InSAR-based Glacier Velocity Mapping in the Parlung Zangbo River Basin, Tibetan Plateau, China

Chang-Qing Ke 1) † · Hoonyol Lee 2) · Lan-Yu Li 3)

Abstract: By applying the method of SAR interferometry to X-band synthetic aperture radar (SAR) image of COSMO-SkyMed, detailed motion patterns of five glaciers in the Parlung Zangbo River basin, Tibetan Plateau, in January 2010 have been derived. The results indicate that flow patterns are generally constrained by the valley geometry and terrain complexity. The maximum of 123.9 m a⁻¹ is observed on glacier No.1 and the minimum of 39.4 m a⁻¹ is found on glacier No.3. The mean values of five glaciers are between 22.9 and 98.2 m a⁻¹. glaciers No.1, No.2, No.4 and No.5 exhibit high velocities in their upper sections with big slope and low velocities in the lower sections. A moraine lake accelerates the speed of mass exchange leading to a fast flow at the terminal of glacier No.3. These glaciers generally move along the direction of decreased elevation and present a macroscopic illustration of the motion from the northwest to the southeast. The accuracy of DEM and registration conditions of DEM-simulated terrain phases has certain effects on calculations of glacier flow direction and velocity. The error field is relatively fragmented in areas inconsistent with the main flow line of the glaciers, and the shape and uniformity of glacier are directly related to the continuous distribution of flow velocity errors.

Key Words: InSAR method, Glacier velocity, Error analysis, Parlung Zangbo River basin

1. Introduction

Mountain glaciers are highly sensitive to climate change and serve as an important indicator for climate change (McCarthy et al., 2011). From a global perspective, the majority of glaciers are in a state of retreat, and this phenomenon is particularly evident in mountain glaciers (Barry, 2006). Although a small number of glaciers have advanced over the past 50 years, 82% of the more than 5000 glaciers in West China have experienced a state of retreat, resulting in a 4.5% reduction in total glacier area (Jiang et al., 2011). On the Tibetan Plateau, the majority of monitored glaciers are showing a trend of retreat (Yao et al., 2012).
Rises in temperature and rainfall precipitation (frequency of rainfall is higher than snow at high latitudes and low elevations) are the primary factors causing the melting of glaciers (Huai et al., 2014), and they have also led to a negative correlation between glacier mass balance and time scale (Kang et al., 2010).

In the context of global warming, real-time monitoring of physical changes and motion patterns of glaciers is necessary for predicting glacier evolution and future climate (Diolaiuti et al., 2012). Glacier surface flow velocity is an important physical factor for mass balance changes and a critical parameter for glacier dynamics research. Accurate measurements of seasonal and inter-annual glacier velocity fields are of great importance to understanding the motion displacement of glaciers and ice sheets caused by climate change (Berthier et al., 2005). In addition, glacier motion provides important information for identifying the glacier mass balance equilibrium line and sea level rise (Dowdeswell et al., 1999).

Field measurements have long been an important method of generating surface flow velocity field maps of glaciers. Compared with traditional measurements using a measuring stake, acquiring surface flow velocity fields by remote sensing methods which generate data on a large scale, is more convenient and has a lower cost (Yan et al., 2013). The synthetic aperture radar (SAR) possesses all-weather operational capabilities of obtaining images in glacier regions and is not affected by clouds or rains, and it has rapidly become a frontier area in remote sensing applications (Cigna et al., 2012). Because glacier motion in SAR image can show distinct variation characteristics, numerous studies have demonstrated the application advantages of SAR data and SAR interferometry (InSAR) techniques in the field of glacier dynamics (Li et al., 2008). Satellites carrying SAR sensors have been launched in a number of countries, and the increasingly numerous SAR data provide more additional information for applied research in glaciology (Jiang et al., 2011). As an efficient and sensitive extraction technology of surface flow velocity field, the wide use of InSAR methods provides rapid and accurate reference information for studies of glacier dynamics (Michel and Rignot, 1999). The majority of previous studies have focused on motion field evaluations of polar glaciers and ice sheet mapping, such as in Alaska, Greenland and Antarctica (Ciappa et al., 2010; Goldstein et al., 1993; Joughin, 2002; Mohr et al., 1998). In addition, the application of InSAR techniques has obtained excellent result for glaciers in the south regions of the Himalayas, Karakoram, Tianshan Mountains and Yigong Zangbo River basin (Jiang et al., 2012; Ke et al., 2013; Kumar et al., 2011; Yan et al., 2013). Glacier observations have potential implications for water resource utilization, local climate research and natural disaster predictions (Liu et al., 2012). Since 2006, China has been conducting comprehensive observational studies of glacier changes in the Parlung Zangbo River basin in southeast Tibet (Yang et al., 2010). However, research on glacial motion is still rare.

Compared with C-band and L-band images, InSAR analysis of X-band images on short time scales can achieve more accurate image pair matching and terrain registration, thus improving the quality of InSAR results (Ciappa et al., 2010; Crosetto et al., 2015; Schubert et al., 2013). Therefore, the use of X-band images has a great advantage in defining glacier boundary and extracting surface flow velocity fields. In this study, the velocity fields of five glaciers in the Parlung Zangbo River basin are mapped with COSMO-SkyMed (Constellation of small Satellites for Mediterranean basin Observation) X-band data. The glacier motion patterns, height and position of their mass balance equilibrium lines are described by using the InSAR technique and accumulation area ratio (AAR) method. Combined with the physical parameters of the COSMO-SkyMed satellite observation system, the accuracies of glacier velocity fields are evaluated, and distribution field of glacier velocity errors are
mapped. The results provide a reference for research on glacier change and rational use of glacier water resources in the southeast Tibetan Plateau.

2. Study area and data

1) Study area

The Parlung Zangbo River basin lies in the southeast Tibetan Plateau at 30.16°-30.40°N, 94.50°-95.20°E (Fig. 1). The basin is located at the junction where the Himalayas traverse along the Tanggula and Hengduan Mountains, and it covers a vast area, with the Namchabarwa Peak as the centre and Great Bend of Brahmaputra lower reaches as the arc. The geomorphological features of the basin area are generally high mountains, deep valleys and wide gullies in an alternative distribution, and the terrain is greatly undulating from 5500 m to 2479 m above sea level (Zeng et al., 2007). The Parlung Zangbo River basin belongs to the subtropical mountainous climate, and it is influenced by the southwest monsoon, with abundant rainfall at ~1000-3000 mm above the glacier mass equilibrium line and mean temperature in summer above 1°C (Chen et al., 2012). The Parlung Zangbo River is the largest tributary to the north of Brahmaputra’s Great Bend, and it originates from the Laigu glacier (also known as Yanong glacier) and flows from the east to the west through Ranwu, Songzong and Guxiang. At Tongmai, the Parlung Zangbo River converges with the Yigong Zangbo River from the west and turns to the southwest, entering the Brahmaputra River at ~40 km. The Parlung Zangbo River is the largest distribution area of maritime glacier in China, and it retains a large range of glacial remains. A total of 2968 modern glaciers are in the Parlung Zangbo River basin, with an average area and thickness of 2.14 km² and 109 m, respectively. The majority of these glaciers are in a state of pressure melting because of intense surface melting and fast movement (Li et al., 1986). The five glaciers in the study area are designated Glaciers No.1-No.5 (Fig. 1).

2) Data

The COSMO-SkyMed satellite observation system is a radar satellite constellation jointly developed by the Italian Space Agency and Defence Department. It consists of four medium-sized X-band (λ = 3.1 cm) near-Earth satellites at a temporal resolution of 16 days, and it is completely launched by the end of 2010 (COSMO SkyMed System, 2010). COSMO-SkyMed images are characterised by high spatial resolution, wide coverage range, selectable incidence angles, and multi-polarization. Combined with precise orbit data, COSMO-SkyMed images have a great advantage in monitoring ground surface deformations using repeat-track interferometry. In local areas, X-band images may be more sensitive and can identify tiny surface deformations (Ciappa et al., 2010; Liu et al., 2011). We investigate the characteristics of glacier surface flow velocity using two single-look-complex (SLC) SAR images (Table 1) in January 2010 on STRIPMAP HIMAGE mode that covers the Parlung Zangbo River basin at a spatial resolution of 3 m. Because of the time interval of only 1 day, the interference fringes are
relatively clear, even in the southeast Tibetan Plateau, which has undulating terrain and complex mountain structures.

Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) at a spatial resolution of 90 × 90 m (version 4) is used for topographic corrections, image registration and geocoding of multi-look SAR images. Additionally, the DEM is adjunctively used to identify the glacier boundary, calculate the slope and aspect, and map the glacial flow velocity. The projection mode is UTM zone 42.

3. Method

1) InSAR principle

Interferometry processes two radar images to obtain the phase difference caused by glacier surface motion, and it then calculates glacier displacement within the acquisition time interval between two images according to the phase difference (Joughin et al., 1995). The two SLC radar images are referred to as the master image and slave image, respectively. The maximum cross-correlation algorithm is used to perform image registration on the two images pixel-by-pixel, which corrects the antenna gain pattern and nonzero Doppler centre, thereby correcting Doppler frequency changes along the orbit caused by side-looking (Joughin et al., 1996). The results of interferometric processing contain amplitude and phase information of the same pixels in the master and slave image after registration. The noise generated by the curvature of the earth is removed with precise orbital information. The SRTM DEM in the study area is used to remove terrain phase, and after the removal of terrain signals, the phase produced by the surface change is unwrapped from the repeatedly observed radar images to obtain the interferogram of glacier surface deformation (Joughin et al., 1998; Massonnet et al., 1993; Muskett et al., 2008; Scharroo and Visser, 1998).

Because of its high sensitivity to glacier surface deformation, InSAR is often used to measure glacier velocity fields (Joughin et al., 2010). InSAR requires an effective interference process to obtain accurate flow velocities (Gourmelen et al., 2011). Feature tracking is also very widely used to exploit glacier motion and mass balance change, and it is more effective than InSAR in areas where coherence is not maintained such as fast-flowing glaciers. The drawback of the feature tracking, compared to InSAR, is that the spatial resolution (and accuracy) for estimating displacements is lower than InSAR. InSAR techniques have been widely used in velocity estimations of glaciers and polar ice sheets (Joughin et al., 2004) and applied to research on surface deformation caused by land subsidence, earthquakes and volcanic events (Cigna et al., 2012; Massonnet et al., 1993). COSMO-SkyMed data have very short time baseline (1 day) and Perpendicular baseline (51 m) (Table 1), and their coherence is effectively maintained, therefore InSAR method is used in this study to estimate the displacement and velocity with higher accuracy.

2) Glacier velocity calculation

We used Gamma software for processing the interferometric pairs listed in Table 1. Firstly, SLC images from level-0 raw SAR data sets are generated, then an interferogram from a pair of sub pixel coregistered SLC images is produced, and the next step is extraction of deformation pattern from interferogram.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Acquisition data</th>
<th>Orbit type</th>
<th>Polarization</th>
<th>Time baseline</th>
<th>Perpendicular baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSKS2</td>
<td>29 January 2010</td>
<td>Descending</td>
<td>HH</td>
<td>1 day</td>
<td>51 m</td>
</tr>
<tr>
<td>CSKS3</td>
<td>30 January 2010</td>
<td>Descending</td>
<td>HH</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
after removing the topographic phase using existing SRTM DEM. During the process of removing the topographic phase, it is hard to coregister accurately the reference phase to the coordinate system of the interferogram, and the offsets between the reference phase and the interferogram will lead to phase error. This error and the errors in SRTM DEM will further result in residual errors in extracting glacier flow patterns. For the purpose of removing most of the topographic phase with the preliminary DEM, an iterative computation to subtract the topography phase was implemented. We chose an ice-free and flat area as the ‘threshold phase region’ and set the value of the threshold phase to approximately zero, and manually set the initial offsets in range and azimuth direction in the range -10 to 10 pixels, in order to compute and subtract the reference phase from the interferogram iteratively with different offsets in range and azimuth direction until the phase of the ice-free area meets the threshold (Zhou et al., 2011). After this processing, most of the topography phase has been removed from the interferogram. The interferogram, which the topographic phase is subtracted cleanly, was unwrapped using algorithms provided by Gamma software and converted the phase to line-of-sight (LOS) velocity of the glacier. Finally, the nunataks near the glaciers were used as a zero motion reference to calibrate the LOS velocity.

From the InSAR processing mentioned above, the measured LOS velocity is merely the surface velocity projected onto the radar line of sight. To obtain the actual glacier surface flow velocity, four assumptions are required (Li et al., 2008): 1) glacier moves in parallel to the direction of surface features; 2) the DEM used to remove terrain phase can accurately reflect the geomorphological features of ground surface; 3) elevation change between image pairs used for interferometric processing can be neglected; and 4) effect of the atmosphere is negligible. Based on these assumptions and the methods proposed by Li et al. (2008) and Kumar et al. (2011), the LOS velocity measurements were projected to the glacier surface to get the actual glacier flow velocity (3D).

3) Estimation of equilibrium line altitude

The glacier mass equilibrium line altitude (ELA) refers to the altitude of the line connecting points with mass accumulation equal to the melting of glaciers in a balance year on a non-shaded plane (altitude of the lower limit of the additional ice belt) (Cui and Wang, 2013). The AAR method is chosen to estimate the mass equilibrium line of the five glaciers, and it assumes that when the glacier is in a steady state, the area of the glacier accumulation zone accounts for a fixed ratio of the total glacier area at a certain altitude, and the ratio is the AAR value, whereas the altitude and location indicate the glacier mass equilibrium line (Meier, 1962). The method of selecting an appropriate AAR value is the key step to estimate ELA by the AAR method. According to the empirical formula (1) proposed by Kern and László (2010), AAR can be calculated.

\[
AAR = 0.0648 \times \ln S + 0.483
\]  
\[
AAR = \frac{S_{ELA}}{S}
\]

where \( S \) is the total area of the glacier, and \( S_{ELA} \) is the area of the steady accumulation zone above the glacier mass equilibrium line. At the same time, based on the calculated empirical AAR value, \( S_{ELA} \) can be calculated with formula (2) according to AAR’s definition by Meier (1962). Thus, the ELA of glacier mass and its location can be estimated in support of SRTM DEM.

4) Error estimation

In glacier dynamics research, it is relatively rare to map the error field of individual glacier, whereas the errors of each pixel point on the glacier surface are a direct reflection of the accuracy of flow velocity calculation. The glacier surface velocity error field \( \Delta D \) is estimated according to the following formulæ
The partial derivatives of the actual displacement $D$ with respect to $\Delta L$ and $\alpha$ are denoted as follows:

$$
\Delta D \approx \frac{\partial D}{\partial L} \times \Delta L + \frac{\partial D}{\partial \alpha} \times \Delta \alpha
$$

(3)

where $D$ is the actual displacement (3 dimension displacement), $L$ the horizontal displacement, $\alpha$ the angle between $D$ and $L$. The sources of the velocity field error $\Delta D$ include three aspects: SAR image registration ($\Delta D_1$), geographic position ($\Delta D_2$), and system errors ($\Delta D_3$) (Wuite et al., 2009). Therefore, $\Delta D$ is further decomposed into three parts: $\Delta D_1$, $\Delta D_2$, and $\Delta D_3$.

$$
\Delta D \approx \frac{\lambda}{2} \times \Delta L + D \times \tan \alpha \times \Delta \alpha = \Delta D_1 + \Delta D_2 + \Delta D_3
$$

(4)

$$
\Delta D_1 = \frac{\lambda}{2} \times \Delta L_2 \\
\Delta D_2 = \frac{\lambda}{2} \times \Delta L_2 \\
\Delta D_3 = D \times \tan \alpha \times \Delta \alpha
$$

(5)

where $\lambda$ is the wavelength. Because the terrain phase has been removed effectively through the interferometric processing of SAR images using Gamma software, the error generated by interpreting the image registration ($\Delta D_1$) can be regarded as 0.

The error of geographic position ($\Delta D_2$) mainly originates from estimations of the vertical baseline length ($B_\perp$) of the observation system and relative height ($\Delta h$) between the DEM and the real elevation, i.e., the DEM error (Zebker et al., 1994):

$$
\Delta L_2 = \frac{2 \times B_\perp \times \Delta h}{\lambda} \times \frac{1}{r \times \sin \theta}
$$

(6)

where $r$ is the range distance of the COSMO-SkyMed observation system, and $\theta$ is the incidence angle of the satellite. The DEM error results in noise streaks when simulating the terrain phase. Therefore, the DEM accuracy should be considered in the error analysis (Kumar et al., 2011). In the southeast Tibet, which has valleys interleaving among the mountains, $\Delta h$ above the altitude of 1750 m is 16 m (Arendt et al., 2002).

$\Delta D_3$ is the error generated when calculating the angle between the surface slope and aspect between the displacement along the LOS and actual displacement. Differences in the geometric characteristics of the orbit between repeatedly observed image pairs result in changes in the relative azimuth angle of the entire observation system (Li et al., 2008). In addition, changes in the satellite orbit cause mismatches of the repeated image pairs in different directions, and these mismatches also generate registration errors during InSAR data processing (Strozzi et al., 2001; Kumar et al., 2011). In this study, a single image pair is chosen to estimate the glacier flow velocity, thus, the change of the relative azimuth angle is 0, i.e. $\Delta D_3 = 0$.

### 4. Results and discussion

#### 1) Glacier velocity

The glacier boundary is identified from the COSMO-SkyMed radar images by visual interpretation and information from the GLIMS (Global Land Ice Measurements from Space) database (http://www.glims.org/). Glacier motion shows a clear relationship with terrain undulation and surface morphological differences, with altitude changes and mountain locations on both sides constraining the magnitude and direction of the overall glacier flow velocity (Fig. 2). For Glaciers No.1, No.2, No.4 and No.5, with a narrow outflow and the larger drop, glacier flow velocities begin to increase from the starting points (firn basins), and continue to increase along the main flow line towards the glacier mass equilibrium line, then decrease in the flat, open area in the middle of the glaciers. In the glacier tongue, lateral and bottom friction become bigger because of the overall gravity action of much glacier mass flowed in from the upper valley, and the flow velocities further gradually decrease. The distribution of glacier surface flow velocity fields has a direct relationship with elevation change. Since the elevation decreases from the northwest to the southeast.
the glaciers mostly move along this direction. However, because of morphological changes in the surface geometry and inverse decreases of elevation, glacier branches No.2b, No.2c, No.2d, No.4b and No.4c flow in a southwest to northeast direction (Fig. 2).

Clearly, the flow direction of Glacier No.1 is significantly affected by the glacier shape and the valley terrain (Fig. 3). The flow velocities are relatively high in steep slope areas near the foot of mountains, with glacial mass accumulated towards the main flow line. Additionally, the flow velocities are generally high in glacier accumulation zones and gradually decrease with increased distance from the glacier mass equilibrium line, and these situations are also observed in the flow velocity fields of glaciers No.2, No.4 and No.5. The surface flow velocity of Glacier No.1 reaches a maximum at the glacier mass equilibrium line. Because of disordered surface undulations in valleys, the surface flow velocity field is discontinuous (Fig. 3).

It is worth noting that the flow velocity of Glacier No.3 at 4790 m elevation is 33.8 m$^{-1}$, and it decreases to 8.6 m$^{-1}$ at 4730 m. However, the flow velocity

Fig. 2. Flow velocity of glaciers in Parlung Zangbo River basin in January 2010.
Fig. 3. Flow velocity and direction of Glacier No. 1.

Fig. 4. Profiles of glacier flow velocity and elevation along the main flow line and mass equilibrium line altitude (ELA).
progressively increases with decreasing elevation and reaches a maximum of 40 $m^{-1}$ at 4500 m. Combined with optical remote sensing images of Landsat 5, we find a glacial lake at the terminal of Glacier No.3. Rapid mass exchange between the lake water and glacier accelerates the flow velocity at the glacier terminal (Björnsson, 1998), and this situation is inconsistent with the decreasing trend in the surface flow velocities of the other four glaciers as elevation decreasing (Fig. 4).

In January, the average flow velocities of the five glaciers are 22.9-98.2 $m^{-1}$, and the maximum velocity occurs for Glacier No.1 at 123.9 $m^{-1}$ (Figs. 3, 4). The average flow velocities of glaciers in the adjacent basin of the Yigong Zangbo River during summer in 2007 were estimated to be 15-206 $m^{-1}$ by Advance Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) images and feature tracking method (Ke et al., 2013). Similarly, based on SAR images, the average flow velocities of Yengisogat Glacier in Karakorum Mountains in 2009 were estimated at 110-182 $m^{-1}$ (Jiang et al., 2011). The average surface flow velocity of glaciers in the West Kunlun Mountains for the period 2007-2010 was 100 $m^{-1}$ (Yasuda and Furuya, 2013), and those of the Inylchek Glacier in Tianshan Mountains for the period 2009-2010 were 91.5-109.5 $m^{-1}$ (Neelmeijer et al., 2014). Our results are close to the motion patterns of valley glaciers mentioned in the above studies and reflect the overall characteristics of glacier motion in western China. Additionally, almost all of the glaciers in this basin belong to maritime glaciers, and their flow velocities are greater than those of continental glaciers influenced by the continental climate during the same season (Huang and Sun, 1982).

2) Glacier movement and its physical features

The flow velocities are higher in the upstream accumulation zone but lower at the end of the glaciers (Fig. 4). For four glaciers (except for Glacier No.3), the flow velocity presents a fluctuating and decreasing trend with decreasing elevation. Overall, although the elevation monotonically decreases along the valleys, the flow velocities along the main flow line do not monotonously decrease with increasing length of the glaciers. Above the glacier mass equilibrium line, because the speed of accumulation is greater than that of melting, along with elevation decrease, the glacier velocity increases and reaches a peak value under the influence of gravity. After crossing the glacier mass equilibrium line, the flow velocities of the four Glaciers gradually decrease.

The five glaciers have different ELAs, but their AAR values are all higher than 0.6 (Table 2). Meanwhile, the Glacier No.1 has the largest AAR value, area and length, and also has the largest flow velocity. Although small area and short length of Glacier No.4, it has the highest ELA of 5038 m because of the terrain, and its maximal and mean velocity are 59.2 $m^{-1}$ and 29.4 $m^{-1}$, respectively. According to the study by Mark and Post (2002), all five glaciers are in a stable state. In the southeast Tibet, the valley glaciers with low latitudes and high altitudes are controlled by the

<table>
<thead>
<tr>
<th>Glacier No.</th>
<th>Maximal Velocity ($m^{-1}$)</th>
<th>Distance from S (m)</th>
<th>Mean Velocity ($m^{-1}$)</th>
<th>Elevation range (m)</th>
<th>Area (km$^2$)</th>
<th>Length (km)</th>
<th>AAR</th>
<th>ELA (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>123.9</td>
<td>6748</td>
<td>98.2</td>
<td>3400-4701</td>
<td>18.6</td>
<td>18.7</td>
<td>0.6724</td>
<td>4329</td>
</tr>
<tr>
<td>2</td>
<td>76.0</td>
<td>2039</td>
<td>26.0</td>
<td>3622-4291</td>
<td>13.0</td>
<td>9.5</td>
<td>0.6492</td>
<td>4247</td>
</tr>
<tr>
<td>3</td>
<td>39.4</td>
<td>7496</td>
<td>22.9</td>
<td>4368-5099</td>
<td>10.7</td>
<td>9.2</td>
<td>0.6366</td>
<td>4843</td>
</tr>
<tr>
<td>4</td>
<td>59.2</td>
<td>2164</td>
<td>29.4</td>
<td>4334-5138</td>
<td>14.8</td>
<td>9.8</td>
<td>0.6576</td>
<td>5038</td>
</tr>
<tr>
<td>5</td>
<td>55.5</td>
<td>839</td>
<td>23.9</td>
<td>4244-5122</td>
<td>15.6</td>
<td>11.0</td>
<td>0.6610</td>
<td>4705</td>
</tr>
</tbody>
</table>
strong humid climate of the southwest monsoon, and their motion state is jointly affected by the evolution of geomorphological process and climate change (Chen et al., 2012).

3) Error analysis

Previous error analyses are mostly confined to the cause of the errors, and the specific velocity error field is rarely mapped. Assuming that the true values of all glacier surface flow velocities are normally distributed, and based on the accuracy requirements of statistics, all of the values greater than the maximum glacier surface flow velocities by one-fold standard deviation are considered incorrect. The difference between the minimum error value and maximum flow velocity is the cut-off value for selection; thus, it is the maximum error distribution.

As shown in the error fields of Glaciers No.1, No.4 and No.5 (Fig. 5), the maximum errors for the three glaciers are 5.70 m a⁻¹, 3.32 m a⁻¹ and 2.55 m a⁻¹, respectively, and relatively large errors occur in the mass accumulation zone at the centre of the glaciers (Because of the complicated terrain, the error fields of Glaciers No.2 and No.3 cannot be calculated). Combined with the glacier shape and error distribution, we find that the length and width of the glaciers are relatively uniform, the flow direction is consistent, and the error distribution is more continuous, which is similar to branch glacier No.1a and No.4a. However, the error distribution is relatively discrete and fragmented as shown in Glacier No.5. The errors are relatively large in areas inconsistent with the main flow direction, such as branch glacier No.4b, No.4c and No.5b. In January, displacement of discontinuous regions occurs in small areas and on short time scales in the glacier accumulation zone, whose instantaneous change will cause local glacier motion in any direction (Bartholomaus et al., 2008). Although such random motion will have a certain impact on the error analysis, this impact only accounts for a small proportion in the entire glacier and can be considered negligible.

5. Conclusions

Based on COSMO-SkyMed X-band data, relatively accurate maps of surface flow velocity fields for five glaciers in the Parlung Zangbo River basin are obtained by InSAR techniques. High-resolution X-band image pairs can more accurately define the boundary of valley glaciers and result in high coherence over a short time scale in InSAR processing. The resulting interference fringes are evident, especially in the cloudy and snowy Parlung Zangbo region. In addition, the superiority of COSMO-SkyMed data in glacier dynamics research using InSAR techniques is illustrated.

The surface morphology and spatial geometric characteristics of valleys determine the direction and velocity of glacier surface flow and further confine their motion state. Among the five glaciers in the Parlung Zangbo River basin, the maximum flow velocity occurs at 123.9 m a⁻¹ in Glacier No.1, whereas the minimum flow velocity occurs at 39.4 m a⁻¹ in Glacier No.3. In
comparison, Glacier No.1 has the largest area and longest length, whereas Glacier No.3 has the smallest area and shortest length. The average flow velocities of the five glaciers range from 22.9 to 98.2 m a⁻¹. These glaciers generally move along the direction of decreased elevation and present a macroscopic illustration of the motion from the northwest to the southeast, with different trends in local areas. The slope aspect also has important effects on the velocity results and accuracy. The error field is relatively fragmented in areas inconsistent with the main flow line of the glaciers. In greatly undulating areas, such as the southeast Tibet, the accuracy of DEM and registration conditions of DEM-simulated terrain phases has certain effects on calculations of glacier flow direction and velocity.

Glacier dynamics research aims to more efficiently reflect the variation patterns of glacier scale over time and more accurately extract the flow velocity distribution at the glacier surface. Mapping glacier velocity field in local areas is important because it can reflect the sensitivity of specific areas to climate. Current limitations of InSAR measurements over glacier include: (1) a degradation of phase coherence when the temporal baseline is larger than a few days, leading to measurement loss and uncertainty in areas of low coherence; and (2) insensitivity to surface displacement in the plane orthogonal to the vector of the LOS, resulting in the incapacity to detect motion in the direction of the satellite ground-track (Gourmelen et al., 2011). However, feature tracking and Multiple Aperture InSAR (MAI) can partially overcome these problems, therefore, we can take full advantages of InSAR, feature tracking and MAI, and overcome their limitations to get a combining result of actual glacier velocity with higher accuracy in the future work.

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