Spatiotemporal Changes of Hazard Intensity-Adjusted Population Exposure to Multiple Hazards in Tibet During 1982–2015

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Abstract The dynamic changes of population exposure to hazards in high-altitude areas are an important factor in the scientific evaluation of environmental risks. In this study, the hazards of hypoxia, earthquakes, and snowstorms in Tibet were respectively described by the percentage of oxygen at sea level, earthquake intensity, and mean annual maximum snow depth. The rates of population affected by hypoxia, earthquakes, and snowstorms were calculated by chronic mountain sickness and historical disaster data. Based on these, the study examined the change in population exposure to the three hazards and their combinations by hazard intensity level at the 1 km × 1 km grid scale in 1982–2015. The results show that population exposures to hypoxia, earthquakes, and snowstorms were about 745 thousand, 97 thousand, and 168 thousand in 2015, respectively, among a total population in Tibet of 3.24 million. These exposures were mainly concentrated in the 3400–5000 m above sea level zone. The population exposed to hypoxia and earthquakes showed a rising trend from 1982 to 2015, while the population exposed to

snowstorms decreased after 2000 due to reduced snow-storm intensity. Hypoxia-earthquake and hypoxia-snow-storm are the main multiple hazard combinations that people in Tibet suffered from and their person-time exposures were estimated at around 842 thousand and 913 thousand in 2015, respectively, with an average annual increase of 1.7% and 1.3%. Hypoxia is the most important health risk in Tibet. The areas of high person-time exposure to multiple hazards of hypoxia-earthquake-snowstorm are the key areas for strengthening integrated risk governance.

Keywords Earthquake · High altitude · Hypoxia
Population exposure · Snowstorm · Tibet

1 Introduction

Areas above 2500 m above sea level (masl) are considered high-altitude areas (Niermeyer et al. 2001; Bigham and Lee 2014; Barton 2016). They cover an area of 5.15 million km² and account for 3.8% of the global land area (excluding Antarctica). In 2015, the population living in high-altitude areas exceeded 107 million and accounted for 1.5% of the world's total population (7.35 billion) (USGS 2011; NASA 2016). With low-pressure hypoxia, high UV radiation, and a sensitive response to global climate change, high-altitude environments affect human survival in major ways (Aldenderfer 2006). Natural hazards that occur in areas of hypoxia have even greater impacts on the safety and health of the population of these regions than they have in other regions. With global warming and the expansion of human activities, the number of people living in high-altitude areas has increased and they are at greater health risks. Thus, the health risk governance of

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environmental and natural hazards in these areas has raised great concern in academia (Chan and Shi 2017).

Elevated altitude leads to lower oxygen levels, and causes increasing hemoglobin concentration (León-Velarde et al. 2000). Oxygen content at an altitude of 4000 masl is only about 60% of the oxygen content at sea level, and the proportion of oxygen entering the blood circulation in the human body is lower, which hinders effective body metabolic reactions (Beall 2007). The effects of a hypoxic environment on human health mainly include acute mountain sickness (AMS) and chronic mountain sickness (CMS) (Roach et al. 1998; Karinen et al. 2010; West 2014). Acute mountain sickness mainly affects recently arrived people who have not adapted to the environment and leads to headaches, nausea, vomiting, and insomnia (Johnson and Rock 1988), and even fatal symptoms of pulmonary edema and cerebral edema (Hackett et al. 1976). Chronic mountain sickness mainly affects people who have lived in a high-altitude area for a long time and causes high blood pressure and related complications (Yue et al. 2017), such as polycythemia (Reeves and Leon-Velarde 2004) and cognitive dysfunction (West 2017). The hypoxic environment also leads to increased oxidative stress, causing other damages to human health (Jefferson et al. 2004). In addition to the studies on the effects of hypoxia on human health, there are many studies on the adaptability of human behavior (Pawson 1976; Aldenderfer 2006; Barton 2016) and the genetic adaptation to hypoxic environments (Yi et al. 2010; Bigham and Lee 2014). However, few comprehensive studies have focused on the relationship between altitude, oxygen content, and population exposure.

Risk is determined by the interaction of exposure, vulnerability, and hazard (IPCC 2014). The common definition of exposure is the area and number of hazard-affected bodies (IPCC 2012). Exposure is the situation of people, infrastructure, housing, production capacities, and other tangible human assets located in hazard-prone areas (UNGA 2016) or the intersection of potential hazard-affected bodies and a hazard in an area (Shi et al. 2014). These definitions may lead to an overestimation of population exposure, by taking into account people who will never be affected by a certain intensity hazard despite living in hazard-prone areas. For example, buildings designed with a seismic fortification against intensity VII earthquakes are resistant to seismic activities with intensities less than VII (Zhang and Jin 2008). In this study, we considered population exposure as the people who actually will be affected in hazard-prone areas instead of the entire population of these areas. To calculate this, we collected historical records of the population affected by natural hazards and derived the population affected rate for each hazard to obtain the actual exposure of the population.

We selected Tibet as the study area for its combination of an extremely hypoxic environment, frequent natural disasters, and dramatic population changes. Tibet is located at the “third pole” of the world, with an average altitude of above 4000 masl, and is an extremely hypoxic region. Studies show that Tibetans have a higher risk of hypertension caused by CMS than people in other high-altitude areas (Wu and Kayser 2006). The CMS risk of the Han population moving into Tibet increased linearly with altitude (Li et al. 2012) and its average prevalence was 5.6%, much higher than the 0.91–1.2% for Tibetans (Sahota and Panwar 2013). According to the 2010 Census,¹ the average life expectancy of Tibetans is 68.17 years, 6.66 years lower than the Chinese average, and this is associated with hypoxia. At the same time, there are many kinds of natural hazards in Tibet, including earthquakes and snowstorms. Research of earthquakes mainly focused on fault activities, earthquake formation mechanisms, and earthquake intensities (Ni and Barazangi 1983; Tilmann et al. 2003). Research on snowstorm disasters mainly focused on the intensity, frequency, forecast, and risk assessment of snowstorms (Wu and Yan 2002; Wang et al. 2013). Most such studies in Tibet focused on hazards or damages, but fewer considered the exposure and vulnerability of hazard-affected bodies. With the rapid economic and social developments in Tibet, the permanent population increased by 1.38 million from 1982 to 2015, with a growth rate of 73.8% (Tibet Autonomous Region Bureau of Statistics and Tibet General Team of Investigation under the NBS 2016). In addition, a large number of temporary migrants have also moved to Tibet in recent decades (Cooke 2003; Fan et al. 2010). The proportion of the urban population increased from 9.5 to 27.7% from 1982 to 2015 (Tibet Autonomous Region Bureau of Statistics and Tibet General Team of Investigation under the NBS 2016), which led to significant changes in the spatial distribution of the population. The annual number of tourists also increased from 18 thousand to almost 20.12 million between 1982 and 2015 (Tibet Autonomous Region Bureau of Statistics and Tibet General Team of Investigation under the NBS 2016). The combination of changing numbers, spatial distribution, and mobility of population led to dynamic changes of population exposure to natural hazards in Tibet. Thus, exploring the relationship between natural hazards, altitude, and population exposure is particularly important.

The purpose of this study was to explore the changes in population exposure to hypoxia, earthquakes, and snowstorms and any of their combinations at the grid scale and by different hazard intensities in this high-altitude environment during 1982–2015. The study adopted a refined approach by excluding people who are well protected from

¹ <http://www.stats.gov.cn/tjsj/pcsj/rkpc/6rp/indexch.htm>.

specific intensities of hazards. Based on the characteristics of high altitude in Tibet, this study considered hypoxia as a unique environmental hazard. We then assessed the population exposure at different altitudes to reveal the spatial difference of exposure, using the population data for 1982, 1990, 2000, 2010, and 2015. The following sections introduce the indicators and calculation methods of population and exposure; provide the population exposure results for each hazard and multiple hazards; and conclude with a discussion of the results.

2 Data and Methods

The basic data of this study are environmental data (digital elevation model, DEM), hazard and disaster data (earthquakes, snowstorms), population data (grid, census, and

residential location data), and land cover and administrative boundaries (Table 1).

Population exposure at the 1 km × 1 km grid scale in this high-altitude environment during 1982–2015 was derived using a refined estimation method based on total population, population affected rate, and hazard intensities. Variables used to calculate the population affected rate included elevation and earthquake and snowstorm intensities. Data processing for deriving the variable values and calculation of population exposure are detailed as follows.

Elevation Elevation is expressed by the 1 km × 1 km DEM. According to the “Sturges rule” (Sturges 1926), we divided elevation into 30 groups with equal intervals between 0 and 6000 masl (there is no permanent population above 6000 masl). Because most of the area and the population are mainly distributed between 2000 and 6000 masl, the results within this elevation range were analyzed emphatically.

Table 1 Basic data for studying hazard exposure in Tibet, 1982–2015

Type	Name	Specification	Source
Environmental data	China DEM Spatial Distribution Data	Raster, 1 km × 1 km	Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC), http://www.resdc.cn/data.aspx?DATAID=123
Hazard data	Seismic Ground Motion Parameter Zonation (SGMPZ) Map	Vector, 1:40,000,000	National standard: GB18306-2015 General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China 2015
	Epicenter distribution of the Ms > 4.0 earthquakes over the Qinghai-Tibet Plateau in 1949–2015	Vector	China Earthquake Administration (internal document)
	Long-term snow depth dataset of China (1978–2016)	Raster, 25 km × 25 km	Cold and Arid Regions Science Data Center (Che and Dai 2011)
Disaster data	Seismic disaster data of Tibet Plateau in 1990–2010	Table records	China Earthquake Disaster Loss Assessment Report Compilation (1990–2010) (internal document); National Disaster Reduction Center database, Ministry of Civil Affairs (internal document); Review of Earthquake Damage Losses in Mainland China in 2015 (Chen and Zheng 2016)
	Snow disaster data of Tibet in 1949–2002	Text records	China Meteorological Disaster Compilation (Tibet volume) (Wen and Liu 2008)
Population data	1995 1 km-grid population spatial distribution	Raster, 1 km × 1 km	Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC), http://www.resdc.cn/data.aspx?DATAID=114
	1982, 1990, 2000, 2010 census data; 2015 township population data	Table records, Township scale	Population Census Office under the State Council, National Bureau of Statistics of the People's Republic of China; China Statistical Yearbook (Township) (Rural Social and Economic Investigation Division of NBS 2016)
Other data	Residential location data	Vector	http://bbs.godeyes.cn/showtopic-383004-1.aspx#474862
	GlobeLand30 land cover data	Raster, 30 m × 30 m	http://www.globallandcover.com/GLC30Download/index.aspx (Chen et al. 2014)
	Tibet township administrative boundary	Vector	Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC), http://www.resdc.cn/data.aspx?DATAID=203

Hazards See Fig. 1. Hypoxia is expressed as a percentage of oxygen content relative to the content at sea level. Seismic hazard is expressed by seismic intensity, which was converted from seismic peak ground acceleration (pga) (National standard: GB18306-2015) and then transformed into 1 km $\times$ 1 km grid data. Snowstorms are expressed by average annual maximum snow depth. The snow depth data were divided into five periods: 1978–1982, 1983–1990, 1991–2000, 2001–2010, and 2011–2016, corresponding to the population data in 1982, 1990, 2000, 2010, and 2015.

Population Population data with high spatial resolution (1 km $\times$ 1 km) were the basis of this study. The method for distributing township level population statistical data generated by the census into grid cells—rasterizing the population data—can be divided into three steps.

- (1) In the first step, because the population of Tibetan townships and villages is low and the spatial span of these settlements is much smaller than the 1 km $\times$ 1 km grid size, we divided populated areas into sparsely populated areas and densely populated areas. Sparsely populated areas include town and village settlements,

which are considered as point distributions. Their locations were obtained from the population grid data of 1995 (representing 1982, 1990, and 2000 settlement locations) and the residential location data of 2012 (representing 2010 and 2015 settlement locations). The population of densely populated areas was treated as planar distribution and the areas were delineated by the construction land (refers to built-up area in the dataset) on the land cover map.

- (2) In the second step, we calculated the weights of the populations of sparsely and densely populated areas separately and integrated them in each cell by using the rural–urban ratio of Tibet. The weights of the populations in village and town settlements in a sparsely populated area also differ. We assumed that the same number of people lives in each house; then, using Google Earth to identify the number of houses in 30 randomly selected townships, we found that the number of houses—and thus people—is roughly 1:3 for a village and a town within township administrative areas, so this ratio was applied to derive their population weights. Population weight in densely

Fig. 1 Intensity of hypoxia, earthquakes, and snowstorms in Tibet

populated areas was calculated by the proportion of construction land area in each 1 km × 1 km grid. For 2000 and 2010, this proportion was directly calculated by using the 30 m resolution land use grid data. For 1982, 1990, and 2015, we first estimated the change rate of construction land between the periods by assuming that the change rate of construction land was proportional to the growth rate of the urban population of Tibet. This resulted in the change rate of construction land between 1982 and 1990, 1991–2000, and 2011–2015, and the proportion of construction land of each grid in 1982, 1990, and 2015 was subsequently calculated. Finally, the two kinds of weights are integrated by the urban–rural population ratio of Tibet.

- (3) In the third step, the township population census data were allocated to the grids. The allocation was done using Peduzzi's method (Peduzzi et al. 2012). Further, the population average annual growth rate (AAGR) (Eq. 1) was calculated.

$$r = \left(y_e - y_b \sqrt{\frac{P_e}{P_b}} - 1 \right) \times 100\% \quad (1)$$

where r is the population AAGR from one of the calculation periods, y_e and y_b are the end and beginning years of the calculation period, respectively, and P_e and P_b are the population of the end and beginning years.

Population Exposure This study defines population exposure as the population that may be affected within the range of a hazard for specific hazard intensities. Equation 2 is the calculation formula.

$$E = R \times P \quad (2)$$

where E is the exposed population, R is the population affected rate (PAR) by a hazard, and P is all population in the hazard area.

The PAR is calculated differently depending on the type of hazards. The PAR of hypoxia refers to Li et al.'s (2012) results on the relationship between CMS prevalence (y) and altitude (x). The empirical model is $y = 0.1712x - 0.5867$ (Table 2). The PAR of seismic and snowstorm disasters was obtained through statistical analysis of the historical disaster records.

For the seismic PAR, a total of 45 events of people affected by earthquakes and 24 seismic events that had magnitude records from 1993 to 2015 on the Qinghai-Tibet Plateau were used to regress the magnitude-affected population relationship and magnitude-epicenter intensity relationship, respectively (Table 2). Then we derived the magnitude (upwards rounded up) and the affected people of the 1960 Ms > 4.0 earthquakes in Tibet from 1949 to 2015 by their epicenter intensity records, and the annual

average affected population under each grade of seismic magnitude was obtained. Finally, Eq. 3 was used to calculate the PAR of seismic disasters and the results are shown in Table 3.

$$R_h = \frac{EP_h}{P_h} \quad (3)$$

where R_h is the PAR for the h seismic intensity area, EP_h is the annual average affected population of h grade epicenter intensity earthquakes, and P_h is the population in the h seismic intensity area.

For the PAR of snowstorm disasters, a linear relationship $y = 0.0081x + 0.0098$ was established between average snow depth (x) and the PAR (y) in historical records. A total of 17 snowstorm disaster events from 1956 to 2002 were included in the analysis. The PAR in each historical record was calculated according to Eqs. 4–6.

$$R_s = \frac{EP}{P} \quad (4)$$

where R_s is the PAR of a snowstorm disaster and, EP and P are the affected population and total population in the affected area of a snowstorm disaster, where P is calculated in two ways depending on the type of the affected area record. When the affected area was recorded as total area, Eq. 5 was used. But when the affected area was recorded as the number of townships, because there are no records of which specific townships were affected by the snowstorm, we assumed that the population of each township was the same within the extent of a snowstorm event. Based on this assumption, we used Eq. 6 to estimate the affected population of the snowstorm.

$$P = A_{\text{affected}} \times PD \quad (5)$$

where A_{affected} is the affected area of a snowstorm disaster, and PD is the average population density of the affected counties.

$$P = \frac{TN_{\text{affected}}}{TN_{\text{total}}} \times TP_{\text{total}} \quad (6)$$

where TN_{affected} and TN_{total} are the number of townships affected in a snowstorm disaster and the total number of townships in the affected counties, respectively, and TP_{total} is the total population in the affected counties.

In this study, population exposure was analyzed with regard to spatial and temporal distributions and disaster types. Spatial heterogeneity of population exposure is revealed by type of disasters and by elevation. Temporal variation of population exposure is reflected by changes in population exposure within each hazard intensity range. Four types of hazard combinations—hypoxia-earthquake, hypoxia-snowstorm, earthquake-snowstorm, and hypoxia-earthquake-snowstorm were examined for multiple

Table 2 Results of regression between chronic mountain sickness (CMS) prevalence and altitude; population affected rate (PAR) of snowstorm disasters and average snow depth; and epicenter intensity/affected population and seismic magnitude in Tibet

<i>x</i>	<i>y</i>	Equation	<i>R</i> -square	<i>F</i>	sig	Method	Time period
Altitude (km)	CMS prevalence	$y = 0.1712x - 0.5867$	0.826	491.25	< 0.001	Linear Fitting ^a	2009–2010
Average snow depth (cm)	PAR of snowstorm disasters	$y = 0.0081x + 0.0098$	0.588	21.401	< 0.001	Linear Fitting	1956–2002
Seismic magnitude	Epicenter intensity	$y = 1.1378x + 0.2659$	0.693	49.669	< 0.001	Linear Fitting	1993–2015
Seismic magnitude	Affected population	$y = 1.895e-05x$	0.9635 ^a	1134.7	< 0.001	Robust Fitting Bisquare weights	1993–2015

^aThe *R*-square of robust fitting cannot be compared with least-squares fitting for it is less affected by outliers

^bLi et al.'s (2012)

Table 3 Affected population of earthquakes in Tibet, 2015

Seismic intensity	VI	VII	VIII	IX
Annual average affected population	19,801	25,759	29,140	42,215
2015 population	1,135,708	1,052,083	973,996	57,660
PAR	1.7%	2.4%	3.0%	73.2%

hazards. Because some people will be affected by two or more hazards, but who will exactly be affected by which hazard is unknown, population exposure to multi-hazards is measured by “person-time” rather than population.

3 Results and Analysis

The spatial distributions of single-hazard and multi-hazard population exposures at the 1 km × 1 km grid level in 1982–2015 and their temporal changes are presented and analyzed in this section.

3.1 Spatiotemporal Differentiation of Single-Hazard Population Exposure

Single-hazard population exposure was calculated on a 1 km × 1 km grid scale and then we summed the grid values to a 5 km × 5 km grid scale to better depict the spatial patterns. Figure 2 reveals the spatial distributions of populations exposed to hypoxia, earthquakes, and snowstorms in 2015. Most of the blank areas had no people living there permanently. The population exposed to hypoxia was over 10 in each populated grid except southern Tibet. In the densely populated areas of Shigatse-Lhasa-Nagqu-Qamdo, over 100 people per grid and even more than 1000 people per grid in city areas were exposed

to hypoxia. The population exposed to earthquake hazards was mainly in the northern Lhasa-Nagqu area, with more than 250 people in most of the grids. Some grids in the Shigatse-Lhasa, Nagqu-Qamdo, and Nyingchi areas also showed relatively high exposure with more than 10 people per grid. The population exposed to snowstorms was mainly concentrated in eastern Tibet. The rest were more evenly distributed in the north of Nyingchi, east of Nagqu, and the areas near the Himalayas. In these areas, population exposure to snowstorms was generally above 10 per grid.

The grid-level population exposure in each elevation interval is shown in Fig. 3. The figure indicates the changes of area, total population, and population exposed to the three hazards by altitude. Because the population of Tibet is mainly settled in areas of 3000–6000 masl and the population above 3000 masl starts to suffer from plateau hypoxia, areas below 3000 masl are merged into one section in Fig. 3. The land surface elevation of Tibet is mainly above 4000 masl, while the population is mainly distributed in the elevation range of 3600–3800 masl. Above this, population decreases with the increase in altitude. In areas where the altitude is higher than 5200 masl, the total population is less than 10,000. The total population of all elevation intervals showed an increasing trend through the study period. The fastest growing population occurred in the elevation range of 3600–3800 masl. This corresponds exactly to the altitude of Lhasa and its surrounding areas.

Fig. 2 Spatial distributions of population exposure to single hazards in Tibet: **a** hypoxia, **b** earthquakes, and **c** snowstorms, 2015

Fig. 3 Population exposure to each hazard by elevation range and time period in Tibet

Populations exposed to hypoxia, earthquakes, and snowstorms were all mainly concentrated in the elevation range of 3400–5000 masl. However, due to the difference of the PAR, the distribution and change trend of population exposure with altitude are very different from the total population. In this elevation range, the population exposed to each type of hazard showed the same tendency of increase with the increase in elevation until above 4600–4800 masl. Comparing the population exposure to

the three hazard types, the population exposed to hypoxia was the highest and was concentrated at 4600–5000 masl. The trends over time in population exposure to hypoxia are the same with the total population. Above 3800 masl, the average annual growth rate (AAGR) of the population exposed to hypoxia tended to decrease with time. As a result, the gap between population exposure to hypoxia at all altitudes gradually decreased. Most people exposed to earthquakes were distributed in the area of

4200–4400 masl, with more than 25,000 people in 2015, and at the altitude of 3600–3800 masl and 4400–4800 masl with more than 15,000 people in 2015. The population exposed to earthquakes showed an increasing trend with time, and the growth was relatively consistent at all altitudes and periods. Most populations exposed to snowstorms lived in the area of 4400–4600 masl. Above this area, the exposed population gradually decreased with increasing elevation. Due to the most dynamic changes in snowstorm intensity, the populations exposed to snowstorms showed significant change through time. In general, from 1982 to 2000, the population exposure to snowstorms increased in all altitude intervals except at 3600–3800 masl. From 2000 to 2010, above 4200 masl the population exposure decreased while below 4200 masl the exposure increased. From 2010 to 2015, the turning point changed to 5000 masl—above this altitude, the population exposure increased and below this altitude it decreased with rising altitude, except at 3000–3200 masl. The decrease in snowstorm-exposed population after 2000 was mainly due to the reduced intensity of snowstorms.

Population exposure to hypoxia, seismic, and snowstorm intensities and time periods, and its AAGR, are shown in Table 4. The population exposed to hypoxia was mainly concentrated in the hazard intensity zone of 50–60% of the sea level oxygen content, accounting for about 2/3 of the

total exposed population to hypoxia. The AAGR of the exposed population has gradually slowed in 1982–2010, and slightly increased in 2010–2015. Although population exposure to 40–50% of the sea level oxygen content hazard zone was rare, its growth rate was relatively high. Earthquake exposure increased with intensity—population exposure in the IX-degree intensity area accounted for about 40% of the total exposed population. The AAGR of the exposed population to earthquakes varied with time in different intensity regions. The AAGR of population exposure in the areas with seismic intensity of VI and VII generally showed a downward trend. This means that the exposed population increased slower with time. While in the areas with seismic intensity of VIII and IX, the AAGR of exposed population fluctuated with time and the overall growth rate was higher than the VI and VII intensity regions. The rapid increase of the total population in the high seismic intensity region led to a rapid increase of the population exposure to earthquakes. The population exposed to snowstorms was more affected by snow depth changes. The populations exposed to snow depths of 0–10 cm and 10–20 cm were similar, and the exposed population was less in the areas of > 20 cm snow depth. In the 2 years with strong snowstorms (1982 and 2000), the exposed population reached around 20% of the total exposed population, but only 10% in 2015 because the

Table 4 Population exposure to each hazard type and average annual growth rate (AAGR) in Tibet, 1982–2015

Hazard intensity	Exposed population					AAGR of exposed population				
	1982	1990	2000	2010	2015	1982–1990 (%)	1991–2000 (%)	2001–2010 (%)	2011–2015 (%)	1982–2015 (%)
%O ₂ of sea level										
60–70	142,035	163,837	197,713	227,933	251,314	1.8	1.9	1.4	2.0	1.7
50–60	295,062	352,902	417,079	466,048	492,694	2.3	1.7	1.1	1.1	1.6
40–50	264	339	410	439	643	3.2	1.9	0.7	7.9	2.7
Total	437,361	517,078	615,202	694,420	744,651	2.1	1.8	1.2	1.4	1.6
Seismic intensity										
VI	12,128	14,239	16,266	18,137	19,803	2.0	1.3	1.1	1.8	1.5
VII	15,110	17,901	21,403	24,798	25,759	2.1	1.8	1.5	0.8	1.6
VIII	15,138	17,662	22,552	26,140	29,142	1.9	2.5	1.5	2.2	2.0
> IX	22,045	25,515	31,253	37,826	42,217	1.8	2.0	1.9	2.2	2.0
Total	52,293	61,078	75,208	88,764	97,118	2.0	2.1	1.7	1.8	1.9
Snow depth										
0–10 cm	57,285	71,605	64,699	72,224	82,508	2.8	– 1.0	1.1	2.7	1.1
10–20 cm	62,313	66,423	83,992	86,615	70,545	0.8	2.4	0.3	– 4.0	0.4
> 20 cm	34,040	22,909	36,873	20,253	15,309	– 4.8	4.9	– 5.8	– 5.4	– 2.4
Total	153,638	160,937	185,564	179,092	168,362	0.6	1.4	– 0.4	– 1.2	0.3

snowstorms were weak in that year. The exposed population had been increasing until 2000, and then decreased. Overall, the population exposed to snow depths > 20 cm showed a decreasing trend, which was mainly due to the weakened snowstorm intensity. The population exposed to snow depths of 10–20 cm increased first and then decreased. At 0–10 cm snow depths, the population exposed to snowstorms showed an increasing trend, which was mainly due to the increase of the total population.

3.2 Spatiotemporal Differentiation of Multi-hazard Population Exposure

Multi-hazard population exposure reflects the population affected by two or more hazards. The unit of multi-hazard exposure is person-time and it is equal in value to the sum of the population exposed to single hazards. Similar to single hazards, multi-hazard population exposure was also calculated at the $1 \text{ km} \times 1 \text{ km}$ grid scale and the results are shown in $5 \text{ km} \times 5 \text{ km}$ grids. Figure 4 reflects the

spatial distribution characteristics of population exposure to four types of multi-hazard combinations in Tibet. The high population exposure areas of hypoxia-earthquake and hypoxia-snowstorm were mostly the same as the population exposure to hypoxia. They were also concentrated in the high population exposure areas of earthquakes and snowstorms. This indicates that the exposure to these two multi-hazard combinations is based on the population exposure to hypoxia and aggravated by earthquakes and snowstorms. Most of the population exposure to earthquake-snowstorm was concentrated in the high-exposure overlapping areas of these two hazards, mainly in northern Lhasa-Nagqu and sporadic townships in Nyingchi. The second highest exposed area was similar to snowstorms because the PAR is very low in seismic intensity below VIII. The highest exposure to the combination of three hazards mainly occurred in the area of Lhasa-Nagqu, where the population exposure was more than 1000 in most of the $5 \text{ km} \times 5 \text{ km}$ grids, and some were even over 2500. In this region, people may suffer from all three hazards. The

Fig. 4 Spatial distributions in Tibet of person-time exposure to multi-hazards: **a** hypoxia-earthquake, **b** hypoxia-snowstorm, **c** earthquake-snowstorm, **d** hypoxia-earthquake-snowstorm, 2015

second highest exposed area was in the valley of the Middle Yarlung Tsangpo River and the plateau of Nagqu–Qamdo. The former is one of the most densely populated areas in Tibet while the latter has a high PAR of hypoxia and snowstorms because of its high altitude and relatively abundant precipitation.

Figure 5 reflects the changes in the population exposed to various combinations of multi-hazards by altitudes over time. The population exposures to the four types of multi-hazard combinations were mainly concentrated in the altitude interval of 3600–4800 masl. As more people were exposed to hypoxia, the person-time exposures to double-hazards including hypoxia were higher than the earthquake-snowstorm exposure. In 2015, more than 100,000 person-time were exposed to hypoxia-earthquake and hypoxia-snowstorm at almost all altitude intervals between 3600 and 4800 masl, and the highest person-time exposure was at the altitude interval of 4200–4400 masl, which is similar to the distribution of the population exposed to hypoxia. The person-time exposure to earthquake-

snowstorm is similar to the population exposure to snowstorms with regard to temporal changes—both increased before 2000 and decreased after 2000, except at 3600–3800 masl and 4400–4600 masl because the population exposed to earthquakes increased rapidly at these altitude intervals. The person-time exposure to hypoxia-earthquake-snowstorm combined the exposure characteristics of hypoxia and snowstorms. The exposure distribution was similar to hypoxia because most people were exposed to hypoxia, and the decrease of snowstorm intensity after 2000 caused the increasing exposure to slow down.

Table 5 shows the person-time exposure and AAGR of hypoxia-earthquake, hypoxia-snowstorm, earthquake-snowstorm, and hypoxia-earthquake-snowstorm exposure. Among the person-time exposures to double-hazards, most were exposed to hypoxia-snowstorm, with 600 thousand in 1982 and about 900 thousand person-time in 2015, an increase of about 50% in 34 years. The largest increase of person-time exposure occurred for earthquake-snowstorm

Fig. 5 Person-time exposure to each multi-hazard combination by elevation range and time period in Tibet

Table 5 Person-time and average annual growth rate (AAGR) of multi-hazard exposure in Tibet, 1982–2015

Multi-hazards	Exposed population (person-time)					AAGR of exposed population				
	1982	1990	2000	2010	2015	1982–1990 (%)	1991–2000 (%)	2001–2010 (%)	2011–2015 (%)	1982–2015 (%)
Hypoxia-earthquake	489,654	578,156	690,410	783,184	841,769	2.1	1.8	1.3	1.5	1.7
Hypoxia-snowstorm	590,999	678,015	800,766	873,512	913,013	1.7	1.7	0.9	0.9	1.3
Earthquake-snowstorm	205,931	222,015	260,772	267,856	265,480	0.9	1.6	0.3	– 0.2	0.8
Hypoxia-earthquake-snowstorm	643,292	739,093	875,974	962,276	1,010,131	1.8	1.7	0.9	1.0	1.4

hazards, at about 72% in 34 years. From 1982 to 2015, all four types of exposure increased in every time period except the exposure to earthquake-snowstorm in 2010–2015, and the growth rate slowed down after 2010. More than 1 million person-time were exposed to hypoxia-earthquake-snowstorm in 2015, nearly one-third of the population in Tibet, that is, on average one in three people was exposed to the multi-hazards of hypoxia-earthquake-snowstorm.

To summarize the current state of population exposure, the population exposed to hypoxia, earthquakes, snowstorms, and any combination of the three and the exposed population proportion of the total population in Tibet in 2015 are shown in Table 6. The results show that the population exposed to hypoxia was as high as 0.74 million in 2015, accounting for 23.13% of the total population in Tibet. The population exposed to snowstorms was the second largest, reaching more than 0.16 million in 2015, accounting for 5.23% of the total population in Tibet. Since 2000, the exposed population showed a decreasing tendency due to the decrease of snowstorm intensity. The population exposed to earthquakes was nearly 0.1 million in 2015, accounting for 3.02% of the total population in Tibet.

With respect to the exposure to multi-hazards in 2015, person-time exposed to hypoxia-earthquake, hypoxia-snowstorm, and earthquake-snowstorm were 842 thousand, 913 thousand, and 265 thousand, respectively. The ratio of multi-hazard exposure to total population refers to the number of times each person was expected to be affected by the hazards. For the hypoxia-earthquake and hypoxia-snowstorm hazard combinations, each person may have a quarter of probability to be exposed in 2015. The person-time exposure of earthquake-snowstorm was far less, and each person only had a possibility of 0.08 to be exposed in 2015. Person-time exposure of hypoxia-earthquake-snowstorm was over 1 million and nearly one-third of the population may suffer from this multi-hazard combination in 2015.

4 Discussion

In this section we explore the exposure of Tibet's tourist population under different hazard intensities to discuss nonpermanent resident exposure, the differences and interactions between hypoxia and other natural hazard exposures with regard to uncertainty and hazard formative mechanisms, and summarize the limitation of this study and give corresponding explanations and prospects.

4.1 Tourist Population Exposure

With the operation of the Qinghai-Tibet railway to Lhasa since July 2006, the number of tourists to Tibet was boosted markedly (Su and Wall 2009) (Fig. 6). The growth rate of the tourist population has been much higher than that of the resident population. Although not reflected in the census data, it is an indivisible part of the population exposure. With an average stay of 6.4 days (Su and Wall 2009) and a total of 20.17 million person-time in 2015 (Tibet Autonomous Region Bureau of Statistics and Tibet General Team of Investigation under the NBS 2016), tourists to Tibet annually are about equal to 354 thousand

Fig. 6 Number of tourists and permanent residents in Tibet, 1982–2015 *Source* Tibet Autonomous Region Bureau of Statistics and Tibet General Team of Investigation under the NBS (2016)

Table 6 Population exposure to single hazards and multi-hazards in Tibet, 2015

Single Hazard	Population exposure	% of exposed population
Hypoxia	744,651	23.13
Earthquake	97,118	3.02
Snowstorm	168,362	5.23
Multi-hazards	Population exposure (person-time)	Number of times for each person to be exposed
Hypoxia-earthquake	841,769	0.26
Hypoxia-snowstorm	913,013	0.28
Earthquake-snowstorm	265,480	0.08
Hypoxia-earthquake-snowstorm	1,010,131	0.31

resident population, or 11% of the total population of Tibet. Most of this tourist population are lowlanders who cannot adapt well to the hypoxia environment. For those people the basal metabolic rate (BMR) is increased by about 17–27% for the first few weeks of exposure to the high altitude (Beall 2007), and the vulnerability of this population is high. April to October is the Tibet tourist season. During this period, the number of tourists accounts for over 90% of the annual tourist total (Li and He 2002; Li and Chi 2014).

Since there are no authoritative data on the spatial distribution of tourists in Tibet, we used the microblog sign-in data² before 1 November 2014 to mark on the map 68 places (scenic spots, hotels, airports, and railway stations) where more than 50 people signed in, and regarded these places as the most frequently visited by tourists. Around 90% of these locations are above 3000 masl, 25% are over 4000 masl, and 51% are above the seismic intensity of VIII degrees. As most people travel to Tibet in the summer, it is not necessary to consider tourists exposed to snowstorms. But there is a high association between the distribution of tourists and the areas of high hazard intensity of hypoxia and earthquakes. As outsiders, tourists are not only exposed to the extreme hypoxic environment but also areas of multi-hazards. They are high-risk groups in Tibet.

4.2 Differences and Interactions Between Hypoxia and Other Natural Hazard Exposure

In this study, although hypoxia is regarded as a hazard, its disaster formation mechanism is very different from other natural hazards such as earthquakes and snowstorms. People living at high altitude are influenced by hypoxia every day and the intensity is basically constant at a specific altitude, while earthquakes and snowstorms are sudden-onset disasters. This results in two main differences between these hazards. First, hypoxia is an ever-present hazard to human health while earthquake and snowstorm occurrences are uncertain in time, space, and intensity. So, the uncertainty of the impact of hypoxia on people mainly depends on their exposure and vulnerability. But the influence of hypoxia is gradual, whereas earthquakes and snowstorms are sudden. These differences entail different prevention and mitigation measures. For hypoxia, as people's adaptation to the condition cannot be changed in a short time, improving medical care and expanding medical coverage may be the best way to mitigate the influence. For earthquakes and snowstorms, however, implementing disaster prevention measures may mitigate the impacts most effectively. In addition, the AMS of newcomers and the higher prevalence of CMS among the Han resident

population make the affected rate of hypoxia ethnicity sensitive and related to the length of time a person has lived at high altitude. The interactions between hypoxia and other natural hazards also are worthy of discussion. One typical case was the Yushu Earthquake in 2010. After the earthquake, both members of rescue teams and other professionals from low-altitude areas faced the problem of hypoxia reactions (Liu et al. 2011), which not only affected the rescue and relief work, but also exposed these people to hypoxia. Since hypoxia as a condition always exists on the Tibetan Plateau, once an earthquake or snowstorm occurs, a multi-hazard combination is bound to occur. This indicates that research on the risk prevention and disaster interaction mechanisms of multi-hazards is very necessary in this high-altitude region.

4.3 Limitations of this Study

This study has some deficiencies in data and methods. The snow depth data were derived from remote sensing data with a resolution of 25 km × 25 km. It is difficult to accurately represent the spatial differences of snow cover. When considering the affected rate of hypoxia, we selected the incidence data of CMS for the young male Han population who had lived at least 5 years in Tibet. Since more than 90% of the people in Tibet are Tibetans, using this prevalence of CMS will overestimate the population exposed to hypoxia. However, with the increasing number of Han people in Tibet, such an estimate is a reasonable proxy. The population data of this study distinguishes between urban and rural population on a township scale, but the spatial variation can only be shown in 1982, 1990, 2000, 2010, and 2015.

Due to the lack of spatial information on building fortifications against earthquakes, we did not consider the fortification standards in the exposure calculation. Therefore, we do not know where people are well protected or exposed but only the total population exposed to seismic hazards in a certain intensity zone. This limits the calculation of multi-hazard exposure as well. If detailed fortification spatial data or detailed disaster data of multi-hazards are available, exposure to multi-hazards will not need to be measured by “person-time” but by population affected by each single hazard and multi-hazards that occur simultaneously.

For hypoxia, in this study we only considered elevation, which determines the oxygen partial pressure. But there may be other influencing factors—for example, vegetation covers and local air pressure changes would also change the oxygen content (Shi et al. 2018).

² <http://open.weibo.com/wiki/2/place/nearby/pois>.

5 Conclusion

This study regards hypoxia as a unique hazard in high-altitude areas and considers that people who live in a hazard-prone area but will never be affected by the hazard should not be included in the population exposure. Based on this, the population exposed to hypoxia, earthquakes, snowstorms, and combinations of the three hazards in Tibet were calculated. The results show that the population exposed to hypoxia was highest due to the wide distribution of the hazard condition and the high prevalence of CMS. Hypoxia is the most important environmental risk in the region and needs to be prevented and controlled. People exposed to each hazard in Tibet reached their highest number at an elevation of 4200–4800 masl. In this zone, oxygen content is lower than 40% of the content at sea level, causing a great impact on human health and increasing people's vulnerability to earthquakes and snowstorms. The population exposed to hypoxia at this altitude was growing but at a decreasing speed. The population exposed to earthquakes grew fastest with an increasing rate of 1.9% a year on average and at an increasing speed in high-intensity areas. The population exposed to snowstorms fluctuated with the intensity of snowstorms, and the trend first increased and then decreased.

With respect to the exposure to multi-hazards, the high exposure area was northern Lhasa-Nagqu for all double-hazard combinations, and the second highest was a large area in the valley of Shigatse-Lhasa and the plateau of Nagqu-Qamdo for the hypoxia-earthquake and hypoxia-snowstorm hazard combinations. In the key areas of multi-hazard exposure, a greater proportion of casualties will occur because the simultaneous occurrence of hazards will increase the vulnerability of the population. With the increase of Tibet's population, this problem will become more prominent and it will be necessary to take advance precautions against disasters in key exposure areas, especially for the risk of hypoxia in such an extreme environment. The person-time exposure of hypoxia-earthquake was growing fastest with an increasing rate of 1.7% per year on average. The person-time exposure of hypoxia-earthquake-snowstorm increased 367 thousand person-time from 1982 to 2015. For each multi-hazard combination, the increasing rate of exposed population is becoming smaller with time and less than the rate of total population increase in Tibet. This shows that during the study period, the population was slowly moving away from high-hazard intensity areas. The results of this study provide some practical reference for natural hazard risk governance in Tibet.

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