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Estimation of mass balance of Dongkemadi glaciers with multiple methods based on multi-mission satellite data

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ABSTRACT

In the context of climate change and variability, the change of glaciers over Qinghai-Tibet Plateau (QTP) has substantial impact on regional water resource and supply in a large geographical area in Asia. In this study, the recent change of glaciers in the Dongkemadi region in the central QTP was estimated by using multi-date Landsat images acquired over 2000–2011 and altimetry data derived from ICESat over 2003–2008. The biased elevation sampling of ICESat footprints in different laser periods was corrected before trend fitting of elevation changes by estimating the gradients of elevation changes. The results show that glaciers experienced notable recession in the last decade, at a linear shrinking rate of 0.21 km^2 (0.26%) y^{-1} in area and a thinning rate of 0.56 m y^{-1}. Mass balances based on ICESat (-421.2 ± 83 mm y^{-1} w.e) and area-volume scaling method (-487.2 ± 96 mm y^{-1}) agree well with the in-situ measurements of Xiao Dongkemadi (-444.6 mm y^{-1} w.e.), giving uncertainties with density assumptions. The results were compared with other studies, and indicate accelerated recession which may be linked with a significant warming trend in recent decades over the QTP. This study demonstrates consistent glacier changes respectively derived from different time-series data, and the potential of consensus estimates by combining multi-mission satellite data.

1. Introduction

The mountain glaciers over the Qinghai-Tibetan Plateau (QTP) and the surrounding areas represent the largest fresh water reserve on the earth outside the polar regions (Yao et al., 2012). The changes of these glaciers can have significant impact on regional hydrological process and water supply in downstream areas as the meltwaters are primary sources of water for many large rivers in Asia (Immerzeel et al., 2010). Traditional estimation of glacier mass balance by glaciological methods is direct and reliable, but such observations are limited to a very small number of small-scale glaciers due to the intensive fieldwork, high costs, and the difficulties in accessing the remote glaciers. For example, only 15 glaciers had been monitored for mass balance among the total of 46,300 glaciers (59,406 km^2) over the QTP, and only 2 glaciers had been investigated among the 1530 glaciers (2213 km^2) in the Tanggula Mountains in central QTP by 2007 (Yao et al., 2007). With the increased availability of multi-mission satellite observations, a number of glacier parameters, including length, area, elevation and ice velocity, and the changes in them, can be determined by different remote sensing data, with near global coverage and regular revisits.

There have been intensive studies on investigating glacier changes by using remote sensing data, including those detecting glacier area changes using aerial photographs and optical satellite images (Landsat MSS/TM/ETM+, ASTER, LISS, CEBERS, SPOT) (Lu et al., 2002; Narama et al., 2010; Yao et al., 2012), and estimating thickness changes based on Digital Elevation Models (DEM) constructed from historical topographical maps and new DEMs such as SRTM or from satellite stereo (Rignot et al., 2003; Berthier et al., 2007; Shangguan et al., 2008; Li et al., 2010). Most of the studies detected glacier changes with two or three records of glacier area in a long time period, or two DEMs separated at decadal time intervals. The sparse sampling of glacier status makes the results subject to uncertainties arising from accuracy of source data, methodologies and the effect of seasonal snow cover, and provided little information about the intermediate process of glacier changes. There is a need to derive more densely sequential measurements of glaciers to reduce uncertainty, and to understand processes of glacier changes and the causes.

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Knowledge about glacier elevation changes has been limited by the availability of elevation data. Fortunately, such multi-date elevation data are now available from the new generation of satellite laser altimetry GLAS (Geoscience Laser Altimeter System) carried by ICESat (Ice, Cloud, and land Elevation Satellite), operational from 2003 to 2009. GLAS/ICESat data have gained intensive attention in monitoring glacier changes in Antarctica and Greenland due to the improved spatial resolution and accuracy (Smith et al., 2005; Slobbe et al., 2008; Ewert et al., 2012). The application of ICESat data over mountain glaciers, however, needs a special analyzing method because of the sparse distribution of measurements over temperate latitude areas compared to high-latitude regions, and the more rugged terrain with steeper slopes than ice sheets of the polar region for which the ICESat was optimized (Sauber et al., 2005; Kääb et al., 2012).

Generally, mass balances, area changes and thickness changes are measurements in different dimensions (three dimensional, two dimensional or one dimensional), derived from various source of data (e.g. in-situ, optical images, geodetic data), and they are often interpreted separately in previous studies. These measurements can be linked internally, but their consistency is seldom evaluated. Furthermore, different types of data have their limitations (spatial and temporal coverage, resolution, types of observation, etc.), and the applied methods for estimating glacier changes are mostly based on certain assumptions and therefore have uncertainties. To derive consistent estimates of glacier changes, these limitations and uncertainties need to be addressed. On the other hand, the increased availability of satellite observations from different sensors provides a potential of a consensus estimate of glacier changes by combining the multi-mission derived measurements. For example, with glacier mapping from optical data and elevation detection from geodetic estimates, it is now possible to estimate mass balances of glaciers with improved accuracy and spatial coverage, and the impact of glacier changes including sea-level contributions and regional hydrological impacts can be assessed more confidently (Barry, 2006; Kääb et al., 2012).

In this study, with a focus on glaciers in the Dongkemadi region in the central QTP, we attempt to provide a detailed investigation of glacier change in recent years by combining sequential multi-spectral images from Landsat satellites and elevation measurements from GLAS/ICESat. All available high quality Landsat scenes were selected to detect the glacier area changes since 2000. Volume changes and mass balances of regional glaciers were then estimated based on the areal and elevation data, and the results were evaluated with in-situ measurements.

2. Study area

There are about 1530 glaciers in the Tanggula Mountain in the central QTP, covering an area about 2213 km^2 with volume estimated about 184 km^3 (Yao et al., 2007). The glaciers we investigated are located at the headwaters of the Yangtze River on the northern slope of the Tanggula Mountain (33°3'–33°10′N, 91°59′–92°8′E). The glaciers consist of a cluster of valley glaciers developed along broad valleys and ice caps over the mountain tops, including the Da Dongkemadi glacier (DDG) and the Xiao Dongkemadi glacier (XDG), Longxiazailongba glacier in the central and Longniyamaigangnalou glacier in the east (Fig. 1). Under the semi-arid continental climate, the glaciers developed in this region are of semi-continental type with annual mass balance mostly dominated by accumulation and ablation in summer (Koji et al., 2000). The relatively smooth glacier surface without any avalanche or surface moraines makes it ideal for remote sensing based mass balance study (Pu et al., 2008). This region is one of the most concentrated glacierized areas in the Tanggula Mountain. The XDG in the southern slope of the ice body is relatively accessible due to its low elevation ranges and smooth surface and has been monitored with field measurements of mass balances since 1989.

3. Datasets and methods

3.1. Datasets

There are about 30 Landsat TM/ETM images covering the study glaciers during 2000–2011 in the United States Geological Survey (USGS) Landsat archive. Despite the considerable number of images acquired, the number of useable images is limited due to seasonal snow and cloud cover. A total of 5 multi-spectral Landsat TM images were selected in this study (Table 1). The selected images were acquired around the end of ablation season (Late August or earlier September), and are cloud-free over the study glaciers with minimum seasonal snow cover. All 5 Landsat images are orthorectified Level 1T standard products processed with systematic radiometric and geometric correction in Universal Transverse Mercator (UTM) map projection.

Elevation data from ICESat were used to detect the inter-annual thickness change of glaciers. The altimeter GLAS/ICESat employs a near infrared (1064 nm) laser pulses to measure elevations within a diameter of 70 m footprint spaced at 172 m along-track. After finishing the calibration campaign (laser period 1AB) in 8-day repeat orbit, the ICESat satellite operated in a 3 by 30-day orbit, with a total number of 18 ICESat operational laser periods (Laser 1AB~3K) spanning from February 2003 to November 2009. The ICESat elevation data can achieve accuracy on the order of centimeters over mild terrains in good weather conditions (Shuman et al., 2006; Ewert et al., 2012). This study obtained level-2 ICESat Global Land Surface Altimetry Data product-GLA14 of release 33 (Zwally et al., 2002) from the National Snow and Ice Data Center. Fig. 1 shows the coverage of ICESat over the study area, including one track in repeated 14 laser periods (from March 2003 to November 2008). The GLA14 product comprises corrected surface elevations referenced to the TOPEX/Poseidon ellipsoid, geoid heights, saturation flags, and other information. We extracted the latitude, longitude, elevation, and geoid data of the footprints by the GLAS Visualizer and NSIDC GLAS Altimetry elevation extractor Tool (NGAT).

The repeated tracks of ICESat did not overlap exactly, as shown in Fig. 1, resulting in maximum distances of 2.4 km. Direct comparison of ICESat elevation measurements is hence unreasonable due to the rugged terrain. We therefore used the 90-m gridded SRTM DEM as a consistent topographic reference over the study region. The SRTM DEM was acquired in February 2000 using radar interferometry (InSAR) techniques and provided by the Consultative Group on International Agricultural Research; http://srtm.csi.cgiar.org/).

3.2. Methods

3.2.1. Mapping glacier extent and areal changes

The common first step in mapping glacier area from optical images is to calibrate the raw digital number (DN) values to surface reflectance. The calibration parameters including band-specific rescaling gain and bias factors, sun elevation angle at the scene center are readily provided in the metadata files, while other necessary parameters such as mean exoatmospheric solar irradiance (ESUN) for different bands and earth-sun distances are summarized by Chander et al. (2009). Atmospheric correction was conducted using the dark-object method which can meet the change detection requirement (Song et al., 2001). Deep lakes, dark in the false-color composite image, are chosen as dark objects.