Decadal changes of Campbell Glacier Tongue in East Antarctica from 2010 to 2020 and implications of ice pinning conditions analyzed by optical and SAR datasets

Hyangsun Han, Seung Hee Kim, and Sanghee Kim

Department of Geophysics, Kangwon National University, Chunccheon, Republic of Korea; Center of Remote Sensing and GIS, Korea Polar Research Institute, Incheon, Republic of Korea; Division of Life Sciences, Korea Polar Research Institute, Incheon, Republic of Korea

ABSTRACT

Changes in ice shelf dynamics significantly impact the discharge rate of grounded ice, sea ice formation, and marine environments. In particular, changes of a sub-shelf pinning point induce complex dynamics of an ice shelf. In this study, we investigated decadal changes (2010–2020) in the area, ice velocity, and grounding line position of Campbell Glacier Tongue (CGT) in East Antarctica, which has an ice pinning point at the southwestern end, and analyzed the effect of the pinning conditions on the dynamics of CGT. Panchromatic band images of Landsat-7 Enhanced Thematic Mapper Plus and Landsat-8 Operational Land Imager, COSMO-SkyMed X-band synthetic aperture radar (SAR), and Sentinel-1 C-band SAR datasets were employed. The surface area of CGT digitized from the optical and SAR imagery decreased by 8% in the last decade, during which four ice calving events that caused icebergs with an area range of 3.8–5.4 km². The largest calving at the ice pinning point occurred in March 2014, which created an iceberg with 4 km². The ice velocity of CGT was measured via the normalized cross-correlation-based image matching of the Landsat panchromatic images. The ice velocity along the flow direction and its anomaly of CGT hardly changed in the hinge zone from 2011 to 2020. The ice velocity increased by ~7% and the flow direction steered abruptly ~7° to the east in the freely floating zone after the 2014 calving at the ice pinning point. Considering the retreat of the local grounding line at the pinning point analyzed by COSMO-SkyMed double-differential interferometric SAR, the advancing glacier tongue came in contact with the sloping eastern flank of the locally elevated seabed at the pinning point after the calving, and the ice-bed contact area decreased, causing a sudden acceleration and eastward rotation of ice flow. It is expected that continuous calving at the ice pinning point of CGT may lead to an abrupt changes in glacier tongue dynamics again, and continuous monitoring is necessary.

1. Introduction

An ice shelf is a floating extension of a grounded ice sheet and it is crucial in climate and ocean environment systems. Ice shelves buttress-grounded ice sheets and control inland ice flow, and their absence induces a great discharge in the ocean, which would then impact global sea level (Alley et al. 2005; Joughin and Alley 2011; Paolo, Fricke, and Padman 2015; Golledge 2020). The mass loss of ice shelves due to calving and basal melting has little effect on the sea-level rise. However, these processes weaken ice shelf buttressing and can cause climate change and sea-level rise (Dupont and Alley 2005; Royston and Gudmundsson 2016; Hill et al. 2018). The changes in freshwater discharge of ice shelves also affect the formation of sea ice (Hellmer 2004; Mahoney et al. 2011; Bintanja, Van Oldenborgh, and Katsman 2015), ocean circulation (Williams et al. 2001; Hattermann and Levermann 2010; Jourdain et al. 2017), and marine ecosystem (Ingels et al. 2020). The ice shelves in an unstable state loss area over time with ice front retreat and show ice flow acceleration (Doake et al. 1998; Khazendar et al. 2015; Lhermitte et al. 2020). These ice shelves significantly affect the Earth’s ice imbalance, hence should be monitored for long-term time scales.

Where a seabed is locally elevated high, the ice shelf is grounded there and forms a pinning point (Matsuoka et al. 2015; Berger et al. 2016). The pinning point is also called ice rise or ice rumple. An ice rise is typically dome-shaped, elevated several hundreds of meters above the surrounding ice shelf, and acts as an obstacle in maintaining the flow direction (Matsuoka et al. 2015; Goel et al. 2020). An ice rumple is typically
elevated only tens of meters or less from an ice shelf surface, where the ice flow maintains the same general flow direction as the surrounding ice shelf (Matsuoka et al. 2015). Ice rise and ice rumple can exist at the ice front of an ice shelf, partially facing an open sea. Changes in the location of pinning points or ice-bed contact areas trigger the changes in the buttressing on the ice sheet (Matsuoka et al. 2015; Favier et al. 2012, 2016; Still, Campbell, and Hulbe 2019). Unpinning can increase the ice velocity and decrease ice shelves’ thickness, which destabilizes them and accelerates the mass flux from the grounded ice into the ocean (Tinto and Bell 2011; Gudmundsson, De Rydt, and Nagler 2017). If the pinning point is located near the ice calving front, the pinning conditions can cause more dramatic changes in ice shelf dynamics (Massom et al. 2015). The characteristics of ice shelf dynamics and their changes due to ice pinning conditions have been mainly analyzed through numerical modeling (Still, Campbell, and Hulbe 2019; Still and Hulbe 2021; Fürst et al. 2015; Robel et al. 2017; Favier and Pattyn 2015; Favier et al. 2016) rather than observations, such as field campaign and remote sensing (Gudmundsson, De Rydt, and Nagler 2017; Berger et al. 2016; Kim, Kim, and Kim 2018).

Campbell Glacier Tongue (CGT) is a fast-flowing floating glacier in Terra Nova Bay (TNB) in East Antarctica. The southwestern end of CGT, near the ice front, has been grounded by the locally elevated seabed (Rignot, Mouginot, and Scheuchl 2011; Han and Lee 2014), which can be defined as an ice rumple partially facing the ocean, considering that it maintains the same general flow direction and has a similar elevation to its surroundings. Landfast sea ice is formed all year round around the CGT, and it serves as a supply route for the Antarctic research stations located in TNB. It is reported that the distribution and strength of the landfast sea ice in this region are affected by the stress due to the flow of CGT and the location of the ice front of CGT (Han and Lee 2018b). The coastal regions around the CGT are major habitats for shellfish, polychaetes, Adélie Penguin, and Weddell seals (Focardi, Bargagli, and Corsolini 1995; Cantone and Pietro 2001; Ancora et al. 2002). Freshwater discharge into TNB due to ice calving, increasing flux by ice flow acceleration or basal melting of the CGT, and the resulting changes in sea ice formation environment are expected to significantly impact the marine ecosystem in the regions. Frezzotti (1993) and Han, Ji, and Lee (2013b), who observed the area change of CGT through analyses of satellite remote sensing data, reported that ice calving of CGT continuously occurs near the ice pinning point. The ice calving at the end of CGT would migrate the pinning point and change the area of ice-bed contact, which can cause changes in its dynamics.

Satellite remote sensing is useful for monitoring Antarctic ice shelves where human access is limited due to extreme weather and obstruction by sea ice. Several glaciological studies have been conducted on the CGT based on satellite remote sensing. Frezzotti (1993) analyzed airborne and spaceborne optical images obtained from 1963 to 1989 for CGT and reported that the extent of CGT remained constant (77–78 km²) due to constant annual ice discharge by ice front calving during the observation period. The ice velocity of CGT in 1989 was measured from 140 ± 20 m/a at a boundary line separating the floating CGT and grounded ice (Campbell Glacier), that is, grounding line, to 240 ± 20 m/a at the ice front by feature tracking of SPOT-1 images (Frezzotti 1993). Based on the analysis of COSMO-SkyMed synthetic aperture radar (SAR) images, the area (Han, Ji, and Lee 2013b), ice velocity (Han and Lee 2015), strain rates (Han and Lee 2017), and the location of the grounding line (Han and Lee 2014) of CGT in 2010–2011 have been reported. Combining the results from the SAR-based studies, the area of CGT has remained fairly constant since 1963 (Han, Ji, and Lee 2013b), whereas the ice velocity at the grounding line has increased by ~50 m/a since 1989, and the flow of ice front has not been changed (Han and Lee 2015).

As described, glacial studies on CGT have been conducted through remote sensing; however, there is no study on the changes in the ice dynamics of CGT due to the ice pinning conditions. Because the ice calving of CGT continuously occurs near the ice pinning point, it is critical to analyze the changes in CGT considering the ice pinning conditions. Further, the East Antarctic Ice Sheet was known to be in a stable state, but it has lost mass of 28 ± 30 Gt/a since 2012 (The IMBIE Team 2018), which implies that the decrease in area and increase in ice velocity of the East Antarctic ice shelves in the 2010s are more varied than before. Changes in CGT in the 2010s are also from before, which can be dramatic if unpinning occurs.
Satellite optical imagery provides a long-term data record, which is useful for monitoring large-scale temporal variations in ice shelves. The Landsat-7 Enhanced Thematic Mapper Plus (ETM+) and Landsat-8 Operational Land Imager (OLI) provide high-resolution (15–30 m) multispectral images, allowing precise observation of ice calving and area change in ice shelves on a decadal scale. The Landsat data are widely used for mapping the velocity of ice shelves based on image matching techniques (Haug, Kääb, and Skvarca 2010; Han, Im, and Kim 2016; Han and Lee 2018a; Yang et al. 2019). Because the satellite optical images are significantly affected by weather and sun altitudes, it is impossible to use them to observe ice shelf dynamics during winter and under inclement weather. SAR can be used for ice shelf monitoring regardless of weather and solar illumination conditions. The European Space Agency has distributed SAR data of the Sentinel-1 satellites, which provide high-quality images with a spatial resolution of a few meters to a few tens of meters depending on imaging modes; these high-quality images enable precise monitoring of ice shelf dynamics. Using the satellite optical and SAR datasets accumulated in the 2010s, such as Landsat-7, Landsat-8, and Sentinel-1, it is possible to investigate the spatiotemporal changes in CGT over the past decade.

In this study, the changes in CGT from 2011 to 2020 were observed in terms of area, ice velocity, and grounding line position using the Landsat-7 ETM+, Landsat-8 OLI, Sentinel-1 SAR, and COSMO-SkyMed SAR (which are commercial data) to analyze the effect of ice pinning conditions on the dynamics of CGT. The 10-year changes in CGT observed from the optical and SAR images were analyzed considering ice pinning conditions.

2. Study area and data

2.1. Campbell Glacier Tongue (CGT)

CGT is an ice tongue located in the Northern Victoria Land in East Antarctica, which is a floating extension of Campbell Glacier flowing into TNB in the Ross Sea (Figure 1). The Jang Bogo Station (JBS), an Antarctic research station operated by South Korea since 2014, and the Mario Zucchelli Station (MZS), an Antarctic seasonal research station operated by Italy since 1986, are located near the CGT. Landfast sea ice forms both sides of CGT, and it has been used as a supply route for the logistics of the two research stations. Air temperature typically varies from −30°C to 5°C annually, according to measurements from an automatic weather station installed at JBS. The maximum tide variation near CGT is approximately 50 cm (Han, Lee, and Lee 2013a; Han and Lee 2014).

CGT comprises of a main flow unit formed along the major flow of the Campbell Glacier and a minor flow unit formed as the aggregation of broken ice chunks. In the hinge zone where ice experiences deflection due to changes in tide height, the spatial variation of ice velocity is large, resulting in the formation of many crevasses, whereas the ice velocity in the freely floating zone was spatially constant (Han, Ji, and Lee 2013b; Han and Lee 2015). The main flow unit was approximately 13.5-km long measured from the grounding line and 4.5-km wide, whereas the minor flow unit was approximately 8.0-km long and 2.5-km wide (Han and Lee 2014). The ice chunks of the minor flow unit of CGT move independent of each other, and their flow velocities change very rapidly (Han, Ji, and Lee 2013b; Han and Lee 2015). The decadal change in ice velocity of the minor flow unit of CGT is not analyzed in this study. The grounding line retreated by 0.3–1.5 km from 1996 to 2011 (Rignot, Mouginot, and Scheuchl 2011; Han and Lee 2014).

According to the grounding line in 1996 reported by Rignot, Mouginot, and Scheuchl (2011), a circular ice rumple (the white polygon in Figure 1) was located at the southwestern end of the main flow unit. The ice front observed in Figure 1 and the 2011 grounding line (Han and Lee 2014) show that the southwestern end of the main flow unit has experienced calving events but was still in contact with the seabed.

2.2. Data

2.2.1. Landsat-7 ETM+ and Landsat-8 OLI images

Landsat-7 ETM+ and Landsat-8 OLI data acquired from December 2010 to December 2020 were used to measure the area and ice velocity of CGT. A total of eight Landsat-7 ETM+ data were obtained at the path/row of 62/113 from December 2010 to March 2013, and a total of 70 Landsat-8 OLI data were obtained at paths of 60–64 and the row of 113 from October 2013 to December 2020 (Table 1). All Landsat data were systematically terrain corrected.
products (Level 1 GT) in polar stereographic projection and were cloud-free over CGT. The panchromatic band of the ETM+ and OLI data, which has a higher spatial resolution (15 m) than other spectral bands (30 m), was used for measuring the area and ice velocity. Among the panchromatic band images acquired at path/row of 62/113, two images from ETM+ and eight images from OLI were used not only for area measurement but also for annual ice velocity from 2011 to 2020 based on an image matching technique (Table 2). Owing to the scan line corrector (SLC) failure (SLC-off), the Landsat-7 ETM+ data acquired after May 2003 have the areas of data gaps that increase away from nadir. The data voids in the SLC-off images cause erroneous ice velocities produced by the image matching techniques (Haug, Kääb, and Skvarca 2010; Heid and Kääb 2012). Nevertheless, CGT is located near the nadir images acquired at the path/row of 62/113 and there are no data gaps for CGT. We tried using the Landsat data at

Table 1. Landsat-7 ETM+ and Landsat-8 OLI data used in this study.

| Satellite/Sensor | Path | Row | No. Scenes | Acquisition period       |
|------------------|------|-----|------------|--------------------------|
| Landsat-7/ETM+   | 62   | 113 | 8          | Dec. 2010 to Mar. 2013    |
| Landsat-8/OLI    | 60   | 113 | 11         | Sep. 2014 to Jan. 2017    |
|                  | 61   | 10  | 10         | Jan. 2014 to Dec. 2016    |
|                  | 62   | 21  | 11         | Dec. 2013 to Dec. 2020    |
|                  | 63   | 18  | 10         | Oct. 2013 to Jan. 2017    |
|                  | 64   | 10  | 10         | Feb. 2014 to Oct. 2016    |

Figure 1. Landsat-7 ETM+ SLC-off true color image of Campbell Glacier Tongue (CGT) obtained on 10 December 2010. The grounding line in 1996 is shown as blue solid line (Rignot, Mouginot, and Scheuchl 2011), whereas the grounding and hinge lines in 2011 are shown as red solid and dotted lines, respectively (Han and Lee 2014). The locations of Jang Bogo Station (JBS) and Mario Zucchelli Station (MZS) are presented as red dots.
the path/row of 62/113 with a time difference of about one year to measure the annual ice velocities. However, there were no cloud-free images in 2011 and 2013. Accordingly, the annual ice velocity for 2011–2012 was measured from the image pair with a time difference of 736 days, and that for 2013 could not be measured.

2.2.2. **COSMO-SkyMed and Sentinel-1 SAR**

Optical images for the observing CGT can only be used under a cloud-free condition in the Antarctic summer. Meanwhile, SAR can observe the surface regardless of the weather and sun altitudes. To continuously observe changes in CGT over time, COSMO-SkyMed SAR and Sentinel-1 SAR images were employed. Details of the SAR images are described in **Table 3**. COSMO-SkyMed is composed of a constellation of four satellites (COSMO-SkyMed-1, 2, 3, and 4) equipped with X-band SAR (a center frequency of 9.6 GHz). Each satellite revisits the same ground track every 16 days. Two satellites among the four revisit the same ground track with a time lag of one day. A total of 26 COSMO-SkyMed SAR single-look complex images acquired in the strip-map (SM) mode over an area of 40 × 40 km² in descending orbit from June 2010 to January 2012 and September 2019 to December 2019 were used for measuring the area of CGT (Table 3). Among them, two one-day tandem interferometric SAR (InSAR) pairs obtained in September and October 2019 were used for identifying the location of the grounding line of CGT (Table 4).

Sentinel-1 is a constellation of two satellites (Sentinel-1A and −1B) equipped with C-band SAR with a center frequency of 5.405 GHz. Each satellite has a revisit time of 12 days; meanwhile, the satellite constellation revisits the same ground track every 6 days. A total of 138 Sentinel-1 SAR single-look complex images acquired in the interferometric wide (IW) swath mode, which captures an area of 250 × 170 km², of the six different ground tracks from May 2015 to December 2020 were used for measuring the area of CGT (Table 3). All Sentinel-1 SAR images were acquired in HH polarization.

| Satellite | Imaging mode | Beam/Track-slice number | Orbit direction | Pol. | Incidence angle (°) | No. Scenes | Acquisition period |
|-----------|--------------|-------------------------|-----------------|------|--------------------|------------|-------------------|
| CSK       | SM           | H4-07                   | Descending      | HH   | 37.5               | 16         | Jun. 2010 to Jan. 2011 |
|           |              | H4-12                   | Descending      | 44.6 | 10                 |            | Sep. 2019 to Dec. 2019 |
| S1        | IW           | 25–1                    | Ascending       | HH   | 40.1               | 4          | May 2015 to Jun. 2015 |
|           |              | 28–3                    | Descending      | 35.4 | 21                 | 21         | Feb. 2017 to Oct. 2017 |
|           |              | 28–5                    | Descending      | 35.4 | 98                 | 98         | Oct. 2017 to Dec. 2020 |
|           |              | 86–2                    | Descending      | 42.4 | 4                  | 4          | Aug. 2015 to Oct. 2015 |
|           |              | 98–1                    | Ascending       | 40.1 | 6                  | 6          | Aug. 2016 to Oct. 2016 |
|           |              | 171–1                   | Ascending       | 40.1 | 5                  | 5          | Mar. 2016 to May 2016 |

**Table 3.** COSMO-SkyMed (CSK) and Sentinel-1 (S1) SAR data used in this study. SM, IW, and Pol. are the strip-map mode, interferometric wide swath mode, and polarization, respectively.

| ID | Dates of master and slave images | Perpendicular baseline (m) |
|----|---------------------------------|---------------------------|
| 1  | 5 September 2019 and 6 September 2019 | −2.8                      |
| 2  | 7 October 2019 and 8 October 2019  | −162.7                    |
Center. The multi-look of the COSMO-SkyMed and Sentinel-1 data was performed using 2 (range) × 2 (azimuth) and 2 × 10 looks, respectively. The SAR image processing was performed using the GAMMA software, whereas the digitizing process was performed using the ArcGIS 10.5. The 2011 grounding line identified by Han and Lee (2014) was used as the boundary for separating the CGT and the Campbell Glacier in this study.

The orthorectified panchromatic band images of Landsat satellites and SAR intensity images of COSMO-SkyMed and Sentinel-1 had a grid size of 15, 4, and 20 m, respectively, and it was difficult to detect the area change due to ice calving or ice propagation on a scale smaller than the grid size of each dataset. The different grid sizes of the dataset could produce different precision in the area measurements by visually digitizing. However, the perimeter and seasonal changes in the area of CGT are tens of kilometers and a few square kilometers, respectively (Han, Ji, and Lee 2013b), which made it possible to analyze the decadal changes without being affected by the different resolutions from 4 to 20 m.

The uncertainty in the area of CGT can be estimated as the standard deviation of the area derived from repeatedly digitizing the same image by a single operator (Ford 2013; Han et al. 2019). The uncertainty in the area measurement of CGT as the standard deviations of the repeatedly digitized areas through visual inspection was small, ranging from 0.2 to 0.6 km².

3.2. Measurement of the ice velocity of CGT

The annual ice velocities of CGT from 2011 to 2020 were measured using the panchromatic band images (Table 3) based on the normalized cross-correlation (NCC) algorithm. The NCC algorithm is an image matching technique performed in the spatial domain, and it has been widely used for glacier velocity measurement from satellite images due to its simplicity (Heid and Kääb 2012). The NCC calculates the correlation coefficient (CC) between a template (reference window) of the reference image (the first image) and a subset (search window) of the search image (the second image) using (Heid and Kääb 2012)

$$CC(i, j) = \frac{\sum_{k,l}(s(i+k,j+l) - \mu_s)(r(k,l) - \mu_r)}{\sqrt{\sum_{k,l}(s(i+k,j+l) - \mu_s)^2 \sum_{k,l}(r(k,l) - \mu_r)^2}}$$

where \((i, j)\) indicates the position in the search area, \((k, l)\) the position in the reference area, \(r\) the pixel value of the reference window, \(s\) the pixel value of the search window, \(\mu_s\) the average pixel value of the reference window, and \(\mu_r\) the average pixel value of the search window. The pixel showing the maximum CC within the search window is used to indicate the displacement of the corresponding reference template. In the NCC algorithm, the CC is normalized, which enables the use of time-series images with different illumination conditions (Heid and Kääb 2012). The NCC algorithm performs well in narrow glacial areas, such as CGT, where small window sizes are required for image matching (Heid and Kääb 2012).

The higher the spatial resolution of an image used for image matching, the better the matching performance can be expected (Warner and Roberts 2013; Kääb 2005) so that the annual ice velocities of CGT from 2011 to 2020 were measured using the panchromatic band images (Table 3) based on the NCC algorithm. The panchromatic images were filtered using a 3 × 3 Sobel filter to make the surface features more distinct as well as reduce the effect of different illumination conditions (Dehecq, Gourmelen, and Trouvé 2015; Mouginot et al. 2017). A reference window size of 16 × 16 pixels was used. The search window size, the most important factor for image matching, was set differently according to the time difference between the reference and search images (Table 3) by referring to the previously reported ice velocity of CGT by Han and Lee (2015), which is because the search window size must sufficiently cover the displacement magnitude between the two images. The reference window size of 16 × 16 pixels corresponded to a 240 m × 240 m grid, which overlapped during image matching to generate ice velocity fields with a grid size of 120 m × 120 m. Displacement fields derived by image matching were obtained for the x- and y-direction of the image geometry. Since all Landsat data were geometrically corrected in a polar stereographic projection, the NCC-derived displacement fields were along the x- and y-directions of the coordinate system.
To eliminate erroneous matching fields from the NCC, the average value of the displacement fields in both image directions (x- and y-direction) over a 9 × 9 window (corresponding to 1080 m × 1080 m) were computed. Assuming that the ice velocity does not vary much spatially, the displacement fields that deviated more than 50 m from the average displacement were regarded as erroneous fields and removed. The removal process of erroneous displacement fields can be effectively used for generating a reliable final ice velocity of CGT because the spatial variation of the ice velocity of CGT was reported within 100 m/a (Frezzotti 1993; Han and Lee 2015).

The validity of the ice velocity calculated using image matching techniques was evaluated using the velocity measurements within regions where no displacement was expected, such as exposed bedrocks near the CGT. When an image pair is correctly registered and the accurate offsets are found, the displacement should be zero. We analyzed all NCC results and calculated velocities in the x- and y-direction in the stable regions. The average velocities were less than 3 m/a, which validated the NCC-based image matching.

### 3.3. Identification of the location of grounding line of CGT

InSAR is a technique for measuring surface topography and displacement by calculating the phase difference between two SAR images acquired at different times for the same region. The InSAR signals include the interferometric phases by topography, displacement, atmospheric distortion, and noise. In glacial areas, the interferometric phases due to atmosphere and noise are smaller than those by topography and displacement, so they can be neglected (Kenji and Kaufmann 2003; Lee et al. 2021). The surface displacement is derived by removing the topographic phases from the InSAR signals. Differential interferometric SAR (DInSAR) signals for ice shelf include both horizontal displacement due to the ice flow and the vertical displacement due to the tide fluctuations. Double-differential interferometric SAR (DDInSAR) is a technique that differentiates two DInSAR images with the same temporal baseline at different times, removes the constant displacement component, and extracts only the difference in displacement that changes with time. If the horizontal flow of an ice shelf is constant over time (as is typically the case) and there is no surface melt or firm compaction, only the difference in the vertical displacement due to tide fluctuations can be obtained through the DDInSAR technique, from which the grounding line of the ice shelf can be identified as the zero-displacement line (Rignot, Mouginot, and Scheuchl 2011; Han and Lee 2014; Milillo et al. 2017; Han, Han, and Lee 2018; Han et al. 2019; Brancato et al. 2020). The local grounding, known as pinning point, can also be identified and located through the DDInSAR technique.

The grounding line of CGT was identified by applying the DDInSAR technique to two COSMO-SkyMed one-day tandem InSAR pairs acquired in September and October 2019 (Table 4). First, the single-look complex images were coregistered for each InSAR pair and an initial interferogram was generated. From each initial interferogram, the topographic phases were removed using TanDEM-X 12-m DEM, and the DInSAR image was generated. Unwrapping the DInSAR phases was performed using the minimum cost flow algorithm (Costantini 1998), and then the DDInSAR images were generated by subtracting the two DInSAR images. The zero-displacement line was detected from the DDInSAR image, which was identified as the grounding line of CGT in 2019.

Time-series change in the area of CGT measured from the optical and SAR data was analyzed, and ice calving at the ice pinning point was investigated. The change in ice velocity of CGT was investigated along with the change in the area at the pinning point. The migration of the ice pinning point was analyzed by comparing the grounding line position in 2011 and 2019.

### 4. Results

#### 4.1. Area changes of CGT

The maximum and minimum CGT area were 77.5 and 70.1 km², respectively, in December 2010 and in April 2020. The area of CGT decreased by 6.3 km² during the period between December 2010 and December 2020, corresponding to 8% of the maximum in 2010 (Figure 2). The general trend shows a steady growth throughout the last decade, except at sudden decline events due to ice calving during the Antarctic summer. In particular, four large ice calving events that created icebergs with an area range of
3.8–5.4 km² have occurred in the past decade (February 2011, March 2014, February 2017, and March–April 2020), resulting in a smaller CGT in 2020. An ice shelf in a stable state usually restores the area reduced by ice calving to its original area after a certain period. CGT showed a pattern of restoration for three years between the calving events. However, the calving in 2017 was the greatest, and the following restored area did not reach the previous maximum (Figure 2).

The calving of CGT has mainly occurred on both sides of the ice front (Figure 3). Figure 3 shows ice edges of CGT on various dates immediately after the calving events to show where ice was lost. Notably, the ice pinning point in 2011 is located at the southwestern edge (Han and Lee 2014). With respect to the ice fronts on 25 December 2010 (cyan polygon) where the maximum surface area was observed over the last decade, the calving occurred in the southeastern end and ice front in February 2011 (blue polygon) as well as the east side and at the ice pinning point in March 2014 (yellow polygon). In February 2017, the eastern edge calved (green polygon), and in March and April 2020, ice calving occurred again at the ice pinning point and the eastern edge (background image). The width of CGT has narrowed over the last decade. Besides, the minor flow unit slightly increased in area as aggregated ice chunks continued to advance, but the increase in area over 10 years was only 0.3 km².

**4.2. Ice velocity change of CGT**

The annual ice velocities of CGT from 2011 to 2020 were measured by applying the NCC to the Landsat panchromatic band images. Figure 4 shows the ice velocity in the x-direction (Figure 4(a,b)) and y-direction (Figure 4(c,d)), and the velocity magnitude (Figure 4(e,f)) in 2011–2012 and 2020 for comparison. The black arrows in Figure 4(e,f) indicate the flow directions and magnitudes. The numbers of valid velocity fields in 2011–2012 and 2020 are inconsistent because of the different temporal baselines and radiometric resolutions of the images used. In 2020, the time difference between image pairs is much shorter than in 2011–2012, and the radiometric resolution of the Landsat-8 OLI is better than that of Landsat-7 ETM+.

For the main flow unit, the ice velocity in the x-direction increased from the grounding line to the ice front in both 2011–2012 and 2020. The negative velocity in the x-direction indicates the ice flow to the east. Meanwhile, the velocity in the y-direction decreased to the ice front. The positive velocity in the y-direction indicates the flow to the south. Finally, the magnitude slightly increased along the flow line from the grounding line to the ice front.

Figure 5 shows the ice velocities along the x- and y-direction, and the velocity magnitude during 2011–2020 along the main flow line of CGT (the white line A–A’ in Figure 4(a)). The shaded area in Figure 5 represents the local grounding in the pinning point.
near the ice front. In general, the ice velocity of CGT along the flow line in the x-direction tended to decrease in the grounded region, hit the minimum in the vicinity of the grounding line, started to increase in the hinge zone, and maintained a stable rate up to the terminus (Figure 5(a)). Figure 5(a) shows that the x-direction velocity remained relatively stable from the grounded ice to the hinge zone for the last decade, whereas remarkable increases were observed in the freely floating zone after the 2011 and 2014 calving events, especially in the vicinity of the pinning point near the ice front (denoted as a gray box between 13 and 15 km) where the x-directional flow was accelerated by 13 m/a between 2011 and 2014 and by 20 m/a between 2014 and 2015. The x-direction velocity has been maintained since 2015, even with large calving at the eastern edge of CGT in February 2017 and April 2020.

The velocity in the y-direction linearly increased, hit the maximum in the hinge zone, and gradually decreased in the freely floating area to the ice front (Figure 5(b)). Similar to the velocity in the x-direction, the y-direction velocity in the freely floating zone, especially near the pinning point, dramatically varied after calving in 2014. It decreased sharply after the 2014 calving (~30 m/a near the ice front) and

Figure 3. The boundary of CGT 25 December 2010 (cyan), 27 February 2011 (blue), 14 March 2014 (yellow), and 20 February 2017 (green) overlaid on a Sentinel-1 SAR image on 26 April 2020. The grounding line in 1996 is shown as a pink solid line (Rignot, Mouginot, and Scheuchl 2011), whereas the grounding and hinge lines in 2011 are shown as the red solid and dotted lines, respectively (Han and Lee 2014).
Figure 4. Ice velocity fields of CGT in 2010–2011 (left column) and 2020 (right column) obtained from the normalized cross-correlation-based image matching of Landsat panchromatic images. (a, b) Ice velocity in the image x-direction component, (c, d) the ice velocity in the image y-direction component, and (e, f) velocity magnitudes. The axes of the image x- and y-direction are shown in (a). The Landsat-7 ETM+ SLC-off panchromatic image obtained on 12 December 2012 and the Landsat-8 OLI panchromatic image obtained on 29 December 2020 were used as the background images of the 2000 and 2014 velocity fields, respectively. The arrows on (e) and (f) represent the local flow direction. The grounding line in 1996 is shown as white solid line (Rignot, Mouginot, and Scheuchl 2011), whereas the grounding and hinge lines in 2011 are shown as red solid and dotted lines, respectively (Han and Lee 2014). The black line in (a) is the profile of the velocity variations as shown in Figure 5. The points P1–P4 in (a) are the locations where the variations in local flow direction are estimated, as shown in Figure 6.
remained until 2016. From 2016 to 2020, the y-direction ice velocity fluctuated, but the annual variation was less than ±5 m/a. From Figure 5(a,b), we could confirm that the ice velocity of CGT is more governed by the x-direction velocity as it goes from the grounding line to the ice front, which means that the flow direction of CGT curves eastward toward the ice front, which is also confirmed in the ice flow vectors in Figure 4(e,f).

Velocity magnitude has hardly changed in the hinge zone over the last decade, and it increased by ~15–20 m/a in the freely floating zone (Figure 5(c)). Because the 2011–2012 image matching did not provide reliable displacement fields near the ice front, it is impossible to quantitatively determine the 10-year ice velocity change in the ice from the NCC of the Landsat dataset. The maximum ice velocity observed at the ice front increased by 14 m/a from 2014 (247 m/a) to 2020 (261 m/a). Considering the maximum ice velocity of 244 m/a observed at the ice front of CGT in 2011, reported by Han and Lee (2015), the ice velocity magnitude at the ice front has increased by ~7% (~17 m/a) over the last decade.

Figure 5. The ice velocity profiles of CGT from 2011 to 2020 along the profile marked as A–A’ in Figure 4(a). (a) The image x-direction velocity, (b) the image y-direction velocity, and (c) the velocity magnitude. The vertical solid and dotted lines represent the location of the grounding and hinge lines in 2011, respectively (Han and Lee 2014). The shaded area represents the local grounding in the ice edge based on the DDInSAR in 2011 (Han and Lee 2014).
The local flow directions measured counterclockwise from the y-direction of the image at the point P1 (a point of the upstream of the hinge zone), P2 (the center point of CGT), P3 (2 km upstream of the pinning point), and P4 (a point near the pinning point) indicated in Figure 5(a) are shown in Figure 6. The local flow direction of P1 was attributed to the inflow fed by grounded ice, which was approximately 18° counterclockwise from the y-direction and had remained almost constant for the last decade. In the hinge zone, the local flow was deflected further east by the obstruction of the minor flow unit. Accordingly, the flow direction at the central point of CGT (P2) was approximately 26° counterclockwise from the y-direction, which showed a few changes with time. However, the local flow direction of P3 was more eastward despite the absence of obstruction by the minor flow unit, and the eastward rotation of ice was more severe toward the ice front (P4). In addition, the local flow direction has changed abruptly (~7° to the east) since 2014. Such changes in the flow direction can be closely related to the pinning point conditions.

4.3. Grounding line location change of CGT

Figure 7 shows the DDInSAR image generated from the COSMO-SkyMed one-day tandem InSAR pairs acquired on September 5 and 6, 2019 and October 7 and 8, 2019 (Table 4). The grounding line that separated Campbell Glacier and CGT hardly changed between 2011 and 2019. Meanwhile, the length of the grounding line at the pinning point was shortened by 1 km in 2019 compared with 2011, and its location migrated ~1.5 km to the east due to ice calving, which supports that the glacier tongue at the pinning point is still in contact with the locally elevated seabed, although there was a large calving event in 2014, but the ice-bed contact area reduced.

The shape of the locally elevated seabed and the ice-bed contact area can be analyzed using a bathymetry map, such as that provided in Bedmap2 (Fretwell et al. 2013) or BedMachine (Morlighem et al. 2020). However, we could not define the elevated seabed at the pinning point of CGT from the bathymetry of Bedmap2 and BedMachine, probably because of the lack of accurate bathymetry data for the region. The grid spacing of the bathymetry maps (1 km for Bedmap2 and 0.5 km for BedMachine) also makes a detailed analysis of small pinning points as in CGT difficult. Nevertheless, it is possible to estimate the shape and area of the ice-bed contact from the grounding line defined from the DDInSAR. The 1996 grounding line at the ice pinning point of CGT was defined as a closed circle, which indicated that the CGT was in contact with the dome-shaped elevated seabed. The 2011 and 2019 grounding lines at the pinning point were defined in the form of lines, indicating that the ice front was in contact with the crest or the sloping eastern flank of the elevated seabed. Changes in the shape and area of the ice-bed contact at the pinning point can be affected not only by the ice calving but also by the reduction in ice thickness. According to the study of Han and Lee (2015), the thickness change rate in the freely floating zone of CGT observed with ICESat observations from 2000 to 2008 was ~6.29 ± 1.37 m/a. If the reported thinning rate was maintained and the locally elevated seabed has a dome shape, progressive unpinning may have occurred, reducing the ice-bed contact area. The reduction of the pinning effect can change the ice velocity and buttressing of CGT.
5. Discussion

The flow of CGT curved eastward from the grounding line toward the ice front because the southwestern edge where CGT was grounded to the elevated seabed prevented the straightness of the ice flow. The ice velocity in the x-direction sharply accelerated between 2014 and 2015 in the freely floating zone, whereas that in the y-direction rapidly decelerated. After the 2014 calving at the pinning point, a sudden change in the flow direction to further east occurred, especially in the area from 2 km upstream of the pinning point to the ice front, as the velocity change in the x-direction was much greater than that in the y-direction. This abrupt change was because the southwestern end of CGT came in contact with the eastern flank of the locally elevated seabed at the pinning point after the 2014 calving. The advancing CGT turned eastward as it meet the sloping flank, and this influence is believed to have reached upstream of the pinning point. A similar phenomenon was observed at the ice front of Mertz Glacier Tongue (MGT) in East Antarctica. According to Massom et al. (2015), the flow direction of the northwestern end of

Figure 7. Rewrapped DDInSAR image of CGT generated by the COSMO-SkyMed one-day tandem InSAR pairs listed in Table 4. The grounding and hinge lines in 2011 are shown as blue solid and dotted lines, respectively (Han and Lee 2014). The grounding and hinge lines in 2019 identified from the DDInSAR image are shown as white solid and dotted lines, respectively.
the MGT rotated ~47° to the east, which was due to that the northward advancing glacier tongue came in contact with the sloping eastern flank of a shoal, and the resulting forces affected the eastward steering of the flow.

Since 2015, the flow direction of the advancing glacier tongue has been maintained, with only a slight increase in the velocity magnitude, which was probably because the southwestern tip was still in contact with the eastern flank of the seabed, but the ice-bed contact area may have decreased due to the effect of the ice thinning (Han and Lee 2015). Large calving occurred at the eastern edge of the CGT in February 2017, but there was little change in the velocity components, which was because the calving event had little effect on the flow characteristics of CGT. In March 2020, another calving event occurred at the pinning point, which implies that the ice-bed contact area further reduced, accelerating the ice velocity due to the weakening of the basal drag effect.

CGT showed a pattern of large calving every three years. The retreated area due to the calving events was 3.8–5.4 km² (4.9%–7.0% of the maximum area in December 2010). The restoration rate has increased rapidly from 1.13 km²/a to 1.85 km²/a since April 2020. This increase is followed by the increase in the advancing speed of CGT as the ice-bed contact area at the pinning point was reduced due to the March 2020 calving and the basal drag was weakened. Since 2017, the calving at the eastern edge of CGT has been observed to significantly contribute to the reduction of glacier tongue area. Most of the reduced area in 2017 (4.62 km²) and half of the reduced area in 2020 (1.93 km²) were attributed to the calving at the eastern edge. The most likely causes of the calving at the eastern edge of CGT are the transverse velocity gradient and ice thinning. As shown in Figure 4, the velocity magnitude increased from the eastern edge of the hinge zone to the center, which created many longitudinal crevasses in the eastern part of CGT (Han and Lee 2017). The longitudinal crevasses were likely developed into rifts and caused the calving at the eastern edge of CGT. Considering the ice thinning rate of CGT of ~6 m/a (Han and Lee 2015), more frequent calving at the eastern edge is expected in the future.

The changes in area, ice velocity, and grounding line position of CGT observed through the optical and SAR remote sensing were comprehensively analyzed, from which we understood that the influences of changes in the ice pinning conditions on the dynamics of CGT. Owing to the continuous calving at the pinning point, the unpinning of CGT is imminent, and a rapid dynamical change of the glacier tongue in a short period is expected. In future work, we will continuously monitor CGT as well as understand the changes in ice dynamics after unpinning and the resulting mass change mechanism.

6. Conclusion

Decadal changes in the area, ice velocity, and grounding line position of CGT were comprehensively investigated from a set of satellite optical and SAR datasets obtained from 2010 to 2020, and the effects of ice pinning conditions on the glacier tongue dynamics were analyzed. The southwestern edge of CGT was grounded on the locally elevated seabed, where the ice pinning conditions changed due to ice calving events.

CGT has experienced four major calving events in the last decade. The time between each calving was about three years, and the area was restored in-between. The restored area was 8% lower than that in 2010. The eastward ice velocity of CGT increased from the grounding line toward the ice front whereas the southward velocity decreased, probably due to the influence of the sub-shelf pinning at the southwestern edge of CGT. The largest change in ice dynamics occurred after massive calving at the ice pinning point in 2014. After the ice calving, the ice bottom at the pinning point came in contact with the sloping eastern flank of the elevated seabed, and the flow direction was abruptly turned more eastward. In addition, the ice velocity was accelerated due to the weakening of the basal drag effect caused by the ice-seabed contact area reduction at the pinning point.

In this study, we comprehensively analyzed the changes in area, velocity, and grounding line position of CGT via optical and SAR remote sensing. Through this study, it was possible to understand the effect of the sub-shelf pinning conditions at the edge of an ice shelf on its dynamics. Optical and SAR imagery accumulated over decades enabled us to analyze the changes in the ice pinning conditions and resulting ice dynamics changes. The findings of this study will contribute to understanding the mass balance.
mechanism of CGT as well as predicting the variations in the ice dynamics of sub-shelf pinned ice shelves.

Acknowledgements

The authors would like to thank the research assistants Jinyoung Kim, Taewook Kim, Hyunsoo Kim, and Jihoon Hong for collecting the Landsat and Sentinel-1 data used in this study.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This study was supported by the Korea Polar Research Institute (PE22140) and the National Research Foundation of Korea (NRF-2021R1C1C1009621 and No. 2019R1A6A1A03033167).

ORCID

Hyangsun Han http://orcid.org/0000-0002-0414-519X
Seung Hee Kim http://orcid.org/0000-0002-6434-5388
Sanghee Kim http://orcid.org/0000-0001-8367-573X

Data availability statement

The data that support the findings of this study are available on request from the corresponding author, (S.H.K). The data are not publicly available due to their containing information that could compromise the privacy of research participants.

References

Alley, R. B., P. U. Clark, P. Huybrechts, and I. Joughin. 2005. “Ice-Sheet and Sea-Level Changes.” Science 310 (5747): 456–460. doi:10.1126/science.1114613.
Ancora, S., V. Volpi, S. Olmastroni, S. Focardi, and C. Leonzio. 2002. “Assumption and Elimination of Trace Elements in Adélie Penguins from Antarctica: A Preliminary Study.” Marine Environmental Research 54 (3–5): 341–344. doi:10.1016/S0141-1136(02)00198-8.
Berger, S., L. Favier, R. Drews, J. J. Derwael, and F. Pattyn. 2016. “The Control of an Uncharted Pinning Point on the Flow of an Antarctic Ice Shelf.” Journal of Glaciology 62 (231): 37–45. doi:10.1017/jog.2016.7.
Bintanja, R., G. J. Van Oldenborgh, and C. A. Katsman. 2015. “The Effect of Increased Fresh Water from Antarctic Ice Shelves on Future Trends in Antarctic Sea Ice.” Annals of Glaciology 56 (69): 120–126. doi:10.3189/2015AoG69A001.
Brancato, V., E. Rignot, P. Milillo, M. Morlighem, J. Mouginot, L. An, B. Scheuchl, et al. 2020. “Grounding Line Retreat of Denman Glacier, East Antarctica, Measured with COSMO-SkyMed Radar Interferometry Data.” Geophysical Research Letters 47 (7): e2019GL086291. doi:10.1029/2019GL086291.
Cantone, G., and N. D. Pietro. 2001. “Benthic Littoral Polychaeta “Sedentaria” of Terra Nova Bay (Ross Sea, Antarctica).” Antarctic Science 13 (1): 3–8. doi:10.1017/S0260305500012623.
Costantini, M. 1998. “A Novel Phase Unwrapping Method Based on Network Programming.” IEEE Transactions on Geoscience and Remote Sensing 36 (3): 813–821. doi:10.1109/36.763767.
Dehecq, A., N. Gourmelen, and E. Trouvé. 2015. “Deriving Large-Scale Glacier Velocities from a Complete Satellite Archive: Application to the Pamir–Karakoram–Himalaya.” Remote Sensing of Environment 162: 55–66. doi:10.1016/j.rse.2015.01.031.
Doake, C. S. M., H. F. J. Corr, H. Rott, P. Skvarca, and N. W. Young. 1998. “Breakup and Conditions for Stability of the Northern Larsen Ice Shelf, Antarctica.” Nature 391 (6669): 778–780. doi:10.1038/35832.
Dupont, T. K., and R. B. Alley. 2005. “Assessment of the Importance of Ice-Shelf Buttressing to Ice-Sheet Flow.” Geophysical Research Letters 32 (4): L04503. doi:10.1029/2004GL022024.
Favier, L., O. Gagliardini, G. Durand, and T. Zwinger. 2012. “A Three-Dimensional Full Stokes Model of the Grounding Line Dynamics: Effect of A Pinning Point beneath the Ice Shelf.” The Cryosphere 6 (1): 101–112. doi:10.5194/tc-6-101-2012.
Favier, L., and F. Pattyn. 2015. “Antarctic Ice Rise Formation, Evolution, and Stability.” Geophysical Research Letters 42 (11): 4456–4463. doi:10.1002/2015GL064195.
Favier, L., F. Pattyn, S. Berger, and R. Drews. 2016. “Dynamic Influence of Pinning Points on Marine Ice-Sheet Stability: A Numerical Study in Dronning Maud Land, East Antarctica.” The Cryosphere 10 (6): 2623–2635. doi:10.5194/tc-10-2623-2016.
Focardi, S., R. Bargagli, and S. Corsolini. 1995. “Isomer-Specific Analysis and Toxic Potential Evaluation of Polychlorinated Biphenyls in Antarctic Fish, Seabirds and Weddell Seals from Terra Nova Bay (Ross Sea).” Antarctic Science 7 (1): 31–35. doi:10.1017/S095410209500006X.
Ford, M. 2013. “Shoreline Changes Interpreted from Multi-temporal Aerial Photographs and High Resolution Satellite Images: Wotje Atoll, Marshall Islands.” Remote Sensing of Environment 135: 130–140. doi:10.1016/j.rse.2013.03.027.
Fretwell, P., H. D. Pritchard, D. G. Vaughan, J. L. Bamber, N. E. Barrand, R. Bell, C. Bianchi, et al. 2013. “Bedmap2: Improved Ice Bed, Surface and Thickness Datasets for Antarctica.” The Cryosphere 7 (1): 375–393. doi:10.5194/tc-7-375-2013.
Frezzotti, M. 1993. “Glaciological Study in Terra Nova Bay, Antarctica, Inferred from Remote Sensing Analysis.” Annals of Glaciology 17: 63–71. doi:10.3189/02603055000012623.
Fürst, J. J., G. Durand, F. Gillet-Chaulet, N. Merino, L. Tavard, J. Mouginot, N. Gourmelen, and O. Gagliardini. 2015. "Assimilation of Antarctic Velocity Observations Provides Evidence for Uncharted Pinning Points." *The Cryosphere* 9 (4): 1427–1443. doi:10.5194/tc-9-1427-2015.

Goel, V., K. Matsuoka, C. Berger, I. Lee, J. Dall, and R. Forsberg. 2020. “Characteristics of Ice Rises and Ice Ripples in Dronning Maud Land and Endnerby Land, Antarctica.” *Journal of Glaciology* 66 (260): 1064–1078. doi:10.1017/jog.2020.77.

Golledge, N. R. 2020. “Long-Term Projections of Sea-Level Rise from Ice Sheets.” *Wiley Interdisciplinary Reviews: Climate Change* 11: e634. doi:10.1002/wcc.634.

Gudmundsson, G. H., J. A. N. De Rydt, and T. Nagler. 2017. “Five Decades of Strong Temporal Variability in the Flow of Brunt Ice Shelf, Antarctica.” *Journal of Glaciology* 63 (237): 164–175. doi:10.1017/jog.2016.132.

Han, S., H. Han, and H. Lee. 2018. “Grounding Line Changes of Ronne Ice Shelf, West Antarctica, from 1996 to 2015 Observed by Using DDInSAR.” *Korean Journal of Remote Sensing* 34 (1): 17–24. doi:10.7780/kjs.2018.34.1.2.

Han, S., H. Han, and H. Lee. 2019. “Analysis of Tidal Deflection and Ice Properties of Ross Ice Shelf, Antarctica, by Using DDInSAR Imagery.” *Korean Journal of Remote Sensing* 35 (6–1): 933–944. doi:10.7780/kjs.2019.35.6.1.5.

Han, J. I., and H. C. Kim. 2016. “Variations in Ice Velocities of Pine Island Glacier Ice Shelf Evaluated Using Multispectral Image Matching of Landsat Time Series Data.” *Remote Sensing of Environment* 186: 358–371. doi:10.1016/j.rse.2016.09.001.

Han, H., Y. Ji, and H. Lee. 2013b. “Estimation of Annual Variation of Ice Extent and Flow Velocity of Campbell Glacier in East Antarctica Using COSMO-SkyMed SAR Images.” *Korean Journal of Remote Sensing* 29 (1): 45–55. doi:10.7780/kjs.2013.29.1.5.

Han, H., and H. Lee. 2014. “Tide Deflection of Campbell Glacier Tongue, Antarctica, Analyzed by Double-Differential SAR Interferometry and Finite Element Method.” *Remote Sensing of Environment* 141: 201–213. doi:10.1016/j.rse.2013.11.002.

Han, H., and H. Lee. 2015. “Tide-Corrected Flow Velocity and Mass Balance of Campbell Glacier Tongue, East Antarctica, Derived from Interferometric SAR.” *Remote Sensing of Environment* 160: 180–192. doi:10.1016/j.rse.2015.01.014.

Han, H., and H. Lee. 2017. “Surface Strain Rates and Crevassing of Campbell Glacier Tongue in East Antarctica Analysed by Tide-Corrected DInSAR.” *Remote Sensing Letters* 8 (4): 330–339. doi:10.1080/2150704X.2016.1271158.

Han, H., and C.-K. Lee. 2018a. “Analysis of Ice Velocity of Nansen Ice Shelf, East Antarctica, from 2000 to 2017 Using Landsat Multispectral Image Matching.” *Korean Journal of Remote Sensing* 34 (6–2): 1165–1178. doi:10.7780/kjs.2018.34.6.2.2.

Han, H., and H. Lee. 2018b. “Glacial and Tidal Strain of Landfast Sea Ice in Terra Nova Bay, East Antarctica, Observed by Interferometric SAR Techniques.” *Remote Sensing of Environment* 209: 41–51. doi:10.1016/j.rse.2018.02.033.

Han, H., S. Lee, J.-I. Kim, S. H. Kim, and H.-C. Kim. 2019. “Changes in a Giant Iceberg Created from the Collapse of the Larsen C Ice Shelf, Antarctic Peninsula, Derived from Sentinel-1 and CryoSat-2 Data.” *Remote Sensing* 11 (4): 404. doi:10.3390/rs11040404.

Han, H., J. Lee, and H. Lee. 2013a. “Accuracy Assessment of Tide Models in Terra Nova Bay, East Antarctica, for Glaciological Studies of DDInSAR Technique.” *Korean Journal of Remote Sensing* 29 (4): 375–387. doi:10.7780/kjs.2013.29.4.3.

Hattermann, T., and A. Levermann. 2010. “Response of Southern Ocean Circulation to Global Warming May Enhance Basal Ice Shelf Melting around Antarctica.” *Climate Dynamics* 35 (5): 741–756. doi:10.1007/s00382-009-0643-3.

Haug, T., A. Kääb, and P. Skvarca. 2010. “Monitoring Ice Shelf Velocities from Repeat MODIS and Landsat Data – A Method Study on the Larsen C Ice Shelf, Antarctic Peninsula, and 10 Other Ice Shelves around Antarctica.” *The Cryosphere* 4 (2): 161–178. doi:10.5194/tc-4-161-2010.

Heid, T., and A. Kääb. 2012. “Evaluation of Existing Image Matching Methods for Deriving Glacier Surface Displacements Globally from Optimal Satellite Imagery.” *Remote Sensing of Environment* 118: 339–355. doi:10.1016/j.rse.2011.10.024.

Hellmer, H. H. 2004. “Impact of Antarctic Ice Shelf Basal Melting on Sea Ice and Deep Ocean Properties.” *Geophysical Research Letters* 31 (10): L10307. doi:10.1029/2004GL019506.

Hill, E. A., G. H. Gudmundsson, J. R. Carr, and C. R. Stokes. 2018. “Velocity Response of Petermann Glacier, Northwest Greenland, to past and Future Calving Events.” *The Cryosphere* 12 (12): 3907–3921. doi:10.5194/tc-12-3907-2018.

The IMBIE Team. 2018. “Mass Balance of the Antarctic Ice Sheet from 1992 to 2017.” *Nature* 558 (7709): 219–222. doi:10.1038/s41586-018-0179-y.

Ingels, J., R. B. Aronson, C. R. Smith, A. Baco, H. M. Bik, J. A. Blake, A. Brandt, et al. 2020. “Antarctic Ecosystem Responses following Ice-Shelf Collapse and Iceberg Calving: Science Review and Future Research.” *Wiley Interdisciplinary Reviews: Climate Change* 12: e682. doi:10.1002/wcc.682.

Joughin, I., and R. B. Alley. 2011. “Stability of the West Antarctic Ice Sheet in a Warming World.” *Nature Geoscience* 4 (8): 506–513. doi:10.1038/NGEO1194.

Jourdain, N. C., P. Mathiot, N. Merino, G. Durand, J. Le Sommer, P. Spence, P. Dutrieux, and G. Madec. 2017. “Ocean Circulation and Sea-Ice Thinning Induced by Melting Ice Shelves in the Amundsen Sea.” *Journal of Geophysical Research* 122 (3): 2550–2573. doi:10.1002/2016JC012509.

Kääb, A. 2005. “Combination of SRTM3 and Repeat ASTER Data for Deriving Alpine Glacier Flow Velocities in the Bhutan Himalaya.” *Remote Sensing of Environment* 94 (4): 463–474. doi:10.1016/j.rse.2004.11.003.

Kenyi, L. W., and V. Kaufmann. 2003. “Estimation of Rock Glacier Surface Deformation Using SAR Interferometry Data.” *IEEE Transactions on Geoscience and Remote Sensing* 41 (6): 1512–1515. doi:10.1109/TGRS.2003.811996.
Khazendar, A., C. P. Borstad, B. Scheuchl, E. Rignot, and H. Seroussi. 2015. “The Evolving Instability of the Remnant Larsen B Ice Shelf and Its Tributary Glaciers.” *Earth and Planetary Science Letters* 419: 199–210. doi:10.1016/j.epsl.2015.03.014.

Kim, S. H., D. J. Kim, and H. C. Kim. 2018. “Progressive Degradation of an Ice Rumble in the Thwaites Ice Shelf, Antarctica, as Observed from High-Resolution Digital Elevation Models.” *Remote Sensing* 10 (8): 1236. doi:10.3390/rs10081236.

Lee, H., H. Seo, H. Han, H. Ju, and J. Lee. 2021. “Velocity Anomaly of Campbell Glacier, East Antarctica, Observed by Double-Differential Interferometric SAR and Ice Penetrating Radar.” *Remote Sensing* 13 (14): 2691. doi:10.3390/rs13142691.

Lhermitte, S., S. Sun, C. Shuman, B. Wouters, F. Pattyn, J. Wuite, E. Berthier, and T. Nagler. 2020. “Damage Accelerates Ice Shelf Instability and Mass Loss in Amundsen Sea Embayment.” *Proceedings of the National Academy of Sciences* 117 (40): 24,735–24,741. doi:10.1073/pnas.1912890117.

Mahoney, A. R., A. J. Gough, P. J. Langhorne, N. J. Robinson, C. L. Stevens, M. M. J. Williams, and T. G. Haskell. 2011. “The Seasonal Appearance of Ice Shelf Water in Coastal Antarctica and Its Effect on Sea Ice Growth.” *Journal of Geophysical Research* 116 (C11): C11032. doi:10.1029/2011JC007060.

Massom, R. A., A. B. Giles, R. C. Warner, H. A. Fricker, B. Lagrésy, G. Hyland, L. Lescarmonnier, and N. Young. 2015. “External Influences on the Mertz Glacier Tongue (East Antarctica) in the Decade Leading up to Its Calving in 2010.” *Journal of Geophysical Research* 120 (3): 490–506. doi:10.1002/2014JF003223.

Matsuoka, K., R. C. A. Hindmarsh, G. Moholdt, M. J. Bentley, H. D. Pritchard, J. Brown, H. Conway, et al. 2015. “Antarctic Ice Rises and Rumples: Their Properties and Significance for Ice-Sheet Dynamics and Evolution.” *Earth-Science Reviews* 150: 724–745. doi:10.1016/j.earscirev.2015.09.004.

Millillo, P., E. Rignot, J. Mouginot, B. Scheuchl, M. Morlighem, X. Li, and J. T. Salzer. 2017. “On the Short-term Grounding Zone Dynamics of Pine Island Glacier, West Antarctica, Observed with COSMO-SkyMed Interferometric Data.” *Geophysical Research Letters* 44: 10: 436–10,444. doi:10.1002/2017GL074320.

Morlighem, M., E. Rignot, T. Binder, D. D. Blankenship, R. Drews, G. Eagles, O. Eisen, et al. 2020. “Deep Glacial Troughs and Stabilizing Ridges Unveiled beneath the Margins of the Antarctic Ice Sheet.” *Nature Geoscience* 13 (2): 132–137. doi:10.1038/s41561-019-0510-8.

Mouginot, J., E. Rignot, B. Scheuchl, and R. Millan. 2017. “Comprehensive Annual Ice Sheet Velocity Mapping Using Landsat-8, Sentinel-1, and RADARSAT-2 Data.” *Remote Sensing* 9 (4): 364. doi:10.3390/rs9040364.

Paolo, F. S., H. A. Fricker, and L. Padman. 2015. “Volume Loss from Antarctic Ice Shelves Is Accelerating.” *Science* 348 (6232): 327–331. doi:10.1126/science.aaa0940.

Rignot, E., J. Mouginot, and B. Scheuchl. 2011. “Antarctic Grounding Line Mapping from Differential Satellite Radar Interferometry.” *Geophysical Research Letters* 38 (10): L10504. doi:10.1029/2011GL047109.

Robel, A. A., V. C. Tsai, B. Minchew, and M. Simons. 2017. “Tidal Modulation of Ice Shelf Buttressing Stresses.” *Annals of Glaciology* 58 (74): 12–20. doi:10.1017/aog.2017.22.

Royston, S., and G. H. Gudmundsson. 2016. “Changes in Ice-Shelf Buttressing following the Collapse of Larsen A Ice Shelf, Antarctica, and the Resulting Impact on Tributaries.” *Journal of Glaciology* 62 (235): 905–911. doi:10.1017/jog.2016.77.

Still, H., A. Campbell, and C. Hulbe. 2019. “Mechanical Analysis of Pinning Points in the Ross Ice Shelf, Antarctica.” *Annals of Glaciology* 60 (78): 32–41. doi:10.1017/aog.2018.31.

Still, H., and C. Hulbe. 2021. “Mechanics and Dynamics of Pinning Points on the Shirase Coast, West Antarctica.” *The Cryosphere* 15 (6): 2647–2665. doi:10.5194/tc-15-2647-2021.

Tinto, K. J., and R. E. Bell. 2011. “Progressive Unpinning of Thwaites Glacier from Newly Identified Offshore Ridge: Constraints from Aerogravity.” *Geophysical Research Letters* 38 (20): L20503. doi:10.1029/2011GL049026.

Warner, R. C., and J. L. Roberts. 2013. “Pine Island Glacier (Antarctica) Velocities from Landsat 7 Images between 2001 and 2011: FFT-Based Image Correlation for Images with Data Gaps.” *Journal of Glaciology* 59 (215): 571–582. doi:10.3189/2013JoG12J113.

Williams, M. J., K. Grosfeld, R. C. Warner, R. Gerdes, and J. Dettmer. 2001. “Ocean Circulation and Ice-Ocean Interaction beneath the Amery Ice Shelf, Antarctica.” *Journal of Geophysical Research* 106 (C10): 22,383–22,399. doi:10.1029/2000JC000236.

Yang, Z., Z. Kang, X. Cheng, and J. Yang. 2019. “Improved Multi-Scale Image Matching Approach for Monitoring Amery Ice Shelf Velocity Using Landsat 8.” *European Journal of Remote Sensing* 52 (1): 56–72. doi:10.1080/22797254.2018.1556073.