An empirical model to predict glacier area changes in China

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Abstract. Prediction of glacier changes is crucial for our society to adapt to the ongoing climate change. First, using correlation analysis, we found that a climate index (annual temperature) is significantly correlated with glacier area changes in China. A linear empirical model was then constructed to predict glacier area changes using temperature projections from the Intergovernmental Panel on Climate Change (IPCC). By using a subset of the glacier area change data as training data and the rest as verification data, we confirmed that the ability of the model to predict is reliable. The model requires only simple inputs and is easy to use. It gives a means of obtaining information on glacier area changes in the future for people in other disciplines as well as glaciologists who only need general information concerning glacier area changes in China.

1. Introduction

The glaciers, with a total area of 59,425 km², in the Tibetan Plateau and surrounding mountain ranges in China, constitute the most extensive glacier cover outside Alaska and the Arctic[1-3]. Over one billion people depend on water from the rivers originating in the region known as the Asian water towers[4]. The majority of these glaciers are experiencing shrinkage[5]. Variations in glaciers can have strong impacts on the water resources of downstream populations and natural systems, and can influence phenomena such as glacial lake outburst floods (GLOFs) and sea-level rise[6,7]. Glacier variations are inextricably linked with climate change[8]. Numerous researches concerning glacier variation and climate change have been carried out, which greatly improved our understanding of the relationship between glacier variation and climate change[4,5,9-14]. It is particularly important to project glacier changes especially for human livelihood.

Current glacier models provide invaluable means to understand the physics of glaciers and useful information on glacier changes both in the past and future[15-27]. But these models are compute-intensive or require many input parameters which are difficult to acquire. For example, a full-Stokes model is so computationally intensive that it is prohibitive for large-scale modeling[28]. It is time-consuming to measure degree day factors for every glacier in a large area when using degree day model. These factors make these models difficult to use by other disciplines. Glacier area is an important property of glaciers and it can serve as a proxy for glacier volume which links directly to glacier runoff. With more observations of glaciers now available, it is possible to build an empirical model based on these observations to predict glacier area change. The objective of this study is to provide a preliminary method to build an empirical model to predict area changes of glaciers in China.
2. Methods

2.1. Processing of glacier area change

There are two sources of the glacier area data: one is delineated by ourselves and the other is from published literature. More details about the data can be found in our previous study[29].

The following processes were performed to get annual glacial area changes. Assuming there are already a number of studies about the glacier area in the desired study area, in order to merge glacier area data, first they need to be interpolated if there are time overlaps between these studies. A linear interpolation method is adopted here. For example, assume there are two studies A and B. The glacier area in study A changes from $A_1$ to $A_3$ during the period 1980-2005. The glacier area in study B changes from $B_1$ to $B_3$ during the period 1970-1990. A glacier area $A_2$ is interpolated linearly in 1990 to study A as well as a glacier area $B_2$ in 1980 to study B. If a study has more than one time overlaps with other studies, we interpolate linearly in the corresponding years.

Subsequently, we calculated the glacier area change using the following method. The area change for time period $i$ ($AC_i$) is

$$AC_i = \frac{\Delta S_i}{S_{0i}} = \frac{\sum_{j=1}^{m} \Delta S_{ij}}{\sum_{j=1}^{m} S_{0ij}}. \quad (1)$$

where $j$ is the order number of studies, $\Delta S_i$ is the summary of the change of glacier area (km$^2$), $S_{0i}$ is the summary of the glacier area at the initial state (km$^2$), $\Delta S_{ij}$ is the change of glacier area (km$^2$) of study $j$ in time period $i$, $S_{0ij}$ is the glacier area at the initial state (km$^2$) of study $j$ in time period $i$, and $m$ is the number of studies for time period $i$.

The average yearly area change for time period $i$ ($AAC_i$) is

$$AAC_i = \frac{AC_i}{\Delta T_i}. \quad (2)$$

where $\Delta T_i$ is the time span for time period $i$.

The area change ($AC$) for the whole time period is

$$AC = \left[ \prod_{i=1}^{n} (AC_i + 1) \right] - 1. \quad (3)$$

where $n$ is the number of time periods.

2.2. Empirical model building

In order to build a reliable empirical model of glacier area change, two steps are needed. First we need to find a climate index that has a strong relationship with glacier area change. Here we use correlation coefficients to show the relationship between glacier area change and the selected climate index. Since glacier area change of the current year may be influenced by the climate index of a particular year or certain years before, we need to calculate the correlation coefficients between the time series of glacier area change and the time series of the climate index which need to be slid and/or accumulated. If the maximum/minimum correlation coefficient (positive/negative linear relationship) that indicates the relationship between glacier area change and the index is both strong and significant, the index is suitable to build the empirical model. Second we can build a linear empirical model from the two time series when the correlation coefficient reaches the maximum/minimum. After we have built the empirical model, if we can get the projection of the index, then glacier area changes can be projected.

3. Projection of glacier area change in China

Three types of data set were used here, namely glacier area changes (Table 1), monthly temperatures of CRU TS3.1[30](http://www.cru.uea.ac.uk/) and temperature projections using different climate
models and different scenarios from IPCC (Intergovernmental Panel on Climate Change) Fourth Assessment Report (https://esgcf.llnl.gov:8443/index.jsp).

Table 1. Glacier area changes in China.

| Year | Average yearly area change(%) | Year | Average yearly area change(%) | Year | Average yearly area change(%) |
|------|-------------------------------|------|-------------------------------|------|-------------------------------|
| 1963 | -0.25                         | 1979 | -0.33                        | 1996 | -0.37                        |
| 1964 | -0.24                         | 1980 | -0.33                        | 1998 | -0.37                        |
| 1965 | -0.23                         | 1982 | -0.33                        | 1999 | -0.38                        |
| 1966 | -0.23                         | 1984 | -0.33                        | 2000 | -0.46                        |
| 1968 | -0.18                         | 1985 | -0.34                        | 2001 | -0.57                        |
| 1969 | -0.17                         | 1986 | -0.34                        | 2002 | -0.59                        |
| 1970 | -0.16                         | 1987 | -0.34                        | 2003 | -0.59                        |
| 1971 | -0.16                         | 1988 | -0.33                        | 2004 | -0.59                        |
| 1972 | -0.16                         | 1989 | -0.32                        | 2005 | -0.61                        |
| 1973 | -0.19                         | 1990 | -0.32                        | 2006 | -0.65                        |
| 1974 | -0.17                         | 1991 | -0.36                        | 2007 | -0.65                        |
| 1975 | -0.17                         | 1992 | -0.35                        | 2008 | -0.64                        |
| 1976 | -0.27                         | 1994 | -0.36                        | 2009 | -0.65                        |
| 1977 | -0.30                         | 1995 | -0.36                        |      |                              |
| 1979 | -0.30                         | 1996 | -0.37                        |      |                              |

The glacier area changes were calculated using the method mentioned in section 2.1. In order to get the average yearly area change of glaciers for each year in each time period, we assume that the change rate is constant during the time period.

We chose the temperatures from CRU TS3.1 instead of temperatures from meteorological stations to analyse the relationship between climate and glacier area change, as the time span of station data is too short for our analysis. The monthly mean temperatures of CRU TS3.1 were aggregated to provide annual mean temperature. Then a time series of the annual temperatures in China was attained using the NCAR Command Language (NCL). In order to verify if temperature data from CRU TS3.1 are suitable for this study, the temperatures from 147 meteorological stations in west China were processed using software package RHtestV3 to make them homogeneous[31, 32]. Then we calculated the correlation coefficient between the time series of temperatures from the stations and the time series of temperatures of CRU TS3.1 from 1957 to 2009. The correlation coefficient is 0.928 (p<0.001) which indicates that the temperatures of CRU TS3.1 are suitable for this study. The time series of temperature projections from IPCC were calculated using the NCL.

We then calculated the correlation coefficients between annual glacier area change and CRU TS3.1 annual mean temperature in MATLAB R2010 (Table 2). Since glacier area change of the current year may be influenced by temperatures of the corresponding year or certain years before. Consequently, we calculated the correlation coefficients between glacier area changes and temperatures in the same year (number of slid year is 0) as well as previous years (number of slid year(s) are 1,2,3 etc). Accumulated temperatures from previous years were also used to calculate the correlation coefficients between glacier area changes and temperatures. When the number of slid years was two and the number of the accumulated years was seven, the minimum correlation coefficient of -0.96649 (p<0.0001) was obtained.
Table 2. The correlation coefficients between annual glacier area changes and CRU TS3.1 annual temperatures in China. When the number of slid years is greater than 5, or the number of accumulated years is less than 4 or greater than 9, the values are not shown. The minimum value is shown in bold.

| Number of slid year(s) | Number of accumulated Year(s) | 4       | 5       | 6       | 7       | 8       | 9       |
|------------------------|--------------------------------|---------|---------|---------|---------|---------|---------|
| 0                      | -0.88490                       | -0.91309| -0.93483| -0.94885| -0.95893| -0.96216|
| 1                      | -0.90935                       | -0.93420| -0.94861| -0.96061| -0.96645| -0.96262|
| 2                      | -0.93194                       | -0.94747| -0.95928| -0.96649| -0.96473| -0.95616|
| 3                      | -0.94114                       | -0.95417| -0.96117| -0.96057| -0.95413| -0.94595|
| 4                      | -0.93350                       | -0.94217| -0.94099| -0.93644| -0.93160| -0.93036|
| 5                      | -0.88490                       | -0.91309| -0.93483| -0.94885| -0.95893| -0.96216|

Using the two time series which produced the minimum correlation coefficient, we built a linear empirical model of glacier area change. It reflects the linear relationship between temperatures and changes of all the glaciers as a whole in China (Figure 1).

![Figure 1. Linear relationship between temperatures and glacier area changes.](image)

In the equation of Figure 1, y is the average yearly area change of glaciers and x is the accumulated temperature from 2 to 8 years before. Using the time series of projected temperatures from IPCC and the time series of temperatures produced using station temperature trend of 0.2786 °C/10yr (from 1951 to 2010), we calculated the glacier area changes in China in the future (Figure 2). By the year 2030, the glacier area will shrink between 11% and 18% (start year 2010) with an average of 14%. By the year 2050, the glacier area will shrink between 24% and 36% with an average of 29%.
Figure 2. Projections of area change of glaciers in China.

In the legend, the first part of the labels (before “_”) is the name and version of the climate model used to project the temperature, and the second part of the labels (after “_”) is the scenario name from IPCC AR4.

To verify the ability of the empirical model to predict glacier area changes in China, we estimated the model parameters using glacier area changes from 1963 to 2004 and then forecasted glacier area changes from 2005 to 2009. The root-mean-square error (RMSE) between the forecasted data and the observed data is 0.0006, which shows that the ability of the empirical model to predict glacier area changes is reliable.

Other climate indices such as annual maximum temperature, annual minimum temperature and annual precipitation were also tested, but the calculated correlation coefficients show that their relationships with glacier area change are less strong than that of annual mean temperatures.

4. Discussion and conclusions
Zhao et al. projected total glacier area loss in high mountain Asia in 2050 to be 22% (in their tuned model) or 35% (untuned) of their extent in 2000 based on a model of glacier response to climate change[25]. We calculated glacier area loss from 2000 to 2050 in China and the values varied between 28% and 40% with an average of 33%. Most of our study area is overlapped with theirs and the average value (33%) is among the range of Zhao et al.’s prediction[25].

However, in order to use the model successfully, there are several factors that need to be considered. First, sufficient information about area changes of glaciers in the desired study area is needed. Second, since glacier area variations can be affected by many factors such as temperature, precipitation, humidity, wind, sublimation, topography, debris cover, size and type or a combination of many factors[5,33], it is essential that the selected study area should have a dominant factor influencing glacier area variations if only one climate index is used. Third, the model should be used in consideration of climate regime shift and the change of the response pattern of glaciers. If one of these conditions has changed, the reliability of the projection will be weak. Fourth, if accurate projection of the climate index is available, the projection of the area changes of glaciers would be more reliable. Finally, glaciers can adapt to climate change within a certain range. If the climate reaches a new equilibrium, glaciers will adapt to the new regime and after some time they will reach a new balance. Because the adaptation of glaciers was not taken into account in the empirical model, the model becomes inaccurate if the trend of the climatic index (i.e., temperature) differs very much from the recent past.
The ability of the empirical models to perform predictions is influenced by the amount of the training data. Larger amounts of data will produce more reliable models. Although we picked annual mean temperature as the climate index, it is possible to choose another climate index or even a synthesized climate index as input. This method to build empirical models of glacier area change may be used to build an empirical model of other glacier properties such as length or volume.

The model requires only simple inputs which are easy to get, and can run on a personal computer. Consequently, it gives a useful means of obtaining information on glacier area changes in the future, in particular for people in other disciplines such as hydrology and agriculture.

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