Flow Velocity Change of David Glacier, East Antarctica, from 2016 to 2020 Observed by Sentinel-1A SAR Offset Tracking Method

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Abstract: This study measures the change of ice flow velocity of David Glacier, one of the fast-moving glaciers in East Antarctica that drains through Drygalski Ice Tongue. In order to effectively observe the rapid flow velocity, we applied the offset tracking technique to Sentinel-1A SAR images obtained from 2016 to 2020 with 36-day temporal baseline. The resulting velocity maps were averaged and the two relatively fast points (A1 and A2) were selected for further time-series analysis. The flow velocity increased during the Antarctic summer (around December to March) over the four years’ observation period probably due to the ice surface melting and reduced friction on the ice bottom. Bedmap2 showed that the fast flow velocities at A1 and A2 are associated with a sharp decrease in the ice surface and bottom elevation so that ice volumetric cross-section narrows down and the crevasses are being created on the ice surface. The local maxima in standard deviation of ice velocity, S1 and S2, showed random temporal fluctuation due to the rotational ice swirls causing error in offset tracking method. It is suggested that more robust offset tracking method is necessary to incorporate rotational motion.

Key Words: David Glacier, Drygalski Ice Tongue, Sentinel-1A, Offset tracking, ice flow velocity

1. Introduction

The changes of ice flow velocity of the Antarctic glaciers are sensitive to climate change, and the subsequent ice loss in Antarctica could be a major cause of sea level rise worldwide. Continuous observation of the ice flow velocity is essential to understand the ongoing climate change and its environmental effect. The ice flow velocity of glacier can be changed by the gradient of mass balance due to accumulation, ablation and melting, englacial and subglacial deformations, and basal sliding. Among them, basal sliding occurs when the basal shear stress is reduced (Zwally et al., 2002). If there is an increase of water at the ice bottom, lubrication reduces friction between ice and bedrock which greatly reduces shear stress and increases glacier flow velocity (Macgregor et al., 2005).

Antarctica is not easily accessible due to environmental
factors, making research by using satellite images more effective than in situ survey. Various studies have been conducted on the change in flow velocity in Antarctic glaciers based on optical or Synthetic Aperture Radar (SAR) satellite images. Optical images are applied to detect the flow of ice shelf or motion of sea ice using image-to-image cross-correlation method (Berthier et al., 2003), image matching based on orientation correlation (Han and Lee, 2018), SIFT (Scale-Invariant Feature Transform), SURF (Speeded Up Robust Features) and ORB (Oriented FAST and Rotated BRIEF) feature tracking techniques (Hyun and Kim, 2018), and particle tracking methods (Park et al., 2018). However, optical images are often discontinuous in year-long temporal acquisitions due to low illumination of the sun. Synthetic Aperture Radar (SAR) images can be taken in all weather conditions, making them particularly effective for the study of Antarctica.

Interferometric SAR (InSAR) technique has been also used for ice velocity measurement due to its centimeter-scale accuracy and day-and-night capabilities of SAR. Many studies have used InSAR to determine ice flow velocity in Antarctica (Kwon et al., 2005; Bell et al., 2007; Han and Lee, 2011; Han et al., 2013). However, it would be difficult to produce interferograms on fast-flowing glaciers because of the low coherence. Han and Lee (2014) overcame this problem by using a year-long COSMO-SkyMED one-day tandem InSAR pairs and observed the Campbell Glacier with maximum velocity of 67 cm/day (Han and Lee, 2018), one of the fast-flowing glaciers in East Antarctica.

Offset tracking method is favored where ice flow velocity is too high for InSAR technique (Nagler et al., 2015; Chae et al., 2017; Baek et al., 2018). It also provide two-dimensional ice velocity field while InSAR gives range motion only (Strozzi et al., 2002).

The purpose of this study is to observe the velocity change of David Glacier, one of the fastest moving glaciers in the East Antarctica, for many years and to identify any seasonal or annual changes. Sentinel-1A/B SAR images provide a good opportunity for long-term observation of this kind of large glaciers.

In this paper, we applied offset tracking method to the Sentinel-1A SAR data obtained for four years from 2016 to 2020 to observe the flow velocity change of David Glacier, especially near the grounding line. Chapter 2 shows the study area and data. Chapter 3 describes the offset tracking method and its measurement accuracy in terms of resolution, temporal baseline, and oversampling rate during the Amplitude Cross-Correlation process. Chapter 4 provides the ice flow velocity map averaged over the four years and the corresponding standard deviation map. Temporal changes at several points with local maximum values of average and standard deviation indicates seasonal variations of ice flow. Chapter 5 conclude the study.

2. Study Area and Data

1) Study Area

The study area is David Glacier in the Northern Victoria Land, one of the fastest-flowing glaciers in East Antarctica (Fig. 1). This glacier is an outlet glacier that forms Drygalski Ice Tongue towards the Ross Sea. David Glacier begins from Dome C and Talos Dome and forms a drainage basin of approximately 250,000 km² (Frezzotti, 1993). It is known to drain about 4% of East Antarctica’s ice through Drygalski Ice Tongue (Zoet et al., 2012). Overall flow velocities increase downward of the glacier, reaching maximum speed as high as ~700 m/yr near the grounding line (Frezzotti, 1993; Frezzotti et al., 2000). This study focused specifically on the upstream region of Drygalski Ice Tongue near the grounding line where maximum velocity occurs. Drygalski Ice Tongue is the largest ice tongue in East Antarctica and has a major impact on the mass balance of the South Antarctic ice sheet. According to Rignot et al. (2019), the average surface
mass balance (SMB) of the David Glacier from 1979 to 2008 is $7.5 \pm 0.4$ Gt/yr. The average ice discharge is 9.5 Gt/yr from 1979 to 1990, 10.2 Gt/yr from 1989 to 2000, 9.7 Gt/yr from 1999 to 2010, and $9.2 \pm 0.4$ Gt/yr from 2009 to 2017 (Rignot et al., 2019).

2) Data

Sentinel-1A/B are C-band (5.405GHz) SAR satellites launched by European Space Agency (ESA) on 3 April 2014 and 25 April 2016, respectively (Geudtner et al., 2014). Sentinel-1A satellite covers the study area maintaining a constant temporal baseline and observation mode since 2016. We used Single Look Complex (SLC) images acquired in Interferometric Wide (IW) swath mode, all in ascending node and HH polarization. Sentinel-1A acquires images every 12 days, but in order to reduce the velocity error (meter/day) for offset tracking by expanding the time interval, a total of 38 images were used for processing from June 13, 2016 to April 17, 2020 at 36 days of interval. Reducing velocity error by increasing the temporal baseline will be described in more detail in Chapter 3. Note that a total of 6 data acquisitions (12-days apart) are missing for 72 days from May 29, 2019 to July 28, 2019 in the study area. Bedmap2 (Fretwell et al., 2013) surface elevation and ice bottom topography of the glacier was plot in two-dimensional profile to interpret the flow velocity and its changes. The grounding line data of Antarctica was also used for data interpretation (Rignot et al., 2011; Rignot et al., 2014; Rignot et al., 2016).

3. Method

Offset Tracking is a tool that measures the displacement of features between two images. In this study, an offset tracking process was performed using two images at 36-day intervals converted from SLC to GRD (Ground Range Detected) products. We used SNAP (ESA’s SentiNel Application Platform) software for data processing. Offset tracking calculates the offset at each point on GCP (Ground Control Point) grid and derives the ice flow velocity in meter per day. The velocity of every pixel is then interpolated from the GCPs. In this study, the GCP grid spacing was set
to 40 pixels for both azimuth and range. Amplitude Cross-Correlation (ACC) was performed with a window size of 128 width × 128 height, and the cross correlation threshold was set to 0.1 to calculate the position of the slave pixels in the master image. The max velocity was set to 5.0 m/day to eliminate outliers, and bi-cubic interpolation was applied. A total of 36 velocity images were acquired out of 38 Sentinel-1A SAR images (Table 1). As mentioned earlier, data from May to July 2019 could not be obtained and the velocity results could not be derived for the 36-day interval between April 23, 2019 and August 9, 2019.

Velocity error of the offset tracking method ($E$) defined in this study can be calculated as follows:

\[
E = \frac{R}{Nt} \tag{1}
\]

where $N$ is the over-resampling rate of the interpolation during the ACC, $t$ is the temporal baseline of two SAR image pair, and $R$ is the resolution either in range or azimuth. In this study, $N$ was set to 8. Instead of the minimum temporal baseline of 12 days obtainable from Sentinel-1A acquisition, we choose 36 days in this study to reduce the velocity measurement error. The range and azimuth resolutions $R$ of Sentinel-1A GRD image are 18.97 m and 14.07 m, respectively. Using Equation (1) and the above parameters, the velocity error in the range direction ($E_{\text{range}}$), the azimuth direction ($E_{\text{azimuth}}$), and the total velocity error, $E_{\text{total}}$, were derived as follows.

\[
E_{\text{range}} = \frac{R_{\text{range}}}{Nt} = \frac{18.97 \text{ (m)}}{8 \times 36 \text{ (days)}} = 0.066 \text{ (m/day)} \tag{2}
\]

\[
E_{\text{azimuth}} = \frac{R_{\text{azimuth}}}{Nt} = \frac{14.07 \text{ (m)}}{8 \times 36 \text{ (days)}} = 0.049 \text{ (m/day)} \tag{3}
\]

\[
E_{\text{total}} = \sqrt{E_{\text{range}}^2 + E_{\text{azimuth}}^2} = \sqrt{0.066^2 + 0.049^2} = 0.082 \text{ (m/day)} \tag{4}
\]

The obtained total velocity errors was used when interpreting the velocity change results.

### 4. Results

1) Average and standard deviation map of ice flow velocity

Average and standard deviation maps of the offset tracking results were generated to analyze the overall ice flow velocity in the study area (Fig. 2). Two points with local peaks in the average velocities were found in the study area, labeled A1 and A2, respectively. The average velocity and standard deviation is 2.35±0.06 m/day for A1 and 1.77±0.08 m/day for A2. The local maxima of ice velocity occurs near the upstream of the grounding line of David Glacier. Points with a large standard deviation were also found near the points with the peak average velocities, denoted as S1 and S2. The average velocity and standard deviation for S1 is 0.82±0.15 m/day and for S2 is 1.17±0.2 m/day. The locations of S1 and S2 differ from A1 and A2, but they appeared along the edge of the local velocity maxima A1 and A2. For a more detailed time series analysis,

### Table 1. Sentinel-1A SAR offset-tracking data pair used in this study

<table>
<thead>
<tr>
<th>No.</th>
<th>Offset tracking pair (YYYYMMDD)</th>
<th>No.</th>
<th>Offset tracking pair (YYYYMMDD)</th>
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<tr>
<td>1</td>
<td>20160613-20160719</td>
<td>19</td>
<td>20180832-20180428</td>
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<td>20180919-20181025</td>
</tr>
<tr>
<td>7</td>
<td>20170115-20170220</td>
<td>25</td>
<td>20181025-20181130</td>
</tr>
<tr>
<td>8</td>
<td>20170220-20170328</td>
<td>26</td>
<td>20181130-20190105</td>
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<td>20180215-20180323</td>
<td>36</td>
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</table>
the change in velocity over time was observed at four points, A1, A2, S1, and S2, in the following sections.

2) Temporal ice velocity changes

Fig. 3 and Fig. 4 shows the change in velocity at two velocity maxima points, A1 and A2 over the four years from 2016 to 2020. The dates on the figures are the later day (slave image) of the 36-day offset-tracking SAR pair. Both points showed the increase in velocity during the Antarctic summer (around December to March), which are indicated by red arrows in each figures. The peak velocities of the A1 occurred on the 20161210-20170115, 20180110-20180215, and 20190105-20190210 pairs, with velocities of 2.52 m/day, 2.44 m/day, and 2.51 m/day, respectively. In A2, the peak velocities for 20180110-20180215, 20190115-20190210, and
Fig. 4. Time-series ice velocity of A2 (a local velocity maximum point). The dates are the later day of the 36-day offset-tracking SAR pairs.

Fig. 5. Time-series ice velocity of S1 (local standard deviation maximum point). The dates are the later day of the 36-day offset-tracking SAR pairs.

Fig. 6. Time-series ice velocity of S2 (local standard deviation maximum point). The dates are the later day of the 36-day offset-tracking SAR pairs.
20200205-20200312 pairs occurred with 2.01 m/day, 1.94 m/day, and 1.89 m/day, respectively. All peak velocities exceed the velocity measurement error ($E_{\text{total}} = 0.082 \text{ m/day}$) from the average ice velocity of $2.35 \pm 0.06 \text{ m/day}$ for A1 and $1.77 \pm 0.08 \text{ m/day}$ for A2 and thus meaningful. The same pattern continued for three years from 2016 to 2020, except for 2020 at A1 and 2017 at A2, which is expected to be due to seasonal changes. It can be inferred that this increase in ice speed might be due to the seasonal surface melting of the glaciers and the increase of the subglacial ice bottom water that contributes the increase of the glacial sliding.

The time series velocity graphs for S1 and S2 are shown in Fig. 5 and Fig. 6. The standard deviation values for S1 and S2 are more than three times higher than A1 or A2. As there were no specific seasonal patterns in S1 and S2, other cause of such random change will be discussed in the following section.

5. Discussion

We discuss the possible cause of the velocity maxima A1 and A2 and the standard deviation maxima S1 and S2 found in the previous section. Google earth image and Bedmap2 were used to find the factors that change the velocity of the four observed points (Fig. 7). First, several crevasses were observed near A1 and A2, upstream of the grounding line. Generally, crevasses appear in a direction perpendicular to the tensile force. The tensile force acts along the flow direction of the glacier, and the change in velocity is also affected by the change of tensile force.

In order to find out the cause of the tensile force in more detail, the surface elevation and sub-glacier topography at the A1 were displayed in Fig. 8 and Fig. 9. The first profile line was set along the flow direction of the glacier (1-1’), and the second profile line was set along the vertical direction of the flow direction (2-2’). Firstly, there is a rapid decrease in surface elevation at the point A1 in the 1-1’ cross-sectional view (Fig. 8). Ice thickness also decreases due to the bottom mount before A1. This rapid decrease in surface and bottom elevation downstream of A1 may have accelerated the flow of the glacier and created tension. Secondly, the 2-2’ cross-sectional view of A1 shows that the thickness of the glacier is relatively thin compared to the mid-glacier area (Fig. 9). As a whole, the velocity of A1 appeared faster than the surrounding area because the
A similar pattern was also observed at A2, so the peak average velocity is dominated by the same mechanism.

Swirls appear around the points S1 and S2 (Fig. 7) where the standard deviation is large and the velocity is relatively slow. Offset tracking is a technique that observes the transpositional changes in range and azimuth direction only. Therefore, it might be difficult to detect rotation by swirls. The random change of S1 and S2 is caused by the errors in offset tracking method that uses amplitude cross-correlation. It is recommend to use other matching techniques that incorporate rotational nature of the surface.

6. Conclusions

This study observed ice flow velocity of David Glacier, East Antarctica, over the period of the year 2016 to 2020 by applying offset tracking method to Sentinel-1A SAR images with 36-day temporal
baseline. Changes in the flow velocity were identified at points where the average velocity shows local maxima (A1, A2) and at points with large standard deviations (S1, S2). Bedmap2 ice surface and bottom topography showed that local velocity maximum occurred where ice flow cross-sections are much narrower in A1 and A2 than surrounding area. Rotation of ice flow occurs in S1 and S2 that caused errors in offset tracking method that deals with transpositional motion only. The velocities of A1 and A2 tended to increase in Antarctic summer for at least three years probably due to the increase of the summer melt in ice surface and thus the increase of bottom sliding.

It is recommended to continuously monitor David Glacier using Sentinel-1 SAR to see whether ice flow follows the seasonal effect. A 3D modeling of ice dynamics is necessary to identify the factors that affect the ice velocity change such as ice surface melting, the impact of crevasses, and bottom sliding. More advanced offset tracking method should be used for the area where rotational ice motion occurs.

Acknowledgements

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References


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