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Recent glacier changes in the Tien Shan observed by satellite gravity measurements

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ABSTRACT

The glaciers in the Tien Shan are extensive and play an important role in water cycle in central Asia. However, it is difficult to accurately monitor glacier variations in the Tien Shan due to the lack of in situ widespread measurements. In this paper, glacier mass variations in the Tian Shan are obtained and investigated from 10 years of monthly GRACE gravity solutions (January 2003–December 2012) and the WaterGAP Global Hydrology Model (WGHM), including seasonal, secular and interannual variations. Results show that significant seasonal variations of glacier mass are found with the maximum normally in April–June and the minimum around in November–December. The trends in all four regions are positive from 2002 to 2005 and negative from 2005 to 2012, indicating that the Tien Shan glaciers are increasing prior to 2005 and significantly melting after 2005. These changes are consistent with the temperature change in the Tien Shan. In addition, in the past decade the precipitation has decreased and evapotranspiration has increased, which have joint influences on glacier mass changes in different regions of the Tien Shan.

1. Introduction

The Tien Shan is located in central Asia, through central Xinjiang Province, China with the western end stretching into Kazakhstan. The total glacier area in the Tien Shan is ~10,100 km^2. Fig. 1 shows the distribution of glaciers in the Tian Shan. The World Glacier Inventory (WGI) (http://nsidc.org/data/glacier_inventory/browse.html) contains information for over 130,000 glaciers in the Tien Shan, including geographic location, area, length, orientation, elevation and classification. However, the Tien Shan has a mean elevation of over 3000 m, and it is thus very difficult to accurately monitor glacier variations due to the lack of in situ widespread measurements (e.g. evapotranspiration, precipitation, surface run-off and soil moisture).

Earth's continental ice sheets are changing, related to the temperature, precipitation, river runoff and evapotranspiration, which affect and are affected by changes in Earth's climate (Jin et al., 2013). Due to recent global warming, some glaciers are melting and cause sea level rise (e.g., Avsar et al., 2016). Glacier shrinkage in the Tien Shan has recently been reported based on remote sensing data (e.g. Aizen et al., 2006; Niederer et al., 2008; Narama et al., 2006; Jing et al., 2006; Li et al., 2006; Shangguan et al., 2006; Liu et al., 2006). However, remote sensing data have some limitations, such as low temporal resolution and limited study area. Furthermore, various types of remotely sensed data with different time periods make them difficult to compare. The recent development of satellite gravimetric techniques has given us a new opportunity to measure glacier mass change (e.g. Jin et al., 2013, 2014). The Gravity Recovery and Climate Experiment (GRACE) mission, launched in 2002, has been very successful to monitore the Earth's time-variable gravity field by determining accurately the relative position of a pair of Low Earth Orbit (LEO) satellites. GRACE satellite gravimetry offers the unique opportunity to directly measure mass redistribution by monitoring gravity change, which has been widely used, such as ice sheet mass balance, terrestrial water storage (TWS), sea level rise, and ocean circulation (e.g. Velicogna and Wahr, 2005; Velicogna, 2009; Frappart et al., 2008; Rodell et al., 2009; Morison et al., 2007; Jin et al., 2010, 2011; Hassan and Jin, 2016). Over the land, the detailed monthly gravity field solutions can estimate TWS variations (Wahr et al., 1998; Jin et al., 2012; Jin and Feng, 2013; Shen et al., 2015). After excluding the surface water, snow, canopy water and groundwater, the ice sheets storage variations can be estimated.

In this paper, the total water storage variation with monthly resolution is derived from 10 years of monthly GRACE measurements (2003 January–2012 December), and ice mass variations in the Tien Shan are obtained by subtracting the surface water, snow, canopy water and groundwater from the hydrological model, WGHM (WaterGAP Global Hydrology Model). The seasonal ice mass variations and trends in the Tian Shan are investigated from ~10 years of monthly ice mass variation time series.

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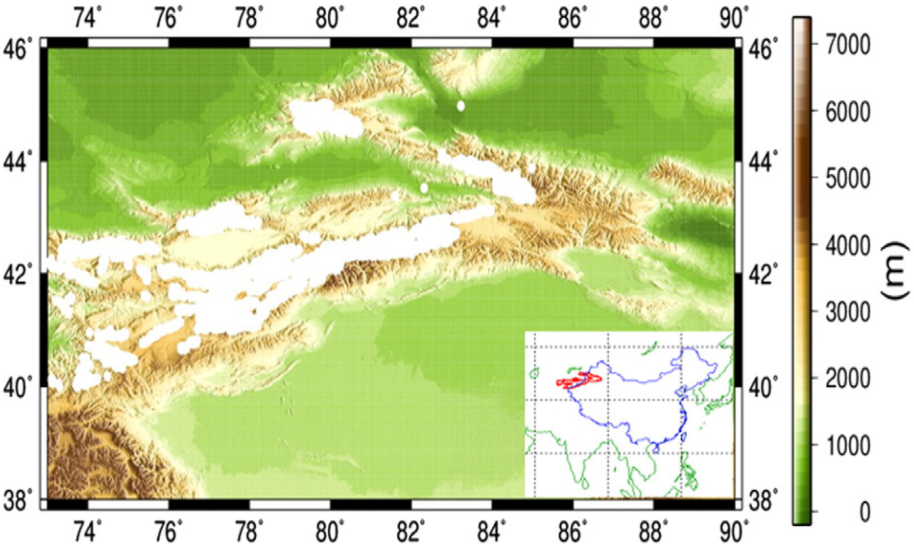

Fig. 1. Distribution of glaciers in the Tien Shan and surroundings.

2. Observations and methods

2.1. Terrestrial water storage from GRACE

The GRACE Project delivers sets of spherical harmonic coefficients describing the temporal Earth's gravity field variations, which can be used to study the Earth's mass redistribution caused by, for example, fluctuations in terrestrial water storage, changes in the polar ice sheets and changes in atmospheric and oceanic mass (Wahr et al., 1998). After atmospheric and oceanic mass effects are removed from climate and ocean circulation models, the remaining signals are mostly related to variations of TWS (Zhao et al., 2015). TWS anomalies over the land, $\Delta\eta_{\mathrm{land}}$ can thus be directly described by gravity coefficient anomalies (ΔC_{lm}, ΔS_{lm}) (Swenson and Wahr, 2002):

$$\Delta\eta_{\mathrm{land}}(\theta,\phi,t)=\frac{a\rho_{\mathrm{ave}}}{3\rho_{\mathrm{w}}}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\tilde{P}_{lm}(\cos\theta)\frac{2l+1}{1+k_l}(\Delta C_{lm}\cos(m\phi)+\Delta S_{lm}\sin(m\phi)) \tag{1}$$

where ρ_{ave} is the average density of the Earth, ρ_{w} is the density of fresh water, a is the equatorial radius of the Earth, $\tilde{P}_{lm}$ is the fully-normalized associated Legendre function of degree l and order m, k_l is Love number of degree l (Han and Wahr, 1995), θ is the spherical co-latitude, ϕ is the longitude and t is the time. Due to measurement errors and noise in the GRACE data, we have used the post-process and applied for a factor to the GRACE data after filtering following Landerer and Swenson (2012): degree 2, order 0 coefficients are taken from satellite laser ranging (Cheng and Tapley, 2004), degree 1 coefficients are replaced from Swenson et al. (2008), a de-striping filter and a 500 km Gaussian spatial smoother are applied (Swenson and Wahr, 2006; Jekeli, 1981) and post-glacial rebound signals are removed according to the model of Paulson et al. (2007) as revised by Geruo et al. (2013). Monthly TWS anomalies are calculated based on GRACE Release 5 (RL05) gravity field data from January 2003 to December 2012 (excluding June 2003, January 2011, June 2011, May 2012 and October 2012 with missing data), provided by the Center for Space Research (CSR) at the University of Texas, Austin (Bettadpur, 2007).

2.2. Land water storage from WGHM model

The WaterGAP Global Hydrological Model (WGHM) (Döll et al., 2003; Güntner et al., 2007) was developed to analyze water resources and water use in river basins, with a resolution of 0.5° × 0.5°. The model computes monthly time-series of surface and subsurface runoff, groundwater recharge and river discharge as well as storage variations of water in canopy, snow, soil, groundwater, lakes, wetlands and rivers. Therefore, the total continental water storage described in the model is the sum of canopy, snow, soil and groundwater storage as well as water stored in surface water bodies, e.g. rivers, wetlands, lakes and reservoirs. Here, we calculate the land water storage, including snow water storage, soil moisture storage, surface water storage and groundwater storage, based on the latest WGHM model's components with 1° spatial resolution from January 2003 to December 2012. In order to be consistent with GRACE results, we firstly use an interpolation method to adjust the spatial resolution from 0.5° to 1° and then use the same Gaussian filter and de-striping filter to process spherical harmonic coefficients from the WGHM model to eliminate errors in the data processing. Thus, the land water storages are obtained based on the processed spherical harmonic coefficients. To mitigate the leakage errors of signals, we convert water storage from WGHM to gravity coefficients for a unit amplitude mass signal over the glaciers in each region using the destriping filter and Gaussian smoothing, which are compared with the unit amplitude mass signal, and we can obtain the scaling factors with about 1.1 for the GRACE estimates.

2.3. Ice mass storage

The TWS estimated from GRACE includes groundwater, snow, glaciers, soil moisture, surface water and biological water. The land water storage from the WGHM model contains groundwater, snow, soil moisture, surface water and biological water, without the ice masses. After subtracting the WGHM land water storage from total continental water storage determined by GRACE, the monthly ice-mass storage changes are obtained in the Tien Shan for the available months.

3. Results and analysis

The ice mass storage variability has strong seasonal and secular signals. We therefore use a model including the annual, semi-annual and linear trend terms to fit the ice mass variation time series as (Jin and Feng, 2013):

$$M(t)=a+bt+\sum_{k=1}^{2}c_k\cos(\omega_k t-\phi_k)+\varepsilon(t) \tag{2}$$