Evolving Instability of the Scar Inlet Ice Shelf based on Sequential Landsat Images Spanning 2005–2018

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Received: 18 October 2019; Accepted: 18 December 2019; Published: 20 December 2019

Abstract: Following the large-scale disintegration of the Larsen B Ice Shelf (LBIS) in 2002, ice flow velocities for its remnants and tributary glaciers began to increase. In this study, we used sequential Landsat images spanning 2005–2018 to produce detailed maps of the ice flow velocities and surface features for the Scar Inlet Ice Shelf (SIIS). Our results indicate that the ice flow velocities for the SIIS and its tributary glaciers (Flask and Leppard Glaciers) have substantially increased since 2005. Surface features, such as rifts and crevasses, have also substantially increased in both scope and scale and are particularly evident in the region between the Leppard Glacier and the Jason Peninsula. Several indicators—including the acceleration of ice flows, the rapid growth of major surface rifts, the heavily enhanced surface crevasses, and the dynamic position of the ice front—point to the evolving instability of the SIIS. These same indicators describe the conditions for the LBIS leading up to its 2002 collapse. To date, however, the SIIS remains intact. The formation of fast ice supporting the ice shelf front, combined with moderate mean summer temperatures, may be preventing or delaying its collapse.

Keywords: Larsen B Ice Shelf; Scar Inlet Ice Shelf; ice flow velocity; ice front position; Landsat

1. Introduction

The Larsen B Ice Shelf (LBIS) is located along the eastern Antarctic Peninsula (65°30′S, 61°W), extending from the northern part of Robertson Island to the southern part of the Jason Peninsula. During the past 25 years, the LBIS has experienced several large-scale disintegration events, losing approximately 2320 and 3250 km² of ice area in 1995 and 2002, respectively [1]. Increased temperatures and altered ocean conditions are considered to be the main causes [2–4]. The collapse of LBIS has led to a decrease in backstress [5,6], a striking flow acceleration of the ice shelf and its tributaries [7–9], and a decline in surface elevation [7,8]. These further led to increased ice discharge and contributed mass discharged into the ocean [10]. Meanwhile, the collapse also caused changes in the regional climate, such as alterations in temperature, surface melting, and precipitation, since LBIS is a climatically sensitive region [11]. Other ice shelves around the LBIS have also been affected by these calving events. In July 2017, the Larsen C Ice Shelf collapsed when a giant iceberg (A-68) calved off; changes to the Larsen C Ice Shelf, the surrounding sea ice, and the nearby shallow seafloor all affected this iceberg’s evolution [12]. Similarly, the Seal Nunataks Ice Shelf retreated and thinned following the Larsen A and Larsen B Ice Shelf collapses in 1995 and 2002, respectively [13]. Turner et al. and Oliva et al. note that the air temperature over the Antarctic Peninsula has gone through a period of cooling since the disintegration of LBIS [14,15].
Since the LBIS collapsed in 2002, most studies have focused on the rapidly changing glaciers in the northern and central parts of the Larsen B embayment, such as the Hektoria–Green and Crane glaciers [10,16–19]. However, recent studies [16,20,21] have reported substantial changes in the remnant LBIS, namely the Scar Inlet Ice Shelf (SIIS), and its tributary glaciers during the same time, suggesting that the ice front retreat, ice flow acceleration, and enhanced surface features are key indicators producing its instability. The dynamic behavior of glaciers and ice shelves affects the contribution of the Antarctic ice sheet to global sea level rise, and one important parameter of ice sheet dynamics is the location of glacier and ice shelf fronts [22]. A change in the position of an ice shelf front reflects a change in the stability of that ice shelf to some extent. The front of the SIIS was found to have retreated significantly after the two calving events in early 2006 and late 2007/early 2008 [16,20]. De Rydt et al. [23] reported a general decrease in backstress across the SIIS (especially along its southeast margin) following the 2002 collapse of the LBIS but found that the tributary glaciers (Flask and Leppard) were largely unaffected. Ice flow velocity is a fundamental, crucial, and sensitive parameter in ice sheet dynamics that affects ice sheet stability and determines the extent of ice discharge and future sea level rise [24–27]. Consistent with the ice front retreat and the reduction of backstress, the surface elevation and ice flow velocity were decelerated and accelerated, respectively. Fricker and Padman [28] found the mean annual surface elevation change rate to be approximately $-0.19 \text{ m/yr}$ from 1992 to 2008. Khazendar et al. [20] found that the Flask and Leppard Glacier surface elevations decreased by 15–20 m from 2002 to 2011, and the ice flow velocity of the Flask Glacier increased by 55% from 1997 to 2012. In a broader study, Wuite et al. [21] found that the ice flow velocities for the SIIS increased by two- to three-fold, and the ice discharges of the Flask and Leppard Glaciers increased by 43% and 46%, respectively, from 1995 to 2013. The mean annual surface elevation change rates for the Flask and Leppard Glaciers were found to be approximately $-2.22$ and $-1.93 \text{ m/yr}$, respectively, based on ice, cloud, and land elevation satellite (ICESat) data. More recently, Chen et al. [6] found that the surface elevation of the SIIS decreased at a rate of $-0.07 \text{ m/yr}$ from 1992 to 2010; surface elevation was more stable after 2002 (as the LBIS retreated), and its ice area in 2015 was slightly larger than its ice area in 2009. Rott et al. [29] found that the ice flow velocities for the Flask and Leppard Glaciers exhibited only modest changes after 2011 but still remained higher than velocities measured before 2002. In addition, Borstad et al. [30] used assimilated observations in a constitutive framework to reproduce the evolution of the 2002 LBIS collapse and concluded that the weakening and fracturing of the ice shelf reduced its buttressing effect. Subsequent rifts may have contributed to damage in the Flask–Leppard Glacier convergence zone and caused ice flows to accelerate. Wuite et al. [21] also observed several major rifts in the SIIS using advanced synthetic aperture radar (ASAR) images captured on 28 January 2004 and suggested that the 2002 collapse of the LBIS was an important factor affecting the instability of the SIIS. Flask and Leppard Glaciers exhibited moderate mass loss, while the smaller glaciers of the SIIS approached equilibrium [29]. Fast ice, also called landfast ice, is sea ice that is “fastened” to the coastline, to the sea floor along shoals, or to grounded icebergs. Massom et al. [31] presented evidence that the absence of a protective fast ice buffer and the direct exposure of the ice shelf front to ocean swells potentially weakened the ice shelf to the point of calving.

Due to the changes in ice front positions, the dynamic acceleration of ice flow velocities and the patterns of ice surface features, such as rifts and crevasses, have been variable both in time and space. Thus, it is meaningful and useful to monitor the long time series evolution and understand the changing mechanism of the remnant section of LBIS after its disintegration. Several detailed analyses of ice front retreat, surface features, and velocities of the SIIS and its tributary prior to 2016 were presented by Khazendar et al., Wuite et al., and Rott et al [20,21,29]. Here, we build upon and provide a continuum framework for the previous work, assimilated and analyzed long-term observations of ice front positions, surface features, and ice flow velocities for the SIIS based on sequential Landsat satellite images spanning 2005–2018, thereby providing a constant change in the frontal position and surface features both in time and space across 14 years and extending the time series to cover ice flow velocities up to 2018. Finally, we combine the mean summer temperatures and the support of fast ice to
reveal the ice shelf’s evolving instability. Following this introduction, Section 2 describes the Landsat image data and related methods used in this study. Section 3 presents and interprets the detailed results. Section 4 presents related discussions of this study in isolation and the broader context of the state of knowledge. Finally, Section 5 summarizes the key findings from this study and considers directions for future research.

2. Data and Methods

2.1. Landsat Imagery and Grounding Line Products

In this study, we used sequential Landsat satellite images (Landsat 7 enhanced thematic mapper plus (ETM+) and the Landsat 8 operational land imager (OLI)), spanning 2005–2018, to depict the evolutionary instability of the SIIS. All the images were carefully selected so that no or few clouds were present in the research region, and band 8 with a 15 m resolution was used for subsequent analysis.

To prepare the images for analysis, we first filled any data-gap region attributable to the scan line corrector (SLC)-off problem in Landsat 7 ETM+ using the ENVI image analysis software, and then a local linear histogram matching technique based on linear transformation between one image and another was used to fill the scanning gap with previously acquired Landsat 7 imagery [32]. The images were then contrast-enhanced using low-pass and high-pass filters [33] to reveal more distinct textures and features in the snow and ice covered regions, which were registered to Landsat 7 imagery on 18 December 2002 using first order polynomial affine transformation with several stable and uniform distributed control points—such as mountain peaks, nunataks, or domes—to support comparative image analysis. The images that have been used for specific applications, including ice flow velocity mapping, ice shelf front positioning, rift and crevasse delineating, and the √ in Table 1, indicate that the image was selected for the corresponding application.

Table 1. Information of the selected sequential Landsat images in this research. (√ indicates that the image was selected for the corresponding application).

| ID | Satellite | Path and Raw | Acquisition Date | Ice Flow Velocity Mapping | Ice Shelf Front Positioning | Rifts Delineation | Crevasses Delineation |
|----|-----------|--------------|------------------|--------------------------|---------------------------|------------------|----------------------|
| 1  | Landsat 7 | 217 and 106  | 8 Jan. 2005      | √                        | √                         | √                | √                    |
| 2  | Landsat 7 | 216 and 106  | 4 Jan. 2006      | √                        | √                         | √                | √                    |
| 3  | Landsat 7 | 217 and 106  | 11 Jan. 2006     | √                        | -                         | -                | -                    |
| 4  | Landsat 7 | 216 and 106  | 5 Feb. 2006      | -                        | -                         | -                | -                    |
| 5  | Landsat 7 | 218 and 106  | 21 Jan. 2007     | √                        | √                         | √                | √                    |
| 6  | Landsat 7 | 218 and 106  | 21 Nov. 2007     | -                        | -                         | -                | -                    |
| 7  | Landsat 7 | 217 and 106  | 2 Feb. 2008      | -                        | -                         | -                | -                    |
| 8  | Landsat 7 | 218 and 106  | 25 Dec. 2008     | √                        | √                         | √                | √                    |
| 9  | Landsat 7 | 217 and 106  | 21 Dec. 2009     | √                        | √                         | √                | √                    |
| 10 | Landsat 7| 218 and 106  | 2 Mar. 2010      | √                        | √                         | √                | √                    |
| 11 | Landsat 7| 217 and 106  | 26 Feb. 2011     | √                        | √                         | √                | √                    |
| 12 | Landsat 7| 217 and 106  | 27 Dec. 2011     | √                        | √                         | √                | √                    |
| 13 | Landsat 7| 217 and 106  | 27 Nov.2012      | √                        | -                         | -                | -                    |
| 14 | Landsat 8| 218 and 106  | 28 Oct. 2013     | √                        | √                         | √                | √                    |
| 15 | Landsat 8| 218 and 106  | 29 Sep. 2014     | √                        | √                         | √                | √                    |
| 16 | Landsat 8| 218 and 106  | 3 Nov. 2015      | √                        | √                         | √                | √                    |
| 17 | Landsat 8| 217 and 106  | 29 Oct. 2016     | √                        | √                         | √                | √                    |
| 18 | Landsat 8| 217 and 106  | 3 Dec. 2017      | √                        | √                         | √                | √                    |
| 19 | Landsat 8| 218 and 106  | 24 Sep. 2018     | √                        | √                         | √                | √                    |

In the subsequent section of ice flow velocity analysis, it is necessary to determine the location of tributary glaciers based on the locations of the grounding line, and the appropriate grounding line should be selected first. So far, five grounding line products have been released, including (1) the MODIS-based mosaic of Antarctica (MOA) grounding line, with an accuracy of less than ±250 m, based
on MODIS images span 2003–2004 (MOA 2004), 2008–2009 (MOA 2009), and 2013–2014 (MOA 2014), covering the entire Antarctica continent and islands [34]; (2) the Antarctic surface accumulation and ice discharge (ASAID) grounding line, with positional accuracies ranging from ±52 m for the land to ±502 m for the outlet glaciers, based on Landsat 7 spanning 1999–2003 and ICESat data spanning 2003–2009 [35]; (3) the ice, cloud, and land elevation satellite (ICESat) grounding line, with an accuracy of approximately ±170 m, based on ICESat data spanning 2003–2009 [36]; (4) the making earth system data records for use in research environments (MEaSUREs) grounding line, with the highest accuracy at about ±100 m, based on ERS-1/2, RadarSAT-1/2, and ALOS PALSAR images spanning 1994–2009, covering 76% Antarctica continent and islands with extraction results from multiple sets of data in some locations [37]; and (5) the synthesized grounding line combining the MOA, ASAID, MEaSUREs, and ICESat grounding line products [38]. Here, we use the most accurate MEaSUREs grounding line product for subsequent analyses.

Figure 1 shows the Landsat image of the SIIS and its tributary glaciers captured on 8 January 2005 (after the 2002 collapse of the LBIS). This image includes the selected ice flow velocity measurement profiles (F1–F2–F3 and L1–L2–L3), rifts, and ice front positions. The stagnant region, the MEaSUREs grounding line (GL), and the Larsen Ice Shelf (LIS) automatic weather station (AWS) are also presented.

2.2. Ice Flow Velocity Mapping

To detect changes in ice flow velocities over time, we used the feature-tracking ability in the IMCORR image correlation software (Release 1.1, http://nsidc.org/data/velmap/imcorr.html) [39]. For two co-registered images captured at different times, the displacement of moving features, namely the ice flow velocity during this time interval, can be obtained by the image-to-image cross correlation algorithm. Each reference image chip from one image is compared to the possible matching chip within the second image. Then, the similarity of the reference chip and the search chips is gauged by the normalized cross-correlation index, and all the correlation values from the entire search area will form a surface to evaluate which is the best match [40].

The inputs of the IMCORR algorithm mainly consist of image names and sizes, parameters determining search chip size, reference chip size, grid spacing, and output filename. IMCORR
measures the degree of correlation between the matched features of two images through the strength of the correlation, which is defined as [39]:

$$S = \frac{(R_{\text{max}} - R_{\text{mean}})}{R_{\text{std}}} + \frac{(R_{\text{max}} - R_{\text{max2}})}{R_{\text{std}}} + 0.2 \cdot (N_{\text{max2}} - 1)$$  \hspace{1cm} (1)$$

where $S$ is the strength of the correlation, $R_{\text{max}}$ is the peak correlation value, $R_{\text{mean}}$ is the mean value of the correlation coefficient, $R_{\text{std}}$ is the standard deviation of the correlation coefficient, and $R_{\text{max2}}$ is the highest value more than 3 pixels away from the peak. $N_{\text{max2}}$ represents the number of “large” values more than 3 pixels away from the peak. The output parameters of IMCORR mainly include the location of the center of the reference chip, the total displacement in pixels, the strength of the correlation and resulting flag, the displacement to best match within the search chip, and the estimated error.

Furthermore, when using the IMCORR software to measure the ice flow velocity, the time interval between the two images should not be too long, so the features of the tie-points on the two images do not change significantly in their appearance; the sizes of the reference chip, search chip, and grid space also need to be appropriate to ensure the accuracy of the matching and to reduce the program’s running time. After trial and error, we used a time interval of approximately 1 year for each image pair. In addition, we set the reference window, search window, and grid space sizes to be 64 × 64, 192 × 192, and 10 × 10 pixels, respectively. Table 2 lists the Landsat images used to detect changes in ice flow velocities, as well as the estimated uncertainties associated with each image pair.

| Image 1   | Image 2   | Interval (d) | Image Co-registration Uncertainty (m) | Ice Flow Velocity at Control Points (m/year) | Ice Flow Velocity Uncertainty (m/year) |
|-----------|-----------|--------------|---------------------------------------|---------------------------------------------|----------------------------------------|
| 8 Jan. 2005 | 4 Jan. 2006 | 361          | 12.87                                 | 19.40                                       | 23.36                                   |
| 11 Jan. 2006 | 21 Jan. 2007 | 375          | 14.78                                 | 29.78                                       | 33.07                                   |
| 21 Nov. 2007 | 25 Dec. 2008 | 400          | 12.03                                 | 20.20                                       | 22.99                                   |
| 25 Dec. 2008 | 21 Dec. 2009 | 361          | 13.73                                 | 16.20                                       | 21.33                                   |
| 2 Mar. 2010 | 26 Feb. 2011 | 358          | 12.97                                 | 27.80                                       | 30.78                                   |
| 27 Dec. 2011 | 27 Nov. 2012 | 336          | 13.56                                 | 18.60                                       | 23.73                                   |
| 28 Oct. 2012 | 28 Oct. 2013 | 335          | 8.83                                  | 16.40                                       | 19.01                                   |
| 28 Oct. 2013 | 29 Sep. 2014 | 336          | 6.81                                  | 12.20                                       | 14.27                                   |
| 29 Sep. 2014 | 3 Nov. 2015   | 400          | 7.54                                  | 32.60                                       | 33.32                                   |
| 3 Nov. 2015 | 29 Oct. 2016  | 360          | 7.75                                  | 21.51                                       | 22.90                                   |
| 29 Oct. 2016 | 3 Dec. 2017   | 400          | 3.70                                  | 13.39                                       | 13.81                                   |
| 3 Dec. 2017 | 24 Sep. 2018  | 295          | 5.61                                  | 27.08                                       | 27.96                                   |

Uncertainty in the ice flow velocity measurements originates in two processes: image co-registration and feature-based image matching [7,41]. Two independent factors—the image co-registration uncertainty and the ice flow velocity at the control points—were used to estimate the ice flow velocity uncertainty using the law of error propagation. The uncertainty of image co-registration is related to deviations of the relative positions in the images caused by the different acquisition times, data sources, and orbits of satellites, which will further affect the result of the ice flow velocity. Moreover, the sun’s illumination can significantly vary due to the different solar azimuth and altitude at the time of image collection, leading to different shadows for the same features in the images. These differences caused by sun illumination, as one of the error sources, can be compensated by adjusting the intensity values of the features in the process of normalized cross-correlation correction within the IMCORR software [39]. The image co-registration uncertainty was within 1 pixel, which is consistent with the results reported by Scambos et al. [7], and the Landsat 8 OLI images performed much better than the Landsat 7 ETM+ images, with only about half of the image co-registration uncertainty (see Table 2). Because the ice flow velocities over stable control points (e.g., mountain peaks,
nunataks, or domes) should approach zero, we used the mean ice flow velocities at these control points as the benchmarks for uncertainties resulting from feature-based image matching. This same method has been widely adopted in previous studies [41,42]. Uncertainties resulting from feature-based image matching (i.e., for the mean ice flow velocity at the control points) were approximately 21.26 m/year or within 2 pixels. Comparatively, Mouginot et al. [43] reported these same uncertainties within 4 pixels. These two sources of uncertainty were combined to produce a mean ice flow velocity uncertainty of 23.88 m/year.

2.3. Ice Shelf Front Positioning

In this study, we manually digitized the SIIS front sequences using Landsat images spanning 2005–2018 (Figure 1). The positional accuracy of the ice shelf front is related to image resolution and co-registration accuracy [44], which can be calculated as follows [45]:

\[ U_T = \sqrt{\sum \lambda^2} + \sqrt{\sum \epsilon^2}, \]  

where \( U_T \) denotes the accuracy in the ice shelf front positions, \( \lambda \) is the spatial resolution of images, and \( \epsilon \) is the co-registration accuracy of each image relative to the reference Landsat image from 18 December 2002. The positional accuracy of the SIIS front sequences was estimated to be approximately 15 m or within 1 pixel.

2.4. Ice Surface Features Delineating

A rift is an isolated crevasse, either perpendicular or parallel to ice flow, that has propagated through the entire thickness of an ice shelf [46]. A rift tends to propagate and expand, resulting in calving and retreating events and threatening the stability of ice shelves [47]. Riffs are mainly distributed in the front and fringe regions of an ice shelf. Frontal rifts result from ice shelf flexion caused by horizontal ice deformation [48–50]. Fringe rifts result from the strong lateral shear stresses generated by rapid ice flow in less-active zones [50]. The Antarctica ice sheet is surrounded by various ice shelves, glacier tongues, and coastal areas without offshore floating ice masses. The dense patterns of crevasses are frequent on fast flowing ice masses (ice streams) [51]. When the internal stresses of the ice exceed its fracture yield stress, cracks perpendicular to the direction of maximum tension form on the surface of the ice shelf or glacier [50,52]. Deformation of the glacier or ice shelf during horizontal motion causes these cracks to expand to form crevasses [48,49,52]. Riffs and crevasses are two main ice surface features, and changes or stagnation among them usually reflect the stability of the ice shelf. In this paper, changes in the rifts and crevasses on the surface of the SIIS were visually interpreted from sequential Landsat series imagery using ArcMap geographical information system (GIS) software (version 10.5). The accuracy of the SIIS front sequences was estimated to be approximately 15 m or within 1 pixel.

2.5. Mean austral Summer Temperature and Fast Ice Monitoring

The surface temperature is an important factor related to the stability of the ice shelf front. For example, the two calving events of the SIIS both occurred in February of 2006 and 2008, when the austral temperature was accumulatively the highest. In this paper, the field observations recorded by the nearest automatic weather station (AWS) in the Larsen Ice Shelf (LIS) (see Figure 1 and the website: http://www.antarctica.ac.uk/met/reader/) were employed to depict the surface temperature changes during the research period, by employing the mean austral summer temperature (MST, mean of December, January, and February in the Southern Hemisphere), considering both the accumulative effect on the summer temperature and the data absence for specific months.

Generally, as protective sea ice for the ice shelf front, fast ice provides support to the ice shelf that may reduce the possibility of disintegration events triggered by sea ice loss and ocean swell [31]. Here, the evolutionary changes of fast ice along the SIIS are evaluated for the austral summer of January and
February when the temperature is high. Due to the insufficient temporal coverage of Landsat imagery within the two months during the research period, MODIS images were employed to illustrate the continuous changes of fast ice in austral summer time. The images collected annually in January and February from 2005 to 2019 were contrast-enhanced and co-registered by using several stable rocks as control points, and the ice fronts were then manually interpreted to discriminate them from ocean water or fast ice.

3. Results

3.1. Changes in the Scar Inlet Ice Shelf Front Positions

Since 2005, two significant calving events have occurred: (1) in February 2006, a calving event caused a 20 km retreat of the SIIS front [16], and (2) in February 2008, a calving event caused an 11 km retreat of the eastern part of the SIIS (no change occurred in the western part of the ice shelf). The mean distances between the ice front of 2005 and those of other years were calculated as the ratio of the area change and the mean glacier width for the time period based on the “open-ended box” method of Moon et al. [53]. From 2008 to 2010, the SIIS front position was relatively stable, showing no obvious backward or forward trends. From 2010 to 2018, the SIIS front slowly advanced at a mean rate of approximately 0.85 km/year, advancing approximately 7 km by 2018. The minimum and maximum advance rates were 0.64 and 1.28 km/year, respectively.

3.2. Changes in the Scar Inlet Ice Shelf Surface Features

3.2.1. Rifts

In this study, we visually interpreted the annual changes of five major rifts in the SIIS from 2005 to 2018. Figure 2 depicts the evolution for four of these five major rifts (because of its indistinctive changes prior to and sudden disappearance following a front calving event in February 2006, Rift 5 is not illustrated in Figure 2).

Figure 2. Cont.
Table 3 details the observed geometric changes for the five major rifts in the SIIS from 2005 to 2018. Khazendar et al. [20] treated Rifts 3 and 4 as a single rift because of their close proximity in the Landsat images. However, in this study, we considered them separately because of their distinct change patterns (i.e., Rift 4 vanished and became the ice front after the calving events in February 2008, while Rift 3 persisted). Just prior to its disappearance in February 2008, Rift 4 exhibited a modest increase in its length and maximum width. This phenomenon was more pronounced for Rift 5. Just prior to its disappearance in February 2006, the length and width of Rift 5 increased by 71% and 81%, respectively. Rift 3 is nearest to the ice shelf front and continued to widen. Rift 2 first appeared in 2012 and has been continuously expanding. Similarly, Rift 1 also continuously expanded from 2005 to 2018, reaching a maximum width of 3.48 km in 2018. Comparatively, Khazendar et al. [20] reported the width of Rift 1 as approximately 1 km in 2009 based on airborne topographic mapper (ATM) data.

| Date           | Rift 1 Length (km) | Rift 1 Width (km) | Rift 2 Length (km) | Rift 2 Width (km) | Rift 3 Length (km) | Rift 3 Width (km) | Rift 4 Length (km) | Rift 4 Width (km) | Rift 5 Length (km) | Rift 5 Width (km) |
|----------------|--------------------|-------------------|--------------------|-------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| 8 Jan. 2005    | 18.80              | 0.27              | –                  | –                 | 20.33              | 0.40              | 18.47              | 1.65              | 29.66              | 2.11               |
| 5 Feb. 2006    | 18.81              | 0.36              | –                  | –                 | 21.83              | 0.62              | 20.91              | 1.81              | 50.77              | 3.83               |
| 2 Feb. 2008    | 18.92              | 0.56              | –                  | –                 | 21.94              | 1.20              | 39.92              | 3.37              | –                  | –                  |
| 25 Dec. 2008   | 19.20              | 0.78              | –                  | –                 | 22.00              | 1.13              | –                  | –                 | –                  | –                  |
| 27 Nov. 2012   | 24.40              | 2.49              | 14.94              | 0.08              | 20.74              | 2.77              | –                  | –                 | –                  | –                  |
| 3 Nov. 2015    | 24.26              | 2.65              | 16.90              | 0.54              | 20.16              | 3.33              | –                  | –                 | –                  | –                  |
| 24 Sep. 2018   | 30.01              | 3.48              | 18.35              | 1.13              | 19.49              | 3.53              | –                  | –                 | –                  | –                  |

3.2.2. Crevasses

In this study, we visually interpreted the annual distribution patterns of crevasses in the SIIS using all the collected Landsat images spanning 2005–2018, and four snapshots on 8 January 2005, 25 December 2008, 27 December 2011, and 3 December 2017 were chosen to show the changes in surface crevasses. Figure 3 depicts these observed changes over time. The region outlined with a red solid line represents the same ice area in the SIIS over time; as the ice shelf moved, the region outlined with a red solid line moved concurrently. Both the schematic and Landsat imagery of the crevasse distribution patterns are presented.
Prior to its 2006 calving event, a denser pattern of crevasses was observed adjacent to the ice shelf front. Following its two calving events in 2006 and 2008, the density of the crevasses increased (based on the 8 January 2005 and 25 December 2008 snapshots). Consistent with the expansion of the major rifts in the SIIS, crevasses on the surface of the ice shelf increased in density during the study period (Figure 3). In December 2017, crevasses in the SIIS divided the ice shelf into thousands of fragments. This same condition preceded the 2002 collapse of the LBIS. Prior to the 2006 LBIS calving event, the crevasses were concentrated along the front of the ice shelf. The crevasses on the surface of the suture zone between the Flask and Leppard Glaciers became denser from 2005 to 2018.

In addition to considering the evolution in crevasse density, we also considered changes in their length. Figure 4 shows the variation in total crevasse length and density in the SIIS from 2005 to 2018, where the density of the surface crevasses was calculated by the annual total length of the surface crevasses dividing the SIIS area, which is bounded by the ice front position extracted in this study. Due to the low quality of the Landsat image caused by cloud cover, no crevasse length result was able to be reported for 2010, and no continuous ice front position was obtained in 2012 to calculate the area. Consistently across the study period, the total length and density of crevasses in the SIIS increased over time, with two exceptions. Following the first calving event in 2006, the total crevasse length sharply decreased due to ice area loss in the front of the ice shelf but began to increase again in the
subsequent year. The same phenomenon was observed following the 2008 calving event. Between 2009 and 2018, the total length of the crevasses in the SIIS doubled.

3.3. Changes in the Scar Inlet Ice Shelf Ice Flow Velocities

To detect the evolution in ice flow velocities in the SIIS, we developed a series of annual ice flow velocity maps using Landsat images from 2005 to 2018 (shown in Figure 5), all of which were smoothed by using the local mean filter. We further displayed the ice flow velocities on the profiles of F1-F2-F3 and L1-L2-L3 in Figures 6 and 7, respectively.

![Figure 4. Evolution in the total crevasse length and density in the Scar Inlet Ice Shelf from 2005 to 2018.](image)

![Figure 5. Cont.](image)
Figure 5. Evolution of the ice flow velocities in the Scar Inlet Ice Shelf from 2005 to 2018, depicted (a–m) spatially by year; (n) graphically at Point R.

Figure 6. Comparative ice flow velocities along the Flask Glacier centerline and its flowline on the Scar Inlet Ice Shelf from 2005 to 2018. The grey dashed line is the making earth system data records for use in research environments (MEaSUREs) grounding line in 1999 (GL 1999). RF is the intersection of a line passing through R and perpendicular to the profile of the Flask flowline on the Scar Inlet Ice Shelf.
Wuite et al. [21], which designated as the Stagnant Region [20]. Consistent with Khazendar et al.’s findings from 2003 to 2008, the ice flow velocities in these flank areas changed little from 2005 to 2018, earning its overall, the ice flow velocities for the SIIS increased rapidly from 2005 to 2012 and remained relatively stable thereafter. Spatially, ice flow velocities gradually increased from Leppard and Flask Glaciers to the front of the SIIS, reaching their maximum in the middle region of the ice shelf front with relatively lower values in both flanks. The ice flow velocities were prominently higher in the Flask Glacier and its downstream area on the SIIS than those in the Leppard Glacier and its downstream area. This finding is consistent with results based on the TerraSAR-X data reported by Wuite et al. [21]. The ice flow in this stagnant part of the ice shelf is lower because there is hardly any ice influx from the sides. This finding is consistent with the lack of texture observed in the Landsat images and with the previous interferometric synthetic aperture radar (InSAR) velocity measurements [20]. In addition, the ice flow velocities in these flank areas changed little from 2005 to 2018, earning its designation as the Stagnant Region [20]. The two calving events in 2006 and 2008 are most evident Figure 5a–d, spanning January 2005–January 2007 and January 2007–December 2008, respectively. The ice flow velocities in the calved parts of the ice shelf were significantly higher than the velocities in the other regions. To quantify the changes in ice flow velocities, we considered evolution at a single reference point (Point R) in the SIIS. In 2006, Point R was located near the ice shelf front. Khazendar et al. used this same reference point in a related study [20]. Consistent with Khazendar et al.’s findings from 2003 to 2013 [20], Figure 5n shows a general increase in ice flow velocities at Point R, from 627 m/year in 2005 to 802 m/year in 2018, reflecting a 27.9% increase. Despite the general increasing trend, the ice flow velocities at Point R exhibited some fluctuations. Following each of the calving events in 2006 and 2008, the ice flow velocities decreased by approximately 50 m/year. In 2013, the ice flow velocities at Point R stabilized, exhibiting a slightly decreasing trend. To further analyze the ice flow velocity dynamics, we compared the inter-annual velocity measurements from 2005 to 2018 along the Flask and Leppard Glacier centerlines (FL–GL and L1–GL) and their corresponding flowlines on the SIIS (GL–F2–F3 and GL–L3). Figures 6 and 7 show the comparative results of the two profiles, respectively. The ice flow velocity measurements from September to November 2009 obtained from InSAR by Wuite et al. [21] were included for comparison. For the same time period, the mean error of the ice flow velocities for the two profiles was reported by Wuite et al. [21], which differed in this study by 9.3 and 10.2 m/year, respectively, with an acceptable standard deviation of 20.7 and 24.2 m/year.
Temporally, the ice flow velocities were overall accelerated with fluctuations from 2005 in the Flask Glacier (Figure 6, see the F1-GL part). The ice flow velocity decreased by an average of 30 m/year between January 2005 and January 2006 and January 2006 and January 2007, and then increased until December 2009; the increasing rate was approximately 32 m/year. After an average deceleration of 40 m/year in March 2010–February 2011, the Flask Glacier showed a slight increasing trend. Spatially, the ice flow velocity decreased from F1 to the grounding line. As for the flowline on the SIIS (GL-F2-F3), the ice flow velocity first decreased to a minimum and then increased. After F2, the velocity showed an accelerated trend, reaching its maximum at F3 or the front of the ice shelf. In 2011, the ice flow velocity increased rapidly, reaching a maximum value of 852 m/year between December 2011 and November 2012, and then again stabilizing.

Similar trends were observed for the Leppard Glacier and its flowline on the SIIS (L1-L2-GL and GL-L3 in Figure 7). Spatially, the ice flow velocity of the Leppard Glacier was stable or slightly increasing. Its flowline on the SIIS showed an obvious accelerating trend, reaching a maximum value of about 300 m/year higher at F3 than that on the grounding line. A more apparent increase in the flowline, with an average increase of about 45 m/year, was observed from January 2006 to November 2007. A similar trend was observed for the Flask flowline. In general, ice flow velocities increased throughout the entire SIIS, suggesting increased instability of the ice shelf consistent with other observed evolutions in surface features and ice shelf front position.

3.4. Major Calving Events of the Scar Inlet Ice Shelf

Unlike the previous 2002 LBIS calving event that resulted in numerous small icebergs, the 2006 and 2008 LBIS calving events each produced only a single large iceberg. After the 2006 calving event with Rift 5 as the edge of its disintegration, the location of Rift 5 became the new front position of the Scar Inlet Ice Shelf. Rift 4 became the new front position of the Scar Inlet Ice Shelf after the 2008 calving event. To further investigate these two calving events, we analyzed the Landsat images just before and just after each event. Figure 8 shows these comparative images. We used a series of corresponding reference points (A1-A2, B1-B2, etc.) to study the process of ice shelf disintegration. In Figure 8, the red font denotes the before conditions and the green font denotes the after conditions for concurrent reference points.

During the 2006 calving event, with Rift 5 as the edge of its disintegration (Figure 8a,b), the entire A-54 iceberg [16] broke away from the front of the SIIS in only 16 days. In Figure 8a, the rift was significantly wider along the southern front of the ice shelf than along the northern front, suggesting a counter-clockwise rotation of the A-54 iceberg. Conversely, in Figure 8b, the rift was wider along the northern front of the ice shelf than along the southern front, and the drift distances for A1-A2, B1-B2, and C1-C2 were approximately 7 to 17 times larger than those for F1-F2 and G1-G2, suggesting a clockwise rotation of the A-54 iceberg after calving. During the 2008 calving event (Figure 8c,d), which calved via Rift 4, numerous small ice floes were observed both before and after the collapse, with nearly uniform drift distances of 3.5–4 km. This finding suggests that the iceberg moved parallel to the ice shelf front during calving.

Despite the observed increases in ice flow velocities and surface features (e.g., rifts and crevasses), no additional calving events occurred in the SIIS between 2008 and 2018.

We next analyzed the evolution of austral summer temperature for the SIIS. Figure 9 shows these results for one, two, and all three of the summer months considered based on data from the LIS AWS. The MST increased prior to and decreased after each calving event (including an earlier calving event that occurred in 2002). Smaller increases of the MST were observed in 2011, 2013, and 2017, with no corresponding calving events.
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As the final task in this study, we considered that the evolution of the fast ice distributed over the front of the ice shelf may provide support. In general, minimal fast ice was observed along the front of the SIIS on 8 January 2005, 7 January 2007, and 1 January 2009. On 5 January 2006, 30 January 2008, and...
27 January 2011, some disaggregated fast ice was observed along the front of the ice shelf. The front of the ice shelf was fully joined with the fast ice and was not in direct contact with the seawater after 2011, which may have contributed to the stability of SIIS. This phenomenon is shown in more detail in the Supplementary Materials (Video S1).

4. Discussion

Following the collapse of the LBIS in 2002, the SIIS experienced incessant retreats due to calving events [20]. However, our results indicate that, from 2005 to 2018, the front position of the ice shelf did not continuously retreat, but instead was in a continuous state of dynamic change.

Since 2005, the lengths and maximum widths of major rifts in the SIIS have increased significantly. This change has been mainly attributed to the strong lateral shear imparted on the stagnant region by the accelerating ice flows between the Leppard Glacier outflow and the Jason Peninsula. Rift 2 first appeared in 2012 and has been continuously expanding, suggesting the growing instability of the Stagnant Region between the Leppard Glacier and the Jason Peninsula. Rift 3, which is nearest to the ice shelf front and continues to widen, will likely bound the next calving event, and if Rift 1 continues to expand at the current rate, it may also bound a future calving event.

In general, the ice flow velocities of the SIIS have increased throughout the entire SIIS during 2005–2018, suggesting the increased instability of the ice shelf, which is consistent with other observed evolutions in surface features and the ice shelf’s front position. Table 4 lists all the variables that contributed to the evolving instability of the SIIS, including the mean retreat distance of the ice front positions from 2005, the length and width changes of rifts, the annual total length of crevasses, and the ice flow velocities from 2005 to 2018. The mean distances between the ice front of 2005 and those of other years as a whole were decreasing, showing the slowly advancing trend of the ice front. The changes of the crevasses and ice flow velocities are consistent with the calving events. The disintegration of SIIS in 2006 and 2008 caused the ice front to retreat, resulting in instant acceleration of ice flow velocities and a decrease in the total length of crevasses, especially in the front part of the ice shelf. From 2008 to 2010, the SIIS front position was relatively stable, showing no obvious backward or forward trends, while the rifts’ widths and ice flow velocity showed an increasing trend. After 2010, the SIIS front slowly advanced by approximately 7 km by 2018, while the crevasses’ length and ice flow velocity increased and gradually became stable. Rift 5 and Rift 4 exhibited modest increases in their lengths and widths prior to their disappearances in 2006 and 2008, respectively. Similarly, Rift 1 and Rift 3 continuously expanded from 2005 to 2018, reaching maximum widths of 3.48 km and 3.53 km in 2018, respectively. Rift 2 first emerged in 2012 and has been continuously expanding ever since.

The two SIIS calving events in 2006 and 2008 resulted in substantial losses of ice area (approximately 650 km² and 140 km², respectively) and a retreat of the ice shelf front. Comparatively, the area of the LBIS decreased from approximately 12,000 km² in the 1980s [4] to 2080 km² in 2016. Scambos et al. [54] identified three types of calving: (1) rift calving, (2) edge wasting, and (3) rapid disintegration. The two SIIS calving events in 2006 and 2008 represent rift calving, at Rift 5 and Rift 4 respectively. These calving events (including an earlier calving event that occurred in 2002) corresponded to sudden increases in the MST measured on the Larsen Ice Shelf and the loss of fast ice support along the front of the ice shelf.

In general, the observed increases in rifts, crevasses, and ice flow velocities combined with a retreat of the ice shelf front suggest the increasing instability of the SIIS. These same indicators were present prior to the 2002 collapse of the LBIS [2,55]. The recent formation of fast ice supporting the front of the ice shelf [31], combined with moderate MST values, may have prevented or delayed its collapse. The mechanism of MST and fast ice preventing SIIS disintegration needs to be further studied.
Table 4. Variables contributing to the evolving instability of the SIIS.

| Year       | Retreat Distance (km) | Rift 1 Length (km) | Rift 1 Width (km) | Rift 2 Length (km) | Rift 2 Width (km) | Rift 3 Length (km) | Rift 3 Width (km) | Rift 4 Length (km) | Rift 4 Width (km) | Rift 5 Length (km) | Rift 5 Width (km) | Crevasses Length (km) | Annual Ice Flow Velocities (m/year) |
|------------|------------------------|--------------------|-------------------|--------------------|-------------------|--------------------|-------------------|--------------------|-------------------|--------------------|-------------------|------------------------|-------------------------------|
| 8 Jan. 2005 | 0.00                   | 18.80              | 0.27              | —                  | —                 | 20.33              | 0.40              | 18.47              | 1.65              | 29.66              | 2.11              | 658.22                 | 627.47                        |
| 4 Jan. 2006 | −0.31                  | 18.56              | 0.34              | —                  | —                 | 21.81              | 0.62              | 20.91              | 1.78              | 30.88              | 3.62              | 719.77                 | 627.47                        |
| 21 Jan. 2007 | 19.29                 | 18.78              | 0.55              | —                  | —                 | 21.50              | 0.79              | 23.79              | 2.43              | —                  | —                 | 461.25                 | 577.11                        |
| 25 Dec. 2008 | 18.64                 | 19.20              | 0.78              | —                  | —                 | 22.00              | 1.13              | —                  | —                 | —                  | —                 | 430.49                 | 635.43                        |
| 21 Dec. 2009 | 18.74                 | 19.71              | 0.96              | —                  | —                 | 21.45              | 2.54              | —                  | —                 | —                  | —                 | 460.72                 | 680.22                        |
| 2 Mar. 2010  | 18.70                 | 19.70              | 0.99              | —                  | —                 | 21.46              | 2.57              | —                  | —                 | —                  | —                 | 447.52                 | 692.42                        |
| 27 Dec. 2011 | 17.42                 | 24.92              | 2.30              | —                  | —                 | 21.20              | 2.64              | —                  | —                 | —                  | —                 | 477.27                 | 792.13                        |
| 27 Nov. 2012 | —                     | 24.40              | 2.49              | 14.94              | 0.08              | 20.74              | 2.77              | —                  | —                 | —                  | —                 | 568.02                 | 792.13                        |
| 26 Oct. 2013 | 16.13                 | 24.24              | 2.50              | 16.62              | 0.25              | 20.86              | 3.01              | —                  | —                 | —                  | —                 | 655.23                 | 822.10                        |
| 29 Sep. 2014 | 15.23                 | 24.25              | 2.64              | 16.81              | 0.36              | 20.47              | 3.17              | —                  | —                 | —                  | —                 | 740.71                 | 800.22                        |
| 3 Nov. 2015  | 14.40                 | 24.26              | 2.65              | 16.90              | 0.54              | 20.16              | 3.33              | —                  | —                 | —                  | —                 | 818.74                 | 799.23                        |
| 29 Oct. 2016 | 13.57                 | 24.23              | 3.17              | 17.63              | 0.80              | 18.77              | 3.43              | —                  | —                 | —                  | —                 | 846.06                 | 817.65                        |
| 3 Dec. 2017  | 12.64                 | 29.66              | 3.15              | 18.00              | 0.95              | 19.27              | 3.51              | —                  | —                 | —                  | —                 | 889.67                 | 810.24                        |
| 24 Sep. 2018 | 11.93                 | 30.01              | 3.48              | 18.35              | 1.13              | 19.49              | 3.53              | —                  | —                 | —                  | —                 | 936.66                 | 803.00                        |
5. Conclusions

In this study, we analyzed long-term observations of ice front positions, surface features, and ice flow velocities for the SIIS based on sequential Landsat satellite images spanning 2005–2018 to reveal its evolving instability. This study builds upon and provides a continuum framework for previous related work.

Our results indicate that the ice flow velocities for the SIIS and its tributary glaciers (Flask and Leppard Glaciers) have substantially increased since 2005, reaching a maximum value of 928 m/year along the ice shelf front. Ice flow velocities increased from 2006 to 2012 but remained relatively stable thereafter. Ice flow velocities increased only along the front of the ice shelf initially but gradually increased throughout the entire SIIS. Surface features, such as rifts and crevasses, have also substantially increased in both scope and scale and were particularly evident in the region between the Leppard Glacier and the Jason Peninsula.

Several indicators—including the acceleration of ice flows, the rapid growth of major surface rifts, the heavily enhanced surface crevasses, and the dynamic position of the ice front—point to the evolving instability of the SIIS. These same indicators described the status of the LBIS leading up to its 2002 collapse. To date, however, the SIIS remains intact. The formation of fast ice supporting the ice shelf front, combined with moderate mean summer temperatures, may be preventing or delaying its collapse. Since 2002, the regional MST has been dropping, limiting any surface melting of the ice shelf. Since 2008, fast ice has been forming along the ice shelf front, providing support and limiting the potential for a calving event caused by the separation of any crevasse-related fragments. A future rise in the MST that causes the fast ice to melt will likely result in an SIIS calving event that produces numerous small icebergs similar to the previous 2002 calving event rather than one large iceberg.

The results of this study substantially contribute to the state of knowledge regarding glacial instability based on sequential Landsat satellite images. Our research is of particular interest because of its implications for detecting and monitoring glacial or other surface feature changes using remote sensing technology. Future research will consider the mechanics and driving forces of SIIS instability and the possible consequences of its future collapse to regional climate change.

Supplementary Materials: The following are available online at http://www.mdpi.com/2072-4292/12/1/36/s1, Video S1: Evolutionary changes in the fast ice along the front of the Scar Inlet Ice Shelf from 2005 to 2019.

Author Contributions: Conceptualization, G.Q.; Data curation, G.Q. and Y.L.; Methodology, Y.L. and S.G.; Investigation, W.Y.; Writing—original draft, Y.L. and S.G.; Writing—review & editing, G.Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the National Key Research and Development Program of China (2017YFA0603102), the National Science Foundation of China (91547210, 41771471), and the National Key Research and Development Program of China (2017YFB0503502).

Acknowledgments: We would like to thank the United States Geological Survey (USGS) for providing the Landsat images used in this study.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Rack, W.; Rott, H. Pattern of retreat and disintegration of the Larsen B ice shelf, Antarctic Peninsula. Ann. Glaciol. 2004, 39, 505–510. [CrossRef]
2. Skvarca, P.; Angelis, H.D.; Zakrajsek, A.F. Climatic conditions, mass balance and dynamics of Larsen B ice shelf, Antarctic Peninsula, prior to collapse. Ann. Glaciol. 2004, 39, 557–562. [CrossRef]
3. Domack, E.; Duran, D.; Leventer, A.; Ishman, S.; Doane, S.; McCallum, S.; Amblas, D.; Ring, J.; Gilbert, R.; Prentice, M. Stability of the Larsen B ice shelf on the Antarctic Peninsula during the Holocene epoch. Nature 2005, 436, 681–685. [CrossRef]
4. Cook, A.J.; Vaughan, D.G. Overview of areal changes of the ice shelves on the Antarctic Peninsula over the past 50 years. Cryosphere 2010, 4, 77–98. [CrossRef]
5. Shepherd, A.; Wingham, D.; Wallis, D.; Giles, K.; Laxon, S.; Sundal, A.V. Recent loss of floating ice and the consequent sea level contribution. Geophys. Res. Lett. 2010, 37. [CrossRef]

6. Chen, J.; Ke, C.Q.; Zhou, X. Variations in the extent and elevation of the Larsen A and B ice shelves, Antarctica, derived from multiple datasets. J. Appl. Remote Sens. 2018, 12, 046019. [CrossRef]

7. Scambos, T.A.; Bohlander, J.A.; Shuman, C.A.; Skvarca, P. Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica. Geophys. Res. Lett. 2004, 31. [CrossRef]

8. Rignot, E. Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf. Geophys. Res. Lett. 2004, 31. [CrossRef]

9. Wang, S.; Liu, H.; Yu, B.; Zhou, G.; Cheng, X. Revealing the early ice flow patterns with historical declassified intelligence satellite photographs back to 1960s. Geophys. Res. Lett. 2016, 43, 5758–5767. [CrossRef]

10. Berthier, E.; Scambos, T.A.; Shuman, C.A. Mass loss of Larsen B tributary glaciers (Antarctic Peninsula) unabated since 2002. Geophys. Res. Lett. 2012, 39, 342–343. [CrossRef]

11. Leeson, A.A.; Van Wessem, J.M.; Ligtenberg, S.R.M.; Shepherd, A.; Van Den Broeke, M.R.; Killick, R.; Skvarca, P.; Marinsek, S.; Colwell, S. Regional climate of the Larsen B embayment 1980–2014. J. Glaciol. 2017, 63, 683–690. [CrossRef]

12. Han, H.; Lee, S.; Kim, J.-I.; Kim, S.H.; Kim, H.-c. 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 Sens. 2019, 11, 404. [CrossRef]

13. Shuman, C.; Scambos, T.; Berthier, E. Ice loss processes in the Seal Nunataks ice shelf region from satellite altimetry and imagery. Ann. Glaciol. 2016, 57, 94–104. [CrossRef]

14. Turner, J.; Lu, H.; White, I.; King, J.C.; Phillips, T.; Hosking, J.S.; Bracegirdle, T.J.; Marshall, G.J.; Mulvaney, R.; Deb, P. Absence of 21st century warming on Antarctic Peninsula consistent with natural variability. Nature 2016, 535, 411–415. [CrossRef]

15. Oliwa, M.; Navarro, F.; Hrbáček, F.; Hernández, A.; Nývlt, D.; Pereira, P.; Ruiz-Fernández, J.; Trigo, R. Recent regional climate cooling on the Antarctic Peninsula and associated impacts on the cryosphere. Sci. Total Environ. 2017, 580, 210–223. [CrossRef]

16. Shuman, C.A.; Berthier, E.; Scambos, T.A. 2001–2009 elevation and mass losses in the Larsen A and B embayments, Antarctic Peninsula. J. Glaciol. 2011, 57, 737–754. [CrossRef]

17. Rott, H.; Müller, F.; Nagler, T.; Floricioiu, D. The imbalance of glaciers after disintegration of Larsen-B ice shelf, Antarctic Peninsula. Cryosphere 2011, 5, 125–134. [CrossRef]

18. Farinotti, D.; Corr, H.; Gudmundsson, G.H. The ice thickness distribution of Flask glacier, Antarctic Peninsula, determined by combining Radio-Echo Soundings, surface velocity data and flow modelling. Ann. Glaciol. 2013, 54, 18–24. [CrossRef]

19. Farinotti, D.; King, E.C.; Albrecht, A.; Huss, M.; Gudmundsson, G.H. The bedrock topography of Starbuck glacier, Antarctic Peninsula, as determined by Radio-Echo Soundings and flow modeling. Ann. Glaciol. 2014, 55, 22–28. [CrossRef]

20. Khazendar, A.; Borstad, C.P.; Scheuchl, B.; Rignot, E.; Seroussi, H. The evolving instability of the remnant Larsen B ice shelf and its tributary glaciers. Earth Planet. Sci. Lett. 2015, 419, 199–210. [CrossRef]

21. Wuite, J.; Rott, H.; Hetzenecker, M.; Floricioiu, D.; De Rydt, J.; Gudmundsson, G.H.; Nagler, T.; Kern, M. Evolution of surface velocities and ice discharge of Larsen B outlet glaciers from 1995 to 2013. Cryosphere 2015, 9, 957–969. [CrossRef]

22. Baumhoer, C.; Dietz, A.; Dech, S.; Kuenzer, C. Remote sensing of antarctic glacier and ice-shelf front dynamics—A review. Remote Sens. 2018, 10, 1445. [CrossRef]

23. De Rydt, J.; Gudmundsson, G.H.; Rott, H.; Bamber, J.L. Modeling the instantaneous response of glaciers after the collapse of the Larsen B ice shelf. Geophys. Res. Lett. 2015, 42, 5355–5363. [CrossRef]

24. Rignot, E.; Mouginot, J.; Scheuchl, B. Ice flow of the Antarctic ice sheet. Science 2011, 333, 1427–1430. [CrossRef]

25. Mouginot, J.; Scheuchl, B.; Rignot, E. Mapping of ice motion in Antarctica using Synthetic-Aperture Radar data. Remote Sens. 2012, 4, 2753–2767. [CrossRef]

26. Teng, L.; Yan, L.; Tian, L.; Fengming, H.; Zhuoqi, C.; Xiao, C. Antarctic surface ice velocity retrieval from MODIS-based mosaic of Antarctica (MOA). Remote Sens. 2018, 10, 1045. [CrossRef]

27. Ai, S.; Ding, X.; An, J.; Lin, G.; Wang, Z.; Yan, M. Discovery of the fastest ice flow along the central flow line of Austre Lovénbreen, a poly-thermal valley glacier in Svalbard. Remote Sens. 2019, 11, 1488. [CrossRef]
28. Fricker, H.A.; Padman, L. Thirty years of elevation change on Antarctic Peninsula ice shelves from multimission satellite radar altimetry. J. Geophys. Res. Ocean. 2012, 117. [CrossRef]

29. Rott, H.; Jaber, W.A.; Wuite, J.; Scheiblauer, S.; Floricicou, D.; van Wessem, J.M.; Nagler, T.; Miranda, N.; van den Broeke, M.R. Changing pattern of ice flow and mass balance for glaciers discharging into the Larsen A and B embayments, Antarctic Peninsula, 2011 to 2016. Cryosphere 2018, 12, 1273–1291. [CrossRef]

30. Borstad, C.; Khazendar, A.; Scheuchl, B.; Morlighem, M.; Larour, E.; Rignot, E. A constitutive framework for predicting weakening and reduced buttressing of ice shelves based on observations of the progressive deterioration of the remnant Larsen B ice shelf. Geophys. Res. Lett. 2016, 43, 2027–2035. [CrossRef]

31. Massom, R.A.; Scambos, T.A.; Bennetts, L.G.; Reid, P.; Squire, V.A.; Stammerjohn, S.E. Antarctic ice shelf disintegration triggered by sea ice loss and ocean swell. Nature 2018, 558, 383. [CrossRef]

32. Warner, R.C.; Roberts, J.L. Pine Island Glacier (Antarctica) velocities from Landsat7 images between 2001 and 2011: Fit-based image correlation for images with data gaps. J. Glaciol. 2013, 59, 571–582. [CrossRef]

33. Schowengerdt, R.A. Remote Sensing: Models and Methods for Image Processing; Elsevier: Amsterdam, The Netherlands, 2006.

34. Scambos, T.; Han, T.; Fahnestock, M.; Painter, T.; Bohlander, J. MODIS-based mosaic of Antarctica (MOA) data sets: Continent-wide surface morphology and snow grain size. Remote Sens. Environ. 2007, 111, 242–257. [CrossRef]

35. Bindschadler, R.; Choi, H.; Wichlacz, A.; Bingham, B.; Bohlander, J.; Brunt, K.; Corr, H.; Drews, R.; Fricker, H.; Hall, M. Getting around Antarctica: New high-resolution mappings of the grounded and freely-floating boundaries of the Antarctic ice sheet created for the International Polar Year. Cryosphere 2011, 5, 569–588. [CrossRef]

36. Brunt, K.; Fricker, H.; Padman, L.; O’Neel, S. ICESat-derived grounding zone for Antarctic ice shelves, U.S. Antarctic Program (USAP) Data Center. Digit. Media 2010. [CrossRef]

37. Rignot, E.; Mouginot, J.; Scheuchl, B. Antarctic grounding line mapping from differential satellite radar interferometry. Geophys. Res. Lett. 2011, 38. [CrossRef]

38. Depoorter, M.; Bamber, J.; Griggs, J.; Lenaerts, J.; Litzenberg, S.; van den Broeke, M.; Moholdt, G. Synthesized grounding line and ice shelf mask for Antarctica. PANGAEA 2013. [CrossRef]

39. Scambos, T.A.; Dutkiewicz, M.J.; Wilson, J.C.; Bindschadler, R.A. Application of image cross-correlation to the measurement of glacier velocity using satellite image data. Remote Sens. Environ. 1992, 42, 177–186. [CrossRef]

40. Fahnestock, M.; Scambos, T.; Moon, T.; Gardner, A.; Haran, T.; Klinger, M. Rapid large-area mapping of ice flow using Landsat 8. Remote Sens. Environ. 2016, 185, 84–94. [CrossRef]

41. Haug, T.; Kääb, A.; Skvarca, P. 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. Cryosphere 2010, 4, 161–178. [CrossRef]

42. Chen, J.; Ke, C.; Zhou, X.; Shao, Z.; Li, L. Surface velocity estimations of ice shelves in the northern Antarctic Peninsula derived from MODIS data. J. Geogr. Sci. 2016, 26, 243–256. [CrossRef]

43. Mouginot, J.; Rignot, E.; Scheuchl, B. Sustained increase in ice discharge from the Amundsen sea embayment, west Antarctica, from 1973 to 2013. Geophys. Res. Lett. 2014, 41, 1576–1584. [CrossRef]

44. Hall, D.K.; Bayr, K.J.; Schönert, W.; Bindschadler, R.A.; Chien, J.Y.L. Consideration of the errors inherent in mapping historical glacier positions in Antarctica from the ground and space (1893–2001). Remote Sens. Environ. 2003, 86, 566–577. [CrossRef]

45. Ye, Q.; Kang, S.; Chen, F.; Wang, J. Monitoring glacier variations on Geladandong mountain, central Tibetan Plateau, from 1969 to 2002 using Remote-Sensing and GIS technologies. J. Glaciol. 2006, 52, 537–545. [CrossRef]

46. Colgan, W.; Rajaram, H.; Abdalati, W.; McCutchan, C.; Mottram, R.; Moussavi, M.S.; Grigsby, S. Glacier crevasses: Observations, models, and mass balance implications. Rev. Geophys. 2016, 54, 119–161. [CrossRef]

47. Borstad, C.; McGrath, D.; Pope, A. Fracture propagation and stability of ice shelves governed by ice shelf heterogeneity. Geophys. Res. Lett. 2017, 44, 4186–4194. [CrossRef]

48. Rist, M.A.; Sammonds, P.R.; Oerter, H.; Doake, C.S.M. Fracture of Antarctic shelf ice. J. Geophys. Res. Solid Earth 2002, 107, ECV 2–1–ECV 2–13. [CrossRef]

49. Larour, E.; Rignot, E.; Aubry, D. Processes involved in the propagation of rifts near Hemmen ice rise, Ronne ice shelf, Antarctica. J. Glaciol. 2004, 50, 329–341. [CrossRef]
50. Glasser, N.F.; Scambos, T.A. A structural glaciological analysis of the 2002 Larsen B ice-shelf collapse. *J. Glaciol.* 2008, 54, 3–16. [CrossRef]

51. Wesche, C.; Jansen, D.; Dierking, W. Calving fronts of Antarctica: Mapping and classification. *Remote Sens.* 2013, 5, 6305–6322. [CrossRef]

52. Glasser, N.F.; Kulessa, B.; Luckman, A.; Jansen, D.; King, E.C.; Sammonds, P.R.; Scambos, T.A.; Jezek, K.C. Surface structure and stability of the Larsen C ice shelf, Antarctic Peninsula. *J. Glaciol.* 2009, 55, 400–410. [CrossRef]

53. Moon, T.; Joughin, I. Changes in ice front position on Greenland’s outlet glaciers from 1992 to 2007. *J. Geophys. Res. Earth Surf.* 2008, 113. [CrossRef]

54. Scambos, T.; Ross, R.; Bauer, R.; Yermolin, Y.; Skvarca, P.; Long, D.; Bohlander, J.; Haran, T. Calving and ice-shelf break-up processes investigated by proxy: Antarctic tabular iceberg evolution during northward drift. *J. Glaciol.* 2008, 54, 579–591. [CrossRef]

55. Vieli, A.; Payne, A.J.; Shepherd, A.; Du, Z. Causes of pre-collapse changes of the Larsen B ice shelf: Numerical modelling and assimilation of satellite observations. *Earth Planet. Sci. Lett.* 2007, 259, 297–306. [CrossRef]