Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Cold Regions Science and Technology 36 (2003) 1–9
cold regions science and technology
www.elsevier.com/locate/coldregions

Modeling Chinese cryospheric change by using GIS technology

Xin Li*, Guodong Cheng, Qingbai Wu, Yongjian Ding

Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, PR China

Received 21 December 2001; accepted 9 August 2002

Abstract

The Chinese Cryospheric Information System (CCIS) is an integrated geographic information system (GIS) for storing, managing and analyzing the cryospheric data within China. Three regions were selected as the case study areas of CCIS. They are the Qinghai–Tibet Plateau, the regions along the Qinghai–Tibet Highway and the Urumqi River Basin of Tianshan Mountain. A draft geo-classification system that can express the logical hierarchy of cryospheric data was established. Based on this, CCIS stored large volumes of data, including maps of glacier, frozen ground and other environmental elements, digital elevation data, observation data of meteorological stations, hydrological gauges and permafrost boreholes and remote sensing data. CCIS is managed by ARC/INFO and can export data to other GIS environments easily, since data exchange interfaces were paid particular attention in the system. Based on CCIS, several GIS-based models about cryospheric processes and cryospheric response to global change have been developed. The models introduced are the following: a response model of high-altitude permafrost to global change, an evaluation model of engineering properties in permafrost regions along the Qinghai–Tibet Highway and a model of glacier mass balance estimation. The modeling results showed that the permafrost and glaciers in Chinese cryosphere will have significant changes under climatic warming.

Keywords: Geographic information system; Cryosphere; Permafrost; Glacier; Model

1. Introduction

The cryosphere is defined as the frozen part of atmosphere, hydrosphere, biosphere and lithosphere. This includes ice sheets, ice shelves, ice caps and glaciers, sea ice, seasonal snow cover, lake and river ice and seasonally frozen ground and permafrost. The importance of the cryosphere in the global climate system is related to the significant seasonal change of snow and ice cover, which affects the amount of energy absorbed at the surface dramatically. Studies have shown that the cryosphere is very sensitive to global change so that the change of cryosphere is considered as an indicator of global change. Global warming can cause a significant shrinkage in cryosphere extent and volume, therefore, impacting greatly on human living. Global warming will also cause a positive feedback between snow and ice albedo and air temperature, and change permafrost area from carbon sink to carbon source. These processes will have great feedback on climate system (IPCC, 1990, 1992; Fitzharris, 1995; Cheng, 1996; Nelson et al., 1993).

China has a vast expanse of cryosphere which contains a large portion of the world's middle- and low-latitude mountain glaciers. China's permafrost

* Corresponding author.
E-mail address: lixin@ns.lzb.ac.cn (X. Li).

0165-232X/03/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0165-232X(02)00075-7

area ranks third in the world and is first in terms of the middle- and high-altitude permafrost area. In particular, the Qinghai–Tibet Plateau plays a very important role in global change. Therefore, the Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences (LIGG) had made efforts to establish a geographic information system (GIS) of the Chinese cryosphere (Li et al., 1997; Li, 1998), namely, the Chinese Cryosphere Information System (CCIS). The objectives of CCIS are as follows:

- To make a detailed design of the CCIS, formulating the system standards.
- To build up a geographic information system integrated closely with cryospheric models.
- To analyze the spatial and temporal change of Chinese cryosphere using GIS technologies.
- To develop some application models of cryosphere response to global change (Li and Cheng, 1999; Li et al., 1998; Wu et al., 1998, 2000; He et al., 1999).

2. Establishment of Chinese Cryosphere Information System

2.1. General structure of CCIS and case studies

CCIS is a comprehensive information system designed to manage and analyze the cryospheric data of China. The establishment of the system, on one hand, meets the demand of the earth system science to provide parameters and validation data for development of GIS-based response and feedback models of frozen soil, glacier and snow cover to global change. On the other hand, it provides a scientific, effective and safe management and analytical tool used to systematically collect and store valuable cryospheric data.

The general structure of CCIS is shown in Fig. 1.

Three regions of different sizes and characters were selected as main study areas of CCIS. They are:

(1) Qinghai–Tibet Plateau, 70–105°E, 25–40°N.
(2) Qinghai–Tibet Highway, approximately 20–30-km width on both sides.
(3) Urumqi river basin in the Tianshan Mountain, 86–89°E, 42–45°N. The key study area is located in the upper reaches of Baiyanggou between 86°45′ – 87°30′ E and 43°00′ –43°30′ N.

2.2. System standards and composition

2.2.1. Geo-classification system of cryospheric data

The classification of cryospheric data should reflect their characteristics, types and interrelationship. CCIS includes three major types of data, namely, cryospheric data, natural environmental data and socioeconomic resource data. Based on the classification of cryospheric data, a draft geo-classification system that expresses the logical hierarchy of cryospheric data has been established. The principles of classifying the data in CCIS are as follows: it must be consistent with the classification of the cryosphere science and should clearly reflect the logical structure of the GIS. In addition, it should be compatible with

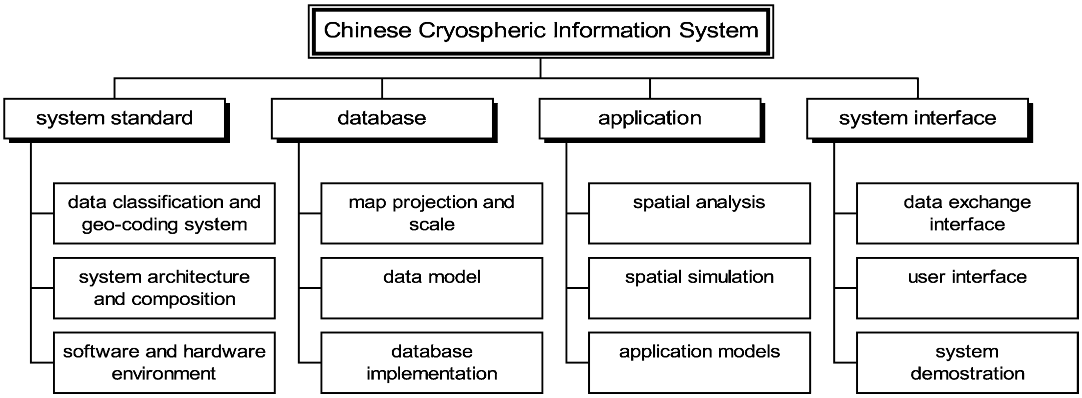

Fig. 1. General structure of the Chinese Cryospheric Information System.

existing international and national standards. The geo-classification schema of CCIS is in the form: Region Code + Source Code + Level Code + Supplement Code. There are nine codes: first is region code, indicating the three case study areas of CCIS; second is source code, indicating the data source; third–sixth are level codes, referring to the high-level classification of cryospheric data; seventh–ninth are supplement codes, referring to the low level classification of cryospheric data.

2.2.2. Software and hardware environment

CCIS is based on a client/sever architecture. Data processing and global database management is performed on a SPARC or windows NT workstation, using ARC/INFO 7.0 from ESRI. The local GIS database is managed by PC ARC/INFO and ArcView 3.0a. PC ARC/INFO and IDRISI are also used to solve simple GIS problems and to develop application models. The data exchange interfaces are designed so that CCIS can export data to other GIS environments.

2.2.3. System compositions

CCIS is composed of four subsystems, namely, data source, data preprocessing subsystem, data analysis subsystem and system users.

(1) Data source: large amounts of data, including maps of glacier, frozen ground and other environmental data, digital elevation data in different scales, observation data of meteorological stations, hydrological gauges and permafrost boreholes, section planar drawings of permafrost-engineering and remote sensing data, have been stored in CCIS.

(2) Data preprocessing subsystem: CCIS receives various sources of data, and then complies and purifies them automatically or in the man–machine interaction way. Then, the processed data are given unique geo-label and stored in CCIS.

(3) Data analysis subsystem: some spatial analysis methods have been developed in CCIS, including grid analysis, irregular triangular network (TIN) analysis, topographic analysis, spatial interpolation, spatial resampling and overlay, etc. We pay particular attention on developing some spatial interpolation methods by combining geostatistics and physical processes because there are so few meteorological stations in China's cryospheric regions.

(4) System user: CCIS is an important tool used to analyze and study cryospheric processes by scientists. It is also a tool used for planning the sustainable development of the cryosphere region by decision makers and planners.

2.2.4. Map projections and data scale

Equal-area conical projection is adopted in the Qinghai–Tibet Plateau, and transverse Mercator projection is adopted in the Qinghai–Tibet Highway and the Urumqi River Basin. The scale of the Qinghai–Tibet Plateau is 1:4,000,000 and the grid resolution is 5 km. The scale of the Qinghai–Tibet Highway is 1:250,000 and the grid resolution is 100 m. The scale of the upper reaches of Urumqi River is 1:50,000 and the grid resolution is 5–100 m.

3. Modeling cryospheric response to global change

3.1. A GIS-aided response model of high-altitude permafrost to global change

3.1.1. Data and climatic scenarios

The original digital elevation model (DEM) of the Qinghai–Tibet Plateau has a high spatial resolution of 1 km. It was resampled to a coarse resolution of 0.5°. The most up-to-date permafrost map, compiled by Li and Cheng (1996), was digitized to provide the base data. The map was converted to a grid map with a resolution of 0.5° by ARC/INFO, so that it can be coregistered with the DEM.

The GCM model HADCM2 (Viner, 1996), which was developed at the Hadley Center for Climate Prediction and Research in Britain, was adopted for climate scenarios. We only use air temperature scenarios in this permafrost response model. In order to preserve the original air temperature forecast results in the HADCM2, the nearest-neighbor method is used to resample the air temperature into $0.5 \times 0.5°$ grids compatible with the DEM for the years 2009, 2049 and 2099. For the above, three times the air temperature will increase by 0.51, 1.10 and 2.91 °C, respectively, on the Qinghai–Tibet Plateau. The maximum air temperature increase would be 1.62, 2.99 and 5.45 °C, respectively.

3.1.2. The altitude model

We used the altitude model to simulate permafrost distribution on the Qinghai–Tibet Plateau. Altitude model is based on the three-dimensional zonation in the distribution of high-altitude permafrost, namely, vertical, latitudinal and aridity (or longitudinal) zonation (Cheng, 1984; Cheng and Dramis, 1992). By using the method of curve fitting, the empirical correlation between lower limit of high-altitude permafrost (H) and latitude (φ) has been obtained. It can be expressed as (Cheng, 1984):

$$H = 3650\exp[-0.003(\varphi - 25.37)^2] + 1428 \qquad (1)$$

Because the altitude model takes the lower limit as the main criterion of high-altitude permafrost distribution, DEM is used to calculate the lower limit of permafrost distribution at every grid cell, and then the lower limit is compared with the altitude of the same grid cell to determine if there is permafrost on the grid. The judgment function can be expressed as:

$$P = \begin{cases} 1, h > H \\ 0, h \leq H \end{cases} \qquad (2)$$

where P is a Boolean variable, $P=1$ means permafrost exists, $P=0$ means permafrost does not exist, h is the altitude (m) of the grid cell.

3.1.3. Validation

Simulation result is compared with the permafrost map by Li and Cheng (1996). The results show that the altitude model can describe the permafrost distribution on the Qinghai–Tibet Plateau very well. If the 1800 spatial samples in the mapping area are taken for regression analysis, the correlation is 0.92 and the coefficient of determinacy is >85%. The permafrost area predicted by Eq. (1) is 1,294,376 km^2; comparing it with the actual area 1,272,709 km^2, the error is only 1.70%.

3.1.4. Permafrost change on the Qinghai–Tibet Plateau

There are no climatic variables in the altitude model. Therefore, some assumptions must be given out to forecast the permafrost response to global change. These assumptions are: (1) The function that describes high-altitude permafrost distribution will not change according to the climate warming. (2) If air temperature increases 1 °C, the vertical zonation will rise to a certain height based on the lapse rate and the lower limit of the high-altitude permafrost will rise to the same height. (3) Lakes, glaciers, deserts will not change.

Based on the above assumptions, and if only air temperature increase is taken into account, the permafrost distribution in the years 2009, 2049 and 2099 can be forecasted by using the altitude model.

The results (Table 1) show that the permafrost on the Plateau will change significantly during 20–50 years, the percentage of the total degraded area will be

Table 1
Permafrost changes on the Qinghai–Tibet Plateau

Air temperature increase (°C)	Permafrost area (km^2)	Degraded percentage (%)	Permafrost will degrade in regions
0.00	1,294,376		
0.51	1,190,394	8.03	Regions around Qinghai Lake, small areas of permafrost around Changdu and the permafrost between Selingcuo Lake and Namucuo Lake
1.10	1,055,613	18.45	Small areas of permafrost around Yushu and the regions with relatively low elevation in southern Qinghai–Tibet Plateau Mountains, especially the permafrost in both side of 30°N
2.91	541,329	58.18	Northeastern Qinghai–Tibet Plateau, except South Shule Mountain, regions east to 93°N and most permafrost in southern Plateau

about 18%. More drastically, by the year of 2099, if the air temperature increases by an average of 2.91 °C on the Plateau, the decrease in the area of permafrost degradation will exceed 58%. Almost all the permafrost in the Southern Plateau and in the Eastern Plateau will be degraded (Fig. 2).

3.2. A GIS-aided evaluation model of engineering properties in permafrost regions along the Qinghai–Tibet Highway

3.2.1. GIS of the Qinghai–Tibet Highway

The impacts of global warming on the Qinghai–Tibet Highway are obvious (Tong and Wu, 1996; Zhu et al., 1995). In the case study along the Qinghai–Tibet Highway, we paid particularly attention to the evaluation of permafrost engineering properties because the frozen soil environment was seriously destroyed when the highway was constructed. The GIS of the Qinghai–Tibet Highway covers the part of the highway from Xidatan to Nagqu, which is about 700 km long and 20–30 km wide on both sides of the highway. It stores digital elevation data, borehole data, ground temperature, the quaternary geology and other permafrost data. The scale of the topographic and thematic maps is 1:250,000 and the grid resolution of digital terrain model (DTMs) is 100 × 100 m. Based on the GIS, two models are developed, the permafrost

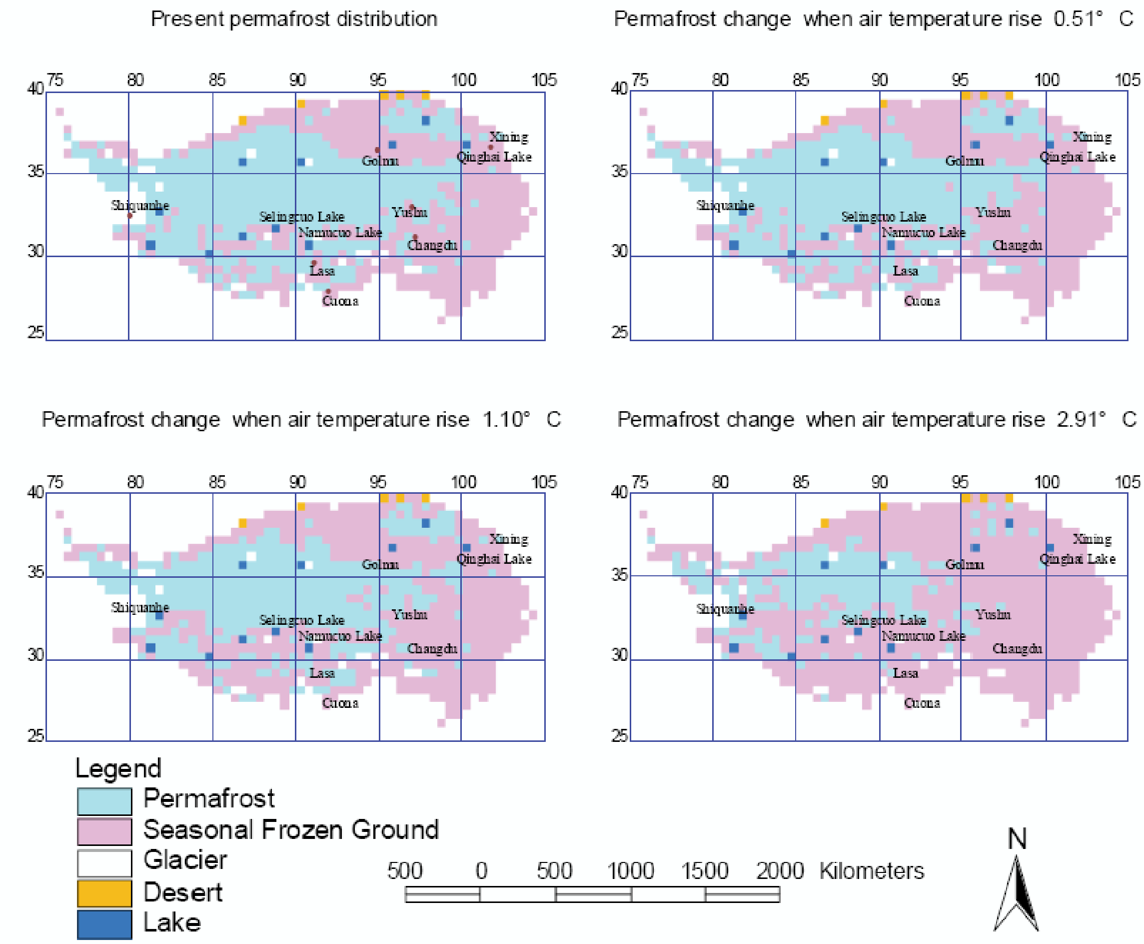

Fig. 2. The altitude model simulation result of permafrost change on the Qinghai–Tibet Plateau.

distribution model and the ground temperature zonation model. The two models evaluate permafrost engineering properties in different stability zones.

3.2.2. Modeling the permafrost stability

Traditional one-dimensional climate permafrost model is difficult to be applied for regional permafrost mapping along the Qinghai–Tibet Highway because of great regional difference in surface characteristics. Modeling of permafrost engineering properties along the Qinghai–Tibet Highway must consider high-altitude permafrost characteristics, permafrost vertical zonation, and mean annual ground temperature (MAGT). First, we use the altitude model presented in Section 3.1.2 to estimate the lower limit of permafrost along the Qinghai–Tibet Highway so that the permafrost distribution area can be delineated. Then, the mean annual ground temperature is computed at each grid cell based on the relationship between MAGT, altitude and latitude. The relationship was obtained using ground temperature measurements along the Qinghai–Tibet Highway (Cheng and Wang, 1982).

$$T = 68.873 - 0.00827h - 0.923\varphi \qquad (3)$$

where T is MAGT, h is the altitude (m) of the grid cell, φ is the latitude (degree). For 40 data samples collected along the highway, the regression coefficient of Eq. (3) is 0.96 (Cheng and Wang, 1982).

The permafrost stability has been divided into five types according to the MAGT (Table 2). Based on these criteria, the MAGT of each grid cell along the Qinghai–Tibet Highway is computed by using Eq. (3). After this, the grid cells are classified into different stability types according to their MAGT. Then, the map of permafrost stability zones is obtained. The results show that the upper zone of permafrost generally exists in high mountain areas, middle zone exists in Chumaer river high plain areas, mountain base areas and river valley areas and the lower zone do not exist alone the Qinghai–Tibet Highway. This result verified the effectiveness of the model.

3.2.3. Change of permafrost engineering properties along the Qinghai–Tibet Highway

The permafrost change due to global warming will induce significant damages in engineering constructions along the Qinghai–Tibet Highway through the increasing frost heaving and thaw settlement (Tong and Wu, 1996). Therefore, predicting the permafrost change along the highway at a reasonable precision is urgent for the mitigation and rehabilitation of engineering hazards and protection of cold region environment. To predict the change of permafrost stability, we set up a relationship between MAGT and mean annual air temperature (MAAT) (Tong and Wu, 1996)

$$T = 0.414\exp(0.326t_a) - 1 \qquad (4)$$

where t_a is MAAT (°C).

Assuming that rising air temperature will result directly in immediate permafrost warming, the rising MAAT limit will result in changing MAGT. Therefore, the increase of ground temperature ΔT can be calculate using Eq. (4), in which ΔT_a can be obtained from output results of HADCM2.

Thus, the response model of permafrost stability zone is proposed by substituting Eq. (4) into Eq. (3)

$$T = 68.873 + (0.414\exp(0.326\Delta t_a) - 1) - 0.00827h - 0.923\varphi \qquad (5)$$

The results show that permafrost stability will change significantly under climatic warming. The area extent of permafrost along the highway will decrease

Table 2
Classification of permafrost zones on the Qinghai–Tibet Plateau (Cheng and Wang, 1982)

Name of the zone		MAGT (°C)	Permafrost thickness (m)	MAAT at lower limit (°C)
Upperzone	Extremely stable type	< – 5.0	170	– 8.5
	Stable type	– 3.0 to – 5.0	110 to 170	– 6.5
Middlezone	Substable type	– 1.5 to – 3.0	60 to 110	– 5.0
	Transition type	– 0.5 to – 1.5	30 to 60	
Lowerzone	Unstable type	+ 0.5 to – 0.5	0 to 30	– 4.0
	Extremely unstable type	> + 0.5		– 2.0 to – 3.0

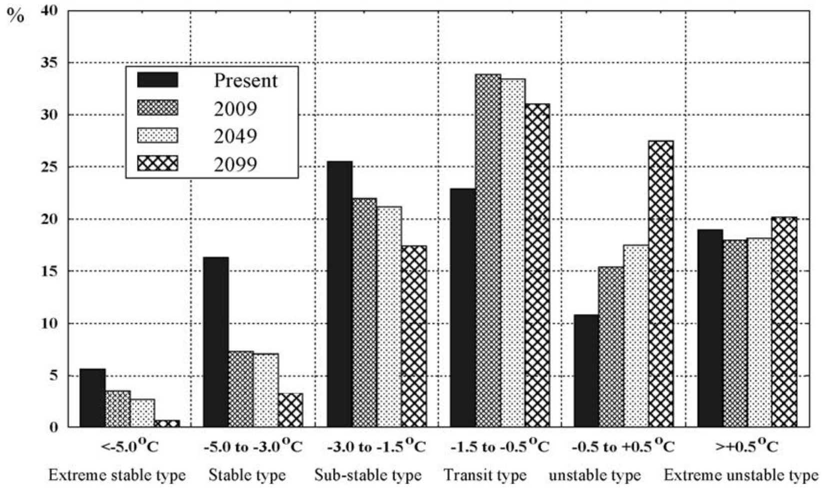

Fig. 3. The change of permafrost stability along the Qinghai–Tibet Highway.

and permafrost zone will move upward and be degrading. The relative changes of permafrost zone in a 30-km buffer area along the Qinghai–Tibet Highway are illustrated in Fig. 3, showing that the areas of extreme stable zone, stable zone and sub-stable zone will decrease, while the areas of transit zone, unstable zone and extreme unstable zone will increase.

3.3. A distributed calculation method for glacier volume change

3.3.1. Calculation method

Five topographic maps of glacier no. 1 in the headwaters of the Urumqi River Basin in different time, namely, 1962, 1964, 1973, 1980 and 1986, were digitized. Then, ARC/INFO was used to make DEMs of the glacier. The resolution of all the DEMs is 5 m.

Traditionally, the pole method has been widely used for estimation of glacier mass balance, which estimates mass balance for a whole glacier from a few typical and discrete records. Therefore, the calculated result depends on the sampling numbers, their accuracy and representativeness. We developed a distributed method for estimating glacier volume change based on the DEMs. With high-resolution DEMs in different periods, the glacier volume change can be obtained on the grid-cell level and thus the mass balance of whole glacier can be estimated. The distributed method can be expressed as:

$$\Delta V = V_i - V_j = S \sum_{k=1}^{n} (H_{ki} - H_{kj})(S = S_i \cap S_j) \quad (6)$$

where ΔV is the volume change, S is the intersection of glacier areas in time i and time j, that means the nonoverlapping areas are not considered, H_{ki} and H_{kj} are DEM values in time i and time j, k is the numbers of DEM grid cells within S.

Compared with traditional pole method, the distributed method is quick, visualized and economical, and can be used by the altitude measurements from remote sensor and GPS directly.

Table 3
Change of the glacier no. 1 at the headwaters of the Urumqi river computed by the distributed method

Year	Height change (m)	Average area change (10^6 m^2)	Average volume change (10^6 m^3)	Total volume change (10^6 m^3)
64–73	− 3.1	− 0.038	− 0.67	− 6.04
73–80	− 6.0	− 0.028	− 1.66	− 11.62
80–86	− 1.7	− 0.105	− 0.48	− 2.87

3.3.2. Glacier volume change

Table 3 shows the result of glacier change by using the distributed method. To verify the method, the computation result is compared with measured mass balance. For example, in the period from 1980 to 1986, the height of glacier surface and ice volume computed by the visualized method decreased about 1653 mm and 2.87×10^6 m^3 and those by the pole method decreased 1961 mm and 3.61×10^6 m^3. If the pole-method measured mass balance is adjusted based on changed glacier area, the decreased height of glacier surface and ice volume is corrected to 1849 mm and 3.30×10^6 m^3. The comparison results show that the distributed method is reliable (He et al., 1999).

4. Summary

In this paper, we described the design, structure, system standards and composition, and some applications of Chinese Cryosphere Information System. CCIS was established for storing, managing and analyzing the cryospheric data within China. It also worked as a platform for building GIS-based models. CCIS has stored large volume of data, including maps of glacier, frozen ground and other environmental elements, digital elevation data, observation data of meteorological stations, hydrological gauges and permafrost boreholes and remote sensing data.

The main purpose of CCIS is to model China's cryospheric change by using GIS technical. Some GIS-based empirical models and visualized methods was established in the framework of CCIS. In this paper, we introduced the response model of high-altitude permafrost to global change, the evaluation model of engineering properties in permafrost regions along the Qinghai–Tibet Highway, and the distributed model of glacier mass balance. Results showed that: (1) The permafrost on the Qinghai–Tibet plateau will degrade about 18% and 58% according to the climate scenarios in 2049 and 2099, respectively. (2) The engineering stability of permafrost along the Qinghai–Tibet Highway will change significantly under climatic warming. The area extent of permafrost along the highway will decrease and permafrost zone will move upward and be degrading. (3) The no. 1 glacier is undergoing area shrink in the last few decades. The distributed model is a quick, visualized and economical method to calculate glacier volume change.

Acknowledgements

This work is supported by the NSFC (National Science Foundation of China) project (grant number: 49971060), the Innovation project of the Cold and Arid Regions Environmental and Engineering Research Institute, CAS (CACX210018) and the Innovation project of CAS (KZCX2-301).

References

Cheng, G.-D., 1984. Problems on zonation of high altitude permafrost. ACTA Geographic Sinica 39 (2), 185–193.

Cheng, G.-D., 1996. The role of cryosphere in climate change. Proceedings of the Fifth National Conference on Glaciology and Geocryology. Gansu Culture Press, Lanzhou, pp. 807–817. In Chinese.

Cheng, G.-D., Dramis, F., 1992. Distribution of mountain permafrost and climate. Permafrost and Periglacial Process 3 (2), 83–91.

Cheng, G.-D., Wang, S.-L., 1982. On the zonation of high altitude permafrost in China. Journal of Glaciology and Geocryology 4 (2), 1–17 (in Chinese).

Fitzharris, B.B., 1995. The cryosphere: changes and their impacts. IPCC Second Assessment Report. Cambridge Univ. Press, Cambridge, UK, pp. 241–265. Chapter 7.

He, C.-Y., Ding, Y.-J., Li, X., 1999. A visualized computation method for glacier variation. Journal of Glaciology and Geocryology 21 (2), 169–174 (in Chinese).

IPCC, 1990. Climate Change: The IPCC Impacts Assessment. Australian Government Publishing Service, Canberra, Australia.

IPCC, 1992. Climate change 1992. The Supplementary Report to the IPCC Scientific Assessment. Cambridge Univ. Press, Cambridge, UK.

Li, X., 1998. The cryospheric information system and its applications. Doctoral dissertation, Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, p. 89. In Chinese.

Li, S.-D., Cheng, G.-D., 1996. Permafrost Distribution Map on the Qinghai–Xizang Plateau. Gansu Culture Press., Lanzhou. In Chinese.

Li, X., Cheng, G.-D., 1999. A GIS aided response model of high altitude permafrost to global change. Science in China, Series D 42 (1), 72–79.

Li, X., Cheng, G.-D., Chen, X.-Z., Feng, X.-Z., Wang, J., 1997. The application of GIS in cryospheric research. Geo-information Science (Special Issue), 55–59 (in Chinese).

Li, X., Cheng, G.-D., Chen, X.-Z., 1998. Response of Permafrost to Global Change on the Qinghai–Xizang Plateau—a GIS-aided model. Seventh International Conference on Permafrost, Yellowknife, Canada. Collection Nordicana 57, 611–657.

Nelson, F.E., Lachenbruch, A.H. et al., 1993. Permafrost and changing climate. Proceedings Volume 2 of Sixth International Conference on Permafrost. South China University of Technology Press, Wushan, Guangzhou, China, pp. 987–1005.

Tong, C.-J., Wu, Q.-B., 1996. The effect of climate warming on the Qinghai–Tibet Highway, China. Cold Regions Science and Technology 24, 101–106.

Viner, D., 1996. The Climate Impacts LINK Projects: Data Sets Available for Climate Change Research. http://www.nerc.ac.uk/ukgeroff/globe24.htm.

Wu, Q.-B., Mi, H.-Z., Li, X., Li, W.-J., 1998. A model to evaluate the engineering geology on frozen ground from Xidatan to Wudaoliang along the Qinghai–Xizang Highway using GIS. Seventh International Conference on Permafrost, Yellowknife, Canada. Collection Nordicana 57, 1155–1159.

Wu, Q.-B., Li, X., Li, W.-J., 2000. The prediction of permafrost change along the Qinghai–Tibet Highway, China. Permafrost and Periglacial Processes 11 (4), 371–376.

Zhu, L.-N., Wu, Z.-W., Liu, Y.-Z., 1995. Permafrost degradation in eastern regions of Qinghai–Xizang Plateau. Journal of Glaciology and Geocryology 17 (2), 120–124 (in Chinese).