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Simulation of decadal alpine permafrost distributions in the Qilian Mountains over past 50 years by using Logistic Regression Model

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Abstract

Based on a bench-mark distribution map of alpine permafrost, topographic factors and meteorological factors in every decade, the decadal distributions of alpine permafrost from 1960 to 2009 in the Qilian Mountains were simulated by using Logistic Regression Model (LM), and the overall accuracy of the simulation results was estimated to above 80\%. Moreover, the changing conditions of alpine permafrost in the Qilian Mountains during each adjoining two decades, as well as over the past 50 years, had also been analyzed. The research results show:

(1) LM simulation in this research not only decreases the dependency on the field survey data, but achieves dynamic simulation of alpine permafrost distribution; (2) the simulated areas of alpine permafrost in 1960s, 1970s, 1980s, 1990s and 2000s are $10.7 \times 10^4$ km$^2$, $9.8 \times 10^4$ km$^2$, $10.0 \times 10^4$ km$^2$, $8.5 \times 10^4$ km$^2$ and $8.7 \times 10^4$ km$^2$ respectively.

Hence, the distribution of alpine permafrost presents an overall degraded tendency with two slight fluctuations.

Keywords: Alpine permafrost simulation; Logistic regression model; Qilian Mountains; Topographic factors; Meteorological factors

1. Introduction

Permafrost distribution, as one of the physical geographical factors being sensitive to temperature, and hence climate change, is one of the most important climatic and environmental indexes (Jiang et al., 2003). Global climate change, especially global warming, has been shown to have a large effect on alpine permafrost distribution (Gardaz, 1997; Vokelj et al., 2010). In mid-latitude mountainous regions, alpine permafrost distribution has a great impact on the...
majority of surface processes, and is hence one of the important regulatory factors of geomorphologic processes and ultimately pattern (Ling and Zhang, 2004; Etzelmüller et al., 2003). Understanding the spatial distribution and changing condition of alpine permafrost is fundamental to predict geomorphologic and landscape change rules (Ishikawa, 2003).

Model simulation is a useful way for investigating alpine permafrost distributions, because these distributions cannot be dependent on field surveying solely (Málevsky-Malevich et al., 2001). Consequently, many models for simulating the distributions of alpine permafrost appeared (Imhof, 1996; Salzmann et al., 2007). A computer model to map the probability of permafrost in the Bernese Alps (in Western Switzerland) was obtained based on topographic parameters (Imhof, 1996). Regional Climate Model (RCM) was validated to simulate the alpine permafrost scenarios (Salzmann et al., 2007). Bottom temperature of snow cover (BTS) was one of the factors that have received much attention, the measurements of which had been used to simulate alpine permafrost distribution in many mountains including the Alps (Hoelzle, 1992; Mühl et al., 2001), the Daisetsu Mountains of Japan (Ishikawa and Hirakawa, 2000) and so on.

Qilian Mountains is located in the northeastern part of the Qinghai-Tibet Plateau (QTP) in China. It comprises one of the most important alpine permafrost distribution regions for the QTP (Wu et al., 2007). In the Qilian Mountains, alpine permafrost degradation induced by climate warming was not only the major driving factor of intensifying desertification, but affected such things as biochemical processes and human infrastructure (Yang et al., 2010). Additionally, alpine permafrost areas on the Qilian Mountains have a good prospecting potential for gas hydrate. The Qilian Mountains had yielded the first physical sample of gas hydrate drilled from global mid-latitude alpine permafrost regions (Zhu et al., 2009). Understanding the spatial distribution and changing conditions of the alpine permafrost in Qilian Mountains, therefore, has both scientific and economic significance.

There were some research achievements about alpine permafrost distribution in the Qilian Mountains, including the altitude model (Cheng, 1984), Map of Snow, Ice and Frozen Ground in China (Shi, 1988), Map of Frozen Ground on Qinghai-Xizang Plateau (Li and Cheng, 1996), Geomorphologic Atlas of People’s Republic of China (1:1,000,000) (Edition Board of Geomorphologic Atlas in People’s Republic of China, 2009) and the results in World Data Centre. These researches presented alpine permafrost distribution in the Qilian Mountains at different
scales and periods. With global warming, it is of much importance to acquire the dynamic distribution of alpine permafrost during a long time series. However, to date there are few models for simulating the alpine permafrost distribution in the whole Qilian Mountains; moreover, the models for dynamically simulating alpine permafrost distributions in several lasting periods are even scarce.

Thus, selecting Map of Snow, Ice and Frozen Ground in China (Shi, 1988) at 1:4,000,000 as a bench-mark map, we assigned the values of the distribution probability of alpine permafrost, topographical and meteorological factors to the sample points. Based on the values at the sample points, Logistic Regression Model (LM) was constructed and then used to simulate the decadal alpine permafrost distributions in the Qilian Mountains over past 50 year. This research provides an effective way for the dynamic simulation of alpine permafrost distribution in different periods.

2. Regional settings

Between Qaidam Basin and Gansu Corridor, Qilian Mountains are located at the western part of China, which has northwest-southeast trend and is composed of a series of parallel mountain chains and broad valleys (Fig.1). With the geographical boundary of about 93.4°-103.4°E and 35.8°-40.0°N, Qilian Mountains has the total area of about 19.5×10⁴ km². In Qilian Mountains, most of the peaks are higher than 4000 m asl, and the largest lake is Qinghai Lake.

Originally as a Paleozoic geosyncline, Qilian Mountains became a fold belt after Caledonian Movement and Variscan Movement, and it finally forms a series of parallel ridges and valleys after the block elevating sinking movement since Cretaceous. The lower section of the mountains mainly distributes arid geomorphology; middle section, fluvial geomorphology; high section, permafrost geomorphology.

Alpine permafrost in the Qilian Mountains belongs to the Qilian-Altun Permafrost Sub Region of the QTP Permafrost Region. The Qilian Mountains is located at the juncture of three climate regions (the monsoon region, arid region and QTP climate region) (Wu et al., 2009). The climate is influenced by the macroscopic atmospheric circulation and high elevation, and the precipitation in Qilian Mountains gradually decreases from east to west, which cause the lower limits of alpine permafrost presenting an increase tendency from east to west.
3. Data sources

3.1 Topographic factors

Topographic factors include elevation, slope, aspect, longitude and latitude.

Elevation is one of the most important factors for the spatial distribution of alpine permafrost to the extent that most alpine permafrost distributions are represented by their upper and lower limits. Elevation data were acquired by processing Shuttle Radar Topographic Mission data with 3-arc seconds spatial resolution (SRTM3), which was downloaded from the version 4 data of the Consortium for Spatial Information of the Consultative Group for International Agricultural Research. The SRTM3 data can provide continuous surface elevation information. Spatial calculations were conducted by using ArcGIS software for every factor, which has the same spatial resolution (0.001°, about 100 m) and geographic projection. In the final elevation data, the highest, lowest and mean elevation values for Qilian Mountains were 5763, 1576 and 3586 m asl respectively.

As the oblique degree of ground surface, slope is the first order derivate of elevation and directly influences the geomorphology by determining the scale and intensity of the flow and energy transformation of ground materials (Zhou et al., 2009; Tang et al., 2005). Hence, slope is one of important topographic factors associated with the alpine permafrost distribution (Etzelmüller et al., 2001). Slope value is computed based on the elevation data. In the final slope data, the value range is 0–69.3° and the average value is 12.1°.

The difference of solar radiation energy induced by aspect not only results in the diversities of land coverage, but the limits change of alpine permafrost distribution (Gao, 1981; Yang et al., 1993). In the Qilian Mountains, the lower limit of alpine permafrost on sunny slope is usually higher than that on shady slope. Aspect data are also computed based on the elevation data. In sloping area, the value range of the aspect is 0–360°; but in flat area, the value is -1.

As aspect data cannot be used directly in the simulation model, they are divided into four classes according to the solar radiation difference affected by aspect direction: Sunny slope (135–225°), 1; Flat area (-1), 2; Half sunny slope (45–135° and 225–315°), 3; Shady slope (0–45° and 315–360°), 4.

Longitude factor represents the “arid zonation” of the alpine permafrost distribution in middle
and low latitude regions (Cheng, 1984; Wu et al., 2009). For longitude data, the value of every pixel is the longitude of its centre location.

Latitude controls the intensity of solar radiation in different place, hence global heat distribution. The acquisition process and characteristics of latitude data are similar to those of longitude data.

3.2 Meteorological factors

Alpine permafrost is sensitive to climate change, which not only affects the distribution of alpine permafrost, but also its thickness and burial depth (Yang and Wang, 2008). The data of meteorological factors are firstly acquired based on 27 meteorological stations in and around Qilian Mountains; then, the accuracy of the meteorological data is validated by using meteorological test stations and glacial and permafrost stations. The locations of all the stations can be seen in Fig.1.

3.2.1 Data acquisition of the meteorological factors

The sparse distribution of the meteorological stations may have had a large effect on the interpolation quality of the meteorological factors. Moreover, most meteorological stations locate in the middle section of the Qilian Mountains (Table 1), which may result in low quality of the interpolation data in high elevation regions. To mitigate this effect, the topographic factors are introduced in the interpolation process. Based on the measurements at the meteorological stations, the mean annual air temperature (MAAT) data, mean annual precipitation (MAP) data, mean annual sunshine hour (MASH) data in the whole Qilian Mountains were acquired for each decade over past 50 years.

Air temperature is a significant factor that influences permafrost evolution (Yang et al., 1993). Freezing cold climate is an important condition for alpine permafrost existence and development (Wu et al., 2007). According to the measurements of the MAAT data at the meteorological stations on Qilian Mountains in previous research, the MAAT data decrease with increasing elevation and the lapse rate is 5.5 °C per 1000 m (Guo, 1983). Using the lapse rate, the MAAT data were interpolated based on the measurements at the meteorological stations and the elevation factor. The residual error of the interpolation results is less than 0.01°C at every meteorological station in every decade. Consistent with the general tendency of climate change, the final MAAT data continue to increase at an accelerating rate in past 50 years (Table 2).
Alpine permafrost in the Qilian Mountains belongs to extreme continental alpine permafrost, so the distribution and development of alpine permafrost is strictly limited by precipitation (Wang, 1992). The regression model between MAP data and the topographical factors is as the follows.

\[ \text{[MAP]} = A \times [\text{elevation}] + B \times [\text{longitude}] + C \times [\text{latitude}] + V \]  

(1)

where [MAP] is mean annual precipitation data; [elevation] is elevation data; [longitude] is longitude data; [latitude] is latitude data; A, B and C are coefficients; V is regression constant.

Based on the measured MAP data and topographical factors at the meteorological stations, the coefficients and regression constant were computed, so the regression models were constructed. In the regression model, regression coefficient (R) was above 0.85 in every decade, so MAP data has evident correlation with topographic factors (Table 3). Based on Eq. (1), decadal MAP data can be simulated using topographic factors. From the 1960s to 2000s, the final MAP data present a generally increasing tendency with an evident fluctuation that is from the 1980s to 1990s (Table 2).

Solar radiation is another important factor which affects the spatial distribution of alpine permafrost. Solar radiation data can be calculated from elevation data directly, but which may have evident correlation with elevation data. Sunshine hour data have a direct impact on solar radiation energy distribution, and thereby has an effect on the distribution of alpine permafrost (Guo, 1983). The regression model between MASH data and topographic factors is as follows.

\[ \text{[MASH]} = A \times [\text{altitude}] + B \times [\text{longitude}] + C \times [\text{latitude}] + D \times [\text{slope}] + E \times [\text{aspect}] + V \]  

(2)

where [MASH] is mean annual sunshine hour data; [altitude] is altitude data; [longitude] is longitude data; [latitude] is latitude data; [slope] is slope data; [aspect] is aspect data; A, B, C, D and E are coefficients; V is regression constant.

The simulation process of MASH data using regression model is similar to that of MAP. In the regression model, R in every decade is above than 0.8 (Table 3), so MAP data have close relation to topographic factors. From 1960s to 2000s, the final MASH data present a generally increased tendency with two slight fluctuations, such as from 1970s to 1980s and from 1990s to 2000s (Table 4).

In the data acquisition process of meteorological factors, the data for the whole Qilian Mountains were firstly computed based on the regression models between the meteorological and topographic factors; then, the residual values between the measured values and the computed
values can be acquired in every meteorological station, so the residual data can be interpolated for
the whole Qilian Mountains; finally, the final data of the meteorological factors were achieved by
adding the residual data to the computed data. This acquisition process not only guarantees the
consistent value at every meteorological station, but also increases the independence of the
meteorological factors by using the residual data.

3.2.2 Accuracy assessment of meteorological data

Two meteorological test stations, one glacial station and two permafrost stations were used to
estimate the accuracy of the meteorological factors.

The measured values and the interpolated values at the test stations are shown in Table 5. So
there exist certain differences between the measured values and the interpolated values, but the
changing conditions from 1960s to 2000s are similar for every meteorological factor.

For the glacial and permafrost stations, only the MAAT data in recent years are found after
careful search. Then, using the same acquisition method, the interpolated MAAT data are acquired
for the whole Qilian Mountains in the approximately same period based on the 27 meteorological
stations. The comparison between the measured MAAT and the interpolated MAAT data is shown
in Table 6. So the overall difference between the measured values and the interpolated values is
about 0.7 °C.

4. Simulation methodology

4.1 Simulation model

LM has been introduced to simulate alpine permafrost distribution in recent years (Lewkowicz
and Ednie, 2004; Janke, 2005; Etzelmüller et al., 2006). It has the advantage that it is agnostic to
input variable types. Therefore, continuous or categorical variables which have either normal or
non-normal distribution patterns can be used as the input data with the LM to carry out the
simulations (Li et al., 2009). The equation for LM is as follows:

\[ \ln \left[ \frac{p}{(1 - p)} \right] = A + Bx + Cy \ldots \] (3)

where \( p \) is the probability of alpine permafrost existing \( (0 < p < 1) \); \( A \) is regression constant; \( B \) and
\( C \) are coefficients; \( x \) and \( y \) are independent variables. Eq. (3) can also be expressed as the follows:
\[ p = \frac{1}{1 + e^{-\left(Ae + B + Cy + \ldots\right)}} \quad (4) \]

4.2 LM construction

The foundations of permafrost part compilation for Map of Snow, Ice and Frozen Ground in China (Shi, 1988) were field survey data, remote sensing interpretation data, meteorological conditions and topographic characteristics which affect the form and distribution of permafrost. As to the alpine permafrost distribution in the Qilian Mountains, it is mainly based on field survey data and aerial photo interpretation (Mi, 1990). This map reflected the distribution features and regional differentiation of permafrost in China comprehensively (Li et al., 1994), which was the important achievement in regional permafrost researches after 1950s (Lu et al., 2007) and widely used in the later research (Wang and French, 1995; Lehmkuhl, 1998; Jin et al., 2000; Yang et al., 2010).

Based on the map, the permafrost distribution status in the Qilian Mountains was acquired (Fig.1). Then we assigned the values of topographic and meteorological factors, and permafrost distribution probability to the 1991 sample points which distributed evenly over the Qilian Mountains at an interval of 0.1°. Based on the sample points, LM was constructed and decadal alpine permafrost distribution can be simulated over past 50 years by using the LM (Fig.2).

As the original data of the map compilation were mainly collected in 1970s, the meteorological factors in the 1970s were used for the LM construction. Taking the left side of Eq. (3) as “\(\ln\)”, the correlation matrix between “\(\ln\)”, topographic and meteorological factors was computed (Table 7). In the correlation matrix, “\(\ln\)” has significant correlation with the elevation and MAAT factors; the correlations between “\(\ln\)” and aspect, “\(\ln\)” and MASH are less evident. Although the correlations between “\(\ln\)” and various factors vary greatly, every factor has some contribution to the LM simulation; MASH has the least correlation with “\(\ln\)”, but it can improve the regression coefficient from 0.679 to 0.681. Therefore, all the factors were employed in the simulation process.

Meanwhile, the regression coefficient and Nagelkerke \(R^2\) are 0.681 and 0.608 respectively. So it is a remarkable correlation between alpine distribution probability and the factors. Using the values of distribution probabilities of alpine permafrost, topographic and meteorological factors in the 1970s at the sample points, the LM was constructed as the follows.
\[ p = \frac{1}{1 + e^{(-39.519 + 0.006h - 0.097s - 0.345a + 0.141l + 0.437b - 0.287r + 0.002r - 1.466*sh)}} \]  

(5)

where \( p \) is permafrost distribution probability; \( h, s, a, l \) and \( b \) are elevation, slope, aspect, longitude and latitude factors respectively; \( t, r \) and \( sh \) are respectively MAAT, MAP and MASH factors.

5. Results and interpretation

5.1 Simulation results

Based on Eq. (5), the distribution probability of decadal alpine permafrost in the Qilian Mountains can be acquired over past 50 years by using the data of topographic and meteorological factors. Taking \( p = 0.5 \) as the cut value, we determined that regions with \( p \geq 0.5 \) are permafrost, while those with \( p < 0.5 \) are non-permafrost (Etzelmüller et al., 2006; Li et al., 2009). Hence, the decadal alpine distribution in the Qilian Mountains can be achieved over past 50 years (Fig. 3).

To quantitatively analyze the distribution status of alpine permafrost, a statistical analysis of distribution area in every decade was conducted (Table 8). The areas which might have permafrost in 1960s but not in 2000s were about 20% of the total permafrost areas. The degraded areas mainly distributed at the boundary between permafrost and non-permafrost regions (Fig. 3).

The degraded area of alpine permafrost was highest from 1960s to 1970s, then from 1980s to 1990s; in the other two periods (from 1970s to 1980s and from 1990s to 2000s), the areas of alpine permafrost had increased slightly (Table 8). On the whole, the alpine permafrost distribution has degraded generally over past 50 years, although there are two slight fluctuations.

5.2 Distribution change of alpine permafrost during the past 50 years

Based on the simulation results, the distribution change of alpine permafrost was first analyzed during each adjoining two decades, such as from 1960s to 1970s, from 1970s to 1980s, from 1980s to 1990s and from 1990s to 2000s, and then over the whole past 50 years, from 1960s to 2000s.

Through computation, “unchanged permafrost” was the steady permafrost, which mainly distributed in the upper parts of Qilian Mountains with high altitudes; “unchanged non-permafrost” was the steady non-permafrost, which mainly distributed in the skirt regions of
Qilian Mountains with lower altitudes; “decreased permafrost” mainly distributed at the boundary between permafrost and non-permafrost regions, the distribution of which was not evident (Fig. 4). In this simulation, the distribution of alpine permafrost was determined by LM simulation, and the distribution change was determined mainly by the data of the meteorological factors. Hence, there existed some small patches of the “increased permafrost”, but they were difficult to find (Fig. 4).

For the adjoining two decades, the areas of “decreased permafrost” were biggest from 1980s to 1990s, and then from 1960s to 1970s; it was limited in the other two periods. The areas of the “increased permafrost” were small in every period. On the whole, the areas of alpine permafrost decreased largely from 1960s to 1970s and from 1980s to 1990s, but increased minimally in the other two periods (Table 9).

During the whole past 50 years, the area of “decreased permafrost” was much higher than that of “increased permafrost”. Hence, alpine permafrost had been degraded heavily (Table 9). The degraded alpine permafrost was widely distributed in the boundary between permafrost and non-permafrost regions (Fig. 4e).

6. Discussion

6.1 Model appraisal

6.1.1 Model effectiveness

Both topographic and meteorological factors can affect whether permafrost preserves. Simulation models for alpine permafrost based on topographic parameters alone are limited because meteorological factors are not included (Imhof, 1996; Etzelmüller et al., 2001); whereas those based on RCM alone lack of topographic data (Salzmann et al., 2007). BTS is another useful way to simulate alpine permafrost distribution (Ishikawa and Hirakawa, 2000; Stocker-Mittaz et al., 2002; Lewkowicz and Bonnavaventure, 2008). However, obtaining BTS data at required density scale can be difficult operationally. Therefore, using BTS models alone to simulate alpine permafrost distribution has its deficiency (Brenning et al., 2005). LM is introduced to simulate permafrost distribution in recent years, which is an open model and any types of the factors can be inputted; meanwhile, the importance of every factor for the model and simulation can be estimated through correlation matrix. Compared with other simulation models and previous LM simulation,
LM used in this research has some unique advantages as the follows.

Firstly, it reduces the dependence on field survey data. Field survey is difficult to conduct on Qilian Mountains because of the large area, high altitude and severe environment. Based on permafrost distribution map, the permafrost distribution status can be assigned to abundant sample points. Using different factors, the simulation model can be constructed based on the sample points. This method provides a way for alpine permafrost simulation in large regions or high mountains where it is difficult to conduct field survey.

Then, this simulation uses multiple factors, including topographic factors and meteorological factors. The distribution change of alpine permafrost is mainly determined by there meteorological factors, so it is more reasonable than that by only MAAT data.

Finally, this method achieves dynamic simulation of alpine permafrost distribution. After the construction of the model, alpine permafrost can be simulated in different periods according to the value change of the factors, so as to acquire the dynamic monitoring of the permafrost distribution.

6.1.2 Model limitations

Although this simulation has valuable advantages, some disadvantages also exist as the follows.

LM was constructed by using the data in the 1970s. As the LM cannot be completely fit in other decades, a little deviation would occur for the simulation results in other decades. Additionally, LM is the scenario-type model, which cannot consider the lag times during permafrost degradation and formations (Bonnaventure and Lewkowicz, 2010). In fact, although the meteorological data had changed, the permafrost distribution status would be fixed for a longer period.

Because of the sparse distribution of meteorological stations, the meteorological factors are computed using the topographic factors, which may decrease the independence between meteorological and topographical factors. Of course, the residual data used in the interpolation process would largely decrease the dependence of using topographic factors.

6.2 Results accuracy estimation

About the total areas of alpine permafrost in the Qilian Mountains, they were $13.6 \times 10^4 \text{ km}^2$ on the Chinese Permafrost Distribution Map published in 1975 (Zhou and Guo, 1982), $9.5 \times 10^4 \text{ km}^2$ on the Map of Snow, Ice and Frozen Ground in China (Shi, 1988), $7.6 \times 10^4 \text{ km}^2$ (Wang et al., 2000) on the Map of Frozen Ground on the Qinghai-Xizang Plateau (Li and Cheng, 1996). The
differences may be due to several factors, such as cartographic method, publishing time, statistical method and map scale. Considering these factors, we deem that the simulation results are generally consistent with the results on these maps. Additionally, in the simulation results, the number of correctly classified sample points is 1709, which accounts for 85.8% of the total number.

To evaluate the accuracy of the simulation results further, we compared the simulation results with the bench-mark map. As the map may have a close relation to the simulation results, we also estimated the accuracy using the interpretation results from remote sensing images and other data.

6.2.1 Accuracy estimation based on the Map

LM was constructed based on the Map of Snow, Ice and Frozen Ground in China (Shi, 1988) by using the factors in 1970s, so the detailed accuracy of the simulation results can be estimated based on the map. Firstly, the simulation results in 1970s and alpine permafrost distribution on the map were compared and overlapped. “Decreased permafrost” mainly distributed near the lower limit of alpine permafrost, especially in the northern river valleys; “increased permafrost” also distributed near the lower limit of alpine permafrost, especially in the eastern Qilian Mountains; “unchanged permafrost” mainly distributed in the central part of the Qilian Mountains with high altitudes, while “unchanged non-permafrost” in the skirt area with lower altitudes (Fig. 5).

Then, the area of each type for the comparison results was computed. The area of “decreased permafrost” is about 9.6% of the total area; while for “increased permafrost”, 6.9% (Table 10). So the accuracy is generally above 80%. Given some factors in the map cartography process, such as cartographic generalization, the accuracy may be higher.

6.2.2 Accuracy estimation based on the interpretation results

The interpretation results were acquired from the Geomorphologic Atlas in People’s Republic of China (1:1,000,000) (Edition Board of the Geomorphologic Atlas in People’s Republic of China, 2009), which were interpreted based on field survey data, remote sensing images, DEM data, topographical index computed from DEM data, geomorphologic maps and so on. In the interpretation results, there were four kinds of permafrost geomorphology (block field, block slope, frost mound and solifluction terrace) in point type, the total number of which was 93 (Fig. 6).

As most of the original data was collected in the 1990s for the atlas, the interpretation results
were compared with the simulation results in 1990s. Through comparison, two points were located in non-permafrost regions and one point, on the boundary between permafrost and non-permafrost regions, while all the other interpreted permafrost points were distributed in permafrost regions from the simulation results in 1990s (Fig. 6). Hence, according to the points of the interpretation results, the accuracy of the simulation results was higher than 95%.

7. Conclusions

Decadal alpine permafrost distribution in the Qilian Mountains is simulated by using the LM over the past 50 years. Though simulation, the following conclusions can be drawn.

1. LM simulation not only decreases the dependence on field survey data, but achieves dynamic simulation of alpine permafrost distribution. The overall accuracy of the simulation results is higher than 80%.

2. The simulated areas of alpine permafrost on the Qilian Mountains in 1960s, 1970s, 1980s, 1990s and 2000s are $10.7 \times 10^4$ km$^2$, $9.8 \times 10^4$ km$^2$, $10.0 \times 10^4$ km$^2$, $8.5 \times 10^4$ km$^2$ and $8.7 \times 10^4$ km$^2$ respectively. Hence, the distribution of alpine permafrost presents an overall degraded tendency with two slight fluctuations.

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References


Change 26, 387-404.


Table 1
The elevation statistical values of the 27 meteorological stations in and around the Qilian Mountains (m)

<table>
<thead>
<tr>
<th>Meteorological station</th>
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Table 2
Statistical analysis of the MAAT data in every decade over past 50 years in the Qilian Mountains (°C)

<table>
<thead>
<tr>
<th>Years</th>
<th>Decades</th>
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<td>-2.0</td>
<td>-1.6</td>
<td></td>
</tr>
<tr>
<td>Std. dev</td>
<td></td>
<td>3.9</td>
<td>3.8</td>
<td>3.8</td>
<td>3.8</td>
<td>3.8</td>
<td></td>
</tr>
</tbody>
</table>

Table 3
Statistical analysis of MAP data in every decade over past 50 years from the Qilian Mountains (mm)

<table>
<thead>
<tr>
<th>Years</th>
<th>Decades</th>
<th>Statistics</th>
<th>1960s</th>
<th>1970s</th>
<th>1980s</th>
<th>1990s</th>
<th>2000s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td></td>
<td>601.4</td>
<td>640.7</td>
<td>757.0</td>
<td>661.1</td>
<td>735.5</td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td></td>
<td>19.7</td>
<td>25.9</td>
<td>21.1</td>
<td>19.8</td>
<td>23.4</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>294.8</td>
<td>307.2</td>
<td>355.1</td>
<td>317.5</td>
<td>365.8</td>
<td></td>
</tr>
<tr>
<td>Std. dev</td>
<td></td>
<td>116.2</td>
<td>113.7</td>
<td>118.3</td>
<td>115.3</td>
<td>116.8</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td></td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td></td>
</tr>
</tbody>
</table>

R is the regression coefficient of the regression model in every decade.

Table 4
Statistical analysis of MASH data in every decade over past 50 years in Qilian Mountains (h)

<table>
<thead>
<tr>
<th>Years</th>
<th>Decades</th>
<th>Statistics</th>
<th>1960s</th>
<th>1970s</th>
<th>1980s</th>
<th>1990s</th>
<th>2000s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td></td>
<td>9.9</td>
<td>10.0</td>
<td>9.8</td>
<td>9.8</td>
<td>9.7</td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td></td>
<td>1.7</td>
<td>4.6</td>
<td>4.5</td>
<td>6.3</td>
<td>6.4</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>7.3</td>
<td>7.8</td>
<td>7.7</td>
<td>8.2</td>
<td>8.1</td>
<td></td>
</tr>
<tr>
<td>Std. dev</td>
<td></td>
<td>1.1</td>
<td>0.8</td>
<td>0.8</td>
<td>0.7</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td></td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.8</td>
<td>0.9</td>
<td></td>
</tr>
</tbody>
</table>

See Table 3 for the meanings of R.

Table 5
The measured and interpolated values of the meteorological factors at the meteorological test stations

<table>
<thead>
<tr>
<th>Factor</th>
<th>Station</th>
<th>Measured values</th>
<th>Interpolated values</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAAT(°C)</td>
<td></td>
<td>MAAT</td>
<td>MAAT</td>
</tr>
<tr>
<td></td>
<td>Cha Ka</td>
<td>1.5</td>
<td>1.7</td>
</tr>
<tr>
<td>MAAT(°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gang Cha</td>
<td>-0.7</td>
<td>-0.5</td>
</tr>
</tbody>
</table>

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Table 6
The measured and interpolated MAAT values at the glacial and permafrost stations (°C)

<table>
<thead>
<tr>
<th>Station type</th>
<th>Station name</th>
<th>Elevation</th>
<th>Measured values</th>
<th>Interpolated values</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glacial</td>
<td>Da Xue Shan</td>
<td>4250</td>
<td>-7.3</td>
<td>-6.8</td>
<td>0.5</td>
</tr>
<tr>
<td>Permafrost</td>
<td>Ya Kou</td>
<td>3932</td>
<td>-3.4</td>
<td>-4.5</td>
<td>-1.1</td>
</tr>
<tr>
<td></td>
<td>Mu Li</td>
<td>4100</td>
<td>-5.3</td>
<td>-5.9</td>
<td>-0.6</td>
</tr>
</tbody>
</table>

Table 7
Correlation matrix for all variables in the LM construction

<table>
<thead>
<tr>
<th>Factor</th>
<th>In</th>
<th>altitude</th>
<th>Slope</th>
<th>Aspect</th>
<th>Longitude</th>
<th>Latitude</th>
<th>MAAT</th>
<th>MAP</th>
<th>MASH</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln</td>
<td>1.000</td>
<td></td>
<td>0.654**</td>
<td>0.064**</td>
<td>-0.052*</td>
<td>-0.154**</td>
<td>0.140**</td>
<td>-0.654**</td>
<td>0.132**</td>
</tr>
<tr>
<td>altitude</td>
<td></td>
<td>0.654**</td>
<td>1.000</td>
<td>0.124**</td>
<td>-0.024</td>
<td>-0.423**</td>
<td>0.274**</td>
<td>-0.954**</td>
<td>-0.030</td>
</tr>
<tr>
<td>Slope</td>
<td></td>
<td>0.124**</td>
<td></td>
<td>1.000</td>
<td>0.054*</td>
<td>0.186**</td>
<td>0.042</td>
<td>-0.178**</td>
<td>0.232**</td>
</tr>
<tr>
<td>Aspect</td>
<td>-0.052*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.085**</td>
<td>-0.007</td>
<td>-0.041</td>
</tr>
<tr>
<td>Longitude</td>
<td>-0.154**</td>
<td></td>
<td></td>
<td></td>
<td>-0.423**</td>
<td>0.186**</td>
<td></td>
<td>-0.714**</td>
<td>0.381**</td>
</tr>
<tr>
<td>Latitude</td>
<td>0.140**</td>
<td></td>
<td>0.274**</td>
<td></td>
<td>0.042</td>
<td>0.085**</td>
<td></td>
<td>-0.714**</td>
<td>0.381**</td>
</tr>
<tr>
<td>MAAT</td>
<td>-0.654**</td>
<td></td>
<td></td>
<td></td>
<td>-0.954**</td>
<td>-0.178**</td>
<td></td>
<td>-0.432**</td>
<td>1.000</td>
</tr>
<tr>
<td>MAP</td>
<td>0.132**</td>
<td></td>
<td>-0.030</td>
<td>0.232**</td>
<td>-0.041</td>
<td>0.841**</td>
<td></td>
<td>-0.566**</td>
<td>-0.044</td>
</tr>
<tr>
<td>MASH</td>
<td>0.018</td>
<td></td>
<td>0.196**</td>
<td>-0.600**</td>
<td>-0.109**</td>
<td>-0.827**</td>
<td></td>
<td>0.476**</td>
<td>-0.107**</td>
</tr>
</tbody>
</table>

** Correlation is significant at the 0.01 level (2-tailed); * Correlation is significant at the 0.05 level (2-tailed).

Table 8
Area of alpine permafrost in every decade over past 50 years (×10⁴ km²)

<table>
<thead>
<tr>
<th>Decade</th>
<th>1960s</th>
<th>1970s</th>
<th>1980s</th>
<th>1990s</th>
<th>2000s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>10.7</td>
<td>9.8</td>
<td>10.0</td>
<td>8.5</td>
<td>8.7</td>
</tr>
</tbody>
</table>

Table 9
Area of each category about alpine permafrost distribution change over past 50 years (×10⁴ km²)

<table>
<thead>
<tr>
<th>Period</th>
<th>Decreased permafrost</th>
<th>Increased permafrost</th>
<th>Unchanged permafrost</th>
<th>Unchanged non-permafrost</th>
</tr>
</thead>
<tbody>
<tr>
<td>From 1960s to 1970s</td>
<td>0.9</td>
<td>0.0</td>
<td>9.8</td>
<td>8.7</td>
</tr>
<tr>
<td>From 1970s to 1980s</td>
<td>0.1</td>
<td>0.3</td>
<td>9.8</td>
<td>9.4</td>
</tr>
<tr>
<td>From 1980s to 1990s</td>
<td>1.5</td>
<td>0.0</td>
<td>8.5</td>
<td>9.4</td>
</tr>
<tr>
<td>From 1990s to 2000s</td>
<td>0.1</td>
<td>0.2</td>
<td>8.5</td>
<td>10.7</td>
</tr>
<tr>
<td>From 1960s to 2000s</td>
<td>2.1</td>
<td>0.0</td>
<td>8.7</td>
<td>8.7</td>
</tr>
</tbody>
</table>
Table 10

Area of the comparison about alpine permafrost distribution type between the simulation results and the bench-mark map (×10^4 km^2)

<table>
<thead>
<tr>
<th>Type</th>
<th>Decreased permafrost</th>
<th>Increased permafrost</th>
<th>Unchanged permafrost</th>
<th>Unchanged non-permafrost</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>1.9</td>
<td>1.3</td>
<td>8.0</td>
<td>8.5</td>
<td>19.5</td>
</tr>
</tbody>
</table>
Fig. 1. Location, relief, station and permafrost distributions of the Qilian Mountains.
Fig. 2. Flowchart of the simulation methodology
Fig. 3. Alpine permafrost distribution on the Qilian Mountains in every decade over past 50 years (a. 1960s; b. 1970s; c. 1980s; d. 1990s; e. 2000s)
Fig. 4. Spatial distribution change of alpine permafrost in the Qilian Mountains over past 50 years (a: from 1960s to 1970s; b: from 1970s to 1980s; c: from 1980s to 1990s; d: from 1990s to 2000s; e: from 1960s to 2000s)

Where (a) “Decreased permafrost”, permafrost in 1960s but degraded to non-permafrost in 1970s; “Increased permafrost”, non-permafrost in 1960s but transformed to permafrost in 1970s; “Unchanged permafrost”, permafrost both in 1960s and 1970s; “Unchanged non-permafrost”, non-permafrost both in 1960s and 1970s. The meaning of every item in (b), (c), (d) and (e) can reference the explanation for (a).
Fig. 5. Comparison of alpine permafrost distribution between the simulation results in 1970s and benchmark map. 
Where “Decreased permafrost” is permafrost predicted in the simulation results but non-permafrost on the map; “Increased permafrost” is non-permafrost in the simulation results but permafrost on the map; “Unchanged permafrost” is permafrost both in the simulation results and the map; “Unchanged non-permafrost” is non-permafrost both in the simulation results and the map.
Fig. 6. Comparison of permafrost distribution between the simulation results in 1990s and the interpretation results.
Research Highlights

► Decadal alpine permafrost distributions are simulated in the Qilian Mountains.
► Logistic Regression Model is built for dynamic simulation. ► Accuracy of the simulation results is estimated to be above 80%.
► Dynamic change of alpine permafrost distribution is analyzed from 1960s to 2000s.
► Simulated distribution of alpine permafrost shows an overall degraded tendency with two slight fluctuations.