

Large-scale assessments and mapping of snow hazards in pastoral areas of the Tibetan Plateau using microwave remote sensing data and ground records

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Abstract The Tibetan Plateau frequently experiences snow hazards that endanger livelihoods of local herders. Fast mapping and risk assessments of snow hazards are significant and prerequisite for decision making in mitigating negative impacts of snow hazards and facilitating social adaptation. In this study, we intended to develop a method for fast mapping multiple grades of snow hazards happened on the Tibetan Plateau relying on satellite microwave remote sensing data that can represent critical snow conditions. First, we calculated pasture burial index and continuous days of snow cover and used the two factors to classify pixels of the study area into four grades of snow hazards. Second, we assessed the grades of snow hazards at county scale using the above two factors and the factor of snow cover percentage over each county. Finally, we assessed the accuracy of predicting multiple grades of snow hazards based on remotely sensed data by comparing the above results with ground-recorded historical snow hazards at county scale. The results indicated that the frequencies of four grades of snow hazards had similar spatial patterns with high frequencies in southeast areas and low frequencies in northeast and southwest areas of the Tibetan Plateau. The evaluation results showed that the overall accuracy of the method developed in this study was over 70% and the accuracy of predicting the severe grade of snow hazards was higher than that of the other grades. In conclusion, the method developed in this study was feasible and practical for mapping multiple grades of snow hazards happened on the Tibetan Plateau.

Keywords Large-scale snow hazard mapping · Remote sensing data · Ground records · Tibetan Plateau

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1 Introduction

Snow hazards are meteorological hazards that can cause mass mortality and debilitation of livestock due to starvation and prolonged exposure to extreme weather conditions. Snow hazards can be caused by one or a combination of environmental factors, including heavy snowfall, extremely low temperature, strong wind, and low productivity of pastures (Tachiiri et al. 2008). In pastoral areas, a great deal of snowfall often leads to pastures being buried and transportation disruption, consequently resulting in the death of a large number of livestock due to extremely cold temperature and lack of forage (Fernandez-Gimenez et al. 2012). The heavy snowfalls in winter and spring can seriously constrain the sustainable development of livestock husbandry and threaten livelihoods of local herders. Thousands of livestock can perish during a severe snow hazard, and the overall impact culminates in peak mortality in early spring when animals are at their weakest conditions. In addition to physical stress, the survivability of animals also depends on the quality of pastures available for grazing. Therefore, the intensity of snow hazards happened in pastoral areas can also be influenced by droughts happened in the preceding summer (Wang et al. 2016b). Owing to their serious disruption of the livelihoods of local herders, snow hazards have attracted a fair share of scientific research with the purpose of developing knowledge that can guide hazard management efforts (IPCC 2012).

Snow hazards are one of the most common natural hazards in the pastoral and semi-pastoral areas of China, including Xinjiang, Inner Mongolia, Qinghai, and Tibet. The Tibetan Plateau with its main parts in Qinghai and Tibet contains the highest pastoral and semi-pastoral areas in the world. The most widely felt climatic hazards on the Tibetan Plateau is snow hazards (Gao and Qiu 2011). Livestock is the backbone of the livelihoods of local herders on the Tibetan Plateau and often the only means of income, food, and fuel for herder households. Livestock products can provide food, fuel for cooking and heating, clothing, transportation, and currency for paying for services and education. In particular, rural herders dependent on livestock grazing are significantly impacted by this type of natural hazards happened there. Harsh physical conditions of snow hazards can prevent livestock from accessing pastures and can result in a large number of livestock perish (Wang et al. 2014). Because of undeveloped agricultural infrastructure in the region, snow hazards in winter or spring often cause the death of a large number of livestock. There were more than 18 million livestock died in snow hazards happened from 1974 to 2009 in the eastern parts of the Tibetan Plateau (Long et al. 2011). The serious impacts of snow hazards on livelihood sustainability of local herders promote a need to gain the knowledge of snow hazards that would assist in the development of adaptation strategies to snow hazards on the Tibetan Plateau (Yeh et al. 2014; Wang et al. 2016a).

The information on spatial and temporal patterns of snow cover on the Tibetan Plateau is important for early warning of snow hazards (Wang et al. 2013). Fast mapping of snow hazards in time can help to mitigate the loss caused by snow hazards. Ground measurements and remotely sensed data are two main data sources of snow conditions. Ground meteorological stations are mostly located in eastern and central populated areas of China, while few ground stations are located in pastoral and semi-pastoral areas of northern and western China, where snow hazards happen frequently. This causes poor representations of continuous days of snowfall and low temperature in pastoral areas of China. Remote sensing technology has been used widely in mapping snow conditions for its synoptic view and high efficiency (Dietz et al. 2012). Moreover, remote sensing data allow the detection of spatial and temporal patterns of snow cover across large geographic areas in inaccessible terrain. Therefore, it can provide useful information on a critical assessment of snow

hazards. Remotely sensed data can be used to timely and accurately monitor the occurrence and development of snowfall and snow cover and further help to minimize the damage caused by snow hazards.

Numerous studies have been conducted on snow cover monitoring, snow depth simulation, risk assessment of snow hazards, snow hazard and avalanche mapping, as well as their relations to climate change using remote sensing data (Frei et al. 2012; Gao et al. 2012; Zhou et al. 2013). Remote sensing data that can be used to quantify snow cover are available from multiple sources, such as visible light data observed by optical remote sensors (Hall et al. 2002; Paudel and Anderson 2011), microwave data obtained from microwave remote sensors (Savoie et al. 2009), as well as data showing the surface area of snow cover based on satellite observations gathered by NOAA AVHRR (Simpson et al. 1998). Optical remote sensing data are greatly influenced by weather conditions. Cloudy or precipitation weather usually makes it difficult to use this kind of data. As the complementary data, passive microwave remote sensing of snow conditions can be used as all-weather monitoring data and has been used to estimate snow depth. Since the year 1978, satellite-based passive microwave remote sensing data have been used to derive hemispheric-scale snow cover maps (Armstrong and Brodzik 2001). Scholars have developed a variety of models and algorithms using passive microwave remote sensing data and combinations of microwave and optical remote sensing data to estimate snow cover extent, snow depth, and snow water equivalent (Foster et al. 1997; Metsamaki et al. 2002; Liang et al. 2008; Gao et al. 2011; Dai et al. 2012; Yu et al. 2012).

Mapping and risk assessments of snow hazards are extremely important for improving the ability to prevent snow hazards and minimize losses in pastoral and semi-pastoral areas of the Tibetan Plateau. Fast mapping of multiple grades of snow hazards can help to estimate damages caused by snowfall events in a particular period and region. The development of snow hazards is not only related to snow conditions, but also connected to many other factors such as continuous days of low temperature, strong wind, area of snow-covered pastures, livestock stocking rate, and capability of hazard prevention, of which many have strong temporal and spatial heterogeneity (Wang et al. 2016b). Data related to most of the above factors cannot be collected readily or not available in details over time and across space. Snow conditions detected using remote sensing data were the only data source that could be readily used for fast mapping of multiple grades of snow hazards on the Tibetan Plateau.

The primary objective of the paper is to develop a new method for fast mapping multiple grades of snow hazards on the Tibetan Plateau using satellite microwave remote sensing data of snow conditions. The results of this study are expected to provide regional-scale assessments of snow hazard risks that can be used as a reference for decision making of snow hazard prevention and relief management for local governments. The paper is organized as follows. In Sect. 2, we present the newly developed method of using remote sensing data to predict multiple grades of snow hazards and the procedure of building the database of historical snow hazards happened in the counties of Qinghai and Tibet using ground records. Then, we present spatial and temporal patterns of snow hazards inferred from remotely sensed data and accuracy evaluations of the above results using the historical snow hazard database in Sect. 3. Finally, we discuss challenges and limitations of this method and summarize the major findings of this work.

2 Methods

First, we developed a method of using satellite microwave remote sensing data for fast mapping multiple grades of snow hazards happened on the Tibetan Plateau. In general, the natural processes associated with snow hazards mainly include three factors, i.e., snow fall period, snow accumulation period, and possibility of reoccurrence. During the first period, snowfall is the first most important factor in the formation of a snow hazard, while the continuous days of snow cover is the second most important factor. Snow depth and continuous days of snow cover are the two indicators of snowfall accumulation and duration of snow cover, respectively. The intensity of snow hazards is usually measured by the geographic area of snow cover and snow depth. In this method, snow depth and continuous days of snow cover derived from microwave remotely sensed data were used as the two most important data sources for mapping multiple grades of snow hazards happened on the Tibetan Plateau. In 2006, China Meteorological Administration issued a national standard for grading snow hazards in pastoral and semi-pastoral areas of China based on snow conditions (China Meteorological Administration 2006; Table 1).

Following the national standard for assessing multiple grades of snow hazards, we used the two factors of pasture burial index and continuous days of snow cover to mapping grades of snow hazards at the pixel scale of remotely sensed data. On the Tibetan Plateau, with its high elevation, cold climate, and widely distributed livestock grazing, the frequency of snow hazards is typically the highest from previous October to April of a specific year. Therefore, we only analyzed snow hazards from October to April of the years between 1981 and 2012. To be specific, we used the dataset of snow depth, snow cover, and grasslands to calculate two indicators, i.e., pasture burial index and continuous days of snow cover, and then to determine the grades of snow hazards at pixel scale according to the national standard (Table 1). Pasture burial index was measured by the rate between snow depth and the average height of grassland communities in each pixel. The time-length of snow cover in each pixel was measured by the continuous days of snow cover in that pixel.

Table 1 The national standard for assessing four grades of snow hazards based on snow conditions

Grades of snow hazards	Conditions of snow cover and its impacts on livestock grazing			
	Percent of pastures buried by snow (%)	Continuous days of snow cover (days)	Percent of pastures covered by snow (%)	Impacts on livestock grazing
Light grade	30–40	≥ 10	≥ 20	Light impact on cattle and sheep grazing; no impact on horse grazing
	41–50	≥ 7		
Medium grade	41–50	≥ 10	≥ 20	Medium impact on cattle and sheep grazing; no impact on horse grazing
	51–70	≥ 7		
Heavy grade	51–70	≥ 10	≥ 40	Heavy impact on grazing of all animals; loss of cattle and sheep
	71–90	≥ 7		
Severe grade	71–90	≥ 10	≥ 60	Severe impact on grazing of all animals; great loss of all animals
	> 90	≥ 7		

The time series of snow depth data covering the Tibetan Plateau were provided by the National Data Center for Cold and Dry Region Studies, Chinese Academy of Sciences. The dataset were created by scientists in the Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences using the passive microwave remote sensing data derived from three sensors, i.e., SMMR (1980–1987), SMM/I (1987–2008), and AMSR-E (2008–2014). Due to the original dataset used for creating the snow depth data derived from three different sensors, there were certain systematic differences over time. Therefore, the science team of creating the snow depth data first calibrated the original data derived from the three sensors to make them temporally consistent. Then, they developed a new algorithm to calculate snow depth from the cross-calibrated data series derived from the above three sensors (Che et al. 2008). The derived snow depth data from the passive microwave remote sensors were validated using ground recorded snow depth by field stations in China. The advantage of using this data is its high temporal resolution (i.e., daily), so we can analyze temporal variability of snow conditions. But, the disadvantage of using this dataset is its coarse spatial resolution (i.e., 25-km). The freely available satellite microwave remote sensing dataset can provide a basis for large-scale and long-term monitoring snow conditions on the Tibetan Plateau.

The data on the types of grasslands and their spatial distributions on the Tibetan Plateau were created by Institute of Botany, Chinese Academy of Science (Fig. 1a). The vegetation map was created based on large-scale field campaigns and samplings. The original scale of the map was 1:1000,000. Moreover, we collected average heights of dominant grassland communities of grassland types based on records in the Flora Encyclopedia of China (Editorial Committee on Flora Encyclopedia of China 2004). Advanced space-borne thermal emission and reflection radiometer (ASTER) DEM data covering the study area were acquired from the NASA Reverb database (<https://reverb.echo.nasa.gov/reverb/>). Based on the spatial distributions of grassland types and the constraint of topographic slope (i.e., less than 50°), we identified the potential grazing areas of the Tibetan Plateau (Fig. 1b). The above figure shows that the areas suitable for grazing under no snow conditions are mainly distributed in southeast areas, with other smaller areas in western, central, and northeast areas of the Tibetan Plateau. Most parts in northwest and northern areas of the Plateau are the potential areas of snow hazards.

Moreover, we proposed a method for fast mapping multiple grades of snow hazards at county scale based on the remotely sensed data. The calculation proceeded as follows. First, we calculated the mean values of pasture burial index and average days of constant snow cover in each county. Then, we included the third factor, i.e., percent of grassland areas covered by snow in each county, which was measured by the rate between areas of

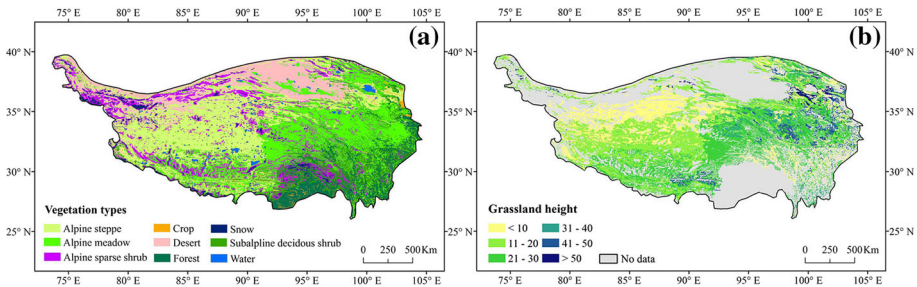


Fig. 1 The vegetation types (a) and average grassland heights of dominant grassland communities in the potential grazing areas (b) of the Tibetan Plateau

snow cover and grassland cover in that county. According to the national standard of assessing multiple grades of snow hazards in pastoral areas of China (Table 1), we determined the four grades of snow hazards in each county based on the values of these three indicators. In addition, in order to measure the frequencies of the four grades of snow hazards happened on the Tibetan Plateau between 1981 and 2012, we measured the numbers of snow hazards in each of the four grades at pixel and county scales.

Second, we built the database of historical snow hazards happened in the counties of Qinghai and Tibet between 1981 and 2012. The database include the time, place, size of impacted grassland area, snow depth, continuous days of snow cover, death rate of livestock, percent of impacted livestock, number of impacted human population, and economic loss of snow hazards. Livestock is the main hazard-affected body in pastoral areas of the Tibetan Plateau. The factors of livestock that could affect the intensity of snow hazards include livestock population at the beginning of a year, livestock population by the end of a year, actual livestock stocking rate, and fraction of small livestock. The Ministry of Agriculture of China issued a national standard for assessing grades of snow hazards in the pastoral areas of China based on conditions of livestock impacted by snow hazards (Ministry of Agriculture of China 2013; Table 2).

Based on the meteorological hazards recorded in the yearbooks of Qinghai and Tibet, we collected the historical records of snow hazards happened in the counties of the two provinces between 1981 and 2012. To be specific, the ground records of historical snow hazards were collected from various sources, including Meteorological Hazard Encyclopedia of China: Volume of Qinghai (Wen 2007), Meteorological Hazard Encyclopedia of China: Volume of Tibet (Wen 2008), Climate Bulletins of Qinghai 2001–2013 (Meteorological Bureau of Qinghai 2013), Climate Bulletins of Tibet 2001–2013 (Meteorological Bureau of Tibet 2013), Qinghai Statistical Yearbooks (Statistical Bureau of Qinghai 2013), and Tibet Statistical Yearbooks (Statistical Bureau of Tibet 2013). Based on information from these ground records, we set basic requirements that a typical case of snow hazard must meet, which include snow depth, continuous days of snow cover, number of livestock loss, and number of livestock impacted by a snow hazard. According to the above national standard (Table 2), we mainly used the death rate of livestock as the critical indicator to determine the grades of snow hazards. If there was no such indicator in a specific county, we calculated the indicator by dividing the number of dead animals caused by snow hazards with the total number of livestock at the beginning of the year. Moreover, we also used the percent of impacted livestock in snow hazards as the secondary information to determine the grades of snow hazards. For the snow hazards that were recorded in multiple sources, we also cross-validated the grades of the snow hazards in those recordings. In

Table 2 The national standard for assessing four grades of snow hazards based on livestock conditions

Grades of snow hazards	Livestock conditions in snow hazards	
	Livestock mortality rate (%)	Percent of livestock impacted by snow hazards (%)
Light grade	3–5	< 30
Medium grade	5–10	30–40
Heavy grade	10–15	40–50
Severe grade	> 15	> 50

sum, we built a high-quality database of historical snow hazards happened in Qinghai and Tibet between 1981 and 2012. The database includes 670 records of historical snow hazards, including 285, 194, 134, and 57 snow hazards in light, medium, heavy, and severe grades, respectively. The data were regarded as the key criteria for judgment of four grades snow hazards predicted using remotely sensed data.

Finally, we analyzed consistencies between the grades snow hazards inferred from remotely sensed data and those from the database of historical snow hazards for the purpose of evaluating the prediction accuracy of the newly developed method. Because historical snow hazards were recorded in counties, the comparisons were also conducted at county scale. By comparing the discrepancy between the results of the two methods, we analyzed the prediction accuracies of the method relying on remotely sensed data. Specifically, we calculated the prediction accuracies of the four grades of snow hazards inferred from remotely sensed data at county scale between 1981 and 2012 using an error matrix.

3 Results

3.1 Spatial and temporal variability of snow depth and snow cover durations

Based on satellite microwave remote sensing data of snow depth covering the grasslands of the Tibetan Plateau, we first analyzed the spatial and temporal patterns of mean annual snow depth and mean annual snow cover days. The main snow season of the Tibetan Plateau is from previous October to April. Thus, for each snowfall season, we calculated accumulated snow depth and accumulated snow cover days between previous October and April of a specific year. Then, we averaged annual values of the two variables between 1981 and 2012 at pixel scale. The results showed that the main snow mass within the southeast areas of the Tibetan Plateau dominates the total amount of snow mass over the study area (Fig. 2a). In the southwest and northeast areas of the Tibetan Plateau, mean snow depth over the study period was relatively lower than the other areas of the Tibetan Plateau. The temporal variations of annual mean snow depth over the study area between 1981 and 2012 showed a decreasing but statistically insignificant trend ($p > 0.1$; Fig. 2b). The two snowfall seasons, i.e., 1985–1986 and 1997–1998, had the highest values of annual mean snow depth over the study period.

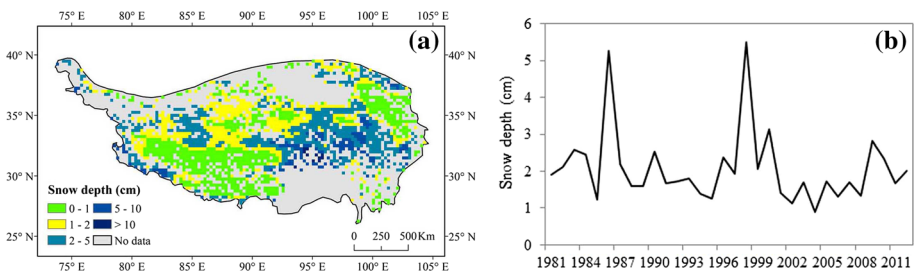


Fig. 2 The spatial and temporal variability of snow depth on the Tibetan Plateau during 1981–2012. **a** Spatial pattern of mean annual accumulated snow depth over the study period at pixel scale and **b** inter-annual variability of mean accumulated snow depth over the study area

Moreover, we also calculated the index of abnormal snow depth to accurately identify the snowfall seasons with extremely high or low snow accumulations (Table 3). The value of abnormal index of snow depth for a specific snowfall season was calculated as the rate between the deviation from the mean and the standard deviation of annual mean snow depth over the study area. As shown in Table 3, the abnormal index had extremely high values for the two snowfall seasons, i.e., 1985–1986 and 1997–1998. This was consistent with the above analysis. Moreover, this indicated that severe snow hazards might happen over the Tibetan Plateau within the two snowfall seasons. The values of the abnormal index of snow depth were high and weakly high in two snowfall seasons, i.e., 1999–2000 and 2008–2009, respectively. These values implied that snow hazards might also happen over the study area in the snowfall seasons.

Table 3 The index of abnormal snow depth in snowfall seasons during 1981–2012 on the Tibetan Plateau

Snowfall season	Abnormal index (<i>I</i>)
1980–1981	– 0.16
1981–1982	0.04
1982–1983	0.50
1983–1984	0.37
1984–1985	– 0.84
1985–1986	3.15
1986–1987	0.11
1987–1988	– 0.47
1988–1989	– 0.47
1989–1990	0.45
1990–1991	– 0.41
1991–1992	– 0.35
1992–1993	– 0.28
1993–1994	– 0.69
1994–1995	– 0.81
1995–1996	0.31
1996–1997	– 0.13
1997–1998	3.39
1998–1999	– 0.01
1999–2000	1.05
2000–2001	– 0.66
2001–2002	– 0.94
2002–2003	– 0.37
2003–2004	– 1.19
2004–2005	– 0.34
2005–2006	– 0.78
2006–2007	– 0.37
2007–2008	– 0.73
2008–2009	0.74
2009–2010	0.26
2010–2011	– 0.34
2011–2012	– 0.06

$I < - 2.0$, extremely low;
 $- 2.0 \leq I < 1.0$, low;
 $- 1.0 \leq I < - 0.5$, weakly low;
 $- 0.5 \leq I < 0.5$, normal;
 $0.5 \leq I < 1.0$, weakly high;
 $1.0 \leq I < 2.0$, high; $I \geq 2.0$,
 extremely high

The snow cover on Tibetan Plateau has the longest duration due to high elevation, although the main snowfall season is from previous October to April. Similar to spatial patterns of mean annual snow depth, the southeast and northwest areas of the Plateau had the longest snow cover durations (Fig. 3a). There exists some permanent snow cover over the Himalaya and the marginal areas of the Tibetan Plateau. Over the past 30 years, the time series of annual mean snow cover days had high inter-annual variability with a statistically significant increasing trend ($p < 0.01$; Fig. 3b). Moreover, the snowfall season 1997–1998 had the longest duration of snow cover over the study period. In the pastoral and semi-pastoral areas of the Tibetan Plateau, the recent expansion in durations of snow cover in snowfall seasons, combined with increased grazing intensity, has led to snow hazards having a drastic negative impact on livestock and livelihoods of local herders to the point where snow hazards is now the most common natural hazards in this region (Wang et al. 2014).

3.2 Spatial patterns of multiple grades of snow hazards inferred from remotely sensed data

First, we analyzed four grades of snow hazards at pixel scale predicted using pasture burial index and continuous days of snow cover, which can show spatially detailed snow hazards over the study area. The severity of snow hazards was assigned into four grades according to the national standard (Table 1), and we also counted the frequencies of snow hazards of each grade at pixel scale between 1981 and 2012. The results indicated that the frequencies of snow hazards in each of the four grades inferred from remotely sensed data had significant spatial variations (Fig. 4). The spatial patterns of the frequencies of snow hazards in the four grades were similar with high frequencies in southeast and northwest areas and low frequencies in northeast and southwest areas of the region. From the perspective of the whole Tibetan Plateau, the high-altitude areas in the hinterland were subjected to a much higher risk of snow hazards than the rest areas of the Tibetan Plateau. For the four grades of snow hazards, the frequencies of snow hazards were all dominated by every 10 years, which means snow hazards happened 0–3 times during 1981–2012. The percentages of grid cells in this frequency of light, medium, heavy, and severe grades of snow hazards were 58.73, 76.29, 81.02, and 78.34%, respectively. The high frequencies of snow hazards (i.e., happened more than 7 times over the study period), especially in heavy and severe grades, were relatively less (i.e., less than 15% of the total number of grid cells) and mainly distributed in southeast areas and southwest and northeast boarder areas of the Plateau. In

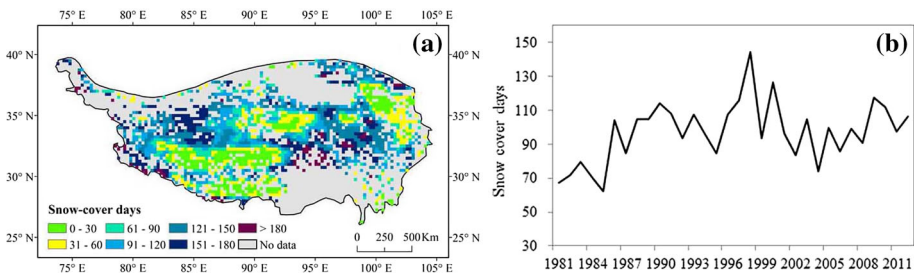


Fig. 3 The spatial and temporal variability of snow cover days on the Tibetan Plateau during 1981–2012. **a** Spatial pattern of mean annual accumulated days of snow cover over the study period at pixel scale and **b** inter-annual variability of mean accumulated days of snow cover over the study area

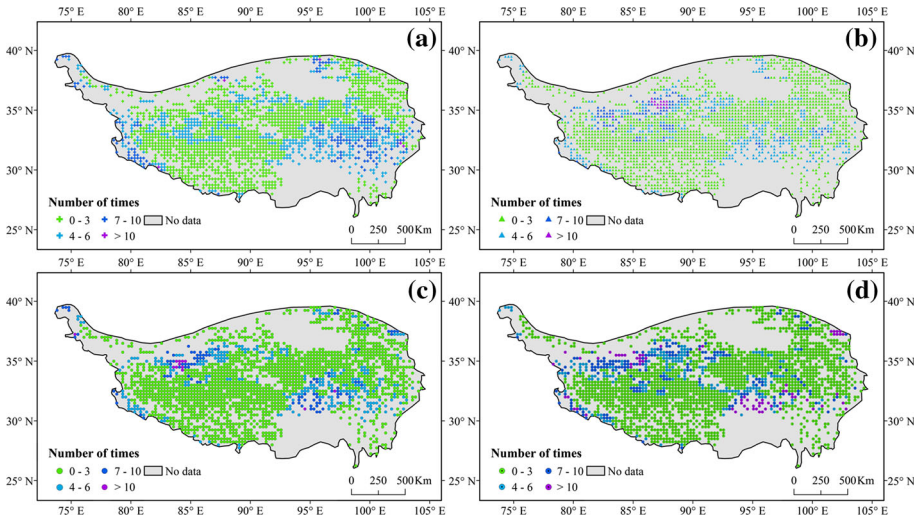


Fig. 4 The frequencies of four grades of snow hazards on the Tibetan Plateau during 1981–2012 at pixel scale, inferred from remotely sensed data **a** light grade, **b** medium grade, **c** heavy grade, and **d** severe grade

addition, the spatial patterns of the frequencies of snow hazards in the four grades were similar to the spatial patterns of mean annual accumulated snow depth and mean annual accumulated days of snow cover. The areas with high snow depth and long durations of snow cover tended to have high frequencies of snow hazards.

Second, we analyzed the four grades of snow hazards at county scale on the Tibetan Plateau, which were measured by pasture burial index and continuous days of snow cover aggregated at county scale and the percent of grasslands covered by snow in each county. In this study, we only included the pastoral and semi-pastoral counties in the analyses, and counties dominated by farming activities (i.e., more than 80% of agricultural income in the county was from farming) were excluded. The results indicated that similar to the spatial patterns at pixel scale, for all of the four grades of snow hazards, the frequencies were dominated by every 10 years (i.e., happened 0–3 times within the study period, Fig. 5). The percentages of counties in this frequency of light, medium, heavy, and severe grades of snow hazards were 55.82, 76.39, 80.45, and 80.17%, respectively. For the high frequencies of snow hazards happened in the study period, five counties had 7–10 times of snow hazards in light grade; two counties had 7–10 times of snow hazards in heavy grade; and one county had more than 7 times of snow hazards in severe grade. The spatial distributions of the high frequencies of snow hazards had similar spatial patterns with those at pixel scale, i.e., counties in southeast areas and southeast and northeast boarder areas of the Tibetan Plateau had high frequencies of snow hazards. With the longest snowfall period in these areas, the number of snow cover days can exceed 200 days, beginning earlier and ending later than in other areas. During the snowfall season from previous October to April, these areas covered with permanent snow were more susceptible to have snow hazards.

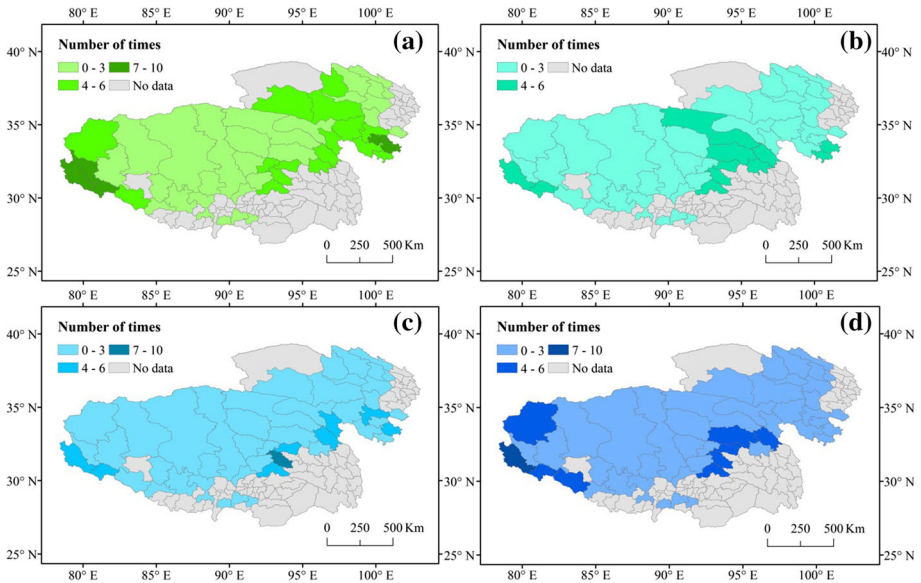


Fig. 5 The frequencies of four grades of snow hazards on the Tibetan Plateau during 1981–2012 at county scale, inferred from remotely sensed data **a** light grade, **b** medium grade, **c** heavy grade, and **d** severe grade

3.3 Evaluations of the remote sensing-based method with ground records of snow hazards

In this study, we built the database of historical snow hazards happened in the counties of Qinghai and Tibet between 1981 and 2012 for evaluations of the four grades of snow hazards inferred from remotely sensed data. Using records from the database, we analyzed the frequencies of snow hazards in four grades at county scale over the study area (Fig. 6). The results showed that the spatial patterns of the frequencies of snow hazards in the four grades from records of the database were similar to the above results inferred from remotely sensed data. The frequencies of snow hazards were dominated by the frequency of every 10 years (i.e., happened 0–3 times over the study period). The percentages of pastoral and semi-pastoral counties in this frequency of light, medium, heavy, and severe grades of snow hazards were 47.30, 71.55, 76.21, and 78.47%, respectively. For the high frequencies of snow hazards happened over the study period, six counties had 7–10 times of snow hazards in light grade; two counties had 7–10 times of snow hazards in medium grade; and three counties had more than 7 times of snow hazards in heavy grade over the study period. In general, the counties with a high frequency of snow hazards were more likely to be adversely affected again.

Based on the ground recorded snow hazards happened in the counties of Qinghai and Tibet between 1981 and 2012, we evaluated the accuracies of the four grades of snow hazards inferred from remotely sensed data using an error matrix (Table 4). In the database of historical snow hazards, the numbers of snow hazards in light, medium, heavy, and severe grades were 285, 194, 134, and 57, respectively. In contrast, the numbers of snow hazards inferred from microwave remotely sensed data of the four grades were 241, 182, 123, and 57, respectively. Moreover, the overall prediction accuracy of 74% suggested that the method developed in this study was in general acceptable. Specifically, the prediction

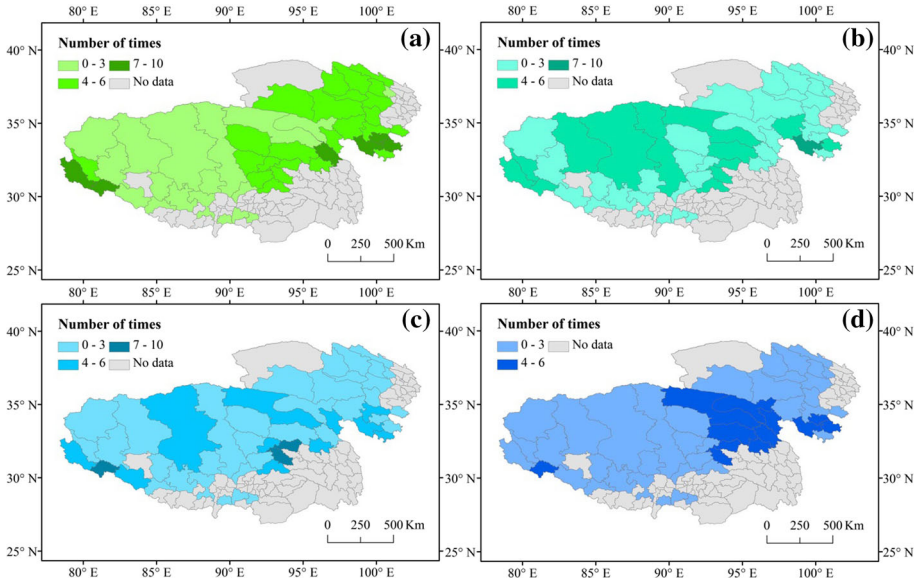


Fig. 6 The frequencies of four grades of snow hazards on the Tibetan Plateau during 1981–2012 at county scale, based on ground records of historical snow hazards **a** light grade, **b** medium grade, **c** heavy grade, and **d** severe grade

Table 4 The error matrix between the frequencies of the grades of snow hazards inferred from remotely sensed data and the frequencies of the grades of ground-recorded historical snow hazards

	Grades of ground-recorded historical snow hazards			
	Light grade	Medium grade	Heavy grade	Severe grade
Grades of snow hazards inferred from remotely sensed data				
No hazard	64	3	0	0
Light grade	201	36	4	0
Medium grade	20	143	18	1
Heavy grade	0	12	102	9
Severe grade	0	0	10	47
Total counts	288	191	134	57
Accuracies of snow hazards inferred from remotely sensed	201/285 \approx 71%	143/194 \approx 74%	102/134 \approx 76%	47/57 \approx 83%
Overall accuracy	(201 + 143 + 102 + 47)/(285 + 194 + 134 + 57) \approx 74%			

accuracies for each of the four grades of snow hazards were all over 70%, with the highest prediction accuracy for the severe-grade snow hazards. For example, for the 57 severe-grade snow hazards recorded in the database, there were 1, 9, and 47 snow hazards in medium, heavy, and severe grades, respectively, inferred from remotely sensed data, and the prediction accuracy was 83%.

In addition, in order to analyze the prediction accuracies of multiple grades of snow hazards using microwave remotely sensed data for a specific snowfall season, we compared the results between the four grades of snow hazards inferred from remotely sensed data and those from local ground records for the snowfall season between winter 1997 and spring 1998 (Fig. 7). Based on the above analyses, both the accumulated snow depth and the time-length of snow cover were extremely high for this snowfall season. The comparison results indicated that accurately predicting snow hazards using the newly developed method was already a great success for the years with high snow accumulations. Overall, the accuracy evaluations demonstrated that the newly developed method of mapping multiple grades of snow hazards relying on remote sensing data had a potential for practical use on the Tibetan Plateau.

4 Discussion and conclusions

Fast mapping and risk assessments of multiple grades of snow hazards in the pastoral areas of the Tibetan Plateau are significant for loss relief and sustainable development of regional livestock husbandry. In the foreseeable future, livestock grazing will remain the dominant livelihood source for rural population in the study area (Goldstein 2012). Therefore, the newly developed method of using microwave remotely sensed data for fast mapping multiple grades of snow hazards is important for snow hazard warning, relief, and prevention. Using the remote sensing-based method, we assessed four grades of snow hazards at pixel and county scales on the Tibetan Plateau between 1981 and 2012. The results were evaluated at county scale with the local records from the database of historical snow hazards built in this study. The prediction accuracies of the four grades of snow hazards demonstrated that the new method developed in this study was practical for fast mapping multiple grades of snow hazards happened on the Tibetan Plateau.

There were a number of challenges that limited our ability of using remote sensing data to accurately mapping snow hazards happened on the Tibetan Plateau over the past 30 years. First, the occurrence of snow hazards was often not just as the result of one heavy snowfall or temperature drop, but also affected by continuous days of snowfall and other biophysical factors, such as wind speed, topographic features of snow-covered areas, and grassland productivity of the previous summer (Wang et al. 2016b). These factors complicate the determination of the grades of snow hazards at regional scale, and data related to these factors were not all readily available. Therefore, these factors were not considered

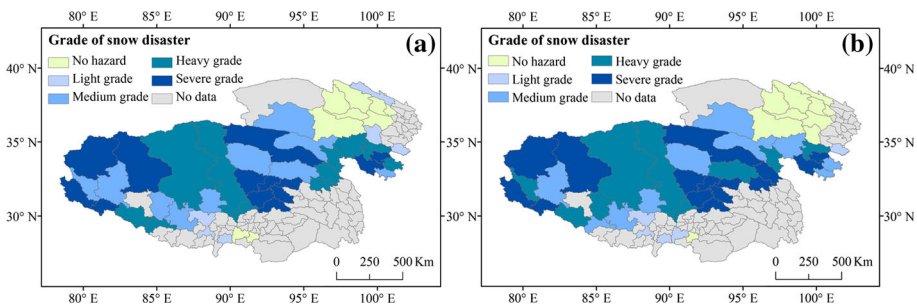


Fig. 7 The comparisons between the grades of snow hazards inferred from remotely sensed data **a** and those from historical ground records **b** happened in the snowfall season during 1997–1998

in this regional-scale study. But, they must be taken into consideration when conducting risk assessments and mapping of snow hazards at landscape scale.

Second, snow accumulation does not always cause a hazard because the occurrence of snow hazards is the result of both natural and social processes (Wang et al. 2014). This was probably one of the main reasons for the discrepancy between the results inferred from remotely sensed data and those from ground records. The method developed in this study was mainly based on satellite remote sensing data, without considering any interference or assistance of humans such as hazard relief by supplying a great amount of forage from other regions. However, snow hazards have both natural and social attributes. The integrated vulnerability of all hazard-affected entities is referred to as physical exposure, of which the amount will influence the grade of a snow hazard. In general, physical exposure is quantified through the amount of death and injury incurred by people and the number of livestock killed during a snow hazard (Wang et al. 2016b). Social processes associated with snow hazards are reflected in vulnerability of a social system to snow hazards (Yeh et al. 2014). In addition, the degree and extent of snow hazards are also related to the local infrastructure (e.g., roads, communications, and sheds for livestock), forage stock in a pastoral area, and hazard rescue efforts (Wang et al. 2014).

Third, the development of snow hazards in the pastoral areas usually has a time lag with the event of snow accumulation. In this study, four grades of snow hazards inferred from remotely sensed data were analyzed between previous October and April. However, for the records of historical snow hazards in the database built this study, we did not have the accurate time that the snow hazards happened within a specific year. Besides time mismatch, there was also mismatch in space. The sizes of the areas impacted by snow hazards usually change from hundreds to thousands of square kilometers, and the area of a snow hazard can cover one or multiple of counties. However, in order to analyze the frequencies of the four grades of snow hazards at county scale and conduct comparisons with ground-recorded historical snow hazards, we aggregated snow conditions derived from remotely sensed data from pixel to county scales. Thus, snow hazards predicted using the aggregated data at county scale were different from those at their natural scales. The mismatches in time and space may cause the discrepancy between the grades of snow hazards inferred from remotely sensed data and the grades of snow hazards recorded in the database.

Our primary focus in this study was on the white snow hazards, defined as significant accumulation of snowfall and abnormally large livestock mortality, which is the most serious type of climate hazards in winter and spring seasons of the Tibetan Plateau. However, there are many other harsh winter conditions, such as no accumulated snow, strong wind and heavy snow, extremely cold temperature, and impenetrable ice cover over pastures. These severe physical conditions could cause great loss of animals in the study area. In the future, we need to conduct further studies to mapping and predicting these types of natural hazards for the purpose of mitigating negative impacts of these hazards in the context of climate change. Moreover, we also need to strengthen the data collection methods and obtain more cases of historical snow hazards with accurate information about livestock losses and other related information, which can be used to validate the grades of snow hazards predicted by the method developed in this study. In conclusion, although there are several limitations of the method relying on remote sensing data for fast mapping of multiple grades of snow hazards in the pastoral and semi-pastoral areas of the Tibetan Plateau, the results of this study have demonstrated that the new method developed in this study was useful and practical for improving our understanding and ability to model, predict, and mitigate the negative impacts of snow hazards happened in the highest pastoral areas of the world.

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