SWE content increases as a function of altitude (Fig. 5). The lowest altitude where seasonal snow accumulates is between 2000–3000 m depending on insolation and slope aspect. The measured maximum annual SWE (average of both years) increases from about 220 mm at 3000 m to about 1078 mm at 4400 m (at 4440 m only Rambrong station existed for both years).

Snow average density is calculated for the period when snow depth is more than 100 mm and before the final spring melt densification takes place. The average snow density decreases as a function of altitude although there is a large difference in the absolute values between the 2 yr (Fig. 6). One explanation for the density differences may be the large difference in the mean winter air temperatures (1 January–1 May 2000: –6.06°C, 1 January–1 May 2001: –4.65°C; at Rambrong), the warmer temperatures promote faster snow metamorphism, rain on snow and denser snow.

The maximum SWE does not vary much between the 2 yr although the snow depth varies by about 50%, which may be explained by the warmer air temperature in the spring of 2001, which would allow larger fraction of the precipitation to fall as rain rather than snow at higher altitudes. This suggests that the total amount of winter precipitation is not reflected in the thickness of the snowpack, and thus the anecdotal evidence may bear little semblance to the true SWE.

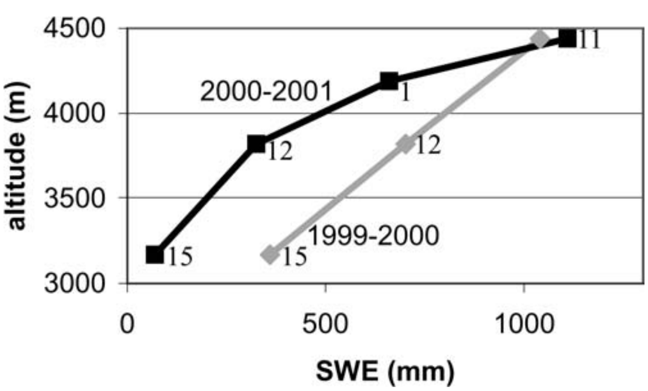

FIGURE 5. Maximum winter snow water equivalent (SWE) for Telbrung (3170 m), Sundar (3820 m), Danfedanda (4190 m), and Rambrong (4440 m) stations for winters 1999–2000 and 2000–2001. The numbers next to data points refer to station identification numbers in Table 1.

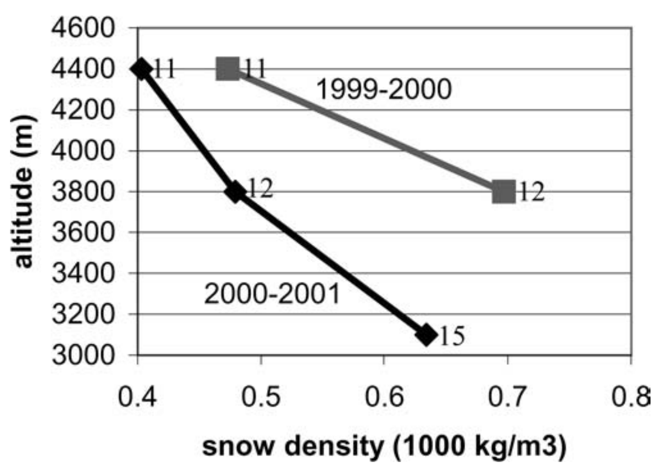

FIGURE 6. Average snow density of the snowpack over two winters prior to onset of the spring melt for Telbrung (3170 m), Sundar (3820 m), and Rambrong (4440 m) for winters 1999–2001. The numbers next to data points refer to station identification numbers in Table 1.

TABLE 1

Station numbers, station names, coordinates (deg, min), mean annual air temperature (°C), snow water equivalent precipitation (mm water), rainfall (mm), station location north or south of divide, and altitudes (meters) on the flanks of Annapurna Range. Stations with less than 75% data coverage not listed

#	Station name	N deg	E deg	Air temp. (°C)	SWE (mm)	Rainfall (mm)	N or S of divide	Altitude (m)
1	Danfedanda	28′28.935	84′18.373	—	1173	1850	N	4194
2	Ganpokhara	28′17.142	84′18.218	13.9	0	3749	S	2120
3	Khudi	28′16.931	84′21.285	20.1	0	2653	S	820
4	Koprung	28′22.863	84′21.047	6.7	284	3591	S	3133
5	Paiyu khola	28′18.037	84′19.848	—	0	3308	S	993
6	Pasqam ridge	28′19.415	84′13.069	—	—	5032	S	2950
7	Pasqam village	28′16.479	84′13.677	—	0	1362	S	1702
8	Probi	28′20.987	84′19.757	—	0	3154	S	1495
9	Purano village	28′18.248	84′21.107	15.5	0	375	S	1787
10	Purkot	28′03.662	84′28.161	21.4	0	1594	S	528
11	Rambrong	28′24.540	84′14.342	−0.5	1408	2089	S	4435
12	Sundar	28′25.070	84′19.694	3.2	439	3031	S	3823
13	Syange	28′23.361	84′24.202	—	0	2388	S	1200
14	Tal	28′28.002	84′22.446	14.9	0	1474	N	1600
15	Telbrung	28′21.185	84′16.769	6.1	284	4199	S	3168
16	Temang	28′31.641	84′18.283	9.4	—	1099	N	2760

One important goal of this study was to quantify snowfall throughout the year. Our highest station is situated at 4440 m, where the mean summertime (June–August) temperature is ~5.2°C. Consequently, despite high amounts of monsoonal precipitation, little summertime snowfall occurs within our network. To determine the altitude above which only snow precipitates, the mean lapse rate is defined, respectively, for June, July, and August 2000, from air temperature recorded at all stations during this period (Table 1). The warmest month is July, and the stations yield a lapse rate of 5.3°C km^{-1}. The mean July air temperature ($T_{air}(z)$ in °C) is given by: $T_{air}(z) = 29.2°C - 0.0053°C\ m^{-1} * z$; where z is altitude above sea level in meters. The mean deviation between observed data and best-fit line is ±0.44°C.

The mean annual air temperatures in the field area range from –0.5°C (4440 m altitude) to 21.4°C (530 m altitude). The relation between mean monthly air temperature and solid precipitation as a fraction of total generally depends on geographical location, altitude, and season (Barry, 1992). The observational data from high altitude (3100 m) in the European Alps suggests that only solid precipitation occurs when the mean monthly air temperature is –3°C (Lauscher, 1976). In central Asia at altitudes between 3500 and 4000 m, the mean monthly air temperature that corresponds to solid only precipitation is placed at –1°C (Barry, 1992). The mean monthly air temperature corresponding to solid-only precipitation in the Annapurna Range is therefore, likely to be –2°C ± 1°C, which converts to 5883 ± 190 m altitude by extrapolating the lapse rate of the warmest month (5883 ± 270 m when the ±0.44°C uncertainty is included in the calculation). According to these calculations, only snow precipitates above this level throughout the year. The reliability of the extrapolation above the observed network can be checked against the MOHPREX free-air soundings in June 2001, that were run within 15 km of the station network (T. Lang, pers. comm., April 2002). The MOHPREX average 0°C altitude is 107 m lower than the extrapolated 0°C station data for June (5398 m) (24 m lower when the ±0.44°C error is included in the calculation). This may be due to slight fluctuation in the altitude of 0°C air temperature from year to year, or simply reflect the fact that surface air is heated by the sensible heat transfer from the ground surface and thus is warmer than the air aloft. These two independent sources generally agree on the altitude of the 0°C air temperature for the warmest month in the summer.

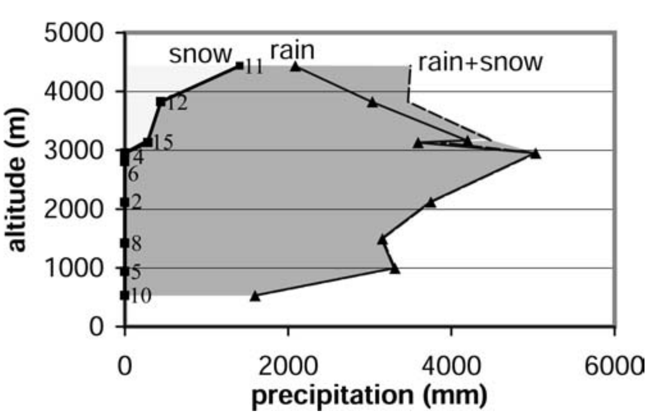

FIGURE 7. Snow, rain, and total annual precipitation as a function of altitude for the south side of the Annapurna Range,1 October 2000–30 September 2001. Note the prominent maximum in the total precipitation at about 3000 m altitude. The numbers next to data points refer to station identification numbers in Table 1.

Discussion

The first ever comprehensive precipitation observations over the Annapurna Range show that the annual precipitation has a strong peak at about 3000 m altitude, which is also the lowest altitude where winter snow accumulates in the region (Fig. 7). This has great implications to the feedbacks between the topography and climate.

The annual rain totals have a marked gradient over the crest of the Himalayas, decreasing sharply into the rain shadow in the North (Fig. 3). However, the limited number of high-altitude snow observations show no general precipitation gradient over the area. The SWE simply scales with the altitude. The horizontal differences in the snowpack are surprisingly small, which is thought to testify of the anomalously low winds in the area and almost nonexistent snow drifting. During winter and spring (1 January 2001–1 May 2001) the mean wind speed for Rambrong was 2.1 m s^{-1} and Koprung was 1.1 m s^{-1}.

The fraction of annual precipitation that falls as snow is 0 at 2000 m and reaches 40% at the highest measurement platform at 4400 m altitude. It is calculated that the fraction is 100% above about 5880 m. It is assumed that the total annual precipitation above 5880 m is enough to sustain the glaciers and permanent snowfields that are depleted by direct sublimation and avalanching. The total mass of snow avalanching down the mountain slopes is not known.

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