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Surface Velocities and Ice-Front Positions of Eight Major Glaciers in the Southern Patagonian Ice Field, South America, from 2002 to 2011

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Abstract

The Patagonian Ice Fields are known to have undergone rapid retreat of frontal positions and significant thinning of its glaciers over the past decades. However, surface velocities have been measured at only a few of these glaciers. Thus, it remains uncertain if and to what extent the glacier dynamics have changed over time and contributed to ice loss in these ice fields. In this study, we examine the temporal evolution of flow velocities and ice-front positions at eight major glaciers in the Southern Patagonian Ice Field (SPI; Hielo Patagónico Sur) by using Advanced Synthetic Aperture Radar (ASAR) images from the Environmental Satellite (Envisat) launched in 2002 by the European Space Agency and Advanced Land Observation Satellite/Phased Array-type L-band Synthetic Aperture Radar (ALOS/PALSAR) data recorded from 2002 to 2011. The examined eight glaciers include Glaciar Jorge Montt, Occidental, Pio XI (or Brüggen), O'Higgins, Viedma, Upsala, Perito Moreno, and Grey. Not all the glaciers revealed significant changes in frontal positions and flow velocities in the study period. We detected significant temporal velocity changes at Glaciar Upsala, Jorge Montt, Occidental, and Pio XI.

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Among these four glaciers, Glaciars Upsala, Jorge Montt, and Occidental revealed significant acceleration and terminus retreat and were undergoing dynamic–thinning. The markedly different absolute velocities but equally large longitudinal near-terminus stretching at the three glaciers support a calving model based on crevasse-depth criteria, which predict a calving position where crevasse–depths are equal to ice thickness; crevasse–depths are controlled by the longitudinal stretching rate. Meanwhile, Glaciar Pio XI revealed complex spatial and temporal evolution in surface velocities without significant retreat, and its dynamics remain enigmatic.

Keywords: glacier velocity, Southern Patagonia, calving glacier, synthetic aperture radar

1 1. Introduction

The Southern Patagonian Ice Field (SPI; Hielo Patagónico Sur) contains the largest temperate glaciers in southern hemisphere and covers approxi-3 mately 13000 km² area from approximately 48.5°S to 51.5°S (Aniya et al., 1996; Figure 1). The SPI consists of 48 outlet glaciers with an average altitude of 1355 m above sea level. All these outlet glaciers, except for two, are 6 calving (Aniya et al., 1996). The ones on the western Chilean side mostly 7 calve into fjords as tidewater calving glaciers, whereas those on the eastern 8 Argentina side terminate into proglacial lakes (Aniya et al., 1996; Warren 9 and Aniya, 1999). Their retreat in the frontal positions and rapid thinning 10 toward the end of the 20th century have been reported, suggesting a signifi-11 cant contribution to global sea level increases (Aniya et al., 1997; Rignot et 12 al., 2003). Moreover, Gravity Recovery And Climate Experiment (GRACE) 13

observation data recorded since 2002 indicate a total mass loss rate from both 14 the Northern Patagonian Ice Field and the SPI to be ranging from -23.0 ± 9.0 15 Gt a^{-1} to -26.0 ± 6.0 Gt a^{-1} (Chen et al., 2007; Ivins et al., 2011; Jakob et 16 al., 2012). GRACE-based mass-loss estimates in the beginning of the 21st 17 century are larger than the corresponding volume loss rate derived in the 18 late 20th century (Rignot et al., 2003). The recently reported surface height 19 change rates, based on a time series of digital elevation models (DEMs), are 20 also consistent with GRACE-based estimates, which indicates an even more 21 rapid drawdown over the past decade (Willis et al., 2012). 22

While near-surface temperature increases associated with global warm-23 ing presumably contribute to ice loss due to melting, the accelerated ice 24 losses reported on Greenland and Antarctica have been linked to changes in 25 glacier dynamics as well (Rignot and Kanagaratnam, 2006; van den Broeke 26 et al., 2009; Pritchard et al., 2009). In particular, many polar glaciers that 27 calve into the ocean have undergone significant acceleration, known as dy-28 namic thinning, and have thus further contributed to ice loss. However, re-29 cent studies demonstrate spatial-temporal complexities of the outlet glacier 30 velocities in Greenland (Moon et al., 2012; Bevan et al., 2012). In contrast 31 to these large polar glaciers, no detailed glacier velocity maps are available 32 for the Patagonian Ice Fields with the exception of those for certain acces-33 sible glaciers (Naruse et al., 1992, 1995; Stueffer et al., 2007; Sugiyama et 34 al., 2011; Rivera et al., 2012a). Satellite-derived velocity maps are also lim-35 ited to Glaciars Perito Moreno (Rott et al., 1998; Michel and Rignot, 1999; 36 Ciappa et al., 2010) and Glaciar Upsala (Skvarca et al., 2003; Floricioiu et 37 al., 2008, 2009; Sakakibara et al., 2013). Thus, it remains uncertain if and 38

to what extent dynamic thinning has affected the Patagonian Ice Fields. 39 In this study, we show the spatial and temporal changes in flow velocities 40 at eight major glaciers in the SPI by applying an offset tracking technique 41 to the intensity images of the Environmental Satellite/Advanced Synthetic 42 Aperture Radar (Envisat/ASAR) and Advanced Land Observation Satel-43 lite/Phased Array-type L-band Synthetic Aperture Radar (ALOS/PALSAR) 44 data recorded from 2002 to 2011. In addition, we used the cloud-free char-45 acteristics of SAR imagery for examining the terminus changes in order to 46 determine whether the ice acceleration is associated with calving episodes. 47 The examined eight glaciers include Glaciars Upsala, Jorge Montt, Occiden-48 tal, Pio XI (or Brüggen), O'Higgins, Viedma, Perito Moreno, and Grev (Fig-49 ure 1). We selected these glaciers not only because their sizes were sufficient 50 to be imaged by the spatial resolution of presently available SAR data but 51 also because they were more frequently imaged than others so that we could 52 increase the temporal resolution, which allowed us to detect rapid changes 53 in the ice dynamics. 54

As in the case of Greenland (Moon et al., 2012), we subsequently show 55 that not all of the glaciers reveal ice acceleration and rapid terminus re-56 treat. Submarine melting has been suggested as a principal triggering mech-57 anism for the accelerated ice motion in Greenland, because the timing of the 58 glacier's acceleration coincided with that of ocean water warming near Green-59 land (Holland et al., 2008; Rignot et al., 2010; Straneo et al., 2011). The 60 rapid retreat and flow acceleration in the SPI, however, occur at both marine 61 and fresh-water terminating glaciers, which suggests the presence of addi-62 tional general processes independent of water salinity. While the physically 63

⁶⁴ based calving model remains elusive (Benn et al., 2007a), we interpret the
⁶⁵ observed data sets on the basis of the calving model based on crevasse-depth
⁶⁶ criteria (Benn et al., 2007a, b; Nick et al., 2010).

67 2. Data and Analysis Method

68 2.1. Satellite data

To generate glacier surface velocity maps, we processed the PALSAR im-69 ages with a wavelength of 23.6 cm recorded from June 2007 to February 2011 70 from ALOS, which was launched in 2006 by the Japan Aerospace Exploration 71 Agency (JAXA) (Table 1, Figure 1). To extend the analysis period further 72 back to 2003, we also used the C-band (wavelength of 5.6 cm) ASAR images 73 from Envisat launched in 2002 by the European Space Agency (Table 1, Fig-74 ure 1), which often contains de-correlation problems; the advantage of the 75 L-band over C-band was shown before (Rignot, 2008; Strozzi et al., 2008). 76 On the basis of our observations of insignificant temporal velocity changes at 77 Glaciar Perito Moreno (supplementary material), the differences in penetra-78 tion depths due to different wavelengths do not appear to affect the inferred 79 velocities. This result is theoretically reasonable because the most significant 80 changes in glacier-flow velocity profile are expected to occur near the glacier 81 bed rather than near the surface (Cuffey and Patterson, 2010). 82

The off-nadir beam angle of PALSAR is 34.3° , which forms $\sim 39^{\circ}$ incident angle at the flat ground in the image center. There are two available imaging modes, fine beam single polarization (FBS, HH) and fine beam dual polarization (FBD; HH and HV). We used data from only HH polarization. The difference between FBS and FBD is the slant range (across track) reso-

lution, which is ~ 4.7 m for the FBS mode and ~ 9.4 m for the FBD mode; 88 the azimuth resolution is 3.1 m regardless of the mode. The FBD data are 89 oversampled twice along the range axis. On the other hand, the ASAR data 90 used in this study were obtained along a descending path with a local inci-91 dence beam angle of $\sim 23^{\circ}$; the ASAR data from an ascending path of the 92 mode IS6 were used only for the analysis of Glaciar Perito Moreno (Table1, 93 supplementary material). This smaller incidence angle lowers the sensitiv-94 ity to the east-west component of displacement, although it can increase 95 the sensitivity of the vertical component. The spatial resolution of ASAR 96 in the slant range and azimuth direction is 7.8 m and 4.1 m, respectively. 97 We processed the PALSAR level 1.0 products and ASAR level 0 products to 98 generate single look complex images. 99

100 2.2. Pixel-offset tracking

Although the other approaches are available, such as radar interferome-101 try (Goldstein et al., 1993) and multiple aperture interferometry (Gourmelen 102 et al., 2011), they are based on phase images that will encounter coher-103 ence loss and phase unwrapping problems to quantify larger displacements. 104 In this study, pixel-offset tracking (intensity tracking or speckle tracking) 105 algorithms, based on maximizing the cross-correlation of the radar image 106 patches, were used to observe surface velocities (Michel et al., 1999; Strozzi 107 et al., 2002; Yasuda and Furuya, 2013). We used the intensity tracking 108 algorithm because it is most suitable for detecting rapidly-flowing glacier 109 velocities with long data acquisition intervals (Strozzi et al., 2002, 2008). 110 Although we experimented with a variety of patch sizes and sampling in-111 tervals, we eventually deemed a search patch of ~ 500 m (range) $\times 600$ m 112

(azimuth) area with a sampling interval of $\sim 90 \text{ m} \times 120 \text{ m}$ as optimum 113 parameters. We set a signal-to-noise ratio (SNR) threshold of 4.0; patches 114 below this level were assigned to the missing data. Lower SNR data occur 115 because of the large spatial separation length (Bperp) of the repeating orbits 116 or temporal changes in the surface scattering characteristics; Bperp denotes 117 the perpendicular component of the baseline projected onto the radar line of 118 sight (LOS). Unfortunately, the Bperp for the PALSAR data pairs in summer 119 was relatively long; however, the operational orbit determination accuracy 120 is now approaching sub-meter level with standard errors of tens of centime-121 ters or less (Scharroo and Visser, 1998; Andersen et al., 1998; Katagiri and 122 Yamamoto, 2008). Moreover, because higher precipitation levels and temper-123 atures occur in summer, we can consider that snowfall and surface melting 124 lower the cross-correlation between the temporally separated image patches, 125 which prevents derivation of velocity data, particularly in the accumulation 126 zones. We did not mask the non-glacier areas in offset-tracking, because it 127 was important to verify that non-glacier areas could indeed be estimated to 128 be non-deforming, and that there were no artifacts due to topography. The 129 no-displacement signals outside the glaciated areas shown below validated 130 the surface velocity data detected along the glacier itself. Over the glaciated 131 areas, however, we occasionally encountered spurious signals that indicated, 132 for instance, extraordinary fast velocities or physically unrealistic disconti-133 nuities in the velocity distributions. We considered that these spurious data 134 were caused by erroneous matching of objects that actually differed; thus, 135 we visually eliminated such noise. 136

137

Because the satellite does not repeat exactly the same paths, the effect

of fore-shortening also differs in each path, which results in an artifact off-138 set over rugged terrain (Michel et al., 1999; Sansosti et al., 2006; Kobayashi 139 et al., 2009). We reduced this artifact by applying an elevation-dependent 140 co-registration by employing NASA's Shuttle Radar Topography Mission 141 (SRTM-4) DEM data with a 3-arcsec resolution, in which the gaps in the 142 original SRTM data were filled (Jarvis et al., 2008). Although the SRTM 143 data may include inherent errors and are nearly a decade old, we used them 144 because there are free of gaps and apparent noise. Because no topography-145 correlated offsets were apparent, we considered the artifact offset to be ade-146 quately corrected; it is unlikely that the errors in the SRTM DEM influenced 147 our velocity data. 148

The pixel-offset tracking technique provides range and azimuth offsets, 149 both of which are linear combinations of the three-dimensional (3D) displace-150 ments. The range offset, U_{ra} , is a projection of the 3D surface displacements 151 onto the slant radar LOS direction, while the azimuth offset, U_{az} , is a projec-152 tion of the 3D surface displacements along the satellite-track direction. Using 153 the satellite's heading angle H measured clockwise from the north and the 154 microwave's incidence angle to the ground I, each offset can be represented 155 as follows: 156

$$\begin{pmatrix} U_{ra} \\ U_{az} \end{pmatrix} = \begin{pmatrix} \cos H \sin I & -\sin H \sin I & -\cos I \\ \sin H & \cos H & 0 \end{pmatrix} \begin{pmatrix} U_e \\ U_n \\ U_z \end{pmatrix}, \quad (1)$$

where U_e , U_n , and U_z are defined as eastward, northward, and upward positive displacements, respectively. The imaging angles and expressions of U_{ra} and U_{az} for each satellite's observation mode are indicated in Table 2.

Because the two displacement maps do not allow us to resolve the 3D 160 displacements, we derived the surface velocity data by using the parallel flow 161 assumption (Joughin et al., 1996). Although either the range or azimuth 162 offset data allow us to derive the surface velocity with the parallel flow as-163 sumption, we used both data sets to solve the over-determined problem by the 164 least-squares method. The local topographic gradient vector was estimated 165 from the SRTM-4 data. Because only the local flow orientation and slope an-166 gles are necessary in the argument of trigonometric functions for parallel flow 167 approximation, the ice-thickness changes that may have occurred between 168 the SRTM and PALSAR/ASAR data acquisition would be insignificant as 169 potential error sources in the computation of a unit vector. 170

Although the effects of atmospheric propagation and inaccurate satellite 171 orbit generate significant errors in the InSAR phase data, these errors are 172 insignificant in the offset tracking data. This is because the errors in the offset 173 tracking data are due to those in the image registration, and are larger than 174 those due to atmospheric propagation and satellite orbit (Strozzi et al., 2002). 175 The uncertainties of the offset measurements have been estimated to be ~ 0.3 -176 0.4 m at the non-deforming rugged terrain in the ALOS/PALSAR data with 177 a 46-day interval (Kobayashi et al., 2009). If the ice is flowing at a constant 178 rate over the data acquisition interval, the error in the velocity estimates 179 can be inferred as 0.005-0.01 m/day, and will be inversely proportional to 180 the data acquisition interval (Strozzi et al., 2002). However, errors in pixel-181 offset tracking can also originate from other sources. The most significant 182 error source is the temporal de-correlation between image patches due to 183 changes in objects' scattering properties. Thus, all the the data pairs shown 184

in this study have the shortest possible 46- and 35-day temporal separation,
which denote the PALSAR and ASAR recurrent periods, respectively. The
ASAR data more often indicated larger errors, probably because the short
wavelength data tend to undergo the de-correlation problem. The magnitude
of errors also varies seasonally from less than 5 m/a up to 30 m/a, depending
on the season of the SAR data acquisition (Yasuda and Furuya, 2013).

For point sites such as those at the Glaciar Upsala and the site C at the 191 Glaciar Jorge Montt, we averaged the velocities at the nearby 500 m^2 area 192 and considered the derived standard deviation as the measurement error, 193 which ranges from less than 0.1 m/day to $\sim 0.5 \text{ m/day}$. For transverse veloc-194 ity profile, we selected five velocity profiles that are closely-located within 100 195 m, and computed the average and standard deviation along the transverse 196 direction. The velocities and error bars for the transverse profiles shown be-197 low were derived by further averaging the data along the transverse direction; 198 the velocity profiles and errors along the transverse direction are shown in 199 the supplementary material. 200

201 2.3. Ice-front position changes

Cloud-free SAR intensity images permit the tracking of ice-front positions 202 over time if clear image contrasts are present between the ice and water sur-203 faces. By using the original single look complex images, the intensity images 204 were derived by multi-looking in range and azimuth directions. The spatial 205 resolution was 40 m \times 40 m. We visually identified the ice-front positions at 206 each SAR intensity image; we did not perform mechanized automatic detec-207 tion. The front position change shown below is referenced to the first SAR 208 image in 2002 or 2003, and represents the average change derived by dividing 209

the total area of each polygon by a fixed width of a reference profile in the 210 upstream direction (Moon and Joughin, 2008). Errors in digitized frontal 211 positions arose mainly from our misidentification of the frontal positions, 212 which could be attributed to image resolution and the lower image contrast 213 between the ice and water surfaces. Images with unclear contrasts between 214 the ice and water surfaces were not used in this study. Bevan et al. (2012)215 evaluated the accuracies of ± 49 m for ERS1/2 and ASAR SAR images. We 216 consider that the accuracies of our identified frontal positions are compara-217 ble to or better than the Bevan et al's estimate, because the resolution is 218 close to those of ERS1/2 and ASAR in PALSAR's FBD mode and better in 219 PALSAR's FBS mode. 220

221 3. Results

Regarding temporal evolution of surface velocities at the eight large glaciers 222 examined in this study from 2003 to 2011, Glaciars Upsala, Jorge Montt, 223 Occidental, and Pio XI revealed significant acceleration of greater than 30 224 %. Although temporal fluctuations possibly due to seasonalities were rec-225 ognized, no large velocity changes were evident at Glaciars Grey, Perito 226 Moreno, Viedma, and O'Higgins. With the exception of Pio XI, these ac-227 celerated glaciers also revealed significant retreating in the frontal positions. 228 In this section, we present the observation results of the Glaciars Upsala, 229 Jorge Montt, Occidental, and Pio XI; the results of the remaining glaciers 230 are shown in the supplementary material. 231

232 3.1. Glaciar Upsala

Glaciar Upsala, the third largest glacier in the SPI, contains three ter-233 mini, of which the westernmost terminus is the largest and calves into Brazo 234 Upsala of Lago Argentino (Skvarca et al., 2003). The water depth is 400-235 500 m (Naruse and Skvarca, 2000). A rapid retreat of the frontal position 236 since 1978 has been reported (Aniya and Skvarca, 1992; Skvarca et al., 1995; 237 Naruse et al., 1997; Naruse and Skvarca, 2000; Skvarca et al., 2002). The 238 thinning rate near the glacier front was reported to be 11 m/a between 1990 239 and 1993 (Skvarca et al., 1995) and 10 ± 2 m/a between 2000 and 2005 (Willis 240 et al., 2012), but accelerated to 24.8 ± 2.4 m/a between 2005 and 2011 (Willis 241 et al., 2012). Annual velocities near the terminus based on satellite imagery 242 were first derived by Skvarca et al (2003), who applied a cross-correlation 243 method to Landsat 7 Enhanced Thematic Mapper Plus (ETM+) images 244 acquired between 2000 and 2001; this approach is similar to the currently 245 used intensity tracking approach. Near the fastest-flowing western terminus, 246 Skvarca et al (2003) derived average velocities of approximately 1600 m/a, 247 equivalent to 4.4 m/day, which were in good agreement with the field mea-248 surement obtained in 1995 (Skvarca et al., 1995). Sakakibara et al (2013) 249 extended the analysis period to 2011. On the basis of TerraSAR-X data 250 acquired between December 2007 and January 2008, Floricioiu et al (2008) 251 reported a maximum velocity of 5.6 m/day, which is significantly faster than 252 the earlier observations in 1995 and 2001; Floricioiu et al (2009) extended the 253 study period. However, the time at which the glacier initiated acceleration 254 and the evolution of the frontal positions remain unknown. 255

256

Surface velocities near the terminus position could not be derived in this

study because of the low SNR in the offset tracking near the ice front. We con-257 sider that the faster ice motion near the terminus caused significant temporal 258 changes in the surface features and hence their scattering characteristics; the 259 46/35-day acquisition intervals in PALSAR/ASAR are too long for tracking 260 the surface features of such a rapidly flowing region with sufficient correla-261 tion. However, the slower velocity data in the upstream could be derived; 262 thus, we examined the temporal changes in velocities at two sites closer to the 263 terminus (A and B in Figure 2a), in which the velocity data were acquired as 264 frequently as possible. We averaged the velocities at 36 pixels (over 500 m^2) 265 for each site and assigned their standard deviations as the error bar in Figure 266 2b. One site was in the main stream of Glaciar Upsala, and the other was 267 in Glaciar Bertachi, one of the western tributaries closest to the frontal posi-268 tion. Figure 2b summarizes the temporal evolution of both surface velocities 269 at the two sites and frontal positions derived in this study. Figure 3 shows 270 the terminus locations visually identified over time. Although we could not 271 generate useful velocity data between 2006 and 2010 because of a satellite 272 orbit problem, we observed a nearly 180 % velocity increase between 2005 273 and 2010 even at a point 7 km from the terminus in the main stream. From 274 2003 to 2005, the near-terminus velocities were 2 m/day, which are in agree-275 ment with Skvarca et al's observations in 2001 (Skvarca et al 2003). Even in 276 Glaciar Bertachi, it is evident that the 2010 surface velocities are nearly 200 277 % those of the 2003–2005 data. In 2010–2011, therefore, the near-terminus 278 region is apparently flowing faster than previously recorded speeds. The 279 frontal position retreated nearly 3.5 km from 2002 to 2011 and approached 280 the lower end of Glaciar Bertachi. The speed up on Bertachi between July 281

282 2010 and January 2011 may be associated with the recent retreat. Although 283 the point A seems stable in Figure 2b, it is likely that the similar speed-up at 284 point A occurred but was not detected by the available data. In view of the 285 TerraSAR-X intensity image in Floricioiu et al (2008), the frontal position in 286 January 2008 was close to that recorded in 2005. While the front gradually 287 retreated from 2002 to 2005 with possible seasonal fluctuations (Figure 3), 288 the retreating appears to have accelerated in August 2008.

289 3.2. Glaciar Jorge Montt

Glaciar Jorge Montt is located at the northern end of the SPI and calves into an unnamed fjord that opened as a result of its glacier retreat to a maximum of 19.5 km from 1898 to 2011 (Rivera et al., 2012b). The maximum thinning rate was estimated to be 17.9 m/a between 1975 and 2000 (Rignot et al., 2003) and 21.5 ± 0.8 m/a between 2000 and 2012 (Willis et al., 2012). In addition, the rate of glacier terminus retreat was estimated to be 200 m/a between 2001 and 2011 (Willis et al., 2012).

So far, few surface velocity measurements of Glaciar Jorge Montt have 297 been reported. Rivera et al (2012a) derived an average velocity of 13 ± 4 298 m/day for the near-terminus region between 2010 and 2011 by using both 299 ground-based cameras and a feature tracking based on ASTER images. Com-300 paring Rignot et al's unpublished velocity data derived from the 2004 C-band 301 Radarsat-1 images, Rivera et al (2012a) suggested an acceleration between 302 2004 and 2010. However, the surface velocity data in the other years and 303 up-glacier parts remain uncertain. 304

Figure 4a shows an example of a velocity map derived from data acquired between January and February 2008. Although we could not derive

the velocity data near the terminus region as was the case for Glaciar Up-307 sala, the derived velocity maps complement the observations of Rivera et al 308 (2012a), because our velocity maps cover the middle to upstream regions of 309 the glaciers. Figure 4b summarizes the temporal evolutions of both frontal 310 location changes and the mean velocities at one flow velocity profile (A–B in 311 Figure 4a) and the other upstream site (C in Figure 4a). While the mean 312 value of the A–B profile is smaller than the mean at the C, this is due to 313 the averaging procedure, and the flow velocity at the center of A–B profile 314 is higher than at C; the velocities and errors along the transverse profile are 315 shown in the supplementary. The measured velocity profile is located 5.5 km 316 upstream from that measured by Rivera et al (2012a). Figure 5 indicates 317 the frontal locations identified at each epoch. The relationship between the 318 retreating rate and flow velocities from 2003 to 2007 remains uncertain be-319 cause not all of the image pairs allowed us to derive the flow velocity data. 320 However, both the retreating rate and flow velocities are not constant over 321 time. Although the frontal position continued to retreat since 2003, it became 322 stagnant from 2007 to 2008 when the flow velocities significantly decreased. 323 From 2008 onward, the retreating rate apparently accelerated, indicating 324 ~ 470 m/a, and the flow velocities in 2011 increased by 130 %, compared to 325 those recorded in 2003. While the flow acceleration reported by Rivera et 326 al (2012a) was derived by comparing the data acquired in 2004 and 2010, 327 Figure 4b suggests that the acceleration was initiated in 2008. 328

329 3.3. Glaciar Occidental

Glaciar Occidental is located on the western side of the SPI and flows into a proglacial lake. On the basis of the analysis of Landsat TM and Advanced Visible and Near Infrared Radiometer-2 (AVNIR-2) on ALOS images, the terminus retreat between 1986 and 2006 was estimated to be 1.1 km, and the terminus shape was found to be disintegrated (JAXA, 2010). Regarding surface elevation change rate, Glaciar Occidental is also thinning at a rate of 2–5 m/a (Willis et al., 2012). To our knowledge, however, no flow velocity data have been published so far.

We selected two transverse profiles at downstream and upstream posi-338 tions (A–B and C–D, respectively, in Figure 6a). In contrast to the rapidly 339 flowing glaciers previously described, this glacier allowed us to derive flow 340 velocity data even near the terminus, likely because the slower flow veloci-341 ties allowed the glacier to maintain its surface features over time. Figure 6b 342 summarizes the temporal evolution of mean velocities at each profile and 343 the frontal position; temporal evolution of the velocity profile is shown in 34 the supplementary material. While the velocities in the upstream were sta-345 ble over time (C–D), those near the terminus in 2008–2010 have apparently 346 increased by more than 200 % over 2004–2005. The near-terminus region ap-347 parently underwent a significant longitudinal stretching. We evaluated the 348 frontal position retreat to be $\sim 2 \text{ km}$ from 2004 to 2011. However, the frontal 340 positions at some epochs are missing because a vague image contrast pre-350 vented clear identification. Instead of a clear frontal position, we observed 351 numerous icebergs that likely disintegrated from the terminus. The rate of 352 terminus retreat accelerated from 55 m/a for the period from 1986 to 2006 353 to ~ 285 m/a for the recent period from 2004 to 2011. 354

355 3.4. Glacier Pio XI

Glaciar Pio XI, the largest glacier in the SPI, flows to the west from 356 a location near Volcán Lautaro (elevation 3380 m) and bifurcates into two 357 tongues to the north and south near its lower end, which flow into 'Lago 358 Greve' and Eyre Fjord, respectively (Figure 7a); the southern front is thus a 359 tidewater front. In contrast to the other glaciers in Patagonia that are rapidly 360 retreating, Glaciar Pio XI was known for its significant terminus advances 361 at both tongues during the 20th century (Warren and Rivera, 1994; Rivera 362 et al., 1997). The front region is reportedly thickening at a rate of greater 363 than 2 m/a (Rivera and Casassa, 1999; Willis et al., 2012). On the basis of 364 ground-based measurements recorded in November 1995, Rivera et al. (1997) 365 reported maximum velocities of 17 to 50 m/day near the southern terminus. 366 Although these faster velocities, in addition to the terminus advances, have 367 led to an interpretation of a surging glacier, the factors controlling the dy-368 namics of Glaciar Pio XI remain uncertain (Rivera et al., 1997). Apparently, 369 this glacier has not been directly responding to the climate change (Warren 370 and Rivera, 1994). 371

We selected three profiles across the northern tongue (A–B in Figure 7a), 372 southern tongue (C–D in Figure 7a), and the main upstream region (E–F 373 in Figure 7a) to reveal the temporal evolution of the surface velocities. Fig-374 ures 7b–7d summarize the temporal evolution of the mean surface velocities 375 at each profile, and the frontal position changes at the northern and southern 376 tongues from 2003 to 2011 are shown in Figures 7b and 7c. The temporal 377 evolution of each velocity profile is shown in the supplementary material. The 378 flow velocity in the main upstream was relatively stable over time, although 379

it revealed deceleration in 2007 (Figure 7d). In contrast, the velocities at the northern and southern tongues were highly variable over time (Figures 7b and 7c). The southern tongue reveals faster signals in 2003, 2005, and 2007, when the velocities nearly doubled those in slower phases. While the northern tongue was slowly flowing at 0.2 m/day in 2003, it gradually accelerated and reached 2.0 m/day in 2007. The upstream thus does not appear to directly control the flow velocities in the downstream.

Despite the highly variable velocity changes to the northern and southern tongues (Figures 7b and 7c), we did not observe any significant retreat as observed in Glaciars Upsala, Jorge Montt, and Occidental. Figure 8 includes the frontal positions over the analyzed period. While these positions have overall advanced from 2003 to 2011, we observed fluctuations in the front positions within a range of ~ 250 m between advancing and retreating periods.

393 4. Discussion and Conclusion

Although the retreat and thinning of glaciers in the SPI over the past 394 decades have been well-documented, we used SAR image analysis to demon-395 strate that not all of the examined glaciers revealed significant changes in 396 frontal positions and flow velocities from 2002 to 2011. Moreover, even for 397 such glaciers that underwent rapid retreat and acceleration, the terminus re-398 treat and flow acceleration occurred sporadically rather than gradually over 399 time, suggesting that positive-feedback processes promoted such movement. 400 This finding was made possible through the use of SAR images that were 401 free from cloud and night time problems, although more frequent image ac-402 quisitions are desirable. 403

The observed rapid retreat and acceleration at Glaciars Upsala, Jorge 404 Montt, and Occidental have important implications for calving mechanisms. 405 In particular, despite the marked differences in absolute flow velocity among 406 the three glaciers, the region toward the terminus at each glacier underwent 407 significant acceleration, which was observed by calculating differences in the 408 velocity map at two epochs (Figure 9). Figure 9 indicates larger velocity 409 increments downstream, which demonstrates longitudinal stretching or ex-410 tension toward the termini. Because longitudinal stretching is observed even 411 at distances greater than ~ 5 km upstream from the 2011 termini, the actual 412 accelerations near the terminus regions of Glaciars Upsala and Jorge Montt 413 will probably be much larger (Figures 9a and 9b). The near-terminus area 414 in Glaciar Occidental flowed at a rate of ~ 0.5 m/day by at least 2005 and 415 began to accelerate in 2007, while the upstream velocities were stable. Such 416 longitudinal stretching toward the terminus is clearly revealed at Glaciar 417 Occidental (Figure 9c). 418

The observed longitudinal stretching at the rapidly retreating glaciers will 419 contribute to increasing the crevasse-depths, and thus appears to support a 420 calving model based on crevasse-depth criteria (Benn et al., 2007a, b; Nick 421 et al., 2010), in which the absolute flow velocity itself is not critical. Benn et 422 al. (2007b) proposed that longitudinal stretching due to the spatial velocity 423 gradient, which determines the location and depth of surface crevasses, and 424 the difference between ice thickness and water depth (effective pressure) are 425 the primary controls for the frontal position of calving. This theory assumes 426 that the basal sliding velocity is equal to the vertically averaged ice velocity. 427 While Benn et al's model predicts the calving front position in which the 428

depth of the surface crevasse equals the ice height above the water line, Nick
et al. (2010) modified the model to predict calving for cases in which both
surface and basal crevasses penetrate the full thickness of the glacier.

The longitudinal stretching and rapid terminus retreat at Glaciar Upsala, 432 Jorge Montt, and Occidental can be regarded as indicators of the on-going 433 dynamic thinning process. These three glaciers have been thinning over 434 the past decade (Willis et al., 2012). Because the glacier thinning reduces 435 the viscous ice velocity due to the decrease of gravitational force, we at-436 tribute the observed speed-up to the enhanced basal sliding velocity. We 437 consider that the basal sliding enhancement is caused by the surface melt 438 input and subsequent reduction of effective pressure due to the water pres-430 sure increase as observed at Greenland (e.g., Sundal et al., 2011). If the 440 basal sliding velocity dominantly contributes to the vertically averaged ve-441 locity, the longitudinal stretching will also increase and allow the crevasses 442 to penetrate further, causing the terminus to retreat up-glacier. As recog-443 nized from a bathymetric survey conducted at Glaciar Upsala (Naruse and 444 Skvarca, 2000), this terminus retreat will likely be halted in shallower water 445 because the effective pressure will increase. Such stabilization of the ter-446 minus retreat is, however, not simply controlled by the local water-depth or 447 ice thickness as in the height-above-buoyancy model by Van der Veen (1996). 448 Physics-based crevasse-depth calving criteria can eliminate the unrealistically 449 large terminus retreats predicted from the height-above-buoyancy criterion 450 (Nick et al., 2010). 451

452 Our observations suggest that even other seemingly stable glaciers be-453 tween 2003 and 2011 may undergo rapid retreat and acceleration in the fu-

ture. The Glaciar Occidental observation provides an important lesson for 454 understanding the sporadic nature of calving processes. However, we cannot 455 determine the point at which glaciers will undergo significant frontal retreat 456 and acceleration in the future because calving processes involve a variety of 457 unknown variables, which remain poorly understood (Benn et al., 2007a). 458 Continuation of frequent surface velocity monitoring and combining the re-459 sults with bathymetric and ice-thickness survey data can more precisely val-460 idate and refine the calving model, which may enable prediction of the initi-461 ation of dynamic-thinning. 462

The behavior of Glaciar Pio XI is enigmatic, and has been suggested as 463 a surging type (Rivera et al., 1997). Transverse velocity profiles derived in 464 this study indicate parabolic shapes with smaller velocities near the edge, 465 which increase toward the center and do not exhibit the plug flow observed 466 in other surging glaciers (Kamb et al., 1985; Murray et al., 2003; Yasuda and 467 Furuya, 2013). However, note that the maximum water depths in front of 468 the calving front at Eyre Fjord are ~ 20 m, and that those at Lago Greve 469 are speculated to be much shallower than 150 m (Warren and Rivera, 1994). 470 These water depths are significantly shallower than those at other glaciers, 471 which may be attributed to the former surging episodes that should have 472 transported a sufficient amount of sediments to raise the bottom depth of 473 the fjord. While it appears unlikely that a rapid terminus retreat will begin 474 in the near future, it is important to continue monitoring Glaciar Pio XI with 475 the same frequency as that of other calving glaciers in the SPI. 476

477 It remains uncertain how much the total ice loss in the Patagonian Ice 478 Fields is split into surface processes (runoff and precipitation) and ice dynam-

ics, and the surface velocity data are indispensable to evaluate the contribu-479 tion from ice dynamics. The velocities presented in this study are still not 480 complete, because the velocities at the very front of the glaciers are missing. 481 Because the missing velocities near the front are probably faster, the inferred 482 ice velocities might be helpful to constrain the lower bound of ice discharge. 483 Nonetheless, given the fact that not all the examined glaciers revealed accel-484 eration and terminus retreat, the contribution from ice dynamics to the total 485 ice loss might be not as high as those in Greenland, where widespread ice 486 acceleration was observed (Joughin et al., 2008) and the partitioning ratio 487 was shown to be equal (van den Broeke et al., 2009). In order to quantify 488 the ice discharge, both surface mass balance and ice thickness data in the 480 Patagonian Ice Fields are also necessary. 490

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Figure 1: Elevation map of the studied area and the glaciers in the South Patagonian Icefield; the elevation data set was obtained NASA's Shuttle Radar Topography Mission (SRTM). Red triangles represent the termini of the eight analyzed glaciers. Blue and lightblue indicate fjord and proglacial lakes, respectively. Glacier outlines were determined on the basis of the Global Land Ice Measurements from Space (GLIMS) dataset, which is available through the US National Snow and Ice Data Center (Dickman, 2007; Delgado, 2009; Masiokas, 2009, 2010; Davies, 2012).

Figure 2: (a) Spatial distribution of surface flow velocities at Glaciar Upsala, derived from PALSAR images obtained on January 4 and February 19, 2011. (b) Temporal changes in the average frontal position and velocities at sites A and B depicted in (a).

Figure 3: Temporal evolution of the frontal position at Glaciar Upsala between 2002 and 2011. Background is a PALSAR-based scattering intensity image acquired on February 19, 2011.

Figure 4: (a) Spatial distribution of surface flow velocities at Glaciar Jorge Montt, derived from PALSAR images obtained on January 11 and February 26, 2008. (b) Temporal changes in the average frontal position and velocities at profile A–B and site C in (a).

Figure 5: Temporal evolution of the frontal position at Glaciar Jorge Montt between 2002 and 2011. Background is a PALSAR-based scattering intensity image acquired on February 19, 2011.

Figure 6: (a) Spatial distribution of surface flow velocities at Glaciar Occidental, derived from PALSAR images obtained on January 4 and February 19, 2011. (b) Temporal changes in the average frontal position and velocities at profile A–B and site C–D in (a). Figure 7: (a) Spatial distribution of surface flow velocities at Glaciar Pio XI, derived from PALSAR images obtained on January 4 and February 19, 2011. Temporal evolution in the average velocity at each of the three profiles (A–B, C–D, and E–F) is shown in (b–d). (b) Temporal changes in the average frontal position and velocity across profile A–B in the northern tongue. (c) Temporal changes in the average frontal position and velocity across profile C–D in the southern tongue. (d) Temporal changes in the average velocity across profile E–F in the main upstream.

Figure 8: Temporal evolution of the frontal position at Glaciar Pio XI between 2002 and 2011. Background is a PALSAR-based scattering intensity image acquired on February 19, 2011.

Figure 9: Velocity increases observed at (a) Glaciar Upsala from January 2003 to January 2011, (b) Glaciar Jorge Montt from January 2003 to January 2011, and (c) Glaciar Occidental from January 2003 to January 2011.

Sensor	Path (Track)	Frame	Acquisition date	Mode	A/D
PALSAR	129	6150	20100216	FBS	А
	129	$6150,\!6160,\!6170,\!6180$	20100519	FBD	А
	129	$6150,\!6160,\!6170,\!6180$	20100704	FBD	А
	129	$6150,\!6160,\!6170,\!6180$	20110104	FBS	А
	129	$6150,\!6160,\!6170,\!6180$	20110219	FBS	А
	130	$6150,\!6160,\!6170,\!6180$	20100605	FBD	А
	130	$6150,\!6160,\!6170,\!6180$	20100721	FBD	А
	130	6150	20101021	FBD	А
	130	6150	20110121	FBS	А
	410	4650	20070619	FBD	D
	410	4650	20070919	FBD	D
	410	4650	20071104	FBD	D
	410	4650	20071220	FBS	D
	411	4650	20070706	FBD	D
	411	4650	20071121	FBD	D
	411	4650	20080106	FBS	D
	414	4600,4620	20070826	FBD	D
	414	4600,4620	20071011	FBD	D
	414	4600,4620	20080111	FBS	D
	414	4600,4620	20080226	FBS	D
ASAR	153	4599,4617,4635	20021220	I2	D
	153	4599,4617,4635	20030228	I2	D
	153	4599,4617,4635	20030613	I2	D
	153	4599,4617,4635	20030718	I2	D
	153	4599,4617,4635	20030926	I2	D

Table 1: The processed SAR images

		(continue)	u)		
Sensor	Path (Track)	Frame	Acquisition date	Mode	A/D
	153	4599,4617,4635	20031205	I2	D
	153	4599,4617,4635	20040109	I2	D
	153	4599,4617,4635	20040910	I2	D
	153	4599,4617,4635	20050722	I2	D
	153	4599,4617,4635	20050826	I2	D
	153	4599,4617,4635	20080815	I2	D
	196	4599	20021223	I2	D
	196	4599	20030616	I2	D
	196	4599	20031208	I2	D
	196	4599	20040122	I2	D
	196	4599	20040322	I2	D
	196	4599	20040426	I2	D
	196	4599	20040531	I2	D
	196	4599	20040913	I2	D
	196	4599	20050620	I2	D
	196	4599	20050829	I2	D
	196	4599	20051003	I2	D
	196	4599	20070730	I2	D
	376	6147	20050703	I6	А
	376	6147	20050807	I6	А
	376	6147	20050911	I6	А
	382	4635	20030629	I2	D
	382	4635	20030803	I2	D
	382	4635	20040125	I2	D
	382	4635	20040229	I2	D
	382	4635	20040404	I2	D

(continued)

(continued)					
Sensor	Path (Track)	Frame	Acquisition date	Mode	A/D
	382	4635	20040509	I2	D
	382	4635	20040613	I2	D
	425	4599,4617	20030108	I2	D
	425	4599,4617	20030212	I2	D
	425	4599,4617	20030423	I2	D
	425	4599,4617	20030702	I2	D
	425	4599,4617	20031015	I2	D
	425	4599,4617	20040407	I2	D
	425	4599,4617	20040512	I2	D
	425	4599,4617	20040825	I2	D
	425	4599,4617	20080903	I2	D

Table 2: The imaging angles and offsets as a function of 3-D displacements

Sensor	Mode (A/D)	H (deg.)	I (deg.)	U_{ra}	U_{az}
PALSAR	А	-20	39	$0.59U_e{+}0.22U_n{-}0.78U_z$	$-0.34U_e + 0.94U_n$
PALSAR	D	-159	39	$-0.59U_e + 0.22U_n - 0.78U_z$	$-0.36U_{e}$ $-0.93U_{n}$
ASAR	IS6 (A)	-22	41	$0.61 U_e{+}0.25 U_n{-}0.75 U_z$	$-0.37U_e + 0.93U_n$
ASAR	IS2 (D)	-162	23	$-0.37 U_e + 0.12 U_n - 0.92 U_z$	$-0.31U_{e}$ $-0.95U_{n}$

Supplementary material for "Surface Velocities and Ice-Front Positions of Eight Major Glaciers in the Southern Patagonian Ice Field, South America, from 2003 to 2011" by Minami Muto and Masato Furuya

We examined the surface velocity and frontal position evolution at eight glaciers in South Patagonian Ice Field, and showed in the main text the results of four glaciers that indicated significant temporal changes. With the exceptions of Glacier Upsala and the site C at Glacier Jorge Montt, we first selected five velocity profiles at nearly the same location across the flow direction of each glacier, and then derived an average and standard deviation of them as a measurement error.

The supplementary figures show temporal changes in the average frontal position and average velocities for the four glaciers not shown in the main text. In addition, the temporal changes of each velocity profile and standard deviation are also shown at the seven glaciers with the exception of Glacier Upsala.

Glacier Perito Moreno



Figure S1: (a) Spatial distribution of surface flow velocities at Glacier Perito Moreno, derived from ASAR images obtained on July 3 and August 7, 2005. (b) Temporal changes in the average frontal position and velocities at profile A-B.



Figure S2: (a) Temporal evolution of the velocity profile A-B in Figure S1. (b) Estimated errors of the velocity profile at each epoch.

Glacier O'Higgins



Figure S3: (a) Spatial distribution of surface flow velocities at Glacier O'Higgins, derived from PALSAR images obtained on January 4 and February 19, 2011. (b) Temporal changes in the average frontal position and velocities at profile A-B.



Figure S4: (a) Temporal evolution of the velocity profile A-B in Figure S3. (b) Estimated errors of the velocity profile at each epoch.

Glacier Viedma



Figure S5: (a) Spatial distribution of surface flow velocities at Glacier Viedma, derived from PALSAR images obtained on January 4 and February 19, 2011. (b) Temporal changes in the average frontal position and velocities at profile A-B.



Figure S6: (a) Temporal evolution of the velocity profile A-B in Figure S5. (b) Estimated errors of the velocity profile at each epoch.

Glacier Grey



Figure S7: (a) Spatial distribution of surface flow velocities at Glacier Grey, derived from ASAR images obtained on July 3 and August 7, 2005. (b) Temporal changes in the average frontal position and velocities at profile A-B.



Figure S8: (a) Temporal evolution of the velocity profile A-B in Figure S7. (b) Estimated errors of the velocity profile at each epoch.





Figure S9: (a) Temporal evolution of the velocity profile A-B in Figure 4 in the main text. (b) Estimated errors of the velocity profile at each epoch.

Glacier Occidental



Figure S10: (a) Temporal evolution of the velocity profile A-B in Figure 6 in the main text. (b) Estimated errors of the velocity profile at each epoch.



Figure S11: (a) Temporal evolution of the velocity profile C-D in Figure 6 in the main text. (b) Estimated errors of the velocity profile at each epoch.



Figure S12: (a) Temporal evolution of the velocity profile A-B in Figure 7 in the main text. (b) Estimated errors of the velocity profile at each epoch.

Glacier PioXI





Figure S13: (a) Temporal evolution of the velocity profile C-D in Figure 7 in the main text. The velocities greater than 5 m/day are saturated in the color scale; see also (c). (b) Estimated errors of the velocity profile at each epoch. (c) Same temporal evolution in (a), but with different color scale and velocity range.



Figure S14: (a) Temporal evolution of the velocity profile E-F in Figure 7 in the main text. (b) Estimated errors of the velocity profile at each epoch.



(a)



4 (m/day) Velocity 2

0

(b)

5





2002/12/20 2003/01/08 2003/02/12 2003/02/28 2003/04/23 2003/06/13 2003/07/02 2003/07/18 2003/09/26 2003/10/15 2003/12/05 2004/01/09 2004/04/07

2004/05/12 2004/08/25 2004/09/10 2005/07/22 2005/08/26 2008/08/15 2008/09/03 2010/05/19 2010/06/05 2010/07/04 2010/07/21 2011/01/04 2011/02/19

(a)





2003/01/08 2003/02/12 2003/04/23 2003/07/02 2003/10/15 2004/04/07 2004/05/12 2004/08/25 2007/08/26 2007/10/11 2008/01/11 2008/02/26 2008/09/03 2010/05/19 2010/07/04 2011/01/04 2011/02/19

(a)



2002/12/23 2003/01/08 2003/02/12 2003/04/23 2003/06/16 2003/07/02 2003/10/15 2003/12/08 2004/01/12 2004/03/22 2004/04/07 2004/04/26 2004/05/12 2004/05/31 2004/08/25 2004/09/13

2005/06/20 2005/08/29 2005/10/03 2007/07/30 2007/08/26 2007/10/11 2008/01/11 2008/02/26 2008/09/03 2010/05/19 2010/06/05 2010/07/04 2010/07/21 2011/01/04 2011/02/19

