TIDE-FREE FLOW VELOCITY AND STRAIN RATE OF CAMPBELL GLACIER TONGUE, EAST ANTARCTICA, MEASURED BY INSAR

Hoonyol Lee[1] and Hyangsun Han[2]

[1]Division of Geology and Geophysics, Kangwon National University, Republic of Korea (hoonyol@kangwon.ac.kr)
[2]Division of Polar Ocean Environment, Korea Polar Research Institute, Republic of Korea (hyangsun@kopri.re.kr)

ABSTRACT ... Measurement of strain rate of a floating glacier is critical to the investigation of detailed flow regime and crevassing mechanism of the ice. We measured the surface deformation of Campbell Glacier Tongue (CGT) in East Antarctica from the 14 COSMO–SkyMed one–day tandem differential interferometric SAR (DInSAR) image pairs obtained in 2011. The vertical tidal deflection of CGT in each DInSAR image was estimated by using the tide deflection ratio generated by the double–differential interferometric SAR technique. By removing the vertical tidal deflection from the DInSAR signals, we derived the tide–corrected ice velocity and strain rate of CGT. The crevasses in CGT formed perpendicular to the axis of the most tensile strain rate, from which we found that they were generated by the gravitational ice flow and not by the vertical tidal deflection.

INTRODUCTION

Surface strain rate is primary indicator of crevasse formation. The surface strain rate of glaciers can be calculated from ice–velocity field. Differential interferometric synthetic aperture radar (DInSAR), a technique to measure surface deformation with sub–cm accuracy, has been widely used to map ice velocity over the glaciers. For fast–flowing glaciers, the DInSAR pairs with short temporal baseline such as one–day were effectively used to map ice velocity, avoiding the temporal decorrelation of glacier surface.

The DInSAR signals over the grounded ice represent the surface deformation by gravitational flow only, while those over the floating glaciers include the vertical deflection due to ocean tide as well (Rignot, 1996). The vertical tidal deflection varies spatially over the floating glaciers, especially in the hinge zone (Han and Lee, 2014). In case of the one–day DInSAR pairs, magnitude of the vertical tidal deflection can be similar to that of daily ice–flow (Han and Lee, 2014).

The spatial variations of the vertical tidal deflection can be investigated by using tide deflection ratio defined as the ratio of the vertical tidal deflection of ice over tide height (Han and Lee, 2014). The tide deflection ratio can be determined by double–differential interferometric SAR (DDInSAR) technique that differentiates two DInSAR images by assuming constant ice–flow during the DInSAR data acquisitions (Rignot, 1996).

In this study, we obtained a series of COSMO–SkyMed one–day tandem DInSAR pairs over Campbell Glacier Tongue (CGT) in East Antarctica and estimated tide deflection ratio by performing DDInSAR technique, to measure tide–corrected strain rate and investigate crevassing mechanism of CGT.

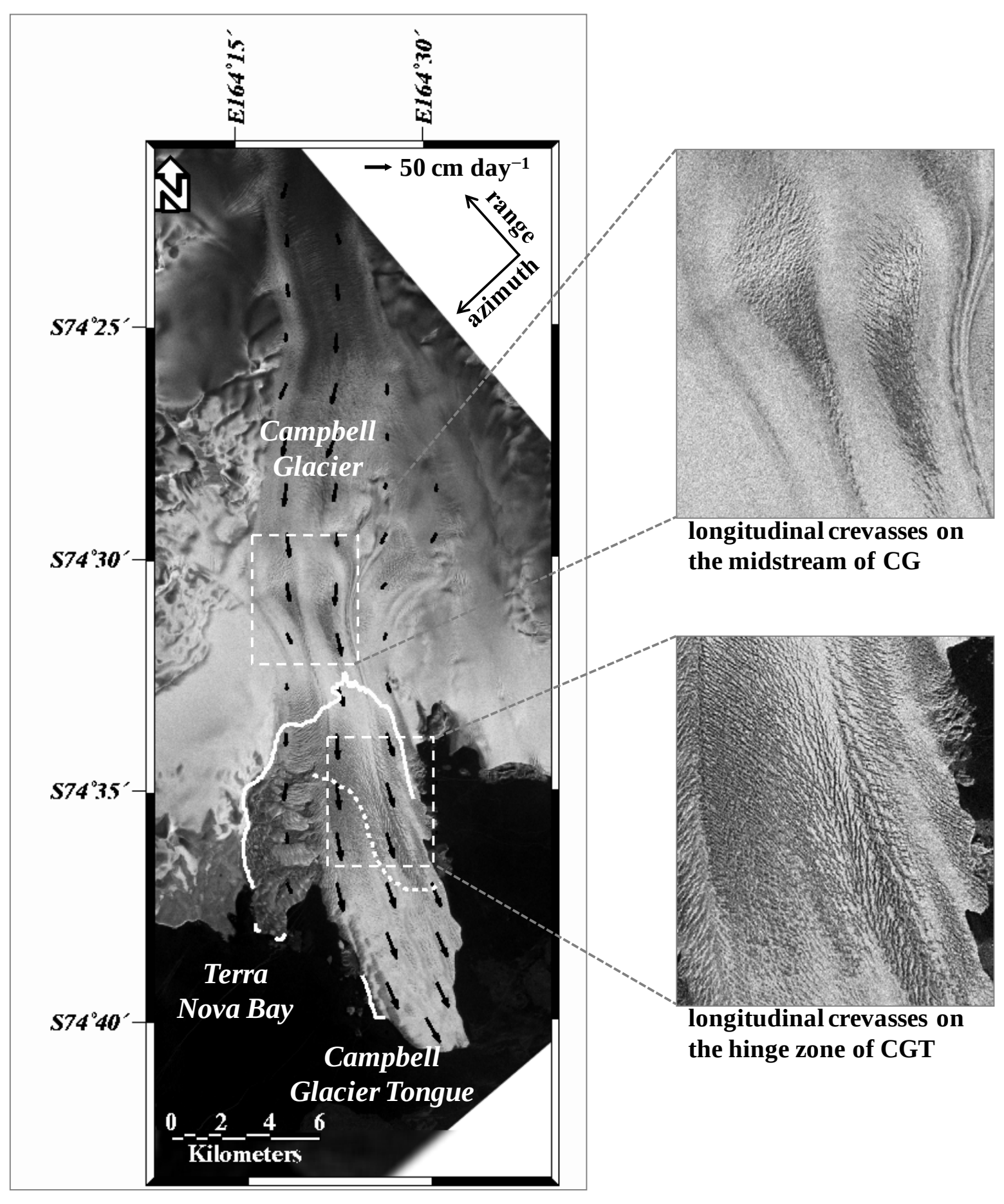

Figure 1. COSMO–SkyMed SAR images over CGT obtained on 27 January 2011. The arrows represent the ice–flow direction estimated from the offset tracking. The white lines represent the location of the grounding line of CGT (Han and Lee 2014).

Table 1. A series of COSMO–SkyMed one–day tandem InSAR image pairs used in this study.

ID	Dates of master, slave (yyyy/mm/dd)	Perpendicular baseline (m)	One–day tide difference (cm)
1	2011/01/26, 2011/01/27	18.9	−11.6
2	2011/02/27, 2011/02/28	5.7	−4.5
3	2011/03/15, 2011/03/16	−44.4	−17.5
4	2011/03/31, 2011/04/01	−39.2	8.3
5	2011/05/02, 2011/05/03	−89.6	8.3
6	2011/05/18, 2011/05/19	75.9	27.8
7	2011/06/03, 2011/06/04	−36.5	−3.3
8	2011/06/19, 2011/06/20	−47.5	−14.7
9	2011/08/22, 2011/08/23	181.7	27.6
10	2011/09/07, 2011/09/08	37.3	1.0
11	2011/10/09, 2011/10/10	−44.4	5.8
12	2011/10/25, 2011/10/26	−110.9	−14.0
13	2011/11/10, 2011/11/11	−91.7	2.0
14	2011/11/26, 2011/11/27	−23.4	7.5

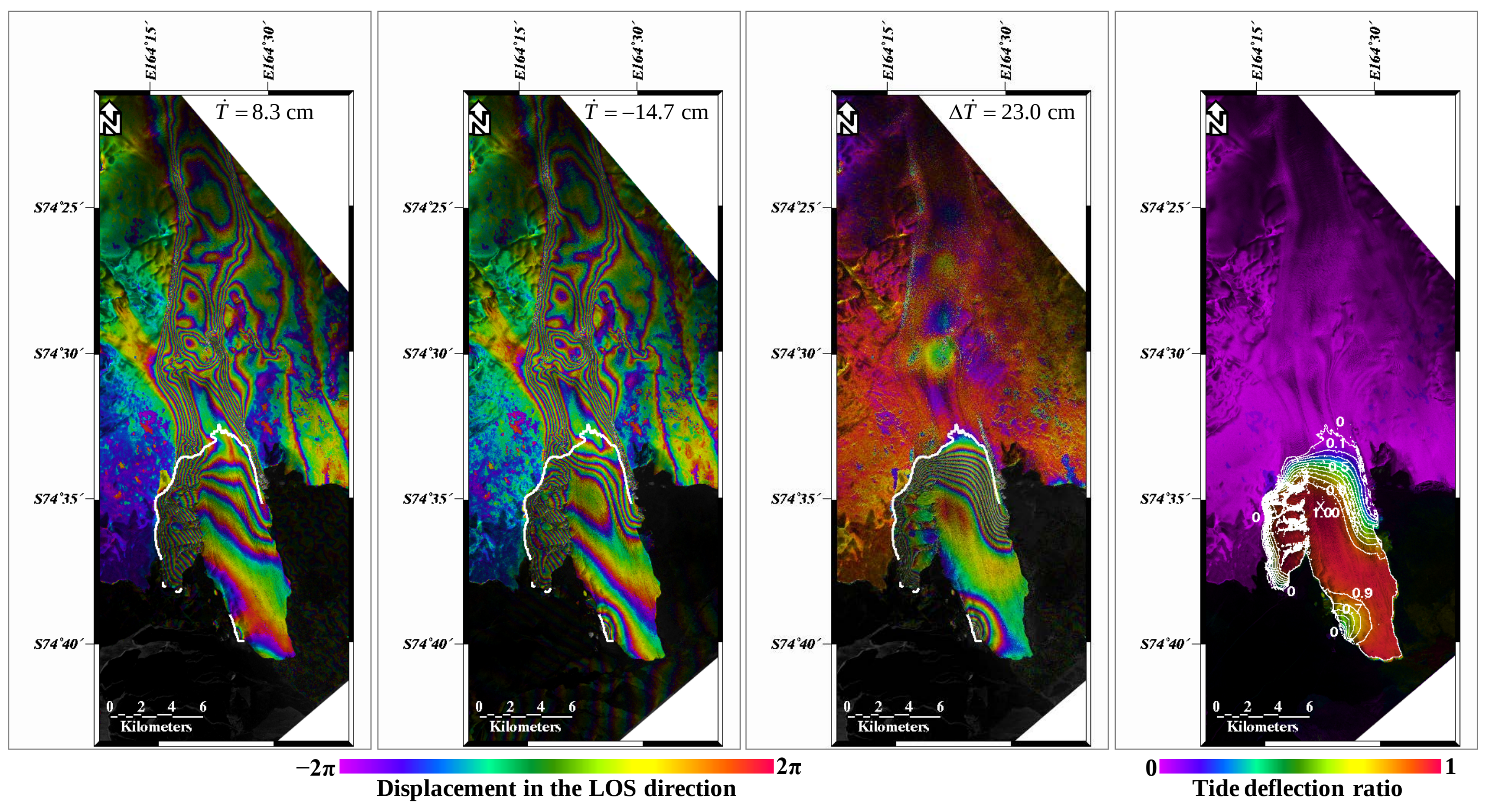

Figure 2. Examples of the COSMO–SkyMed one–day DInSAR images over CGT, generated from the InSAR pairs obtained on (a) 31 March and 1 April, and (b) 19 and 20 June 2011, respectively. $\dot{T}$ represents the one–day difference of tide height predicted by the IBE–corrected Ross_Inv. (c) DDInSAR image generated by differentiating Figure 2(a) and (b). $\Delta\dot{T}$ represents the tidal variation between the two DInSAR observations. The white lines in (a), (b) and (c) represent the location of the grounding line of CGT (Han and Lee 2014). (d) Map of tide deflection ratio over CGT.

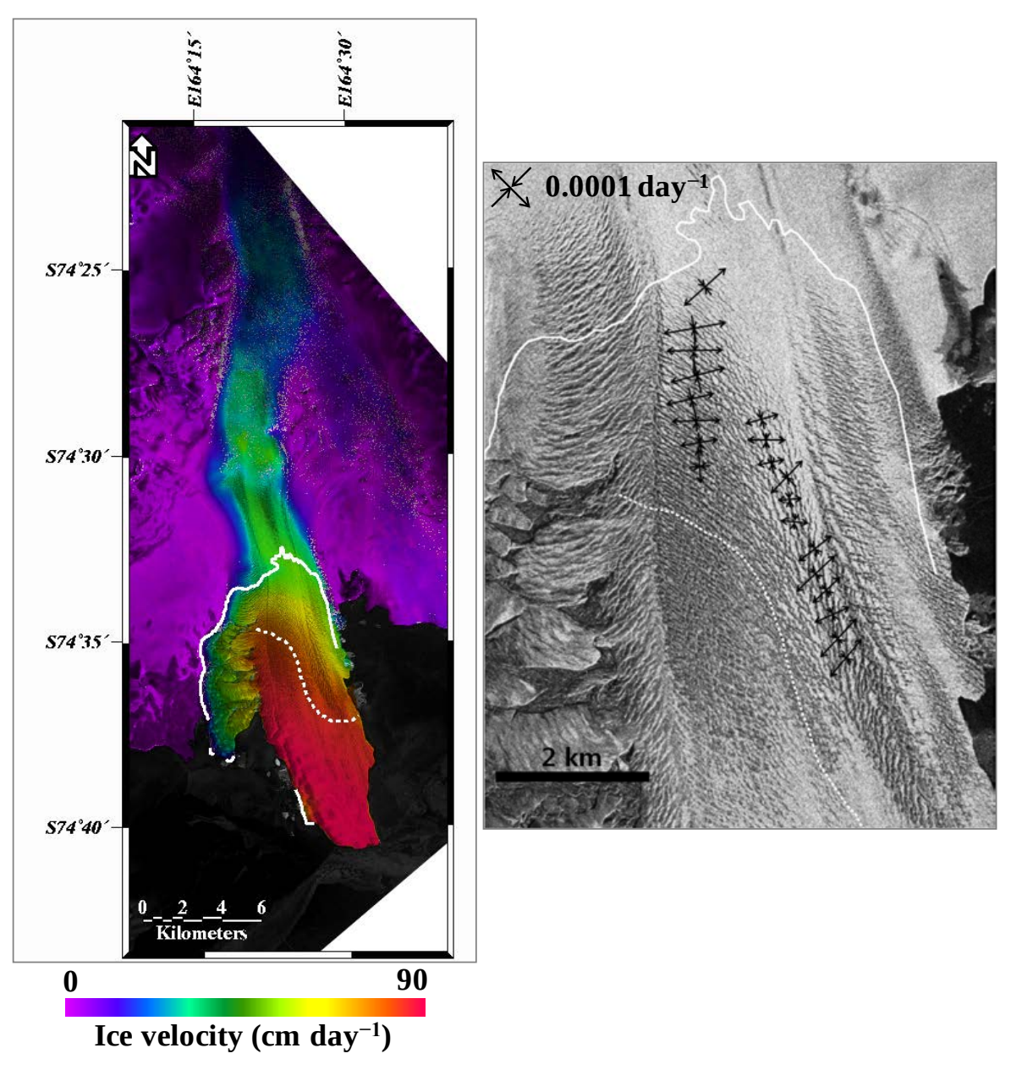

Figure 3. (a) Map of the tide–uncorrected ice velocity of CGT from a DInSAR image with $\dot{T}$ of 27.6 cm (ID 6 in Table 1). (b) Axes of the principal strain rate plotted on the crevasses of CGT, calculated from the tide–uncorrected ice velocity. The white lines represent the location of grounding line, while the white dotted line represents the seaward edge of the hinge zone of CGT, defined from the α–map (Figure 2(d)).

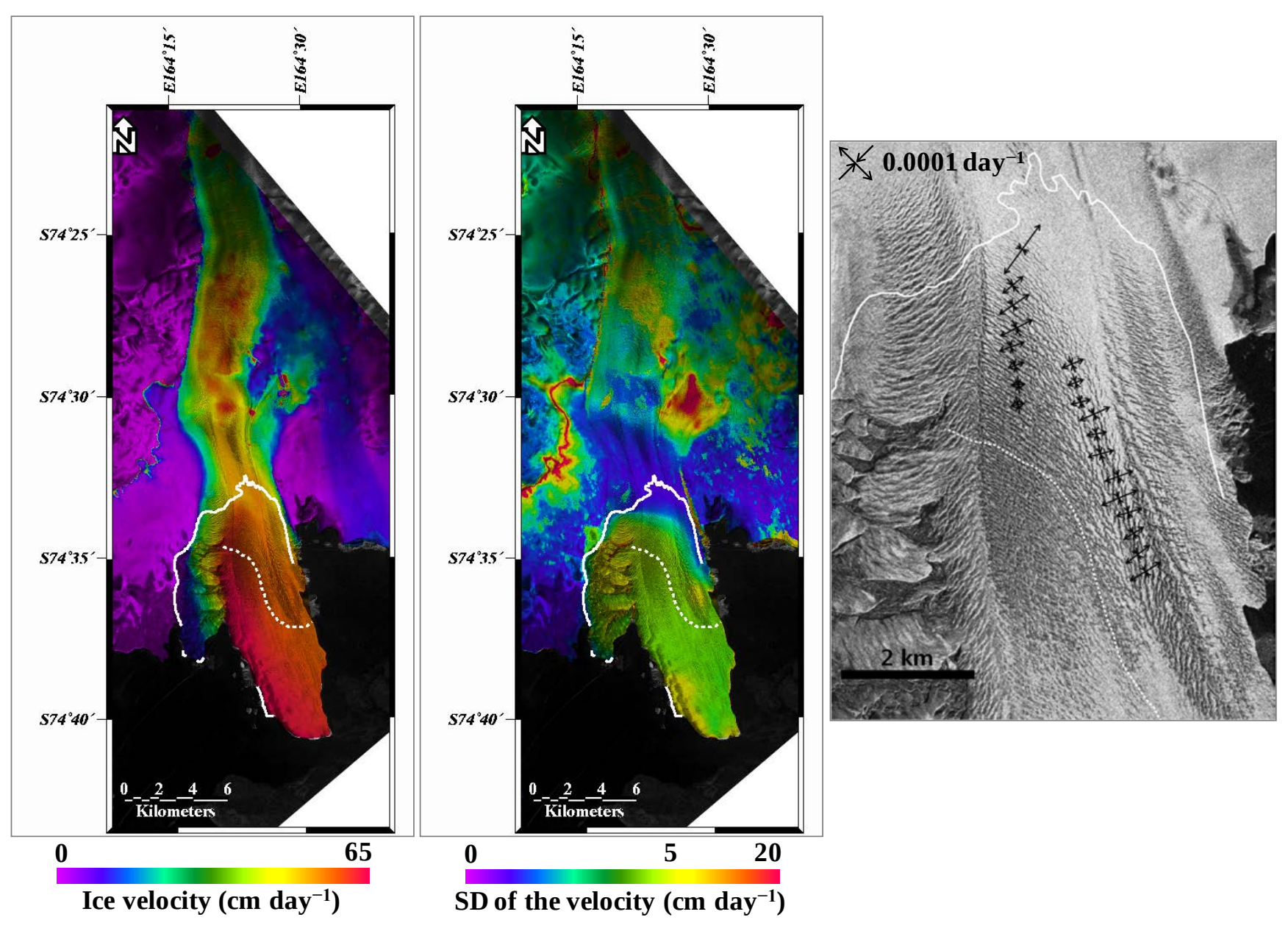

Figure 4. Maps of (a) the averaged ice velocity of CGT and (b) its standard deviation (SD), derived from the tide–corrected one–day DInSAR images. (c) Axes of the principal strain rate plotted on the crevasses of CGT, calculated from the tide–corrected ice velocity. The white lines represent the location of grounding line, while the white dotted line represents the seaward edge of the hinge zone of CGT, defined from the α–map (Figure 2(d)).

MATERIALS AND METHODOLOGY

Study area

CGT is a seaward extension of Campbell Glacier (CG), which flows into the northern Terra Nova Bay in Ross Sea, East Antarctica. Figure 1 shows a COSMO–SkyMed SAR image over CGT obtained on 27 November 2011. The white lines represent the location of the grounding line of CGT (Han and Lee, 2014). CGT is composed of two ice streams: one is the main stream in the east and the other is the branch stream composed of broken ice chunks in the west. Many crevasses are formed on the midstream of CG and the hinge zone of CGT (see the dotted boxes in Figure 1). Annual ice velocity of CGT was 180–270 m a⁻¹ measured by the offset tracking of the COSMO–SkyMed SAR images between 2010 and 2011 (Han et al., 2013). CGT experiences the vertical tidal deflection up to 60 cm during a day (Han and Lee, 2014), in which the magnitude is similar to daily ice–flow of the glacier tongue.

Data

We used 14 one–day tandem interferometric SAR (InSAR) pairs over CGT obtained from January to November 2011 by COSMO–SkyMed satellites equipped with X–band SAR (Table 1). All SAR images were acquired in strip–map mode (3 m spatial resolution), VV–polarization, and an incidence angle of 40° in descending orbit at around 3:45 UTC. Global Digital Elevation Model (GDEM) of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (Fujisada et al., 2005) was used to remove topographic phases from the one–day interferograms. The vertical accuracy of the GDEM is 20 m which is enough to remove topographic phases from the interferograms due to very short perpendicular baselines of the InSAR pairs.

Ross Sea Height–Based Tidal Inverse Model (Ross_Inv) (Padman et al., 2003), the optimum tide model in Terra Nova Bay (Han and Lee, 2014), was used to predict tide height at a centre point of the free–floating zone of CGT. The load–tide effect on the predicted tide height was corrected by TPXO6.2 Load Tide model (Egbert and Erofeeva, 2002). The inverse barometer effect (IBE) on the predicted tide height was corrected by using in situ atmospheric pressure measured by an automatic weather system installed near CGT.

Methodology

First, the one–day surface deformation over CGT in the line of sight (LOS) direction was extracted from the 14 differential interferograms. DInSAR signals over the grounded part of CG represent gravitational ice flow only, while those over CGT represent the vertical tidal deflection as well. We generated total 91 DDInSAR images from the 14 differential interferograms and extracted the vertical tidal deflection of the glacier tongue. The DDInSAR images clearly show the location of grounding line and the spatial variation of the vertical tidal deflection in the hinge zone of CGT. By the following methodology mentioned in Han and Lee (2014), we generated a map of tidal deflection ratio over CGT by the pixel–based linear regression between the DDInSAR–derived vertical tidal deflection and tidal variations during the DDInSAR observations predicted by the IBE–corrected Ross_Inv.

The flow velocity map was converted into the flow direction estimated by the offset tracking between two SAR images obtained on 25 October and 10 November 2011. To represent annual state of ice velocity, we generated the maps of the averaged one–day ice velocity and its standard deviation from the 14 tide–corrected one–day ice flows.

We calculated the flow–oriented strain rate such as longitudinal ($\dot{\varepsilon}_l$), transverse ($\dot{\varepsilon}_t$) and shear strain rate ($\dot{\varepsilon}_s$) by (Bindschadler et al., 1996)

$$\dot{\varepsilon}_l = \dot{\varepsilon}_{xx}\cos^2\beta + 2\dot{\varepsilon}_{xy}\sin\beta\cos\beta + \dot{\varepsilon}_{yy}\sin^2\beta$$
$$\dot{\varepsilon}_t = \dot{\varepsilon}_{xx}\sin^2\beta - 2\dot{\varepsilon}_{xy}\sin\beta\cos\beta + \dot{\varepsilon}_{yy}\cos^2\beta$$
$$\dot{\varepsilon}_s = \left(\dot{\varepsilon}_{yy} - \dot{\varepsilon}_{xx}\right)\sin\beta\cos\beta + \dot{\varepsilon}_{xy}\left(\cos^2\beta - \sin^2\beta\right)$$

where $\dot{\varepsilon}_{xx}$, $\dot{\varepsilon}_{yy}$ and $\dot{\varepsilon}_{xy}$ are the strain rate with respect to the image axes x and y directions calculated from ice velocity, and β is the flow direction measured counter clockwise from the x axis.

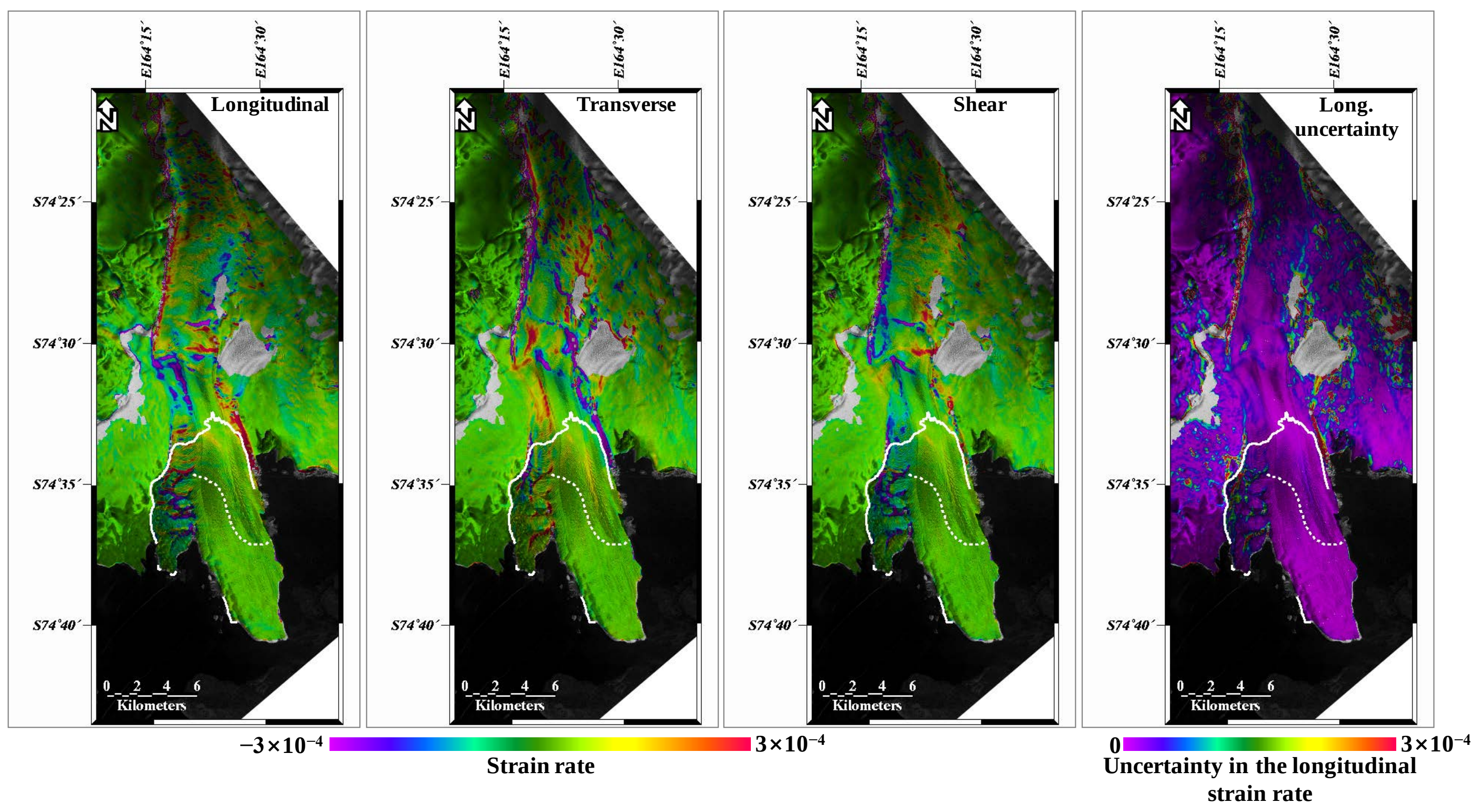

Figure 5. Maps of (a) longitudinal, (b) transverse and (c) shear strain rate over CGT. (d) The uncertainty in the longitudinal strain rate.

CONCLUSION

This study showed a method to measure tide–corrected strain rate of a floating glacier by using a series of COSMO–SkyMed one–day tandem DInSAR dataset for CGT, and analyzed the flow regime and crevassing mechanism of the ice. The vertical tidal deflection of CGT was estimated by multiplying the tidal variations corresponding to the DInSAR images by the DDInSAR–derived tide deflection ratio, which was removed from the DInSAR signals to extract ice velocity only. The orientation of crevasses in CGT was nearly perpendicular to the direction of the most tensile strain rate calculated from the tide–corrected ice velocity. This demonstrates that the crevasses form by ice flow in respect of the DInSAR accuracy, not by tidal deflection. The tide correction of DInSAR signals over floating glaciers by using the DDInSAR–derived tide deflection ratio is useful for extracting accurate ice velocity and strain rate for analyzing crevasses. The tide–corrected ice velocity and strain rate will thus be of great value in a better understating of ice dynamics of floating glaciers.

ACKNOWLEDGEMENTS

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