



- 1 Present-day high-resolution ice velocity map of the Antarctic ice sheet
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#### 13 Abstract:

14 Ice velocity constitutes a key parameter for estimating ice-sheet discharge rates and is crucial 15 for improving coupled models of the Antarctic ice sheet to accurately predict its future fate 16 and contribution to sea-level change. Here, we present a new Antarctic ice velocity map at a 17 100-m grid spacing inferred from Landsat 8 imagery data collected from December 2013 18 through March 2016 and robustly processed using the feature tracking method. These maps 19 were assembled from over 73,000 displacement vector scenes inferred from over 32,800 20 optical images. Our maps cover nearly all the ice shelves, landfast ice, ice streams, and most 21 of the ice sheet. The maps have an estimated uncertainty of less than 10 m yr<sup>-1</sup> based on robust 22 internal and external validations. These datasets will allow for a comprehensive continent-23 wide investigation of ice dynamics and mass balance combined with the existing and future 24 ice velocity measurements and provide researchers access to better information for





- monitoring local changes in ice glaciers. Other uses of these datasets include control and
  calibration of ice-sheet modelling, developments in our understanding of Antarctic ice-sheet
  evolution, and improvements in the fidelity of projects investigating sea-level rise. All data
  presented here can be downloaded from the Data Publisher for Earth & Environmental Science
  (https://doi.pangaea.de/10.1594/PANGAEA.895738).
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### 33 1 Introduction

34 Global warming could lead to significant mass changes in the Antarctic ice sheet. The ice mass 35 of this sheet has a displacement potential equivalent to a sea level rise greater than 60-m 36 (Fretwell et al., 2012; Alley et al., 2005), which would alter oceanic conditions and marine 37 ecosystems, such as ocean currents, water temperature, and fishing ground distributions (Gutt 38 et al., 2011). Monitoring the glacial dynamics of the ice sheet is a primary scientific goal to 39 determine whether the ice sheet is stable, growing or shrinking. Thorough and continued 40 monitoring of ice-sheet dynamics is also of utmost importance for accurate predictions of ice-41 sheet behaviour in the future(Lucchitta and Ferguson, 1986). Ice velocity, which is one key 42 parameter representing ice dynamics, affects the estimates of ice-sheet mass balance and the 43 corresponding sea level rise(Scheuchl et al., 2012) and plays a crucial role in studies on glacier 44 dynamics and mass balance. The ice velocity of peripheral outlet glaciers is one of the primary 45 parameters needed to determine the ice discharge rate, because these glaciers act as channels 46 for ice transportation from the ice-sheet interior to the ice shelves and ocean. A 47 comprehensive and lasting observation of ice velocity is important to better understand a wide 48 range of processes related to glacial mass fluxes, such as glacier response to climate and 49 climatic changes, glacier physics and flow modes, glacier flow instabilities (e.g., surges), 50 subglacial processes (e.g., erosion), and supra- and intra-glacial mass transport.





51 Ice velocity has been measured by traditional ground-based measurement techniques (e.g., 52 GPS, electronic distance, aerial photograph) since the 1970s in the Antarctic ice sheet (Manson 53 et al., 2000; Zhang et al., 2008; Kiernan, 2001; Rott et al., 1998). However, obtaining a 54 complete real-time survey is difficult due to the remoteness of the continent and extremely 55 cold climate. Moreover, the sporadic and discontinuous measurements prohibit the study of 56 ice-sheet mass balance as a whole. Recently, glaciologists have begun to present a complete 57 picture of the ice velocity in Antarctica by using multi-satellite interferometric synthetic 58 aperture radar (InSAR) at a 450-m spatial resolution(Rignot et al., 2011). Additionally, an 59 updated dataset of annual InSAR-derived ice velocity was recently released at a 1000-m spatial 60 resolution, and another continent-wide ice velocity map from Landsat 8 (L8) images was also 61 reported (Mouginot et al., 2017) in a variety of spatial resolutions (300-1000 m). Long-term 62 and continuous measurements of ice velocity are a precondition for developing a complete 63 understanding of the ice dynamics of the continent of Antarctica. Furthermore, ice velocity 64 products with a higher resolution can facilitate more thorough investigations on localized ice dynamics(Nath and Vaughan, 2003;Favier and Pattyn, 2015), such as the production of 65 66 crevasses and the role of ice rises on ice sheet stability. These factors highlight the need for a 67 new set of high-resolution ice velocity observations over Antarctica.

68 Deriving the surface velocity of glaciers and ice shelves using optical satellite images is a 69 rapid, cost-effective method to obtain the large-scale ice velocity field, especially in remote 70 Antarctica, which has been widely used in glaciology(Bindschadler and Scambos, 71 1991;Lucchitta and Ferguson, 1986;Burgess et al., 2013;Copland et al., 2009;Sam et al., 2016). 72 However, the Antarctic-wide ice velocity based on optical satellite images remains difficult to 73 determine, although relevant work has been performed since the mid-1980s. The near global 74 coverage and high repeat rate of optical satellites now provides the possibility for continent-75 wide mapping and monitoring of glaciers and ice-sheet dynamics, especially the L8 mission. L8 76 is the newest generation of satellites in the Landsat family and provides continuous coverage

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of earth's surface with a 16-day revisit cycle at a 98.2 inclination. The Operational Land Imager
(OLI) on L8 can provide improved radiometric and geodetic performance with a high spatial
resolution (up to 15 m). The combination of a high repeat rate and good performance creates
an opportunity to generate a continent-wide ice velocity map in Antarctica(Heid and Kääb,
2012).

82 Here, we present a high-resolution ice velocity mosaic of Antarctica (except for the area 83 south of 82.5°S) inferred from L8 images from the United States Geological Survey (USGS) 84 Earth Resources Observation and Science (EROS) Center. These velocity data have the highest 85 spatial resolution of 100 m achieved to date and were assembled from more than 73,000 86 scenes of displacement vectors. The vectors are inferred from more than 32,800 orthorectified 87 panchromatic band scenes with a 15-m spatial resolution acquired by the OLI on L8 from 88 December 2013 to March 2016 using the optical offset method (see Sect. 2). The flowchart for 89 producing and validating the ice velocity data is shown in Figure 1. These newly generated 90 datasets could be valuable in quantitative determination of ice discharge rates and mass 91 balance of the Antarctic ice sheet at present and contribute to climatic modelling studies. 92 Section 2 presents detailed information on extracting the ice velocity, including an ice velocity

generation method from displacement vectors and an error estimation approach. Section 3
presents the results and data records. Section 4 summarizes the accuracy validation process,
including the technical validation and internal validation using independent data. The last
section presents the conclusions.

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### 101 Figure 1. Flowchart for producing and validating the generated L8 Antarctic ice velocity

### 102 dataset.

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#### 103 2 Data and methods

- 104 In this section, we first briefly present the satellite imagery data and existing ice velocity data
- 105 collected using InSAR and field surveys (Sect. 2.1) and then summarize the pairing strategy of
- 106 images (Sect. 2.2). Sections 2.3 to 2.5 summarize the feature tracking method of displacement,
- 107 post-processing, ice velocity generation and mosaicking of Antarctic ice velocity maps.

#### 108 2.1 L8 imagery data and other independent ice velocity measurements

- 109 In this study, the L8 orthorectified panchromatic band scenes are used to generate ice velocity
- 110 maps using the optical offset method, which will be summarized in Section 2.3.(Leprince et al.,
- 111 2007), and the quality assessment (QA) band provides a cloud ratio to identify the spatial
- 112 distributions of clouds and water, which are masked in displacement scenes. In addition, the
- 113 supporting data contain the InSAR-derived Antarctic ice velocity data, Antarctic rock outcrop





data inferred from L8, and previous ice velocity measurements compiled and managed by the 114 115 National Snow & Ice Data Center (NSIDC) and the Chinese Antarctic Center of Surveying and 116 Mapping. Antarctic rock outcrop data and the InSAR-derived Antarctic ice velocity data are used to identify the stagnant region for absolute calibration and to assess our maps. The 117 118 existing measurements of ice velocity consist of satellite-derived measurements and in situ measurements, which total over 144,000 measurements. The data include more than 1100 in 119 120 situ measurements from a variety of geodetic techniques, such as GPS, and electronic 121 distance, which provide an external validation of our ice velocity maps.

### 122 2.2 Landsat 8 product and pairing strategy of images

123 The L8 Level 1 Systematic Terrain Corrected (L1GT) products in GeoTIFF file format were 124 obtained from the USGS EROS Data Center (https://earthexplorer.usgs.gov/). The products 125 consist of ten 30-m spectral bands with coverage of visible, near infrared, and shortwave 126 infrared bands, a 15-m panchromatic band, product-specific metadata and a QA file. Here, we only use the panchromatic band because of its high resolution, product-specific metadata and 127 QA file. More than 32,800 L1GT data have been processed to generate displacement vector 128 129 scenes. To overcome the cloud contamination and improve the amount of measurements, we 130 use the multiple reference strategy in image pairing, which means that all images in the same Worldwide Reference System (WRS-2) could be taken as reference images in the pairings. In 131 addition, paired images are generated using a time interval of three years as a maximal 132 133 temporal baseline with a minimum time separation of 16 days. Finally, more than 73,000 134 paired images are obtained to produce the surface displacement of the ice sheet.

#### 135 2.3 Feature tracking processing

To determine the horizontal displacement vectors due to ice motion, we use a feature tracking method(Scambos et al., 1992;Bindschadler and Scambos, 1991;Leprince et al., 2007), also known as the phase-shift method. The orthorectified L8 images are directly used to produce the displacement vectors by means of the co-registration (or cross-correlation) method in the





140	Co-registration of Optically Sensed Images and Correlation (COSI-Corr) software package
141	developed at the California Institute of Technology(Leprince et al., 2007). Many studies have
142	proven that this technique is more efficient for images under different illumination
143	conditions(Heid and Kääb, 2012;Brown, 1992), especially in low visual contrast areas, such as
144	Antarctica. The method produces displacement vectors by a phase-shift technique of low
145	frequency calculated by a Fourier-based frequency correlator(Leprince et al., 2007), which is
146	produced repetitively within a specific sliding window (or patch) on the paired images. The
147	result is given by a three-band file consisting of an E-W displacement map (positive towards
148	the east), an N-S displacement map (positive towards the north), and a signal-to-noise ratio
149	(SNR) band as an indicator of the measurement quality. The technique can resolve sub-pixel
150	displacements of less than 1/20 of the pixel resolution at a high SNR, which is generally greater
151	than 0.9.

152 Specifically, the feature tracking processing has two stages. The first stage (namely, coarse 153 co-registration) approximately estimates the pixelwise displacement between two patches. In 154 general, if noisy images or large displacements are expected, a large initial sliding window 155 should be used. In this study, the size of the initial sliding window varies from 64 to 256 pixels 156 in both the X and Y directions according to a priori knowledge from the InSAR-derived Antarctic 157 ice velocity and the time interval between two paired images. Once the initial displacements are estimated, the second stage consists of fine co-registration to retrieve the sub-pixel 158 159 displacement using a smaller window. The new size of 32×32 pixels is tentatively adopted to 160 yield reliable estimates for the displacement at densely independent points. Other parameters 161 of the frequency correlator include the step sizes between sliding windows in both the X and 162 Y directions (in pixels), the frequency masking threshold, the number of iterations for 163 robustness, resampling and gridded output. The step size is set to a constant value of 7 pixels 164 in each dimension or approximately a 100-m spatial resolution. A frequency masking threshold





165 of 0.9 is adopted as the optimum value as recommended in a previous study(Leprince et al.,

166 2007).

#### 167 2.4 Post-processing displacement vectors

Generally, the frequency-based co-registration method is more accurate than statistical 168 169 methods but more sensitive to noise contamination. L8 images can minimize the effect 170 because of the good radiometric and geodetic performances, but decorrelation still exists due 171 to large ground motion, lack of measurable ground features (e.g., crevasses or rises), sensor 172 noise, illumination conditions, atmospheric changes (e.g., clouds) and topographic artefacts 173 (thereby producing imprecise orthorectified data). To overcome these problems, we devise 174 three steps to enhance the signal and exclude unreliable measurements. First, we suppress 175 the noise on each displacement scene using an adaptive filter and a median filter. The adaptive 176 filter is the local sigma filter (Eliason and McEwen, 1990) that features a filter size of 9 pixels 177 and a sigma factor value of 2. A median filter is further applied to remove "salt and pepper" noise in ice displacement scenes. Second, the areas covered by clouds and water are excluded 178 from the displacement scenes using the QA band(Zanter, 2016). In the QA band, each pixel 179 180 contains a 16-bit integer that represents bit-packed combinations of surface, atmospheric, and 181 sensor conditions at different confidence levels. The pixels covered by cloud and water in 182 paired images are unpacked from the QA band using the procedures we have developed, and 183 the pixels marked as clouds and water at high confidence levels (67–100%) are used to build a 184 mask layer. These pixels are then masked in displacement scenes. Note that the identification 185 of cirrus clouds is problematic in raw images based on our analysis, since radiometric 186 characteristics of ice and cirrus clouds are generally indistinguishable. Here, we use only clouds 187 to build a mask layer. Third, since frequency correlation easily causes errors at the edges of 188 displacement scenes, the results of the displacement vectors are neglected at the edge 189 regions.

190 2.5 Ice velocity measurement

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191	Cloud contamination is a major challenge in ice velocity estimation using optical images, which
192	is particularly significant in polar regions(Toon and Turco, 1991). To overcome this problem,
193	we process all image pairs using a time interval of three years as a temporal baseline with a
194	minimum repeat cycle of 16 days in WRS-2. Some images in adjacent paths in the WRS-2 are
195	also paired to determine the ice velocity for some void areas where no valid scenes with the
196	same path and row are available. A three-year time interval is used in our processing. Although
197	the decorrelation becomes more apparent with the increase in the time interval, many surface
198	features on ice sheets remain preserved and visible over many years(Lucchitta and Ferguson,
199	1986). Finally, more than 73,000 image pairs are organized from more than 32,800 scenes of
200	L8 panchromatic images and are processed to generate ice velocity estimates.

201 Despite the improved geometric accuracy of L8, the residual geolocation errors (~8 m 202 circular error (90%)) of the L8 panchromatic band contribute most of the uncertainties in ice 203 velocity products. These errors will lead to an offset between the displacement scenes and 204 should be removed(Fahnestock et al., 2016). In fact, offset tuning is often called absolute 205 calibration of the ice velocity data. In Antarctica, absolute calibration is a challenging issue 206 because the ice is active almost everywhere and available rock outcrops are extremely scarce. 207 Here, we use both rock outcrop data (Figure 3e) derived from L8 images(Burton-Johnson et 208 al., 2016) and the InSAR-derived Antarctic velocity map(Mouginot et al., 2017) to determine the relatively stagnant areas (i.e., areas with InSAR-derived ice velocities of <10 m yr<sup>-1</sup>) for the 209 210 absolute calibration of our ice velocity estimates.

The velocity calibration consists of three steps. First, the differences in the displacements between the InSAR-derived velocity map and our calculated ice velocity maps from Landsat images are calculated in the stagnant areas. Second, to eliminate outliers, a 3  $\sigma$  filter is applied recursively on these differences. In this technique, the measurements of the differences are removed if the magnitudes of the values are larger than three times the standard deviation (3  $\sigma$ ). Third, the mean of the remaining differences is considered the offset





- 217 of the displacement scenes. Furthermore, the offsets for the displacement scenes outside of 218 the stagnant areas (such as in the Ross and Ronne ice shelves) are estimated by overlapping 219 neighbouring scenes captured at approximately the same time. The offsets of two velocity 220 components are independently estimated. In addition, to be computationally efficient, 221 Antarctica is divided into 16 gridded sub-regions, which are shown in Figure 2a, and data 222 stacking is processed independently. Finally, the 14 sub-regions are mosaicked to generate an 223 ice velocity map for all of Antarctica because two sub-regions do not cover the grounded ice 224 sheet. 225 The mosaicked velocity maps are produced based on the displacement scenes. To increase
- the accuracy of the mosaicked velocity maps, we stack all displacement scenes after removing the pixels with an SNR less than 0.95. In general, the velocity map contains dozens of scenes in each location. For a specific pixel denoted by *i*, all displacement scenes (m=1, 2, ..., n) are
- stacked to obtain the estimate of the ice velocity ( $V_i$ ) as follows:

230 
$$V_{i} = \frac{\sum_{m=1}^{n} \Delta d_{m}^{i}}{\sum_{m=1}^{n} \Delta t_{m}^{i}}$$
(1)

231

232 where  $\Delta d_m^i$  denotes the generated displacement during the time interval  $\Delta t_m^i$ .

233 3 Results and validations

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### 234 3.1 Antarctic-wide ice velocity map

Over Antarctica, valuable L8 images are available for only the summer and fall seasons, i.e., in November, December, January, February and March, which means that the L8 ice velocities represent mainly the summer/fall ice velocity. In Figure 2a, we show a mosaicked Antarctic ice velocity map inferred from over 73,000 L8 images acquired from December 2013 to March 2016. Our maps cover nearly all of the ice shelves, ice streams, and the majority of the ice sheet. Here, Figure 2b shows a count map to indicate the number of images used to produce





241	the ice velocity data. The predominant year of the images is 2015 (Figure 2b), and there are
242	generally more than 20 displacement vectors, with up to 200 in some regions. The L8 ice
243	velocity map shows the same pattern as the InSAR-derived ice velocity map, and Figure 3
244	shows some ice velocity and the difference graphs from the two ice velocity products. The
245	spatial resolution of the L8 ice velocity data is 3 to 10 times finer or higher resolution than that
246	of the recent L8-derived (Gardner et al., 2018) and InSAR-derived ice flow maps (Mouginot et
247	al., 2017; Rignot et al., 2011), reaching up to 100 m. Here, we show the velocity map of James
248	Ross Island in the Antarctic Peninsula as an illustration of our high-resolution results (Figures
249	2c and 2d). The results reveal that the L8 velocity map can provide details of the ice velocity
250	pattern for the Antarctic ice sheet, such as for James Ross Island and small glaciers (Figures 2c
251	and 2d). Thus, our ice velocity map provides the first opportunity to investigate localized ice
252	dynamics, such as crevasse formation, and the roles of ice rises and rumples in ice-sheet
253	dynamics and evolution. These maps also have good coverage over Antarctica, except for
254	south of 82.5°S. The mosaicked ice velocity map covers the majority of the Antarctic ice sheet
255	and nearly 99% of the fast-flowing glaciers and ice shelves, as well as fast ice, except for a few
256	ice streams located on the Ronne Ice Shelf (e.g., Academy and Foundation Glaciers) and on
257	the Ross Ice Shelf (e.g., Whillans Glacier in the Siple Coast).







259	Figure 2. L8-derived ice velocity estimates from Landsat 8 images from December 2013 to
260	March 2016. (a) L8-derived Antarctic ice velocity map (gridded lines delineate the 16 sub-
261	regions); (b) footprint map of L8 presenting the number of valid displacement vectors used to
262	produce the ice velocity map in a specific grid (pixel); (c) magnified view of the ice velocity map
263	of James Ross Island, Antarctic Peninsula, corresponding to the box in Figure 2a; and (d) L8
264	image corresponding to Figure 2c, in which the red solid line shows the coastal lines. The L8-
265	derived ice velocity maps are drawn on a 500-m grid. The maps were created using The Generic
266	Mapping Tools (http://gmt.soest.hawaii.edu/), Version 5.2.1.(Wessel et al., 2013)
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## Figure 3. Velocity profile and the difference graphs comparing the L8 (2015) and InSAR (2008) 272 273 ice velocity data. (a) Recovery Glacier; (b) Slessor Glacier; (c) Mellor Glacier; (d) Evans Glacier; (e) AMM RAMP Antarctic mosaic(Jezek and Team, 2002), in which the brown area shows the 274 275 areas covered by rock outcrop. The black solid lines and the letters show the geolocations of the velocity profiles in a-i; (f) Fisher Glacier; (g) Bindschadler Glacier; (h) MacAyeal Glacier; and 276 277 (i) Lambert Glacier. Left y-labels represent velocity magnitudes of glaciers, and the right y-278 labels are the differences of velocity magnitudes along sampling paths shown in figure e. Black 279 triangles represent the location of grounding lines. The maps were created using The Generic 280 Mapping Tools (http://gmt.soest.hawaii.edu/), Version 5.2.1.(Wessel et al., 2013)

281 3.2 Data Records

282	The	ice	velocity	map	and	supporting	data	are	archived	at
283	https:,	//doi.pa	angaea.de/10	0.1594/P	ANGAEA	.895738. The file	e format (	used is tl	he ENVI Stand	lard.
284	Examp	oles of t	he data prod	lucts are	shown ir	n Figure 2.				
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200										

- 286 3.2.1 Ice velocity map and error map
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288	The 100×100-m gridded ice velocities for all of Antarctica are stored in a 16-bit long point ENVI
289	file format under a polar stereographic projection with a true latitude of 71°S. The gridded ice
290	velocity has been equally divided into 4 subsets in the X and Y directions in consideration of
291	file size and computer processing speed (Table 1). Note that ENVI file sizes have been kept to
292	approximately 1 Gigabyte for user friendliness and easy downloading. Each ENVI file contains
293	three bands that show velocity vectors in both the X-direction and Y-direction and a gridded
294	error map of the ice velocity. The structure of the ice velocity filenames is
295	Velocity_I8_*year*_*subset*_*XY*.dat, where Velocity represents ice velocity data and I8
296	indicates the L8 satellite from which images are used to produce the ice velocity map. *year*
297	is the predominant year of the images in the file, *subset* shows whether the ice velocity file
298	has been cropped due to considerations of file size and computer processing speed, and *XY*
299	indicates the relative coordinates among all files, where X is the column number starting with
300	one and Y is the row number starting with one. Each ENVI file is associated with a head file
301	with the same filename. The head file contains the coordinate information (see xstart and
302	ystart) for the subset among the Antarctic gridded ice velocity data.

# 303 Table 1. Filename structure of the ice velocity ENVI files. Two tiles do not include any valid

304 ice velocity values.

Ice velocity filenames	column	row	year	subset
Velocity_l8_2015_1_11.dat	1	1	2015	1
Velocity_l8_2015_2_12.dat	2	1	2015	2
Velocity_l8_2015_3_13.dat	3	1	2015	3
Velocity_l8_2015_4_14.dat	4	1	2015	4
Velocity_l8_2015_5_21.dat	1	2	2015	5
Velocity_l8_2015_6_22.dat	2	2	2015	6
Velocity_l8_2015_7_23.dat	3	2	2015	7
Velocity_l8_2015_8_24.dat	4	2	2015	8





Velocity_l8_2015_9_31.dat	1	3	2015	9
Velocity_l8_2015_10_32.dat	2	3	2015	10
Velocity_l8_2015_11_33.dat	3	3	2015	11
Velocity_l8_2015_12_34.dat	4	3	2015	12
Velocity_l8_2015_13_41.dat	Not provided. S	Subset does not	cover the grou	nded ice sheet.
Velocity_l8_2015_13_41.dat Velocity_l8_2015_14_42.dat	Not provided. S	Subset does not	cover the grou	nded ice sheet.
Velocity_l8_2015_13_41.dat Velocity_l8_2015_14_42.dat Velocity_l8_2015_15_43.dat	Not provided. S	Subset does not	cover the grou	nded ice sheet.

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### 306 3.2.2 Landsat ground footprints

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308 Landsat gridded footprints are stored in 8-bit integer point ENVI files (Figure 2b), which show

309 the number of displacement vectors used to produce the ice velocity at a specific location.

310 These files also have the same file structure and projection as the gridded ice velocity map.

311 The naming convention of the footprint maps is Footprints\_I8\_\*year\*\_\*subset\*\_\*XY\*.dat,

312 which has the same naming convention as the ice velocity maps, except for "Footprints", which

- 313 indicates the content of the product.
- 314

### 315 4 Technical Validation

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Verification of the continent-wide ice velocity in the Antarctic ice sheet is the most difficult task in the absence of other independent measurements, which are difficult to obtain because of the remoteness of the continent and the harsh climate in Antarctica. Here, we describe and assess the precision by internal validation and comparison with in situ measurements. For internal validation, we produce the gridded error maps for the velocity maps. Furthermore, we compared our velocity maps with the InSAR-derived ice velocity map and in situ





323 measurements as well as pre-existing measurements from remote images using co-

324 registration vectors.

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### 326 4.1 Internal validation

In the absence of other synchronously independent measurements of ice velocity, the uncertainty in the ice velocity maps from empirical analysis is generally used as an estimate of the accuracy of the ice velocity product. The error sources of L8-derived ice velocity are primarily attributed to the following three aspects: image co-registration, paired image time interval, and stacked data quantity.

332 Image co-registration represents a process of geometrically aligning two or more satellite 333 images to obtain the corresponding pixels or feature representing the same surface objects, 334 which is a main factor that influences the ice velocity accuracy. The image co-registration 335 accuracy is largely determined by the following three factors: (1) decorrelation due to dramatic 336 ground changes and a lack of measurable features between the scenes due to long time 337 intervals or low-contrast land cover (e.g., snow or ice); (2) low image quality caused by sensor 338 noise, pixel oversaturation, aliasing and cloud contamination; and (3) topographic artefacts 339 caused by shadowing differences and inaccurate orthorectification of satellite attitudes. In 340 fact, quantifying the effects of the three error sources is very difficult, especially on a pixel-by-341 pixel scale. In general, the co-registration accuracy is given empirically based on the validation 342 of the matching algorithm. Here, the co-registration accuracy is equal to 1/10 of the pixel size 343 in the E-W and N-S displacement components. This value is greater than 1/50 of the pixel size proposed by Leprince et al. (2007)(Leprince et al., 2007). 344

The second factor is the time interval of the paired images, because ice velocity is a function of displacements and time. Ice velocity is calculated by the displacement divided by the time interval of paired images. The uncertainty of the displacement is primarily attributed to image





- 348 co-registration as mentioned above. Thus, a longer time interval suggests higher precision of
- 349 the ice velocity (see Eq. 2).
- 350 The third factor is the amount of stacking data. Hence, more displacement data are stacked
- 351 and will be more accurate. As a result, the gridded error map of ice velocity data can be
- 352 obtained pixel by pixel based on the method of error propagations using the co-registration
- accuracy, time interval and total amount of stacking data.
- According to the mosaicking method discussed above (Eq. 1), the uncertainty in one mosaicked velocity component at the *i*-th pixel (denoted by  $\sigma_{v_i}$ ) can be estimated using the following error propagation formula under the assumption that the errors from different sources are independent and any temporal errors are negligible:

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$$\sigma_{V_i} = \pm \sqrt{\sum_{m=1}^{n} (\sigma_m^i)^2 / \left(\sum_{m=1}^{n} \Delta t_m^i\right)^2}$$
 (2)

where  $\sigma_{\rm m}^{\rm i}$  is the co-registration error, i.e., the standard deviation of the *m*-th displacement observation during the time interval  $\Delta t_{\rm m}^{\rm i}$ . Since the co-registration errors are constant in the spatial (the whole scene) and temporal domains (all stacked displacements), if  $\sigma_{\rm m}^{\rm i}$  is assumed to be a constant of  $\sigma$ , Equation (2) can be simplified as follows:

363 
$$\sigma_{V_i} = \pm \sqrt{n} \sigma / \sum_{m=1}^{n} \Delta t_m^i$$
(3)

Since the E-W and N-S components at the *i*-th pixel have the same uncertainty, which can be calculated with Equation (3), the uncertainty is valid for the magnitude of the velocity vector. The error map (Figure 4a) in the magnitude of the mosaicked velocity vector is generally better than 10 m yr<sup>-1</sup>, except for some areas in the Antarctic Peninsula and Marie Byrd Land in West Antarctica. Fewer valid satellite images are obtained from the two regions due to heavy cloud coverage. Relatively large uncertainties in these areas were mainly caused by a small amount of valid displacement vectors. For comparison, the error map of the InSAR ice velocity





- 371 estimates is shown in Figure 4b, which quantifies the achieved accuracy of the ice velocity
- 372 maps of this study.



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Figure 4. Uncertainty maps of the L8-derived Antarctic ice velocity (a) and InSAR-derived ice
velocity(Mouginot et al., 2017) (b) MBL: Marie Byrd Land. The maps were created using The
Generic Mapping Tools (GMT, http://gmt.soest.hawaii.edu/), Version 5.2.1.(Wessel et al.,
2013)

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### 379 4.2 Comparisons with other datasets and in situ measurements

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381 A comparison of our velocity measurements with previous velocity measurements would be very beneficial. However, this comparison is very difficult due to the variability of glacier 382 383 flow. Some glacier flow may vary significantly on daily, seasonal and yearly scales. Here, we collected historical long-term ice velocity measurements compiled and managed by the 384 385 project of Velmap(Raup and Scambos). Our ice velocity results are compared with only the in situ measurements located in the slow-flowing areas (<100 m yr<sup>-1</sup>) because highly dynamic 386 changes in ice velocity in fast-flowing areas (e.g., ice shelf) are expected. Furthermore, the ice 387 388 velocity measurements on Byrd Glacier determined by photogrammetric methods and on 389 Amery ice shelf from theodolite/EDM and GPS methods are used to illustrate the performance 390 of our ice velocity map(Brecher, 1982;Brecher, 1986;Allison, 1979). A total of 609 sites in slow-





391	flowing areas were chosen for comparison and analysis, and their differences are shown with
392	dots in Figure 5a, where the colours of the dots denote the magnitude of the differences.
393	Figure 5b shows the histogram of the differences between our velocity data and the in situ
394	measurements. Except for three sites (two in Lambert-Amery Basin in East Antarctica and one
395	on the Siple Coast in West Antarctica) (Figure 5a), the points are all less than 40 m yr $^{-1}$ , and
396	593 sites, representing more than 97% of the total check points, have differences in the ice
397	velocity magnitude of less than 10 m yr <sup>-1</sup> . The differences have a –0.7 m yr <sup>-1</sup> mean value and a
398	3.2 m yr <sup>-1</sup> standard deviation. For comparison, the differences between the InSAR velocity and
399	field surveying data are shown in Figure 5c. A total of 589 points are less than 10 m yr <sup>-1</sup> . These
400	points have a mean value of 0.3 m yr $^{-1}$ and a standard deviation of 3.3 m yr $^{-1}.$ To further
401	investigate the performance of the L8 ice velocity data in slow-flowing areas, we compared
402	the L8, InSAR and in situ measurements with ice velocity magnitudes of less than 20 m yr $^{-1}.$
403	The analysis results are shown in Figure 6. Figures 6a and 6b show the difference between the
404	L8 ice velocity data and in situ measurements and the statistical results of these differences.
405	The near-zero y-intercept and nearly unitary slope of the data in Figure 6a confirm that the L8
406	ice velocity data are very consistent with the in situ measurements, even in the stable interior
407	ice sheet. Figure 6c shows the InSAR results and the similar performance with the L8 ice
408	velocity data. In summary, the L8 ice velocity data have an accuracy of 10 m yr $^{\text{-1}}$ (3 $\sigma$ ).

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Figure 5. Accuracy assessment of L8 ice velocity and InSAR velocity. (a) Differences between in situ measurements and L8 ice velocity, where the colour dots show the geolocations and velocity differences between the L8 and in situ measurements (background maps are from the AMM RAMP Antarctic mosaic(Jezek and Team, 2002)); (b) histogram of the differences between the L8 and in situ ice velocity data; and (c) histogram of the differences between the InSAR and in situ ice velocity data.

418



420 Figure 6. Comparison between the in situ measurements and L8 ice velocity (a) and InSAR

421 (b)





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423 To assess the reliability of the L8 ice velocity data in fast-flowing areas, here, we show two 424 illustrations of Byrd Glacier (80°S, 160°E) and Amery ice shelf (69°S, 71°E). For Byrd Glacier, 425 the in situ ice velocity measurements were determined by photogrammetric methods from 426 two sets of aerial photographs acquired on 6 December 1978 and 21 January 1979(Brecher, 427 1982). In total, ice velocities of 470 sites on the main ice stream were determined by the 428 change in location of natural features over the 56-day interval between two flights. Here, we 429 analysed 436 sites where the velocity is greater than 100 m yr<sup>-1</sup>. The near unitary slope of 430 Figure 7b shows that L8 and the aerial ice velocity data have a good correlation, except for a 431 small number of sites that have a relatively large difference. Figure 7a shows that the sites 432 with large differences are located mainly on the lateral side of the glacier (see red and dark 433 blue dots in Figures 7a and 7b). The large difference may be caused by the following factors: 434 (1) errors in the two datasets, (2) relatively low resolution of the L8 ice velocity relative to the 435 aerial method and high-velocity gradient on the sides of the glacier, which easily causes large 436 differences, and (3) velocity changes between the long time intervals. For comparison, we also 437 show the InSAR and aerial ice velocity in Figure 7c, which shows that the L8 and InSAR ice 438 velocity in fast-flowing areas have the same performance as those shown in Figures 7b and 7c. On Amery ice shelf, the in situ ice velocity measurements were determined by using a 439 440 combination of standard surveying techniques, including electronic distance and theodolites 441 and GPS. The ice velocity observations on Amery ice shelf were mainly collected during two 442 time periods (December 1968—January 1970; December 1988—January 1991). Finally, the ice 443 velocity measurements of 120 sites were compared with the L8 and InSAR ice velocity data. The vast majority of differences are less than 200 m yr<sup>-1</sup>, except for a small number sites 444 445 beyond the range (Figure 7d). The sites with large differences are mainly located on the front 446 of the ice shelf. The L8 ice velocity data agree well with the in situ measurements in Figure 7e. 447 For comparison, the InSAR and in situ measurements are also shown in Figure 7f. An increase





- 448 in the ice velocity is observed between the two time periods along the lateral route at an
- 449 average velocity of 800 m yr $^{-1}$  (Figures 7d and 7e), and this phenomenon is also shown in Figure
- 450 7f. The apparent changes in ice velocities may suggest different patterns in the dynamic
- 451 characteristics.



453 Figure 7. Comparison among the L8, InSAR and in situ measurements. (a) Byrd Glacier and the differences between the L8 and in situ ice velocity data (colour dots); note that the black 454 dots represent differences of less than -200 m yr<sup>-1</sup>, and the white dots represent differences 455 of greater than 200 m yr<sup>-1</sup>, (b) comparison between the L8 and in situ measurements on Byrd 456 457 Glacier, (c) comparison between the InSAR and in situ measurements on Byrd Glacier; (d) Amery ice shelf and the differences between the L8 and in situ ice velocity data (colour dots), 458 459 (e) comparison between the L8 and in situ measurements on Amery ice shelf, and (f) 460 comparison between the InSAR and in situ measurements on Amery ice shelf.

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### 462 5 Conclusions

463 Cold regions are very sensitive to the impacts of climate change. Long-term monitoring of ice464 sheet dynamics is crucial for precise assessments of the glacial responses to climate change.
465 We constructed a new Antarctic-wide high spatial resolution ice velocity map inferred from





- Landsat 8 imagery data collected between 2013 and 2016. The new map will provide a
  opportunities to comprehensively investigate Antarctic ice dynamics in combination with
  existing and future ice velocity maps, which will provide insights into the ice sheet's mass
- 469 balance.
- 470 Data availability
- 471 The latest dataset is available at the Data Publisher for Earth & Environmental Science
- 472 (https://doi.pangaea.de/10.1594/PANGAEA.895738)
- 473

### 474 Author contributions

- 475 Q.S. conceived of, designed and conducted the experiment. H.W. contributed to the
- 476 research framework and helped develop the methodology. C.K.S. and L.J. performed
- 477 the data analysis. H.T.H. contributed to analysing the results. J.D., S.M. and F.G.
- 478 contributed to the data processing. All authors contributed to the discussion and writing
- 479 of the manuscript.
- 480 Competing interests
- 481
- 482 The authors declare that they have no competing interests.
- 483

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