



## Collision with Seamount Triggers Breakup of Antarctic Iceberg

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17



18 **Abstract**

19 Iceberg A68a calved from Larsen C ice shelf, experienced several major calving when  
20 drifting around the South Georgia Island in late 2020. Here, we show for the first time  
21 that the decisive factor for its calving was a collision with the surrounding seamount. By  
22 treating the iceberg as a deformable body in an established ice-flow model, we show  
23 how its collision with the seafloor created huge stresses within the iceberg that led to its  
24 disintegration. The drifting and rotating of the iceberg, while grounded, further enhanced  
25 its breakup. Moving over a grounded shoal increased the tensile stresses by a factor of  
26 almost one hundred more than immobile grounding alone, and rotational motion about  
27 the pinning point increased the stresses by another twenty percent. Modeling the  
28 fracture and breakup of a large tabular iceberg is an essential step toward better  
29 understanding the life cycle of an iceberg. The possible collapse of the marine-based  
30 sectors of the great ice sheets in a warming world may lead to a massive increase in the  
31 number of icebergs in the surrounding oceans. It will be crucial to be able to understand  
32 where such icebergs drift and how they ultimately disintegrate into the ocean.

33 **Keywords:** iceberg A68a; iceberg grounding and calving; calving modeling; the South  
34 Georgia Island;



35 **1. Introduction**

36 Tabular icebergs in the Southern Ocean are primarily calved from three large ice  
37 shelves in Antarctica: the Ross (Lazzara et al., 1999; Joughin and MacAyeal, 2005),  
38 Filchner-Ronne (Scambos et al., 2005), and Amery Ice Shelves (Fricker et al., 2005). In  
39 the last two decades, ice shelves in the Antarctic Peninsula have become more  
40 unstable and experienced rapid calving (Scambos et al., 2004; Rignot et al., 2004;  
41 McGrath et al., 2012). After calving from an ice shelf, an iceberg starts its journey  
42 through the Southern Ocean, along the way playing a significant role in sea-ice  
43 formation (Massom et al., 2001, 2018), polynya occurrence (Robinson & Williams,  
44 2012), dense shelf water export (Williams et al., 2010), and ocean primary production  
45 (Arrigo et al., 2002; Arrigo & van Dijken, 2003). An iceberg may even affect penguin  
46 colonies when grounded on a continental shelf (Kooyman et al., 2007). Driven by wind  
47 forcing, ocean currents, and the Coriolis force (Gladstone et al., 2001; Wagner et al.,  
48 2017), Antarctic icebergs usually drift vast distances around the continental shelf,  
49 occasionally, drifting north and eventually melting into the surrounding ocean (Merino et  
50 al., 2016; Silva et al., 2006). During drift, tabular Icebergs survive rapid surface melting  
51 (Jansen et al., 2005), basal melting (Russell, 1980; Jansen et al., 2007; Braakmann-  
52 Folgmann et al., 2022), ocean wave rush (MacAyeal et al., 2006), and ocean current  
53 shear (Huth et al., 2022). Eventually, they break up and release smaller icebergs  
54 (Wagner et al., 2014), hurrying up their melting into the ocean. Breakup is a natural  
55 process for tabular icebergs drifting in the ocean, but the breakup mechanism of tabular  
56 icebergs has yet to be fully understood.

57



58 Rapid change and breakup of tabular icebergs in the Southern Ocean are frequently  
59 monitored by remote sensing satellites that observe lateral changes in areal extent  
60 (Stuart and Long, 2010; Scambos et al., 2005; Braakmann-Folmann et al., 2022).  
61 Further combining altimetry measurements, vertical changes of tabular icebergs can be  
62 accurately quantified (Braakmann-Folmann et al., 2022), providing important ancillary  
63 information to understand an iceberg breakup event. Breakup results from ice fracture  
64 and subsequent rift formation in response to stresses that cause crevasse propagation  
65 (Benn et al., 2007; Cuffey & Paterson, 2010; Alley et al. 2008). When stresses exerted  
66 on an iceberg exceed some threshold, fracture tends to occur and develop  
67 perpendicular to the maximum tensile stresses. As the highest frequency of remote  
68 sensing observation is at best daily, the rapid ice fracture and breakup process are  
69 difficult to capture by such. Because of a lack of observation data, studies have yet to  
70 be conducted to understand the breakup of tabular icebergs (Bouhier et al., 2018).  
71  
72 A calving event on the Larsen C Ice Shelf off the Antarctic Peninsula in July 2017 gave  
73 birth to one of the most enormous tabular icebergs ever recorded, named A68, with an  
74 area of almost ten percent of the ice shelf (Hogg & Gudmundsson, 2017). In early 2021,  
75 the main body of A68 (hereafter A68a) drifting in the Southern Ocean disintegrated and  
76 disappeared quickly in the ocean. Before its rapid vanish, several major breakup  
77 occurred (Braakmann-Folmann et al., 2022) which may have played important role in  
78 its rapid disappearance. When drifting in the ocean, two major breakup of A68a when  
79 A68a drifting away from the South Georgia Island was attributed to the large shear  
80 forces caused by differences in ocean currents (Huth et al., 2022). When A68a melting



81 in the ocean, it cooled down and diluted the surrounding ocean water (Smith and Bigg.  
82 2023), causing deepening of the underlying water mass (Tarling et al. 2024), having  
83 significant influence on the surrounding marine ecosystem. However, the first breakup  
84 when A68a drifting close to the South Georgia Island was not fully understood, but likely  
85 to be caused by collision with seafloor (Huth et al., 2022). More investigation and  
86 evidence is required to better understand this breakup as this collision may have  
87 weaken the iceberg, causing its rapid melting into the surrounding ocean.

88

89 This research uses available multi-source remote sensing data to investigate the  
90 breakup of A68a when it drifted close to the South Georgia Island in the Southern  
91 Ocean. We begin by revealing its grounding status through remote sensing data. Then,  
92 we turn to an established ice-flow model to calculate the tensile stresses exerted on the  
93 iceberg under various drift scenarios while grounded. We uncover the breakup  
94 mechanism of the large tabular iceberg A68a due to its interaction with seafloor shoals  
95 on its drift across the Southern Ocean.

96

## 97 **2. Data**

98 We use Sentinel-1A/B Extra Swath GRD data from July 2017 to February 2021 and  
99 MODIS image from December 2020 to May 2021 (Fig. 1, 2, Table S1 and S2) to  
100 observe the major breakup, drifting trajectory, and boundary changes of A68a. Iceberg  
101 location from July 2017 to July 2019 from Brigham Young University (BYU) Microwave  
102 Earth Remote Sensing (MERS) Antarctic Iceberg Tracking Database (Budge and Long,  
103 2018) is used to show part of the drifting trajectory of A68a (Fig. 3). Five tracks of



104 Cryosat-2 Synthetic Aperture Radar (SAR) Geophysical Data Record (GDR) data during  
105 November 1 to December 16, 2020 are used to extract the freeboard of A68a (Fig. 4).  
106 The freeboard data were used to invert ice thickness by using firn air thickness data  
107 (Holland et al., 2011). Seafloor Bathymetry data from the General Bathymetric Chart of  
108 the Oceans (GEBCO) is used to investigate the grounding section of A68a (Fig 3b).  
109 Tide height data from CATS2008 (Padman et al. 2002) is used to investigate sea  
110 surface changes in the vicinity of A68a. ERA-5 data from December 2020 from ECMWF  
111 are used to analyze wind speed and direction change, and pressure change near the  
112 sea surface around A68a. Monthly averaged ocean current data from Circulation and  
113 Climate of the Ocean (ECCO) V4r4 data from every December during 1992-2017 is  
114 used to characterize the upper ocean currents around A68a.

115

116 Insert Figure 1 here

117 Insert Figure 2 here

118

### 119 **3. Method**

120 In this study, we use remote sensing images to detect area, drifting trajectory, drifting  
121 and rotating speed of iceberg A68a first, and then use satellite altimetry to detect  
122 freeboard, invert thickness of A68a when the iceberg drifted close to the South Georgia  
123 Island. The mass of A68a before breaking up was predicted and the rift line where A68a  
124 calved along was extracted. Grounding status was detected using thickness and  
125 seafloor bathymetry data. Finally, using all parameters extracted above, Ua model was



126 set to investigate the deviatoric stresses exerted on iceberg A68a. The methods for all  
127 the processing are described as follows.

128

### 129 **3.1 Drifting Trajectory and Area Changes of Iceberg A68a**

130 Part of the drifting trajectory of A68a from the Antarctic Iceberg Tracking Database until  
131 July 2019 is shown in Fig. 3a. Using Sentinel-1A/B GRD and MODIS data, the  
132 boundaries of iceberg A68a at different observation dates are extracted by human  
133 interpretation (Wang et al. 2016) using ArcGIS, and multiple polygon shapefiles are  
134 generated. Then, the centroid locations of all shapefiles are calculated using the  
135 Geometry Calculator with ArcGIS. Finally, the drifting trajectory of iceberg A68a  
136 between July 2017 and April 16, 2021, is generated using these centroid locations  
137 (black star in Fig. 3a). In Fig 3a, the red (A68 iceberg) and the grey (A68a iceberg)  
138 circle points are obtained from the Antarctic Iceberg Tracking Database (Budge & Long,  
139 2018) . The black star points (A68a) are extracted from Sentinel-1 and MODIS satellites  
140 (Supp. Material). The observation dates of the A68a position are formatted as  
141 'yyymmdd' and illustrated in black. AP stands for Antarctic Peninsula. The grounding  
142 line of the Antarctic Ice Sheet is marked with a blue curve. The background is  
143 topography (Arndt et al. 2013), including the Antarctic Peninsula, South Georgia Island,  
144 and intervening the seafloor.

145

146 Insert Figure 3 here

147



148 The outline, calving progress of A68a when drifting close to the South Georgia Island is  
149 shown in Fig 3b. The background in Fig. 3b is the topography in and around South  
150 Georgia Island (Lambert azimuthal equal-area projection). The inset in the upper right of  
151 Fig. 3b is a zoom-in of the region indicated with a black square box in the panel,  
152 revealing a seamount feature. It shows a seafloor shoal (symbolized by the letter S) with  
153 bathymetry increasing from -250 m to close to sea level at a peak (symbolized by the  
154 letter P). The isobaths from -250 to 0 are drawn with an interval of 50 m.  
155 The boundary polygon shapefiles extracted from remote sensing images are projected  
156 to an equal area projection (Lambert Azimuthal Equal Area) using ArcGIS and the area  
157 change of A68a is fitted with the least square method (Fig. 3c). The areas of derivative  
158 icebergs A68b, A68c, A68d, A68e, A68f, and A68g during several major breakup events  
159 are indicated with color circles. The accelerating areal-losing rates for three distinct  
160 periods (referred to as the first, second, and third phases of the iceberg's journey) are  
161 illustrated with grey line segments and the rates specified in  $\text{km}^2/\text{a}$ .  
162  
163 **3.2 Drifting and Rotating Speed of Iceberg A68a**  
164 The centroid location and the time interval of both observations of A68a are used to  
165 calculate the drifting velocity, assuming a linear drift of A68a. The drifting velocity of  
166 iceberg A68a is obtained by dividing the time interval with drifting distance. Besides  
167 drifting, A68a also rotated in a clockwise direction (Fig. 3b). It is assumed iceberg A68a  
168 rotated around the center of mass (centroid). The rotating velocity is obtained by  
169 following two steps: (1): centroid normalization, and (2): rotation angle extraction.  
170 Centroid normalization is first conducted to make sure both boundary files have (0, 0) as



171 their centroid. Rotation angle calculation is decided by how many degrees are required  
172 to be rotated until the best match of both outlines is found. Then the angular velocity of  
173 iceberg A68a is calculated by dividing the drifting period with rotation angle.

174

### 175 **3.3 Freeboard of Iceberg A68a before Breakup**

176 Cryosat-2 measurements less than 55 m (Holland et al. 2011) over A68a can be  
177 identified virtually from five different tracks in Fig. 4 (A68a is the only large iceberg that  
178 appeared in this region). Following the method from Wang et al. (2016), the sea surface  
179 height and top of the iceberg are determined for each track, and mean freeboard of  
180 A68a from each track of Cryosat-2 is calculated by Eqn. 1.

$$181 F_i = E_i - S_i \quad (1)$$

$$182 F = \frac{1}{5} \sum_{i=1}^5 F_i \quad (2)$$

183 where  $E_i$ ,  $S_i$  and  $F_i$  indicates the ice surface height, sea surface height and mean  
184 freeboard of iceberg A68a from track  $i$  of Cryosat-2.

185 We assume iceberg A68a has a uniform freeboard here. The final freeboard of A68a,  
186 which is  $32.5 \pm 1.0$  m (1.0 m as the standard deviation of freeboard, Table S3) is  
187 calculated as the mean of all the five freeboards estimated (Eqn. 2).  $F$  indicates the  
188 mean freeboard of the iceberg A68a.

189

190 Insert Figure 4 here

191

### 192 **3.4 Rift Line Extraction of Iceberg A68a**



193 MODIS observation on December 16, 2020 (Fig. 2e), was contaminated by clouds and  
194 not used to extract the outline of A68a. However, the A68a outline extracted from  
195 Sentinel-1A images (December 15, 2020) was shifted and rotated to match A68a shown  
196 in MODIS observation using the method introduced above. In this way the outline of  
197 A68a corresponding to MODIS observation time on December 16, 2020, is extracted.  
198 The Sentinel-1A image on December 15 was georeferenced to MODIS observation time  
199 using 17 Ground Control Points (Table S4, Fig. 2e). The georeferencing reached an  
200 accuracy of 36.1 m.  
201 In the same way, the outline of A68a extracted from Sentinel-1 image on December 21,  
202 2020, is shifted and rotated back to position on MODIS observation time, December 16,  
203 2020, by using 11 Ground Control Points (Table S5). The georeferencing reached an  
204 accuracy of 5.8 m. One rift line is extracted by comparing two different boundaries of  
205 A68a before and after the breakup (Fig 5 and 6a).  
206 Image of A68d from Sentinel-1 on December 21, 2020, was georeferenced to MODIS  
207 observation time using five Ground Control Points (Table S6). The georeferencing  
208 reached an accuracy of 51.6 m. In this way, another rift line is extracted (Fig 5 and 6a).  
209  
210 Insert Figure 5 here  
211  
212 **3.5 Thickness and Draft of Iceberg A68a before Breakup**  
213 The firn layer thickness must be considered to invert ice thickness but is seldom known  
214 as no simultaneous measurement of the iceberg A68a is available. However, the firn air  
215 content of Larsen C ice shelf varied from 8.0 to 18.0 m at the calving front (Holland et al.



216 2011). The firn layer on the surface of iceberg A68a may change due to surface snow  
217 accumulation, melt and refreezing process during its drifting to the north. However, it is  
218 difficult to calculate the firn air content because of lacking in-situ observation data. In  
219 this study, a mean air content of 13.0 m of iceberg A68a is assumed since A68a calved  
220 off Larsen C ice shelf and we neglect the firn air content change after the calving of  
221 A68a. Meanwhile, we give 2 m uncertainty for this approximation. Finally, the ice  
222 thickness of A68a is inverted assuming hydrostatic equilibrium, Eqns. (3) and (4).

223  $\rho_w(T - F) = \rho_i I + \rho_a A$  (3)

224  $T = I + A$  (4)

225 where  $\rho_w = 1028.0 \text{ kg m}^{-3}$ ,  $\rho_i = 918.0 \text{ kg m}^{-3}$ , and  $\rho_a = 2.0 \text{ kg m}^{-3}$  are densities of  
226 seawater, pure ice, and englacial air respectively (taken from Holland et al. 2011).  $T$ ,  $I$   
227 and  $A$  is the thickness of the iceberg, pure ice, and air layer respectively (in this study,  
228  $A=13.0\pm2.0 \text{ m}$ ).

229 In this way, the thickness of iceberg A68a is inverted using Eqns. (3) and (4), which is  
230  $195.5 \pm 19.1 \text{ m}$ , and the ice draft is  $163.0 \pm 19.1 \text{ m}$ .

231 The uncertainty of ice thickness inversion is calculated with Eqn. (5)

232  $d_T = \frac{\rho_a - \rho_i}{(\rho_w - \rho_i)} d_A + \frac{\rho_w}{(\rho_w - \rho_i)} d_F$  (5)

233 where  $d_A$  and  $d_F$  are the uncertainty of air layer thickness and freeboard of A68a,  
234 respectively.

235

### 236 **3.6 Mass of Iceberg A68a before Breakup**

237 Before the breakup, the area of A68a was close to  $3825\pm89.0 \text{ km}^2$  (December 15,  
238 2020). When taking  $195.5\pm19.1 \text{ m}$  as the average thickness of A68a which includes



239 13.0±2.0 m meter firn air and 182.5±19.2 m pure ice and using the ice and air density in  
240 Eqn. (3), the total mass of iceberg A68a was 642.2±69.0 Gt (1Gt=10<sup>9</sup> t).

241

### 242 **3.7 Grounding Detection of Iceberg A68a**

243 The method for grounding detection introduced by Wang et al. (2016) is adopted in this  
244 study. It is also assumed that the iceberg is floating first, and compare the ice draft  
245 inverted from the freeboard with seafloor topography. The region with ice draft lower  
246 than seafloor bathymetry indicates grounding (negative comparison result in Fig. 6b-c).  
247 A large negative value indicates a heavily grounding section of an iceberg. This process  
248 is performed by following Eqns. (6) and (7)

249  $D = E_d - E_b$  (6)

250  $E_d = T - F$  (7)

251  $E_d$  and  $E_b$  are the elevations of ice draft and seafloor bathymetry respectively.  $D$  is the  
252 elevation difference of ice drift and seafloor bathymetry.

253

254 Insert Figure 6 here

255

### 256 **3.8 Ua modeling Setting of Iceberg A68a collision with Seamount**

257 Ice tends to fracture under critical tensile stresses forming rifts along which ice breakup  
258 occurs. In this study, a 2d shallow-ice-shelf approximation glacier model  $Ua$   
259 (Gudmundsson. 2008, 2012, 2013) is employed to investigate the deviatoric stresses  
260 when iceberg A68a interacts with seafloor shoals. Because A68a was drifting and



261 rotating before colliding with the sea mountain, the drifting and angular velocity of A68a  
262 must be inverted first by exerting an appropriate drag force on the iceberg in  $U_a$ .

263 Since the drifting of large icebergs (length>10 km) is primarily affected by ocean  
264 currents (Wagner et al. 2017), it is assumed that the drifting and rotating of A68a was a  
265 consequence of ocean currents only. In  $U_a$ , the ocean drag term is applied by following  
266 Eqn. (8)

$$267 \quad t = (1 - \mathcal{G}) C_o^{-\frac{1}{m_o}} (v_b - v_o)^{\frac{1}{m_o} - 1} \overrightarrow{(v_b - v_o)} \quad (8)$$

268 where  $t$  stands for ocean drag,  $\mathcal{G}$  floating/grounding mask of the iceberg. The drag  
269 coefficient is indicated with  $C_o^{-\frac{1}{m_o}}$ , where  $v_o$  and  $v_b$  stand for ocean current and basal ice  
270 velocity, respectively.

271 In  $U_a$ , the freeboard and thickness extracted from Section 3.3 and 3.5 was used to  
272 configure the surface (32.5 m) and bottom (-163.0 m) elevation of iceberg A68a. The  
273 seafloor bathymetry was input to set the lower boundary for ice-seafloor interaction  
274 modeling. The temperature of iceberg was set as -20 °C. The parameter A and n in  
275 Glen flow law was set as  $2.9377 \times 10^{-9}$  and 3 respectively. Surface and basal mass  
276 balance of the iceberg when interacting with the seafloor was set as 0 and neglected.  
277 Since the drifting of large icebergs (i.e., length >10 km) is primarily affected by ocean  
278 currents (Wagner et al. 2017), an appropriate ocean drag parameterization is of critical  
279 importance in  $U_a$ . The ocean drag coefficient  $C_0$  was set as  $0.4 \times 10^4$  (See section 5.1 for  
280 more details of this setting). A tuning choice reproduces the observed drifting and  
281 rotation speed of A68a before seamount impact. The drifting velocity of the iceberg in x



282 and  $y$  direction was set as 24.5 cm/s and -3.0 cm/s respectively. The rotational velocity  
283 of the iceberg was set as  $15.1^\circ/d$ . It allows investigation of the deviatoric stresses  
284 exerted on the iceberg during seamount grounding. It implicitly assumes that the  
285 iceberg is rigid during the simulated seamount interaction. No calving law is applied.  
286 The air drag was not considered in the ice-seafloor interaction modeling. Detailed  
287 setting of ice-seafloor interaction modeling in  $U_a$  can be found from Table 1.

288

289 Insert Table 1 here

290

## 291 **4. Results**

### 292 **4.1 Life History of A68a**

293 After the birth of A68a, it drifted north and finally disappeared in the Southern Ocean in  
294 May 2021 (Fig. 3, 2a-2d). The drifting trajectory and areal changes of A68a from remote  
295 sensing (Fig. 3a, 3c) indicate that iceberg A68a has lasted almost four years, from July  
296 2017 to May 2021. The maximum latitude A68a reached was 52 °S (Fig. 3a, and Fig.  
297 2a-2d). A68a experienced six major breakup events (Fig. 1). The total areal ice loss in  
298 generating nascent icebergs during these breakups was  $> 2000 \text{ km}^2$  (Fig. 3c), more  
299 than a third of the original iceberg A68a. This suggests that the decimation of a large  
300 tabular iceberg in Antarctica occurs through a sequence of breakups.

301

302 The lifespan of A68a shows three different areal-losing rates (Fig. 3c) during its  
303 evolution, which are  $-156 \text{ km}^2/\text{a}$ ,  $-1204 \text{ km}^2/\text{a}$ , and  $-11,990 \text{ km}^2/\text{a}$ , sequentially. The  
304 increasing areal-losing rates demarcate three distinct evolutionary periods of this well-



305 documented, large tabular iceberg adrift in the Southern Ocean. The ratio of areal-  
306 losing rates for three different phases is approximately 1:8:80, which signals that once  
307 an iceberg has arrived at the third phase, it is well on its way to rapidly vanishing into  
308 the surrounding ocean. The survival time ratios of 6:2:1 and total ice loss ratios of  
309 1:3:11 of the three different phases combine to indicate that the rate and volume of ice  
310 loss of the A68a iceberg accelerate over time.

311

312 A major breakup event ensued when A68a eventually drifted to South Georgia Island,  
313 and A68a gave birth to another iceberg, A68d (Fig. 1c, and 3b). Moderate Resolution  
314 Imaging Spectroradiometer (MODIS) data show that the breakup event occurred on  
315 December 16-17, 2020 (Fig 2e, 2f). Sentinel-1A/B synthetic aperture radar data reveals  
316 that after the breakup, A68a decreased to  $\sim 3582 \pm 8$  km<sup>2</sup>, and the area of A68d was  
317  $147 \pm 1$  km<sup>2</sup> (Fig. 3c). Using satellite observations from MODIS, Sentinel-1A/B, and  
318 adding in Cryosat-2 radar altimeter data (Fig. 4) the bulk properties of A68a were  
319 established during December 15-16, 2020. At that moment, it was  $\sim 195 \pm 19$  m thick,  
320 weighed some  $\sim 642 \pm 69$  Gt, drifted at a speed of  $24 \pm 2$  cm/s, and rotated with an angular  
321 velocity of  $\sim 15 \pm 2$ °/d, clockwise. Furthermore, the drifting speed during the previous two  
322 days, December 15-16, 2020, did not change much from the days preceding them,  
323 December 13-15, 2020 (Table. S7). This indicates the sizeable tabular iceberg had  
324 large inertia to sustain a relatively constant motion.

325

## 326 **4.2 Seafloor Grounding**



327 Bathymetric data illustrates that in the vicinity of South Georgia Island, there is a  
328 seamount with a subsea elevation rising from about -250 m to the surface (Fig. 3b, 6a).  
329 MODIS geospatial data (Fig. 2e, 6a) shows that A68a hovered over part of the  
330 seamount on December 16, 2020. The grounding status of A68a at this juncture in time  
331 has been assessed by assuming hydrostatic equilibrium, employing firn-layer thickness  
332 (Holland et al. 2011) and ice thickness inverted from remote sensing. The result  
333 indicates  $> 3 \text{ km}^2$  of the iceberg (18 pixels) was grounded on the seamount (Fig. 6b and  
334 6c). At its most severely grounded point, the iceberg was estimated to be lifted about  
335 30 m out of floatation. Grounding on the seamount resulted in a sudden basal drag on  
336 the rapidly drifting and rotating iceberg. A seafloor drag's abrupt appearance  
337 dramatically altered the dominant balance of forces of the wind and currents and the  
338 iceberg's internal stresses.

339

340 To visualize the rift along which A68a calved during December 16-17, 2020, boundary  
341 outlines of A68a and A68d, extracted from Sentinel-1A on December 21, are  
342 georeferenced to MODIS data on December 16 by matching ground control points (Fig  
343 5d and 5e). The georeferenced icebergs reflect two rifts (named Rift 1, Rift2) on  
344 December 16 (Fig. 5e and 6a). During the breakup event, a region formed between the  
345 two rifts, and about  $2 \text{ km}^2$  was lost. The timing of the breakup, as seen from remote  
346 sensing, suggests this modest loss was a contributing factor in the more significant  
347 breakup. Coincidentally, analysis reveals that Rift 1 was overlaying the most severely  
348 grounded region (Fig. 6a and 6e), which suggests that the area is critical to the breakup  
349 of A68a.



### 350 **4.3 Maximum Tensile Stress for Iceberg-Seafloor Interactions**

351 Using the standard  $Ua$  parameter settings (Table. 1), the basal ice speed, ice surface  
352 elevation, and deviatoric stresses exerted on A68a are simulated in Fig. 7a-d.  
353 Examining rifts extracted from remote sensing, the maximum surface elevation of A68a  
354 is observed to be located on Rift 1. Furthermore, the simulation indicates that the  
355 maximum tensile stresses appear over grounded regions, and the location of maximum  
356 tensile stresses is on Rift 1 (within <200 m, Fig. 7b-c). The rift observed from remote  
357 sensing crosses the simulated location of maximum tensile stresses exerted on iceberg  
358 A68a which support the theory from (Benn et al. 2007) that the tensile cracks tend to  
359 occur perpendicular to the maximum tensile stresses.

360

361 Insert Figure 7 here

362

## 363 **5. Discussion**

### 364 **5.1 Ocean Drag Coefficient in $Ua$**

365 The drag coefficient is set differently for iceberg and sea-ice studies (Bigg et al 1997;  
366 Flato & Hibler 1992). Since  $Ua$  is a two-dimension glacier model and external forces  
367 exerted on the sidewall of an iceberg are not considered, we assume an iceberg is a  
368 thick piece of sea ice and only consider the basal drag applied to the iceberg in this  
369 study. Flato and Hibler (1992) suggested the ocean drag coefficient was 0.0055 and the  
370 ocean drag was quadratic to ocean current velocity, from which one can get the  
371 following settings:  $m_o = 0.5$ ,  $C_o = 0.4$  (unit:  $\sqrt{(m/s)/Pa}$ ).



372 Without considering the ocean drag force, the basal ice velocity and deviatoric stresses  
373 of A68a from diagnostic runs is shown in Fig. 8a and 8e. Uniform deviatoric stresses are  
374 shown inside of the iceberg and no abnormally large stresses occur at the boundary of  
375 A68a. However, after applying ocean drags and zero ocean currents in  $U_a$ , enlarged  
376 deviatoric stresses are found at boundary nodes when the ocean current is set as zero  
377 (Fig. 8b-8d, 8f-8h). This result indicates that the setting about  $C_o=0.4$  is not appropriate  
378 because no significant drag at the boundary would occur when putting an iceberg in a  
379 still ocean. The variation of maximum deviatoric tensile stresses exerted on A68a is  
380 shown in Fig. 8 when is set to various values.

381

382 Insert Figure 8 here

383

384 Without more observation data related to iceberg drifting, it is difficult to determine the  
385 values of  $C_o$  accurately. However, Fig. 8i indicate that smaller setting of  $C_o$  leads to  
386 larger stresses ocean drag exerted iceberg and larger tensile stresses at the boundary  
387 of the iceberg. When  $C_o > 0.4 \times 10^4$ , the maximum tensile stresses exerted on A68a in  
388 the still ocean is approaching that from diagnostic runs without applying ocean drags.  
389 Based on this,  $C_o=0.4 \times 10^4$  is assessed as an appropriate setting since neither  
390 significant direction change of deviatoric forces occurred inside of the iceberg A68a, nor  
391 large tensile stresses at the boundary.

392 **5.2 Relation of Maximum Tensile Stress With Grounding, Drifting and**  
393 **Rotating Status**



394 The *Ua* glacier model is used to investigate further the relationship of maximum tensile  
395 stresses to grounding, drifting, and rotation of A68a. As a sensitivity experiment, the  
396 model seamount is lowered by 50 m so that iceberg A68a experiences no drag in the  
397 vicinity of the seamount. Tensile stresses no more significant than 0.1 MPa are  
398 simulated inside the iceberg (Fig. 9). In the next experiment, restoring the seamount to  
399 its observed height, with A68a drifting with a speed consistent with observations from  
400 remote sensing but with no rotation, the maximum tensile stress jumps to 9 MPa over  
401 the grounding region (Fig. 7d). An increase of almost a factor of one hundred. When  
402 further incorporating the rotation of A68a, the maximum tensile stress increases to 10  
403 MPa (Fig. 7d), a further twenty percent increase. These sensitivity experiments  
404 demonstrate that grounding a rapidly drifting and rotating iceberg on a seafloor shoal  
405 leads to significant tensile stresses inside the iceberg. Since icebergs tend to fracture  
406 under significant tensile stresses, and the rifts from remote sensing and maximum  
407 tensile stresses from glacier modeling coincide, it is concluded that substantial tensile  
408 stresses associated with grounding triggered the breakup of A68a.

409

410 Insert Figure 9 here

411

412 Modeling results indicate that grounding only A68a on the seamount, with no motion,  
413 would generate maximum tensile stress < 0.2 MPa, even considering seafloor changes  
414 by  $\pm 20$  m. However, the maximum tensile stress increases to about seventy times when  
415 additionally applying half of the drifting speed observed from remote sensing, reaching  
416 eighty times than grounding only when full drifting speed is simulated. Simulations



417 suggested that larger tensile stresses could occur in A68a when further raising the  
418 seafloor, thus simulating more severe grounding. When lowering the seafloor by 20 m  
419 (other settings the same as Table 1), the maximum tensile stress was about 6.0 MPa.  
420 When raising the seafloor by 20 m, the maximum tensile stresses experienced by A68a  
421 increased to > 20 MPa. This confirms that grounding an iceberg with a considerable  
422 drifting speed generates significant tensile stresses inside the grounded section of the  
423 iceberg. Less obvious, perhaps, more severe grounding non-linearly increases the  
424 maximum tensile stresses.

425

426 The rotation of the iceberg is another factor influencing the maximum tensile stresses.  
427 When iceberg A68a is simulated to rotate as observed by remote sensing data (15.1°/d,  
428 clockwise direction, other settings the same as Table 1), a maximum tensile stress > 10  
429 MPa appears over the grounding region of A68a. Modeling results indicate that for the  
430 same seafloor bathymetry, more significant angular velocity exerts more considerable  
431 tensile stresses on A68a. Using all data from different grounding statuses of A68a, the  
432 maximum tensile stresses increase by about 10, 20, and 30 percent when additional  
433 angular velocity at 8 °/d, 15°/d, and 23°/d are applied. In short, rotation enlarged the  
434 maximum tensile stresses experienced in A68a by about twenty percent, contributing to  
435 the breakup during December 16-17, 2020.

436

437 **5.3 How Polar Cyclone and Ocean Tide Contributing to Breakup of**  
438 **A68a**



439 As mentioned, the drifting of large tabular icebergs (>10 km) is primarily driven by ocean  
440 currents (Wagner et al. 2017). The currents derived from monthly averaged (December)  
441 ECCO V4r4 data (Wunsch et al. 2009) over the region of A68a is shown in Fig 10a.  
442 Historical ocean current data indicate a constant eastward flow (Fig. 10a and Supp.  
443 Animation 1), which can help to explain the primary eastward drifting of A68a towards  
444 the seamount. The average of 10-meter U and V wind components from ERA5  
445 (Hersbach et al. 2020) during December 1-16, 2020 over A68a, which was captured by  
446 MODIS at 12:45 UTC on December 16 (white polygon) in shown in Fig.10b. The  
447 average west wind extracted from the reanalysis data, supports the eastward drifting  
448 A68a. When A68a drifts to the vicinity of South Georgia Island, sea surface changes  
449 associated with atmospheric pressure changes and ocean tide could alter the  
450 interaction of A68a with the seamount, effectively lifting the iceberg over the seamount  
451 to some extent.

452

453 Insert Figure 10 here

454

455 The tide height changes during December 15-17 from CATS2008 (Padman et al. 2002)  
456 (Fig. 10e) indicate that the sea surface height change caused by the tide around iceberg  
457 A68a reached > 1 m. The surface elevation change by tides may facilitate A68a to  
458 reach higher seafloor shoals during high tide and further cause iceberg A68a to be  
459 grounded more during low tide when it is lowered and dropped back onto the shoals.  
460 ERA5 data show that during December 15-17, 2020, a polar cyclone passed by A68a  
461 (Fig. 10c-d, and Supp. Animation 2-3). The pressure in Fig. 10e is calculated by



462 averaging over the region from Latitude: -55° to -56°, to longitude: -37.25° to -37.75°  
463 (iceberg location seen in Fig. 10b) and is indicated with blue curves. This region's  
464 standard deviation of pressure is used as the error bar. When the polar cyclone moved  
465 close to A68a, the mean sea level pressure dropped about 30 hPa (Fig. 10e), which  
466 could significantly raise the sea surface by approximately 0.3 m (Fig. 10f) and facilitate  
467 A68a climbing up to a higher region of the seamount.

468

469 Fig. 10e also show the tidal height predictions derived from the tide model CATS2008.  
470 The curves marked with asterisks and circles show the tide-height prediction from the  
471 northern (37.371° W, 54.979° S) and southern (37.548° W, 56.106° S) tips of A68a,  
472 respectively. The red star indicates the minimum tidal height at the major breakup  
473 event. Fig. 10f shows the total sea surface change from tide and cyclone effects. Before  
474 MODIS observation on December 16, a peak sea surface elevation occurs, one can  
475 assist A68a in a climb up to the most elevated location on the seamount. After the  
476 MODIS observation, the most significant sea surface drop occurred almost a day later  
477 (Fig. 10e, f), when A68a would ground most severely on the seamount, effectively  
478 shipwrecked. The red star indicates the minimum sea surface from pressure and tide  
479 changes at the major breakup event. The vertical blue, red, and green dashed lines in  
480 Fig. 10e, and f give the observation time of the Sentinel-1 image on December 15, and  
481 MODIS observation on December 16 and 17, respectively. Since larger tensile stresses  
482 tend to occur at more severe grounding icebergs, iceberg A68a most likely broke up at  
483 that time (17:00 UTC on December 16).

484



485 **6. Conclusion**

486 Large tabular icebergs experience breakup while drifting in the ocean, ultimately melting  
487 and vanishing into the ocean, the destiny of all icebergs. The breakup generates many  
488 smaller icebergs and increases the area for iceberg-ocean interaction, speeding up the  
489 iceberg melting. Seafloor shoals, such as a seamount, lead to iceberg grounding and  
490 are a barrier to iceberg drift. When an iceberg drifts toward a seafloor shoal with a  
491 relatively large speed, if the seafloor is higher than the iceberg draft, a grounding event  
492 occurs, even despite an iceberg having a large mass and inertia to maintain its speed.  
493 Grounding of rapidly drifting and rotating icebergs tends to create significant deviatoric  
494 stresses inside an iceberg, which may trigger the formation of rifts and facilitate iceberg  
495 breakup.

496

497 For an iceberg that drifts towards a seafloor shoal, the sea surface change caused by a  
498 rising tide and weather events, such as a polar cyclone, may make the iceberg drift to a  
499 higher region of the seafloor shoal. After the passing of a polar cyclone and during low  
500 tide, a follow-on significant sea surface drop can make iceberg grounding more severe  
501 on the seafloor shoal, generating even more enormous tensile stresses in the iceberg  
502 and facilitating the breakup of the iceberg across the maximum tensile stress point.

503

504 The later, rapid vanishing of iceberg A68a into the ocean is fully explained by the  
505 breakup event that occurred on December 16, 2020, caused by the collision of A68a  
506 with a seamount. We demonstrate the first successful case of using a large tabular  
507 iceberg as a natural laboratory, with remote sensing observations as a data source and



508 a glacier model as a tool to investigate iceberg calving, expanding glacier-seafloor  
509 interaction research. Looking to the future, the possibility of a collapse of the marine-  
510 based-portions of the great ice sheets has been raised. The concomitant rapid dispersal  
511 of numerous icebergs into the ocean would influence local ocean circulation and local  
512 atmosphere temperature by providing freshwater input into the ocean surface, affecting  
513 the ocean-mixed layer regime, vertical convection, and the surface albedo. As  
514 demonstrated in this study, understanding the trajectory of such icebergs and their  
515 breakup mechanism will contribute to better forecasting an iceberg's fate and the state  
516 of the polar oceans.

517



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526



527 **Data availability**

528 Sentinel-1A/B data are downloaded from Copernicus Open Access Hub  
529 (<https://scihub.copernicus.eu/>). MODIS data are downloaded from Level-1 and  
530 Atmosphere Archive & Distribution System Distributed Active Archive Center  
531 (<https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/modis/>).  
532 Cryosat-2 GRD data are downloaded from Earth Online, European Space Agency  
533 (<https://earth.esa.int/eogateway/catalog/cryosat-products>). Seafloor Bathymetry data  
534 are obtained from the General Bathymetric Chart of the Oceans (GEBCO)  
535 (doi:10.5285/a29c5465-b138-234d-e053-6c86abc040b9) . The trajectory of A68a from  
536 2017 to July 2019 is downloaded from The Antarctic Iceberg Tracking Database  
537 (<https://www.scp.byu.edu/iceberg/>). CATS2008 model is obtained from Earth & Space  
538 Research (<https://www.esr.org/research/polar-tide-models/list-of-polar-tide-models/cats2008/>). ERA5 data are obtained from ECMWF  
539 (<https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5>). ECCO V4r4  
540 monthly averaged ocean current data are obtained from NASA Estimating the  
541 Circulation and Climate of the Ocean (<https://www.ecco-group.org/products-ECCO-V4r4.htm>). The location and area of A68a extracted from remote sensing data and the  
543 ground control points for breakup line extraction can be found in Supp. Material.  
544

545 **Glacier modeling code availability**

546 *Ua* glacier model is available on Github (<https://github.com/GHilmarG/UaSource>). The  
547 code associated with glacier modeling using *Ua* is available on request from X. Wang.

548



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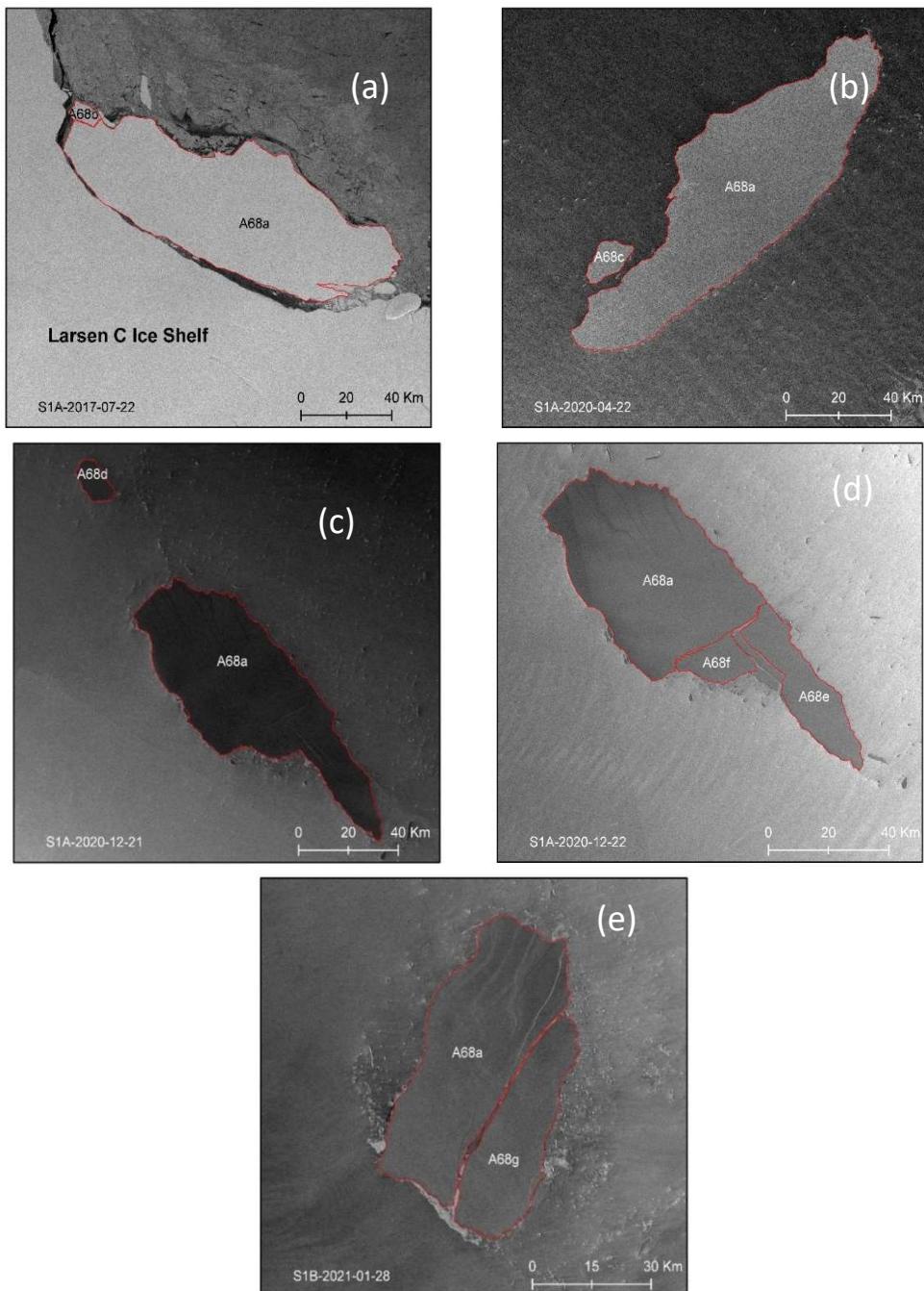


**Table 1. Parameters used to configure the control run of Ua glacier model.**

Parameters	Setting
Iceberg Density (Considering firn layer thickness)	857 kg/m <sup>3</sup>
Ocean Density	1028 kg/m <sup>3</sup>
Iceberg Freeboard	32.5 m
Iceberg Draft	163.0 m
Iceberg Temperature	-20 °C
A-Glen Law	$2.9377 \times 10^{-9}$
n-Glen Law	3
Surface Mass Balance	0 m/a
Basal Mass Balance	0 m/a
Ocean Drag Coefficient (Co in Ua)	$0.4 \times 10^4 \sqrt{(m/s)/Pa}$
$m_o$ in Ua	0.5
U of ocean current	24.5 cm/s
V of ocean current	-3.0 cm/s
Angular Velocity	$15.1^\circ/d$
Air Drag Coefficient (Ca in Ua)	$> 1 \times 10^{10}$ (close to $+\infty$ )
$m_a$ in Ua	0.5

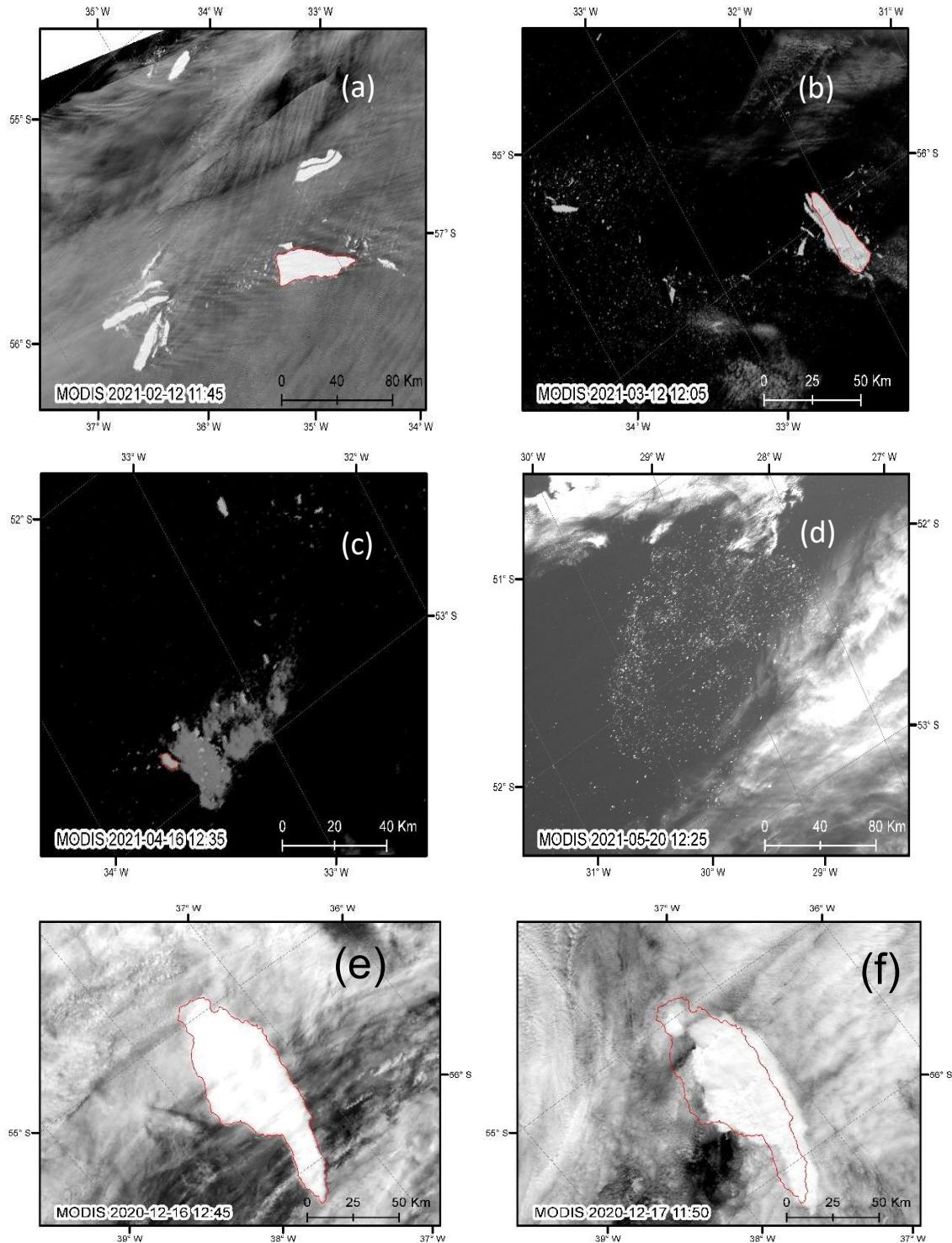


**Figure 1. (a) to (e)** show sequential snapshots of the major breakup events of Iceberg A68a spanning the period 2017 to 2021. The exact observation date of each of the Sentinel-1A/B images is marked in the lower left. The icebergs generated after the breakup and the main body of iceberg A68a are marked.



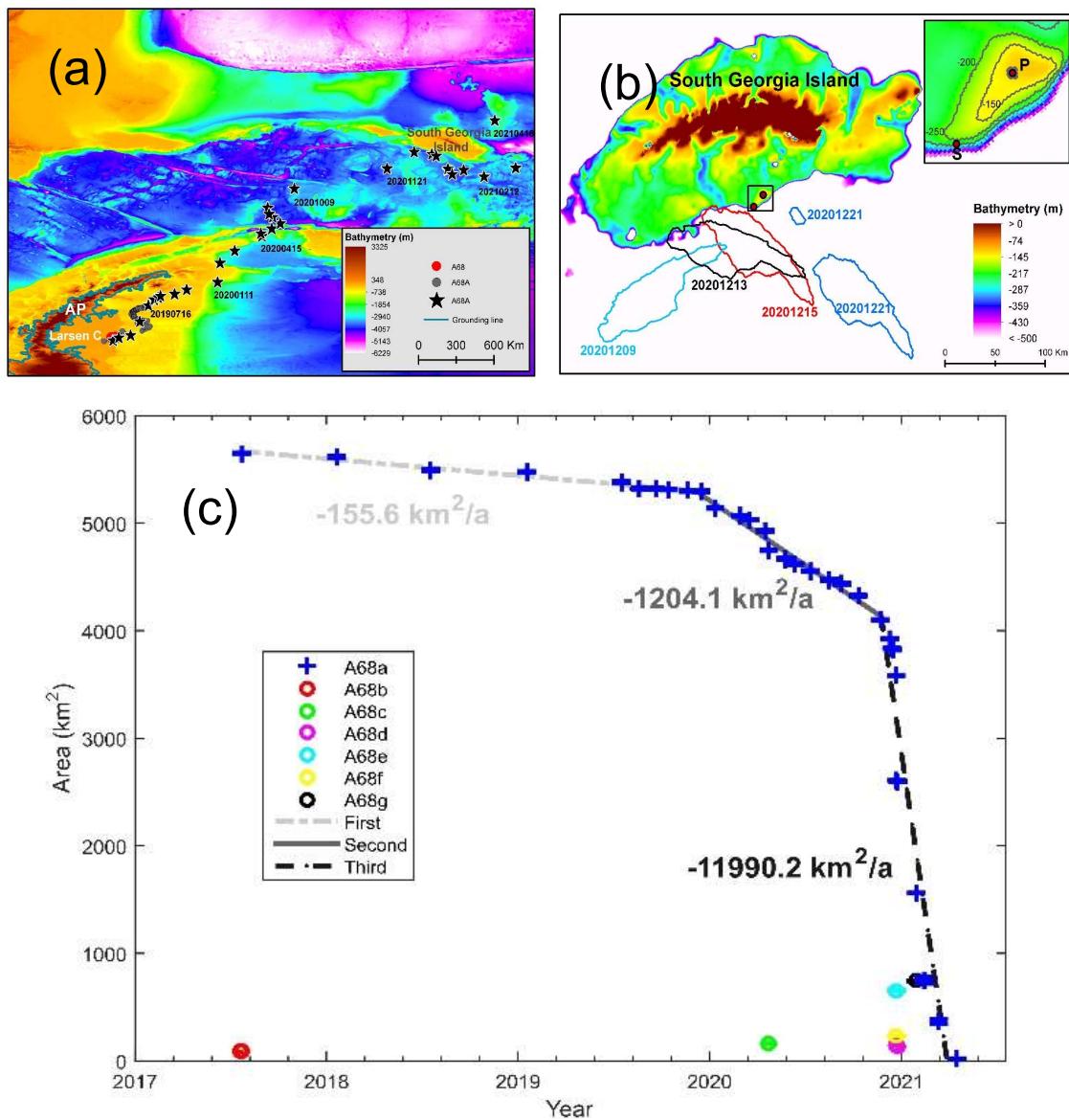


**Figure 2.** (a) to (d) shows sequential locations, outlines, breakup, and vanishing of A68a during 2021. The exact observation date of each of the MODIS images is marked in the lower left. (e) Location of A68a at 12:45 UTC on December 16, 2020, (MODIS). The outline of A68a is indicated with red polygon. (f) State of the A68a breakup at 11:50 UTC on December 17, 2020 (MODIS). The red outline is taken from (e).



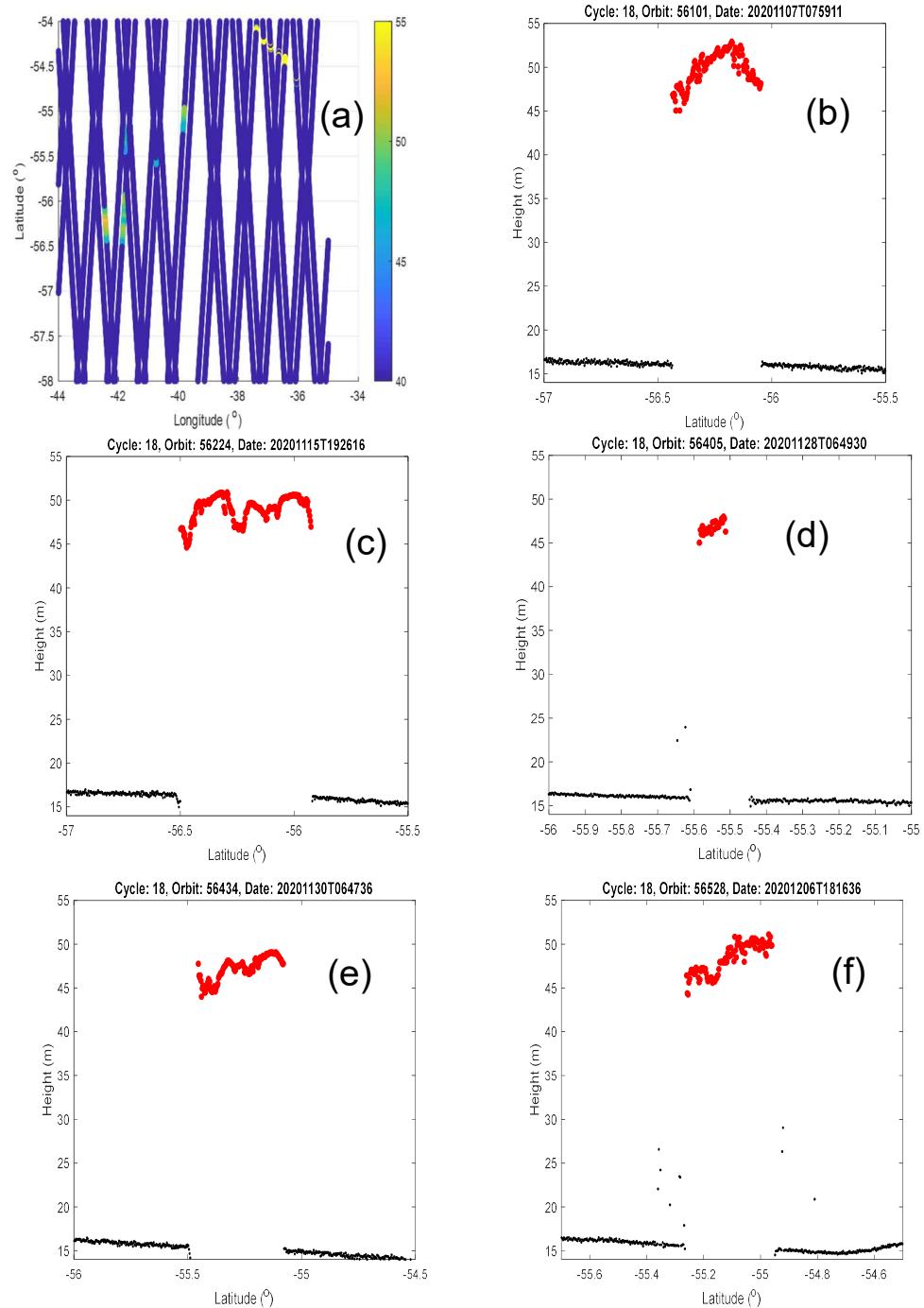


**Figure 3.** Drifting trajectory, areal changes, the major breakup, the appearance of rift lines, and the vanishing of iceberg A68a. **(a)** Drifting trajectory of A68a following its calving from Larsen C Ice Shelf in July 2017. **(b)** Outline and location of A68a before and after a breakup event in mid-December 2020. **(c)** Areal changes of A68a from calving to vanishing (left to right) as blue plus signs.



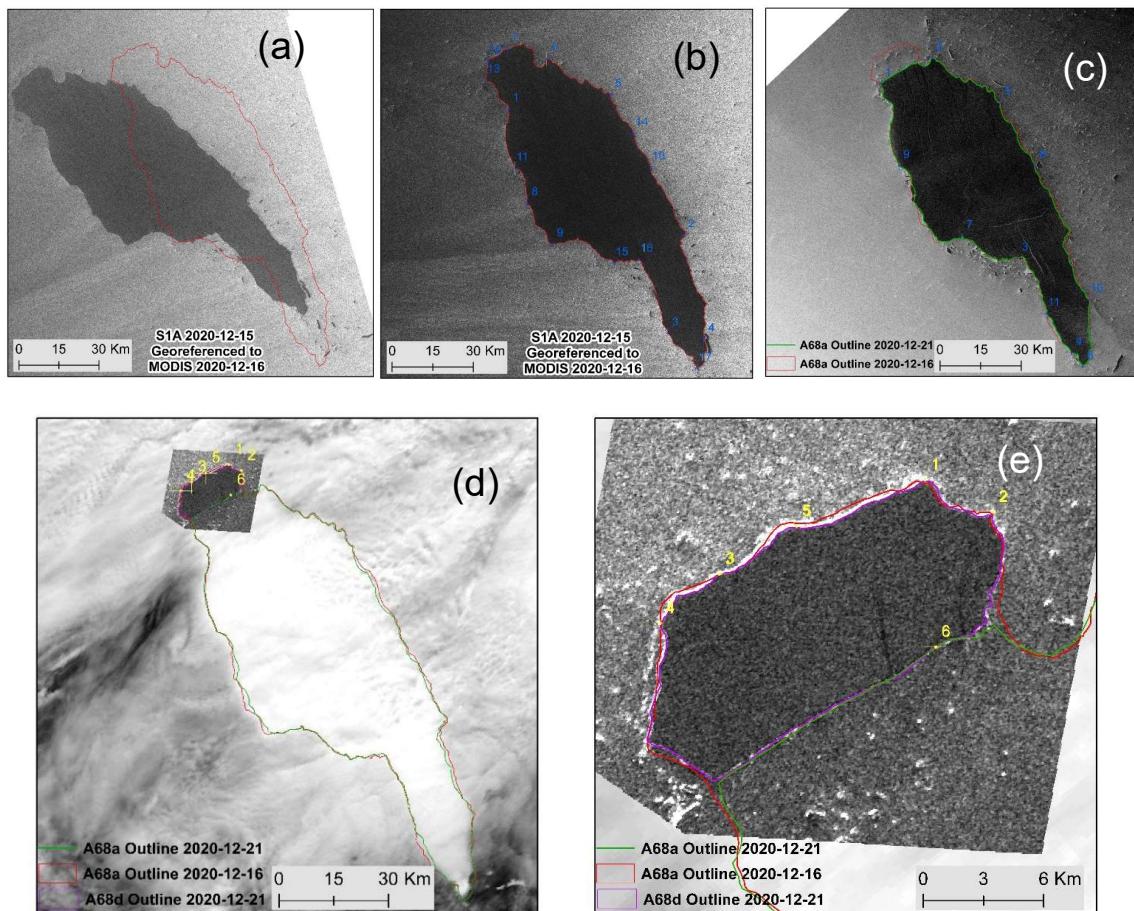


**Figure 4. (a)** ground tracks of Cryosat-2 from November 1 to December 16, 2020, in the vicinity of South Georgia Island used to extract the freeboard of iceberg A68a. The freeboard height distribution ranging from 40 m to 55 m (relative to a geoid) is indicated by blue to yellow. Yellow dots in the upper-right indicates the presence of South Georgia Island. **(b) to (f)** mark tracks of Cryosat-2 used in detecting iceberg A68a. The cycle, orbit, and observation date are given in the heading of each panel. Red dots indicate measurements over the surface of iceberg A68a; black dots indicate the sea surface.



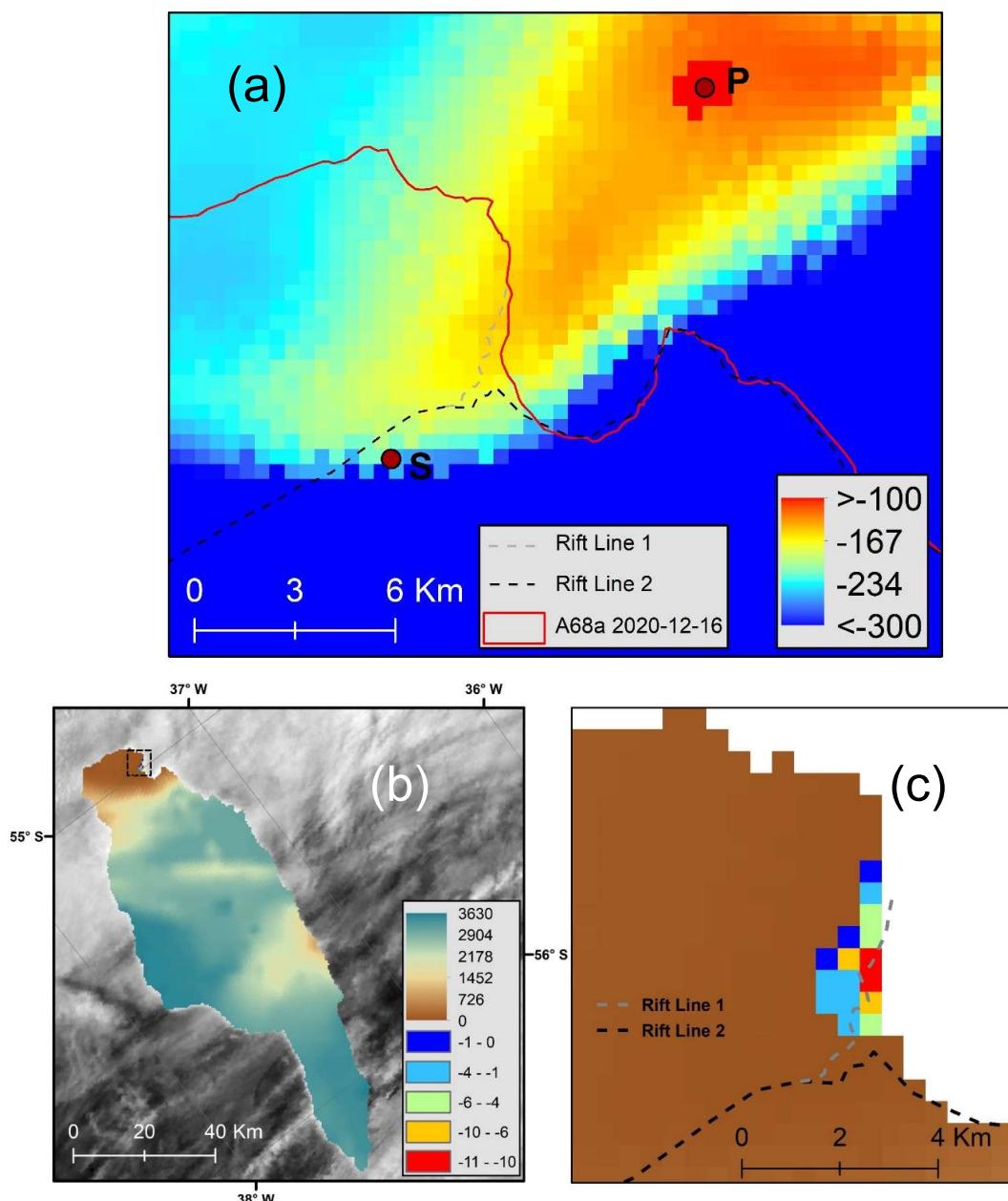


**Figure 5.** Breakup line extraction procedure. **(a)** Sentinel-1A observation on December 15, 2020, and an outline of iceberg A68a from MODIS on December 16 (red polygon). **(b)** to **(d)** show the georeferencing of Sentinel-1A observations on December 15, 21, and again 21 to the A68a location on December 16, respectively. **(e)** zoom-in of the upper part of **(d)** from which two different breakup lines are extracted.



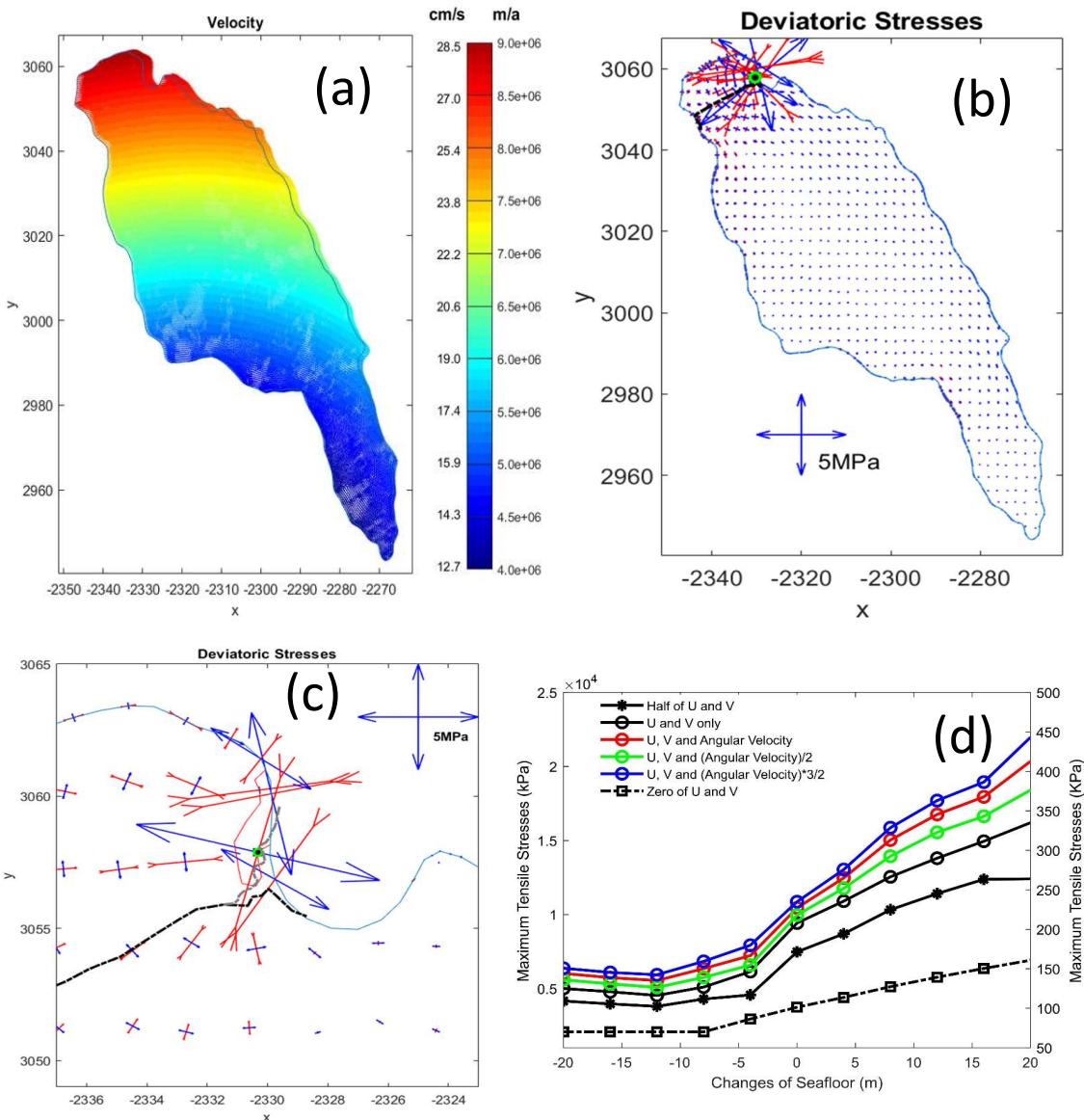


**Figure 6.** Grounding of A68a on seamount of the South Georgia Island. **(a)** Two rifts seen on December 16, 2020 (MODIS). The rift contour is extracted from Figure 5. **(b)** Grounding detection of A68a at 12:45 UTC on December 16, 2020 (MODIS). Negative values indicate grounded regions of A68a. **(c)** Zoom-in of the black box marked in **(b)**. Two rift lines are indicated with dashed curves (grey, black).



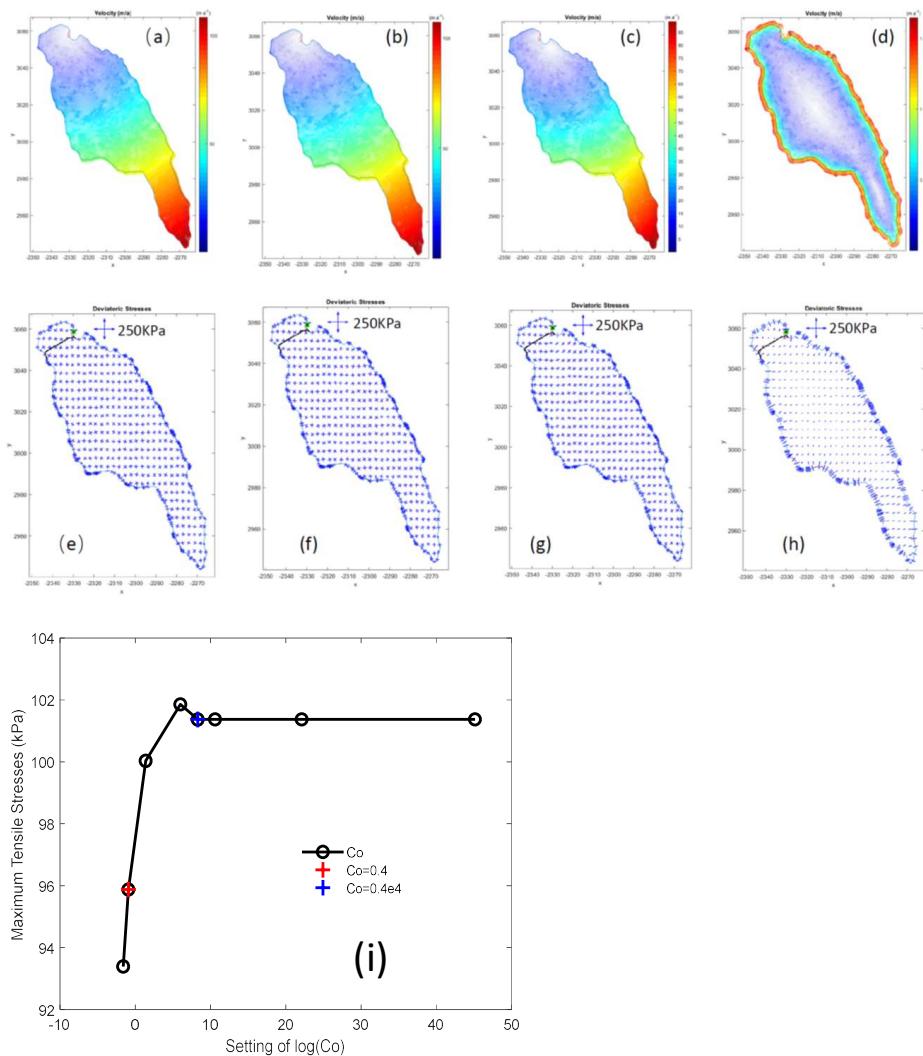


**Figure 7.** Modeling the interaction of iceberg A68a and the seafloor using  $U_a$ . **(a)** Basal ice velocity of A68a inverted from  $U_a$ , **(b)** Deviatoric stresses of A68a inverted from  $U_a$ . Red vectors are tensile; blue vectors are compressive. The maximum tensile stress is indicated with a green dot. **(c)** Zoom-in of deviatoric stresses on the grounded region of A68a. **(d)** Changes in maximum tensile stress of A68a under different settings of seafloor depth and iceberg angular velocity. Values along the x-axis stand for changes in seafloor bathymetry.  $U$ ,  $V$ , and angular velocity base values are derived from remote sensing, which are equal to 24.5 cm/s, -3.0 cm/s, and 15.1 °/d, respectively. Other model parameter settings are as listed Table 1. Maximum tensile stress (black-dashed line) for zero of  $U$  and  $V$  corresponds to the small stress values as indicated by the y-axis on the right side. Stresses for other non-zero  $U$  and  $V$  correspond to the large stress values of the y-axis on the left side.



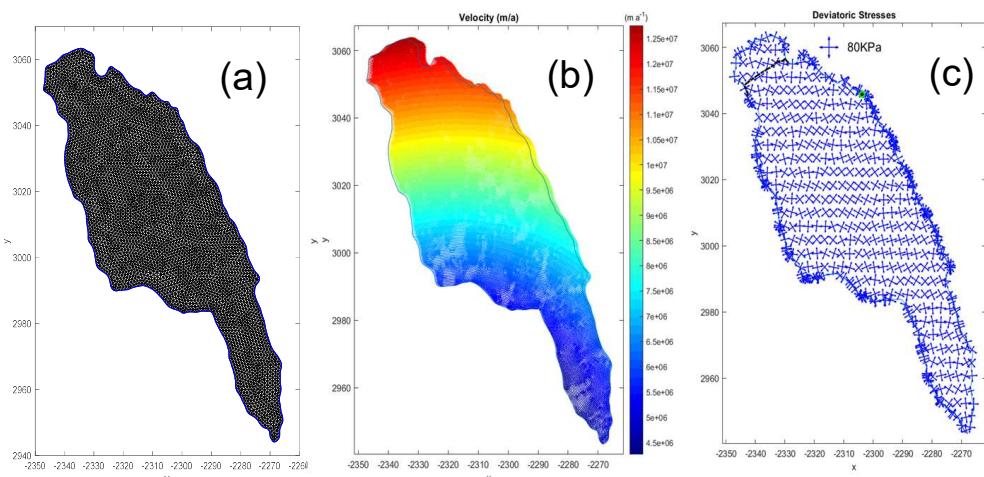


**Figure 8.** (a) to (d) basal ice velocity of A68a inverted from  $U_a$  when setting ocean-ice coefficient of drag  $C_o$  as  $0.4e5$ ,  $0.4e4$ ,  $0.4e3$ , and  $0.4$ , respectively (motionless ocean). (e) to (h) corresponding deviatoric stresses of A68a inverted from  $U_a$  when setting  $C_o$  as  $0.4e5$ ,  $0.4e4$ ,  $0.4e3$ , and  $0.4$ , respectively (motionless ocean). The location of maximum tensile stress is marked with a green dot. (i) shows the maximum tensile stress changes of A68a with  $C_o$  in the still ocean. More can be found from Supplementary Material.



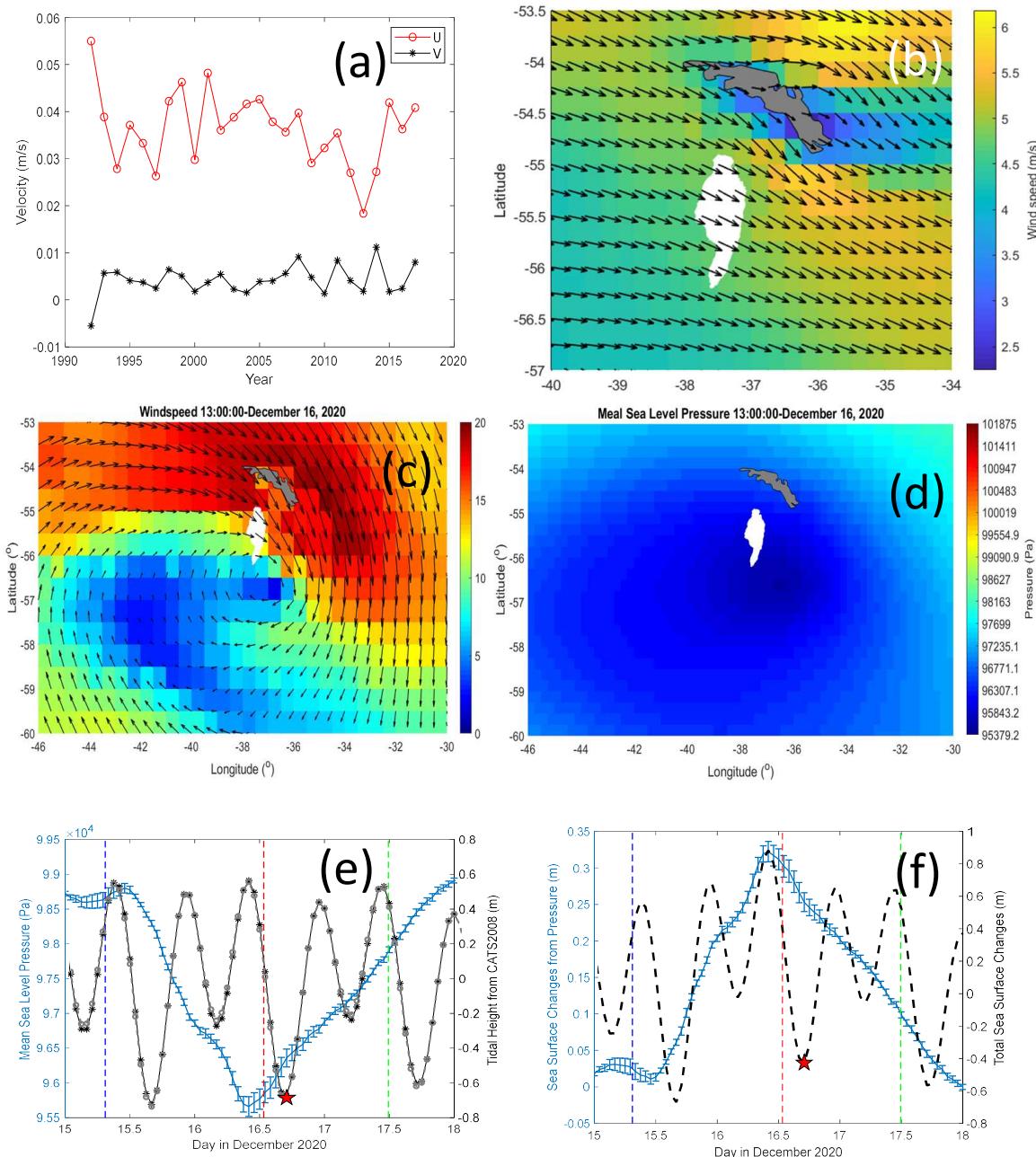


**Figure 9.** Sensitivity experiment in which the seafloor is lowered by 50 m, but other parameter settings are the same as in Extended Table 1c. **(a)** mesh grid of iceberg A68a as used in *Ua* modeling. **(b)** basal ice velocity of A68a inverted from *Ua*. **(c)** deviatoric stresses of A68a with the maximum tensile stress, marked by a green circle, showing a remarkably low value of 70 KPa.





**Figure 10.** Ocean and atmosphere influences near A68a. **(a)** Historical ocean current patterns (m/s) from 1992 to 2017. **(b)** Hourly-averaged wind speed (m/s) around South Georgia Island (grey polygon). **(c)** Wind speed and direction at 13:00 UTC on December 16, 2020, during an intense polar cyclone during the time of the breakup. (ERA-5 data synchronized with MODIS observation) . **(d)** Sea-level pressure during the intense polar cyclone, 13:00 UTC, December 16, 2020. **(e)** Mean sea-level pressure change and tidal height changes in the region of A68a. **(f)** Sea surface change (m) caused by pressure change (y-axis left side) and total sea surface change (m) from tide and pressure changes (y-axis right side)..





**Competing Interests:**

The authors declare that they have no conflict of interest.