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Vulnerability of mountain glaciers in China to climate change

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Abstract

Mountain glaciers in China are an important water source for both China and adjoining countries, and therefore their adaptation to glacier change is crucial in relation to maintaining populations. This study aims to improve our understanding of glacial vulnerability to climate change to establish adaptation strategies. A glacial numerical model is developed using spatial principle component analysis (SPCA) supported by remote sensing (RS) and geographical information system (GIS) technologies. The model contains nine factors—slope, aspect, hillshade, elevation a.s.l., air temperature, precipitation, glacial area change percentage, glacial type and glacial area, describing topography, climate, and glacier characteristics. The vulnerability of glaciers to climate change is evaluated during the period of 1961−2007 on a regional scale, and in the 2030s and 2050s based on projections of air temperature and precipitation changes under the IPCC RCP6.0 scenario and of glacier change in the 21st century. Glacial vulnerability is graded into five levels: potential, light, medial, heavy, and very heavy, using natural breaks classification (NBC). The spatial distribution of glacial vulnerability and its temporal changes in the 21st century for the RCP6.0 scenario are analyzed, and the factors influencing vulnerability are discussed. Results show that mountain glaciers in China are very vulnerable to climate change, and 41.2% of glacial areas fall into the levels of heavy and very heavy vulnerability in the period 1961−2007. This is mainly explained by topographical exposure and the high sensitivity of glaciers to climate change. Trends of glacial vulnerability are projected to decline in the 2030s and 2050s, but a declining trend is still high in some regions. In addition to topographical factors, variation in precipitation in the 2030s and 2050s is found to be crucial.

Keywords: Mountain glaciers; Climate change; Vulnerability; Projection

1. Introduction

It has been reported that since 1850, most glaciers in the world have been shrinking due to climate warming (Oerlemans, 2005; Arendt, 2011; Bolch et al., 2012), and the shrinkage has continued over the last two decades (Ren et al., 2004; Liu et al., 2006a,b; IPCC, 2007a, 2013; Arendt, 2011). Glacier melting has already made considerable impacts on both regional and global scales. For example, the contribution of glacier melting to sea level rise increased from (0.50 ± 0.18) mm per year in 1961−2004 to (0.77 ± 0.22) mm per year in 1991−2004 (IPCC, 2007a), and such a rise in sea level threatens coastal lowlands and small island countries. In high altitude regions of Asia, such as the Tibetan Plateau and high mountainous areas of central Asia, disasters including glacial lake outbursts, glacial floods, and glacial debris flow have occurred frequently in relation to rapid glacier melting (Mool et al., 2001a, 2001b; Che et al., 2004, 2005; Wang,

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2008; Pradhan et al., 2012), and such occurrences have severely threatened the socio-economic development and ecological patterns in both mountainous areas and downstream regions (UNDP, 2007; Xu et al., 2008). In the short-term, there are advantages from glacial melting, such as increases in river flow alleviating short-term water shortage in arid and semi-arid regions. However, the flow will reduce in the long-term with prolonged glacier melting, and its effects on food production and economic growth are likely to be unfavorable in the high altitude regions of Asia. In addition, it is considered that the flow reduction in the long-term would then give rise to a further demand for water and food supplies—a demand that is already increasing in this region (WB, 2005; UNDP, 2006; IPCC, 2007c). Therefore, glacial changes and associated effects have captured the attention of international politics and the academic world.

There are 48,571 glaciers covering a total area of 51.8×10^3 km^2 in China (Liu et al., 2015). The glaciers are distributed mainly on the Tibetan Plateau and in the high mountains of West China: the Altai, Tianshan, Karakorum, Kunlun, Qilian, Hengduan, and Himalaya Mountains. The glaciated areas in western China represent the sources of the ten largest rivers in Asia: the Yangtze, Yellow, Tarim, Salween, Mekong, Ili, Ertix, Brahmaputra, Indus, and Ganges Rivers, and they thus have a very prominent effect on the formation and change of the water resources of these rivers. For example, glaciers in western China provide rivers with approximately 60.47×10^9 m^3 of meltwater per year, which is equivalent to the average annual runoff of the Yellow River into the sea.

Glacier meltwater is of considerable importance in the inland arid area of Northwest China. In the Tarim River Basin, the largest inland river basin in China, and the most glacierised watershed in arid Northwest China, there are 11,665 glaciers covering a total area of 19,878 km^2. The ratio of glacial meltwater to runoff for each tributary is above 30%, and for some this ratio rises to 80%. A number of oases are generated and maintained in the arid hinterland of China. These would not exist without glaciers, and the region would therefore no longer be able to support populations.

China implemented the West Development Project in 2000 to improve the living standard of people in western China, and to reduce differences in development between eastern and western China, with the aim of bringing the Chinese economy into a period of rapid, stable, harmonious, and sustainable development. Although the year 2011 marked the second step in the 10-year development plan, water resources are a restrictive factor for rapid development. If future changes in glacial water supply hamper the sustainable development of society, both the economy and ecological conservation will suffer in the arid area. Thus, water supplies are keys to realizing the strategic objective of western China development. It remains both a practical and strategic issue for the Chinese central government and related local governments to gain an understanding of how to adapt to a series of natural, social, and economic effects resulting from glacier variations in the near future, and how to cope with the threatening long-term effects of continuous warming and diminishing of glacier water resources.

An assessment of the vulnerability of glaciers to climate change forms the basis for scientific adaptation to glacial variations. However, studies on glacier vulnerability to climate change have been seldom reported, and thus adaptive countermeasures formulated by Chinese government departments lack a scientific basis, and fail to achieve optimal results in practice. It is thus evident that further studies relating to glacial changes and associated impacts, glacial vulnerability, and adaptation are necessary. Vulnerability is a versatile concept that is widely used in many fields, such as climate change, risk assessment, disaster management, food security, and public health, and so on. Therefore, its associated underlying concepts can differ widely. Recently the integrated vulnerability concept of the IPCC has been gradually accepted, particularly in global change and climate change researches (IPCC, 2001b). The IPCC Third Assessment Report (TAR) (IPCC, 2001a, 2001b) defines vulnerability as the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes, which is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity. A system can be a nature, a society, an ecosystem, or in cases where one largely depends on the other, a human-environmental system.

Based on the above definition of vulnerability, Yang and Zhang (2010) defined cryospheric vulnerability as the degree to which cryosphere and its elements are susceptible to adverse effects of climate change, especially from air temperature and solid precipitation, and it is a function of the character, magnitude, and rate of climate variation, its sensitivity, and its self-adaptive capacity. The vulnerability of cryospheric change was defined as vulnerability of a system to cryospheric change, including the environment-oasis system in arid regions, ecosystems in cold regions, and other human-environmental system (Yang and Zhang, 2010). Researches on the vulnerability of both cryosphere and its change are still in initial stage. There are only a few studies addressing these issues. The composite index assessment method used widely was mainly introduced to this field. Based on the definition of vulnerability provided by the IPCC, He et al. (2012) selected seven indicators to assess the vulnerability of cryospheric change in China, from 2001 to 2020 and from 2001 to 2050 in A1 and B1 scenarios. Glacier is a very important component of the cryosphere, and it is very vulnerable to climate change, especially air temperature rise and precipitation variations.

In this paper, glaciers in China are chosen as the object of study. Based on the IPCC vulnerability definition, the authors aim to comprehensively assess the vulnerability level of glaciers to climate change, with the object of revealing temporal and spatial variations in glacier vulnerability, and to advance the understanding of glacier vulnerability in China.

The paper is organized as follows: In Section 2, we present our approach relating to a vulnerability assessment, which introduces a set of index systems for use in evaluating glacial vulnerability (Section 2.3.2). In addition, we introduce a