

Postprint: Current Status and Future Key Scientific Questions of Natural Hazards on the Qinghai-Tibet Plateau

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Abstract

The Tibetan Plateau, characterized by intense tectonic uplift, complex topography and landforms, and a sensitive and variable climate, constitutes a high-incidence region for disasters including earthquakes, debris flows, collapses, landslides, glacial lake outbursts, mountain torrents, snow disasters, droughts, and frost heave and thaw settlement. Influenced by regional geological structure, topographic conditions, hydrometeorological conditions, and human activities, the spatial distribution of natural disasters on the Tibetan Plateau demonstrates characteristics of dense clustering along fault structural belts, banded distribution along deeply incised high mountain-canyon regions, zonal distribution, and concentrated occurrence in areas of high-intensity human activity. Disaster activities are characterized by high intensity and high frequency, sudden onset, seasonality, quasi-periodicity, clustering, and chain-reaction effects. Against the backdrop of climate warming and active crustal movement, the hazard level of natural disasters on the Tibetan Plateau is progressively intensifying, while disaster risks continue to escalate with increasing population size and socio-economic development. Furthermore, it analyzes the current problems faced in disaster formation mechanisms, disaster prevention and control, and risk management of natural disasters on the Tibetan Plateau, and on this basis proposes key scientific and technological issues requiring future attention and corresponding research directions, including regional patterns of disaster-causing factor variations and disaster development, dynamic processes and catastrophe mechanisms of natural disasters, evolution patterns of catastrophic disasters under the coupling effects of climate change and seismic activity, risk assessment and risk management of natural disasters on the Tibetan Plateau, and key technologies for monitoring, early warning, prevention, and control adapted to the characteristics of alpine cold regions.

Full Text

Preamble

The Tibetan Plateau experiences intense tectonic uplift, complex topography, and sensitive, variable climate conditions, making it a region highly prone to natural hazards including earthquakes, debris flows, rockfalls, landslides, glacial lake outbursts, flash floods, snow disasters, droughts, and freeze-thaw subsidence. Influenced by regional geological structures, terrain conditions, hydro-meteorological factors, and human activities, the distribution of natural hazards on the plateau exhibits four distinct characteristics: dense distribution along fault zones, banded distribution along deeply incised alpine valleys, zonal distribution patterns, and concentrated distribution in areas of intensive human activity. Hazard events display features of high intensity and frequency, sudden onset, seasonality, quasi-periodicity, clustered occurrence, and chain reactions. Against the backdrop of climate warming and active crustal movement, the hazard risk in the Tibetan Plateau is gradually intensifying, and disaster risk will continue to increase with growing population and socioeconomic development. This paper analyzes current challenges in disaster formation mechanisms, prevention, and risk management for natural hazards on the Tibetan Plateau, and proposes future scientific and technological priorities including: changes in disaster-forming factors and regional patterns of hazard development, dynamic processes and catastrophic mechanisms of natural hazards, evolution of mega-disasters under coupled climate change and seismic activity, risk assessment and management of natural hazards on the Tibetan Plateau, and key technologies for monitoring, early warning, and prevention suitable for alpine environments.

Keywords: Tibetan Plateau, natural hazards, disaster risk, climate change, tectonic activities

The Tibetan Plateau represents the region with the world's greatest elevation difference, most intense tectonic uplift and seismic activity, and most significant climate change impacts. Its natural conditions favor hazard development, with disasters characterized by large quantities, great magnitudes, and frequent formation of disaster chains that cause catastrophic damage with severe regional economic impacts. Simultaneously, this region is an alpine border area with relatively backward economy, high poverty rates, and strategic importance for China. The widespread and frequently occurring natural hazards exert enormous impacts on society, economy, politics, and national defense.

To support socioeconomic development, political stability, and national defense security, China has launched a series of infrastructure construction, ecological protection, and livelihood projects on the Tibetan Plateau. In transportation, the planned projects include the Sichuan-Tibet and Yunnan-Tibet railways, Sichuan-Tibet expressway, and South Asian land ring corridor. In commerce and tourism, development plans rely on the Zhangmu, Gyirong, Burang, and Yadong ports to expand the Bangladesh-China-India-Myanmar Economic Corridor and implement Belt and Road construction in the southern Himalayas. In

hydropower development, plans include constructing cascade hydropower bases on the transboundary Yarlung Tsangpo River' s middle and lower reaches, with total installed capacity exceeding 80 million kW. In national defense and border security planning, proposals include strengthening border residents' living facilities and targeted poverty alleviation. In mountainous town and village development, plans involve developing debris flow alluvial fans to alleviate land shortage for urban construction. Meanwhile, large-scale ecological protection projects are being advanced across the plateau and river source areas. All these major projects and livelihood initiatives are constrained by regional natural hazards, making hazard investigation and prevention on the Tibetan Plateau strategically important.

Types and Distribution of Natural Hazards on the Tibetan Plateau

Main Types of Natural Hazards

The Tibetan Plateau features well-developed fault structures, strong neotectonic activity, complex and variable lithology, intense weathering and erosion, and broken rock masses with strong water vapor exchange, providing excellent conditions for hazard formation. Hazard types mainly include earthquakes, debris flows, rockfalls, landslides, glacial lake outbursts, flash floods, snow disasters, droughts, and freeze-thaw subsidence. Natural hazards on the Tibetan Plateau are widespread and numerous, with specific distributions shown in Figure 1 [Figure 1: see original paper].

Distribution Characteristics

Influenced by regional tectonic activity, topography, hydrothermal conditions, and human activities, natural hazards on the Tibetan Plateau exhibit four distribution characteristics.

Along Fault Zones The Tibetan Plateau experiences active crustal movement and strong surface uplift, with most earthquakes above magnitude 6.0 in mainland China concentrated in this region. Seismic activity is distributed in bands along the east-west arcuate structures, densely concentrated in the Himalayan plate boundary tectonic belt and within intraplate fault-block regions and their secondary block boundary active tectonic belts. Rock masses in fault zones are broken with well-developed fractures, facilitating the formation of secondary hazards such as rockfalls and landslides while providing abundant loose solid material for debris flows. Particularly earthquakes with intensity greater than VIII can easily trigger secondary mountain hazards. For example, the 1950 Zayü earthquake (MS=8.6) and the 2008 Wenchuan earthquake (MS=8.0) triggered dense distributions of secondary rockfalls, landslides, and debris flows along fault zones. The Wenchuan earthquake area alone experienced over 2,300 landslides and rockfalls during the co-seismic period.

Along Deeply Incised Alpine Valleys In alpine valley regions, strong river downcutting creates steep terrain with large elevation differences and favorable potential energy conditions, making rocks and soils prone to instability and sliding that induce rockfalls and landslides. The topographic lifting effect in alpine valleys causes frequent local rainstorms, providing favorable conditions for debris flow and flood development. Therefore, alpine valleys possess the most favorable combination of hazard-forming conditions, resulting in banded hazard distribution along river valleys. For example, the Sichuan-Tibet Highway passes through the famous Hengduan Mountains alpine valley region and the Parlung Tsangpo River basin, where mountain hazards are extremely well-developed and constitute the main disasters affecting transportation.

Zonal Distribution (1) Horizontal Zonality. Influenced by the Indian Ocean monsoon, the Tibetan Plateau receives abundant rainfall from May to September each year, concentrating 80% of annual precipitation. Due to uneven water vapor distribution across the region, large-area droughts and floods frequently occur. Droughts mainly distribute across most of Nagqu region's southern area centered on Lhasa, Shigatse region, and Shannan region, as well as northeastern Qinghai, western Sichuan plateau, and the vast area at the junction of northeastern Tibet and Qinghai. Flood disasters mainly occur in the eastern Kunlun Mountains section, Qilian region, western Karakoram section, and parts of the plateau's southeastern margin, followed by the southern Tibetan valley. Large-scale snow disasters mainly occur in areas with the most significant interannual snow cover fluctuations in the eastern plateau, with two snow disaster high-incidence centers: one near the Himalayan region in Shannan, Tibet, especially Zhongba, Saga, Gyirong, Nyalam, and Tingri counties, which experience 1-2 snow disasters annually on average and represent China's highest snow disaster frequency area; the other located at the junction of southern Qinghai and northwestern Sichuan, most severely affecting Madoi and Chindu counties in Qinghai and Shiqu County in Sichuan.

(2) Vertical Zonality. At the southeastern and southern margins of the Tibetan Plateau, huge topographic elevation differences create obvious vertical natural zones. Hazard-forming conditions, particularly hydrothermal conditions, exhibit vertical zonation characteristics, leading to vertical zonation in mountain hazard development and distribution. Taking the Parlung Tsangpo River basin as an example, near the snow line at 4,500-4,700 m elevation, active glaciers form numerous glacial lakes and glacial meltwater-supplied glacial debris flows are concentrated. In valleys below 3,500 m elevation, rainstorm-supplied debris flows mainly develop. Landslide distribution shows similar patterns: in high-altitude mountain areas, freeze-thaw type landslides mainly develop under freeze-thaw action influence, while in lower-altitude valley areas, rainfall-induced landslides predominantly occur.

Concentrated Distribution in High-Intensity Human Activity Areas With population growth and increasing engineering projects, human activities'

triggering effects on slope deformation disasters are strengthening. In plateau mountain areas, large-scale slope excavation, waste dumping, and filling during highway, railway, hydropower, mining, and urban construction often cause slope instability and alter hydrological conditions, leading to landslides and debris flows. For example, along the Sichuan-Tibet Highway (both southern and northern routes), over 1,000 debris flow gullies have formed disasters, mainly distributed in the Hengduan Mountains area east of Boshula Ridge and in the southeastern Tibet region.

Activity Characteristics and Impacts of Natural Hazards on the Tibetan Plateau

Natural hazards on the Tibetan Plateau generally exhibit characteristics of high intensity and frequency, sudden onset, seasonality, periodicity, clustered occurrence, and chain reactions.

High Intensity and Frequency

The Tibetan Plateau is China's region with the most intense modern tectonic and seismic activity. Since seismic records began, the plateau has recorded as many as 18 earthquakes above magnitude 8 and over 100 earthquakes of magnitude 7-7.9. In the past 50 years, over 40 earthquakes above magnitude 7 have occurred, with the highest historical magnitude reaching 8.6 (the 1950 Zayü earthquake). Additionally, high-intensity earthquakes frequently occur around the plateau, causing casualties and socioeconomic losses. For example, at 14:11 on April 25, 2015, a magnitude 8.1 earthquake occurred in Nepal on the southern slope of the Himalayas, with a focal depth of 20 km. Within one week, the earthquake caused 26 deaths, 3 missing persons, and 856 injuries in China's Tibet Autonomous Region; numerous houses collapsed or were damaged, and lifeline projects such as roads and communications as well as water conservancy infrastructure were severely damaged (Figure 2a [Figure 2: see original paper]).

Sudden Onset

Under the influence of seismic activity and extreme climate, glacial lake outbursts, ice and snow avalanches, debris flows, rockfalls, landslides, and other natural hazard processes on the plateau exhibit sudden onset characteristics. Taking debris flows as an example, their sudden onset is manifested in abrupt outbreak and short duration—a single debris flow event generally lasts only several minutes to several tens of minutes, with flow velocities in the channel reaching over 30 m/s. This sudden onset makes accurate forecasting and early warning difficult, preventing effective prevention. For instance, on July 14, 1987, due to glacier surging, approximately 3.6×10^6 m³ of ice mass detached from the glacier tongue and slid into Guangxie Co in Midui Gully, causing the lake level to rise by an average of 1.4 m and generating surge waves that led to sudden moraine dam failure. The lake drained in only 2 hours, with floodwaters

eroding loose solid materials along the path and transforming into dilute debris flows. Without sufficient time for effective prevention, the debris flow swept away Midui Village in the gully, destroyed large areas of farmland, and simultaneously destroyed 27 km of Sichuan-Tibet Highway embankment downstream.

Seasonality

The outbreak of debris flows, landslides, floods, and other natural hazards is mainly triggered by continuous rainfall, rainstorms, and especially extreme rainstorms. Therefore, hazard occurrence timing coincides with concentrated rainfall periods, showing obvious seasonality. Debris flows and landslides mostly occur from June to September each year, with statistics showing that debris flow disasters occurring during these four months account for over 90% of all debris flow disasters in the region.

From the perspective of snow disaster seasons, they mainly concentrate in winter, predominantly from November to February of the following year, though some years see snow disasters lasting until May or even June of the following year. Large snow disasters spanning years are generally extreme snow disasters. For example, from May 25 to June 1, 2009, Nagqu region experienced large-area snowfall with average snow thickness of 10 cm and maximum thickness of 50 cm, causing 58,857 livestock deaths (Figure 2b [Figure 2: see original paper]).

Based on occurrence timing, drought disasters on the Tibetan Plateau can be divided into spring drought and summer drought. Spring drought mainly results from low precipitation during March-May, strong solar radiation, high winds, and strong evaporation. Summer drought generally occurs during June-August each year, mainly caused by delayed rainy season onset or intermittent droughts during the rainy season.

Quasi-Periodicity

Affected by temperature changes, the active layer thickness of permafrost and the area of seasonal frozen soil on the Tibetan Plateau also show strong seasonal characteristics. Due to influences from earthquakes, seismically affected solid materials, and climate fluctuations (temperature and precipitation), landslide and debris flow activities exhibit fluctuation and certain periodicity. When extreme climate and seismic activity are superimposed, they often form peak periods of debris flow and landslide activity. For example, after its first occurrence in 1953, Guxiang Gully debris flow has occurred over 50 subsequent times, repeatedly blocking National Highway 318 and burying vehicles (Figure 2c [Figure 2: see original paper]).

Statistical results show that snow disasters on the Tibetan Plateau follow an activity pattern with approximately 3-year cycles. For example, in northern Tibet, periodic snow disasters occurred continuously during 1985-1986, 1988-1989, 1992-1993, and 1995-1996.

For seismic disasters, since the 20th century, magnitude 7+ earthquake activity in northern Tibet can be divided into three stages: 1920-1962 with relatively short intervals averaging one earthquake every 6 years; 1963-2000 with longer intervals averaging one every 13 years; and 2001-2012 with only two magnitude 7+ earthquakes occurring at 8.5-year intervals due to the short time period.

Clustered Occurrence

The Tibetan Plateau has good hazard-forming conditions and high hazard susceptibility. Under the same triggering factors (such as rainfall), numerous disasters often occur simultaneously across large areas, particularly debris flow, rock-fall, and landslide activities showing obvious clustered occurrence. For example, in 1979, over 40 gullies simultaneously erupted debris flows in five counties of northwestern Yunnan's Nujiang Prefecture (Lushui, Lushui, Fugong, Gongshan, and Bijiang), forming the most numerous and severe clustered debris flow disaster in nearly 30 years.

Hazard Chaining

Due to topographic constraints, different hazard types can mutually trigger and transform under certain conditions, forming disaster chains that extend disasters temporally and spatially. For example, the Yigong landslide that occurred in Bomi County, Tibet on April 9, 2000 was a typical landslide→dammed lake→outburst flood→debris flow disaster chain event (Figure 2d [Figure 2: see original paper]), causing 30 deaths, over 100 missing persons, 50,000 homeless people, and destruction of more than 20 bridges in downstream India.

Development Trends and Disaster Risk on the Tibetan Plateau

Climate Warming and Crustal Activity Intensifying Hazard Risk

Over the past 50+ years, the frequency of extreme temperatures (extreme high and low temperatures) and extreme precipitation events on the Tibetan Plateau has shown varying degrees of increase. In the next 100 years, the plateau's temperature and precipitation will show a basic trend of continued increase. With climate warming, the permafrost active layer on the Tibetan Plateau is thickening annually, while the permafrost table temperature is also rising at a rate of approximately 0.3°C per decade, causing severe permafrost degradation in some areas. In alpine valley regions, high temperatures accelerate ice and snow melting, increasing surface runoff and enhancing the probability of superimposed ice-snow meltwater and high-intensity rainfall, altering local hydrological conditions and making loose soil (moraine) more susceptible to failure and glacial lake outbursts, forming mountain hazards. Additionally, research shows that since instrumental earthquake recording began in 1900, the Tibetan Plateau has experienced three clustered high tides of seismic activity: 1920-1937, 1947-1976, and 1955-present. Influenced by the global high tide of seismic activity,

the Tibetan Plateau, particularly the Bayan Har fault block, southern Tibetan Plateau region, and middle-southern section of the north-south belt, is likely to experience earthquakes above magnitude 7 in the coming period. Overall, the future hazard risk (H) on the Tibetan Plateau tends to increase.

Population and Economic Growth Increasing Disaster Risk

According to the 2012 Tibet Autonomous Region Statistical Yearbook, the total population of Tibet showed a continuous growth trend from 1951-2007, more than doubling to 2.7359 million by the end of 2007. Over the past 50 years, the region's GDP has shown stable growth. Since reform and opening up, especially since the Third and Fourth Central Tibet Work Forums, economic development in the Tibet Autonomous Region has accelerated more rapidly, with the region's GDP reaching 34.219 billion yuan in 2007. Due to spatial overlap between high-density population/economic zones and high-hazard-risk zones, the larger the economy and population as hazard-bearing bodies, the greater the loss probability once affected by disasters—that is, the greater the vulnerability (V). Therefore, future disaster risk (R) on the Tibetan Plateau will significantly increase with rising hazard risk (H) and vulnerability (V) (Figure 3 [Figure 3: see original paper]).

Challenges in Disaster Prevention and Mitigation on the Tibetan Plateau

Due to the plateau's vast area, insufficient financial resources, and lack of technological capacity, disaster mitigation capabilities are very weak and far from meeting the needs posed by widespread, severely damaging, and increasingly risky natural hazards. Current disaster prevention challenges mainly include five aspects:

1. **Complex hazard-forming environments and disaster processes with insufficient understanding of physical mechanisms.** Under the influence of plate tectonic movement and extreme climate, particularly frequent earthquakes in southeastern Tibet and the Himalayas, freeze-thaw action and dry-wet cycles intensify, with frequent meteorological and seismic disasters. Natural hazards including rockfalls, landslides, debris flows, glacial lake outbursts, and floods driven by earthquakes and extreme climate have complex causes. Currently, there is a lack of clear understanding and quantitative description of their physical processes, making effective disaster prediction difficult.
2. **Difficulty in preventing low-frequency, large-scale disasters.** Low-frequency, large-scale debris flows, glacial lake outbursts, and landslides are difficult to engineer against, while water sources for induced disasters include rainstorms, ice-snow meltwater, and glacial lake outbursts, making early warning indicators difficult to determine and resulting in low accuracy of non-engineering monitoring and early warning.

3. **Shortage of emergency disaster prevention technologies for large-scale events.** Since large-scale disasters develop across thousands of kilometers of mountainous areas, disaster investigation, identification, and treatment technologies cannot meet the requirements of accurate and rapid emergency response.
4. **Disaster prevention and mitigation theoretical research still cannot meet practical needs.** Natural hazards on the Tibetan Plateau are characterized by extremely large scale, sudden outbreak, and wide impact range. Research on debris flows, landslides, glacial lake outbursts, and other disasters is closely linked to regional strong earthquakes and climate change, and associated with regional crustal uplift and surface erosion processes. Therefore, there is an urgent need to strengthen research on natural hazard formation mechanisms and develop new disaster prevention models based on mechanisms and processes to support disaster reduction.
5. **Lack of comprehensive basic data and systematic planning for disaster reduction.** Due to the lack of professional technical forces on the Tibetan Plateau, different disasters are managed by different departments. To date, no systematic and comprehensive natural hazard survey has been conducted for the entire Tibet Autonomous Region. The lack of basic hazard data has prevented the formulation of a regional disaster prevention and mitigation plan, seriously affecting strategic deployment of disaster reduction in the autonomous region.

Future Scientific and Technological Priorities for Disaster Prevention and Mitigation

Key Scientific and Technological Issues Requiring Attention

Given the characteristics of current natural hazards on the Tibetan Plateau, existing challenges in regional disaster prevention and mitigation, and future risks, the following scientific and technological issues should be prioritized:

1. Changes in disaster-forming factors and regional patterns of hazard development
2. Dynamic processes and catastrophic mechanisms of natural hazards
3. Evolution of mega-disasters under coupled climate change and seismic activity
4. Risk assessment and management of natural hazards on the Tibetan Plateau
5. Key technologies for monitoring, early warning, and prevention suitable for alpine environments

Future Work

Addressing these scientific and technological issues requires future efforts in the following aspects:

1. **Systematically investigate natural hazards on the Tibetan Plateau and establish a basic database.** Conduct comprehensive and systematic investigations of natural hazards on the Tibetan Plateau, documenting major historical hazard types and improving attribute characteristics including disaster scale, frequency, causes, and properties. Supplement basic data on hazard-forming environments (hydrology, ecology, climate, geology, topography, socioeconomic conditions, etc.) and multi-source, multi-resolution remote sensing data (optical, InSAR, LiDAR) to establish a relatively complete basic database for natural hazards on the Tibetan Plateau.
2. **Analyze hazard-forming environments and their changing characteristics.** Analyze soil lithology, geological structure, topography, climate and meteorology, hydrology, ecology, and other hazard-forming conditions for different types of natural hazards on the Tibetan Plateau, identify key disaster-causing factors, and reveal the status and changing trends of hazard-forming environments for different disaster types.
3. **Reveal catastrophic mechanisms and hazard development trends.** Analyze temporal and spatial distribution characteristics and activity features of different natural hazard types on the Tibetan Plateau, consider impacts of extreme climate change and super-strong seismic activity on hazard development, construct disaster catastrophe mechanism models co-driven by endogenic forces (tectonic movement) and exogenic forces (climate change), and estimate hazard development trends considering socioeconomic development and engineering disturbance.
4. **Conduct disaster risk analysis and assess mitigation needs.** Based on the aforementioned investigation work, analyze future risks of different natural hazard types on the Tibetan Plateau, response capabilities, and adaptability, and propose future disaster reduction needs in combination with regional socioeconomic and national defense development requirements.
5. **Strengthen natural hazard monitoring and early warning.** Establish integrated “space-air-ground” natural hazard monitoring technology and networks to obtain regional-scale observation data. Conduct long-term monitoring of major and potential hazards, and deploy monitoring networks in typical hazard-dense areas to comprehensively monitor surface data (subsidence deformation, plate displacement, meteorology, soil moisture, etc.).
6. **Improve disaster prevention and treatment technologies.** Understand the current status of natural hazard prevention technologies on the Tibetan Plateau, summarize disaster reduction models, technologies, and experiences, analyze existing technological deficiencies, improve methods for determining engineering design parameters for disaster prevention, develop optimized design technologies for disaster treatment suitable for

alpine environments, and improve disaster treatment effectiveness.

The Tibetan Plateau features diverse natural hazard types, widespread distribution, frequent activity, and severe impacts, posing significant threats to local socioeconomic development and human life safety. Due to the lack of precise survey and observation data, quantitative understanding of disaster mechanisms is relatively insufficient for different hazard types in the Tibetan Plateau. Additionally, there is a need to develop disaster reduction technologies suitable for the plateau's special environmental conditions. It is recommended that during the second comprehensive scientific expedition to the Tibetan Plateau, in addition to systematically obtaining basic data and studying disaster mechanisms and processes, attention should also be paid to analyzing current disaster reduction technology capabilities and achieved disaster reduction accomplishments and experiences. Considering the hazard-forming characteristics, activity patterns, development trends, and future risks of natural hazards, along with regional socioeconomic development goals and national major project and defense needs, future disaster reduction needs should be analyzed and determined, and disaster reduction countermeasures proposed.

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Note: Figure translations are in progress. See original paper for figures.

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