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Statistical estimation of the impacts of glaciers and climate change on river runoff in the headwaters of the Yangtze River

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A B S T R A C T

Impacts of glacier and climate change on river runoff in the source region of the Yangtze River (SRYR) were investigated. The non-parametric Mann–Kendall test was used to detect monotonic trends in the glacier area, which was manually digitized from aerial photographs and satellite images. An exponential function between glacier volume and glacier area was established through glacier volume and area data at the SRYR, and glacier melt runoff was calculated on the basis of the function and glacier area change. Results showed that overall the climate of the SRYR became warmer and wetter during 1964–2009. During this period, the mean air temperature (MAT) showed a statistically significant increasing trend that showed a decrease before 1986 and a steady increase since 2001. The total glacier area loss from 1986 to 2009 was approximately 119.3 km^2, i.e., 10.1% of the total area in 1986 and was mainly caused by an increasing trend of air temperature in the basin. The area of the glacier in the Geladandong region exhibited an increasing trend from 1964 to 1986, which was mainly caused by an increasing trend of precipitation as snowfall in the frozen season that led to increased glacier accumulation. The glacier melt runoff from 1986 to 2009 was 2.02 $\times$ 10^8 m^3/10 y at the SRYR, which accounted for 17.5% of the total runoff changes. The increase in runoff induced by precipitation was 9.47 $\times$ 10^8 m^3/10 y, and the evapotranspiration-induced runoff consumption was 39.95 $\times$ 10^8 m^3/10 y, which accounted for 81.0% of precipitation. These results imply that less than 20% of precipitation could be transformed into runoff at the SRYR.

1. Introduction

Because glacial changes are easily understood by the public, they are regarded as some of the best climate indicators. Glacier retreat, which is an important response to climatic warming, has been identified in regions of low to high latitudes, including tropical areas (Jomelli et al., 2011), Greenland (Gardner et al., 2011), New Zealand (Kaplan et al., 2010), the Antarctic (Shepherd and Wingham, 2007), and the Arctic (Otto-Bliesner et al., 2006). Runoff at the basin scale is sensitive to long-term changes in both precipitation and temperature, particularly in temperate glaciated areas. Changes in precipitation amount tend to affect the volume of runoff and, in particular, the maximum snow accumulation that usually occurs at the end of the frozen season. There is no doubt that temperature changes affect the temporal distribution of runoff; for example, increasing temperatures lead to earlier melt runoff. However, different opinions have been reported on the impact of increasing temperature on runoff volume. Some studies showed that increasing temperatures can reduce streamflow in the melt season because of less glacier mass caused by glacier retreat (Pelto, 1996, 2008; Barnett et al., 2005; Nolin et al., 2010); others concur that increasing temperatures tend to induce glacier retreat and increase runoff through a rise in meltwater amount (Liu et al., 2003; Li et al., 2010; Zhang et al., 2011). These opposite opinions may be attributed to the different lengths of study periods because the change in runoff volume does not correlate with increasing temperatures. Runoff in a warmer climate will at first increase owing to higher temperatures and more meltwater. However, this effect is gradually reduced when the glacier area begins to decline as a result of continued glacier mass loss (Ye et al., 2003; Rango et al., 2007; Huss, 2011). River runoff will increase for a given period before showing a sharp decline in glacier basins.

In addition, meltwater in glacier basins is also affected by the evapotranspiration changes that may affect regional water availability. Unfortunately, there is little agreement on the direction and magnitude of historical or predicted evapotranspiration trends. Observations from various countries in the Northern Hemisphere show that pan evaporation has been steadily decreasing for the past

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50 years, which is contrary to the expectation that warming would cause increased evaporation (Peterson et al., 1995; Golubev et al., 2001). Barnett et al. (2005) put forth two proposals to explain this paradox. Therefore, it is important to assess the effects of climate changes on river runoff in glacier regions, which include changes in the glacier, precipitation, and evapotranspiration at the basin scale.

Remote sensing studies, coupled with *Geographic Information System* (GIS) and field investigations, are vital for obtaining baseline information on glacier changes, which improves understanding of the complex linkages between atmospheric and glaciological processes (Bishop et al., 2004). The increased availability of imagery from remote sensing platforms with adequate spatial and temporal resolution, near-global coverage, and low expense allow the measurements of glacier parameters to be extended over larger areas and longer durations (Racoviteanu et al., 2008). Remote sensing approaches that include microwave data and optical imagery are useful for monitoring alpine glaciers, particularly in glacier areas.

The source region of Yangtze River (SRYR), which is located in the interior of the Qinghai–Tibet plateau, has a unique natural environment with a specific ecological function for water conservation of abundant natural resources. The natural environment and the ecosystem are highly fragile to water availability. Therefore, it is essential to assess the effects of glacier and climate changes on runoff because such changes can ultimately affect the region's natural environment and ecosystem.

Several studies have examined climate and glacier changes over the SRYR. Glacier retreat, with strong regional variability, has been observed in the Qinghai–Tibet plateau (Yao et al., 2004). Glacier changes related to the SRYR have been investigated by Ye et al. (2006) and Zhang et al. (2008). Ye et al. (2006) used remote sensing and GIS technologies to monitor glacier variations on Geladandong Mountain, where the largest glacier near the SRYR is located. Results show a general retreat in the glaciers in the Geladandong Mountain region of 1.29 km^2/y during 1969–2002; this retreat accelerated later in the period. Zhang et al. (2008) used topographical maps and satellite images to monitor glacier changes in the Tuotuo River basin, which serves as the headwater for the SRYR. Results indicate that most of the glaciers in the basin have retreated from 1968–1971 to 2001–2002, and their shrinkage area is 3.2% of the total area measured in the late 1960s. In consideration of such rapid warming and glacier retreat, a key scientific issue of concern is the manner in which glacier change affects the regional water resources at the SRYR. However, few studies have examined this topic and the effects on runoff in the region.

In this study, the effects of glacier and climate change on runoff for the entire SRYR are assessed. The three main parts of this study include detection of long-term trends of runoff, precipitation, and air temperature; estimation of glacier change; and assessment of the effects of glacier and climate changes on runoff.

2. Materials and methods

2.1. Study area

The SRYR, which is defined as the upstream region controlled by the Zhimenda hydrological station, is located in the central eastern part of the Qinghai–Tibet Plateau (Fig. 1). This region includes one of the highest major river basins in the world at approximately 4754.5 m a.s.l., and the basin area is approximately 1.4×10^5 km^2. The three main headwater rivers include the Tuotuo, Dangqu, and Chumar rivers. Glaciers of the SRYR are primarily distributed on the northern slope of the Tanggula Mountains, the south slope of the Kunlun Mountains, and Sedir Mountain (Fig. 1). According to the Chinese Glacier Inventory (Shi et al., 2005), 753 glaciers are included in the SRYR. The total volume of glaciers within this region has a water equivalent of approximately 887.5×10^8 m^3, which is five times the annual discharge of the Zhimenda hydrological station (Shi et al., 2005). The climate of the SRYB is arid to semi-arid. The mean annual precipitation, which varies from 280 mm to 480 mm and increases from the upstream to downstream regions of the basin, is affected by the location and the topographical features of the Qinghai–Tibet Plateau. The SRYB is sensitive to environmental changes.

2.2. Data

The observed runoff at two hydrological stations (Fig. 1), including monthly, seasonal, and annual series from 1956 to 2009, was used as the hydrological data in this study. Runoff data of the Tuotuohe station for this period were only available from May to October. Hydrological data were obtained from the Tibet Hydroelectric Investigation, Designed Research Institute.

For meteorological data, observed precipitation and mean air temperature (MAT), including monthly, seasonal, and annual series, were obtained from four National Meteorological Observatory (NOW) stations in and near the YZRB and included a comprehensive series of data recorded between 1964 and 2010. All data used in this study passed data quality control measures. The geographical locations and spatial distribution of these stations are shown in Fig. 1.

For satellite images and aerial photographs, two data sources used to delineate the glacier areas in the different periods included aerial photographs obtained in 1964 and Landsat 4 and 5 Thematic Mapper (TM) satellite images obtained in 1986 and 2009. The spatial resolutions of the aerial photographs and TM images are approximately 2 m and 30 m, respectively. Satellite images and aerial photographs were obtained from http://earthexplorer.usgs.gov/.

2.3. Methods

2.3.1. Glaciers' area delineation

Several features of glaciers and their regions were mapped from the TM images and aerial photographs (Allen, 1998). Automatic mapping of glaciers is constrained by topographic shadows in mountainous regions (Gao and Liu, 2001). Therefore, manual interpretation, which has proved to be the best method for delineating glacier areas from satellite imagery based on assessments of the Global Land Ice Measurements from Space (GLIMS) project (Bishop et al., 2004; Raup et al., 2007), was selected to delineate glacier areas at the SRYR. This method is particularly effective when delineation is conducted by the same person using a combination of different types of imagery (Paul et al., 2002). The glacier area was manually digitized from satellite images and aerial photographs based on GIS, which is an efficient tool for analyzing current states and changes in glaciers (Li et al., 1998). The glacier outlines were mapped manually by using false color composite TM bands 5, 4, and 3 as red, green, and blue, respectively.

2.3.2. Mann–Kendall test

The rank-based nonparametric Mann–Kendall test is commonly used to assess the significance of monotonic trends in hydrometeorological time series (e.g., Hirsch and Slack, 1984; Chiew and McMahon, 1993; Gan, 1998; Fu et al., 2009; Xu et al., 2010). In this test, the standard normal statistic Z is estimated and compared with the standard normal deviate $Z_{\alpha/2}$. The test statistic Z is not statistically significant if $-Z_{\alpha/2} < Z < Z_{\alpha/2}$. Correspondingly, this test shows a statistically significant trend if $Z < -Z_{\alpha/2}$ or $Z > Z_{\alpha/2}$ (Gan, 1998). The standard normal statistic Z is estimated by the following formula as (Hirsch and Slack, 1984; Gan, 1998)