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Investigating mountain glacier motion with the method of SAR intensity-tracking: Removal of topographic effects and analysis of the dynamic patterns

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ABSTRACT

Accurate knowledge of glacier motion variations can provide critical information for assessing glacier mass balance changes. For fast-flowing high mountain glaciers, SAR Intensity-tracking may be the most appropriate technique to measure their motions. However, due to the slant range imaging mode, topographic relief can give rise to pixel disalignments in SAR image and then bring errors to SAR Intensity-tracking. As a result, the application of SAR Intensity-tracking has been limited to SAR pairs with short baselines, because the use of image pairs with long baselines would suffer significant topographic effects over mountainous regions. This paper presents an improvement to SAR Intensity-tracking by adding an explicit procedure of topographic correction. Such correction will not only significantly increase the accuracy of the SAR pairs with shorter baselines, but also allow the image pairs with longer baselines to be taken advantage of, instead of letting them to be dismissed otherwise. Using the improved SAR Intensity-tracking technique, we derive the highly precise motion variation patterns of 11 giant glaciers in Tuomuer–Khan Tengri Mountain Ranges, one of the largest glacial centers in Tien Shan. The results manifest that most glaciers there saw flow deceleration during the observation interval (6 January 2007–4 March 2011), except the Northern and Southern Inylchek Glacier. Regarding the glacier motion mechanism, ice thermal character and climate features there, we deduce that the flow acceleration and deceleration should be the sign of glacier mass gain and loss, respectively, and the sharp and slight flow decelerations should correspond to remarkable and mild mass loss, respectively. We confirm these deductions by exploring the close link between the long-term motion variations and the dynamic patterns of these glaciers. The obvious diversities of the dynamic patterns among the studied glaciers are ascribed to the discrepancies of the glaciers' location and scale. Longer observations are still needed to confirm or redefine these findings in the future though. Provided that the precipitation keeps increasing, whether the glaciers in Tuomuer–Khan Tengri Mountain Ranges will regain mass or not has not been determined yet.

Contents

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1. Introduction

The dynamics of mountain glaciers is extremely sensitive to the climate change and it has been recognized as the most suitable indicator of global climate change by the scientific community, including the Intergovernmental Panel on Climate Change (IPCC). Along with the global climate warming, the interest in the dynamics of high mountain glacier has greatly increased due to the observations of the accelerated mass loss of mountain glaciers since 1980. That process has been linked to the sea level rises (Dyurgerov and Meier, 1997; Berthier et al., 2010; Immerzeel et al., 2010) and the remarkably intensified natural hazards such as droughts, floods, mudslides and avalanches (Kääb et al., 2003; Quincey et al., 2007; Gardelle et al., 2011). Several indexes have been adopted to represent or measure glacier mass balance changes, such as glacier thickness, area coverage, terminus position, equilibrium line latitude, accumulation area ratio, ablation degree day factor and runoff (Hagg et al., 2008; Racoviteanu et al., 2008; Han et al., 2010). However, one index, the glacier motion, which is closely correlated with the mass balance, has not been given sufficient emphasis due to lack of efficient spatial mapping technique. For glaciers, mobility is one of their essential characters (Ren, 1990). It is the glacier motion that controls the balance of mass flux between accumulation and ablation zone, and determines the glacier's geometry and extent directly (Kääb, 2005). A glacier flows at a balance velocity, when its driving and resisting forces are in equilibrium. The driving forces are the stresses generated as a result of gravity that is factored by the glacier mass and bed slope. Since in general glaciers have already adjusted their bed slope to produce sufficient stresses to maintain the balance velocity, glaciers' mass becomes the major determinant of driving forces. Significant deviations from the balance velocity are likely to be a result of losing balance between driving and resisting forces (Nesje and Dahl, 2000). For tide glaciers, due to the collapse of ice shelves which buttress them, the flow resisting forces decrease and therefore the flow velocities increase (Rignot et al., 2004). The exact mass balance changes of tide glaciers can be directly derived by measuring the flow velocity variations at the grounding line, since ice calving into sea is the major way of their mass loss. However, for land terminated mountain glacier the mass loss is mainly in the form of shrinking or down-wasting (stationary thinning). Therefore, it is difficult to derive exact mass balance changes from motion measurements. However, since on land the variation of flow driving force is more likely to occur than that of the resisting force, precise knowledge of glacier motion can still provide critical information on mountain glacier's dynamics in response to climate change.

In situ measurements, optical remote sensing Feature-tracking and space-borne Synthetic Aperture Radar (SAR) techniques are three primary ways to derive glacier motion. In situ measurements, e.g., stake network plantation (Mayer et al., 2008) and ground-based SAR (Luzi et al., 2007), can provide the most accurate results but present some serious limitations for high mountain glaciers. Due to the remoteness and large spatial extension of mountain glaciers, conducting regular in situ measurements on an entire glacier may encounter safety problems, logistical difficulties and political or cultural conflicts of territory access, and at the same time, is costly and time-consuming, or even impossible (Racoviteanu et al., 2008). Possessing the advantages to avoid the above problems, Feature-tracking between repeat optical remote sensing images is confirmed to be a superior technique (Berthier et al., 2005; Kääb, 2005; Mayer et al., 2008; Scherler et al., 2008). It estimates the glacier surface motion by tracking the features such as crevasses and debris that remain discernible over the images' acquisition periods. However, optical images rely on solar illumination and are severely limited by cloud cover. Acquiring enough cloudless optical image pairs to model glacier motion patterns in high mountain areas, where strong weather phenomenon occurs frequently, is generally very difficult (Erten et al., 2009). By contrast, characterized by being independent of cloud cover and solar illumination, SAR (referring to space-borne SAR in the following context) has provided invaluable tools to study the mountain glaciers. Up to now, two categories of SAR techniques, i.e., the interferometry-based techniques (e.g., conventional Differential Interferometric SAR (D-InSAR) and Multiple Aperture InSAR (MAI)) and the correlation-based techniques (e.g., Coherence-tracking and Intensity-tracking), have been adopted for glacier studies. Having the potential of detecting displacement at the precision of centimeter or even millimeter, the D-InSAR and MAI have revolutionized the study of glacier motion (Goldstein et al., 1993; Gourmelen et al., 2011). However, the way that D-InSAR and MAI detect displacements, computing the phase differences between two SAR acquisitions, is subject to good coherence maintaining. For the high mountain glaciers, not only the movements but also the surface feature changes are quite rapid. As a result, the coherence often degrades to be unreliable within even the shortest revisit time interval for most of the sensors (e.g., 24 days for Radarsat, 35 days for ERS/Envisat, and 46 days for ALOS) (Berthier et al., 2005; Lange et al., 2007). The successful examples, in deriving the motion of high mountain glacier with D-InSAR or MAI, although existed, are only limited to very few cases, see e.g., Mattar et al. (1998), Rabus and Fatland (2000) and Kumar et al. (2011). Being with poorer precision but capable of detecting the absolute displacements, the correlation-based techniques turn out to be attractive alternatives. Among the options, SAR Intensity-tracking, with the characteristic of being coherence-independent, enables the detection of large glacier displacements that occur within a long time span (Strozzi et al., 2002). Therefore, SAR Intensity-tracking appears to be the most appropriate technique to derive the motion of high mountain glaciers.

SAR Intensity-tracking estimates the displacements by computing the coordinate offsets between the optimally cross-correlated master and slave images. The computed offset contains contributions from satellite orbit differences, surface displacements (e.g., glacier motion), topographic relief and ionospheric effects. To acquire the surface displacements, the other components must be separated. A high-pass filter could eliminate the ionospheric effect if it existed (Wegmüller et al., 2006). Assuming that most parts of the SAR pair are stationary,