



Collision with Seamount Triggers Breakup of Antarctic Iceberg

1

2

3

4 Xianwei Wang^{1, 2, 3*}, G. Hilmar Gudmundsson⁴ and David M. Holland^{2, 5}

5

6 1. School of Oceanography, Shanghai Jiao Tong University, Shanghai, China

7 2. Center for Global Sea Level Change, New York University Abu Dhabi. Abu Dhabi, United Arab

8 Emirates.

9 3. Key Laboratory of Polar Ecosystem and Climate Change (Shanghai Jiao Tong University), Ministry of

10 Education, Shanghai 200030, China.

11 4. Department of Geography and Environmental Sciences, Northumbria University, Newcastle, UK.

12 5. Courant Institute of Mathematical Sciences, New York University. New York 10012, United States of

13 America.

14

15 *Correspondence: xianwei.wang@sjtu.edu.cn

16

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-Folgmann et al., 2022).
61 Further combining altimetry measurements, vertical changes of tabular icebergs can be
62 accurately quantified (Braakmann-Folgmann 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-Folgmann 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 firm 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 'yyyymmdd' 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 km^2/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.

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

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

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 ± 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.



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

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

$$T = I + A \quad (4)$$

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
seawater, pure ice, and englacial air respectively (taken from Holland et al. 2011). T , I
and A is the thickness of the iceberg, pure ice, and air layer respectively (in this study,
 $A=13.0\pm2.0 \text{ m}$).

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

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

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

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

3.6 Mass of Iceberg A68a before Breakup

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



239 13.0±2.0 m meter firm 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=10⁹ 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)

$$249 \quad D = E_d - E_b \quad (6)$$

$$250 \quad E_d = T - F \quad (7)$$

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 Ua .

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 Ua , the ocean drag term is applied by following
 266 Eqn. (8)

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

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 Ua , 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 2.9377×10^{-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 Ua . The ocean drag coefficient C_0 was set as 0.4×10^4 (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°/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 Ua 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 km² (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 km²/a, -1204 km²/a, and -11,990 km²/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 $\sim 3582 \pm 8 \text{ km}^2$ and the area of A68d was
 317 $147 \pm 1 \text{ km}^2$ (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 $\sim 195 \pm 19 \text{ m}$ thick,
 320 weighed some $\sim 642 \pm 69 \text{ Gt}$, drifted at a speed of $24 \pm 2 \text{ cm/s}$, and rotated with an angular
 321 velocity of $\sim 15 \pm 2^\circ/\text{d}$, 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 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.



4.3 Maximum Tensile Stress for Iceberg-Seafloor Interactions

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

Insert Figure 7 here

5. Discussion

5.1 Ocean Drag Coefficient in Ua

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



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 ± 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



6. Conclusion

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

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

The later, rapid vanishing of iceberg A68a into the ocean is fully explained by the breakup event that occurred on December 16, 2020, caused by the collision of A68a with a seamount. We demonstrate the first successful case of using a large tabular 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



518 **Acknowledgments**

519 X.W. was supported by the National Natural Science Foundation of China (grant
520 42276237), the Oceanic Interdisciplinary Program of Shanghai Jiao Tong University
521 (grant SL2022PT205) and the Shanghai Frontiers Science Center of Polar Science
522 (SCOPS). D.M.H. was supported by the Center for global Sea Level Change (CSLC) of
523 New York University Abu Dhabi Research Institute (grant G1204), and the National
524 Science Foundation (grants PLR-1739003, PLR-2151295) of the USA. We thank Won
525 Sang Lee and Alex Fraser for their advice and helpful discussion on iceberg calving.
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-](https://www.esr.org/research/polar-tide-models/list-of-polar-tide-models/cats2008/)
539 [models/cats2008/](https://www.esr.org/research/polar-tide-models/list-of-polar-tide-models/cats2008/)). ERA5 data are obtained from ECMWF
540 (<https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5>). ECCO V4r4
541 monthly averaged ocean current data are obtained from NASA Estimating the
542 Circulation and Climate of the Ocean ([https://www.ecco-group.org/products-ECCO-](https://www.ecco-group.org/products-ECCO-V4r4.htm)
543 [V4r4.htm](https://www.ecco-group.org/products-ECCO-V4r4.htm)). The location and area of A68a extracted from remote sensing data and the
544 ground control points for breakup line extraction can be found in Supp. Material.

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



550 References

- 551 Alley, R. B., Horgan, H. J., Joughin, I., Cuffey, K. M., Dupont, T. K., Parizek, B. R., ... &
 552 Bassis, J. (2008). A simple law for ice-shelf calving. *Science*, 322(5906), 1344-
 553 1344.
- 554 Arndt, J. E., Schenke, H. W., Jakobsson, M., Nitsche, F. O., Buys, G., Goleby, B., ... &
 555 Wigley, R. (2013). The International Bathymetric Chart of the Southern Ocean
 556 (IBCSO) Version 1.0—A new bathymetric compilation covering circum-Antarctic
 557 waters. *Geophysical Research Letters*, 40(12), 3111-3117.
- 558 Arrigo, K.R. & van Dijken, G.L., (2003). Impact of iceberg C-19 on Ross Sea primary
 559 production. *Geophysical Research Letters*, 30(16).
- 560 Arrigo, K.R., van Dijken, G.L., Ainley, D.G., Fahnestock, M.A., & Markus, T., (2002).
 561 Ecological impact of a large Antarctic iceberg. *Geophysical Research Letters*,
 562 29(7), pp.8-1.
- 563 Benn, D.I., Warren, C.R. & Mottram, R.H., (2007). Calving processes and the dynamics
 564 of calving glaciers. *Earth-Science Reviews*, 82(3-4), pp.143-179.
- 565 Bouhier, N., Tournadre, J., Rémy, F., & Gournes-Cousin, R., (2018). Melting and
 566 fragmentation laws from the evolution of two large Southern Ocean icebergs
 567 estimated from satellite data. *The Cryosphere*, 12(7), 2267-2285.
- 568 Boy, F., Desjonquères, J. D., Picot, N., Moreau, T., & Raynal, M., (2016). CryoSat-2
 569 SAR-mode over oceans: processing methods, global assessment, and benefits.
 570 *IEEE Transactions on Geoscience and Remote Sensing*, 55(1), 148-158.
- 571 Braakmann-Folgmann, A., Shepherd, A., Gerrish, L., Izzard, J., & Ridout, A. (2022).
 572 Observing the disintegration of the A68A iceberg from space. *Remote Sensing of*
 573 *Environment*, 270, 112855.
- 574 Budge, J. S., & Long, D. G. (2018). A comprehensive database for Antarctic iceberg
 575 tracking using scatterometer data. *IEEE Journal of Selected Topics in Applied*
 576 *Earth Observations and Remote Sensing*, 11(2), 434-442.
- 577 Cuffey, K.M. & Paterson, W.S.B. (2010). *The Physics of Glaciers*, 4th edition: Academic
 578 Press. 704.
- 579 Depoorter, M.A., Bamber, J.L., Griggs, J.A., Lenaerts, J.T., Ligtenberg, S.R., van den
 580 Broeke, M.R. & Moholdt, G., (2013). Calving fluxes and basal melt rates of
 581 Antarctic ice shelves. *Nature*, 502(7469), pp.89-92.
- 582 Fricker, H.A., Young, N.W., Coleman, R., Bassis, J.N. & Minster, J.B., (2005). Multi-year
 583 monitoring of rift propagation on the Amery Ice Shelf, East Antarctica.
 584 *Geophysical Research Letters*, 32(2).
- 585 GEBCO Bathymetric Compilation Group (2020). The GEBCO_2020 Grid – a continuous
 586 terrain model of the global oceans and land. British Oceanographic Data Centre,
 587 National Oceanography Centre, NERC, UK.
- 588 Gladstone, R.M., Bigg, G.R. & Nicholls, K.W., (2001). Iceberg trajectory modeling and
 589 meltwater injection in the Southern Ocean. *Journal of Geophysical Research:*
 590 *Oceans*, 106(C9), pp. 19903-19915.
- 591 Gudmundsson, G. H. (2008). Analytical solutions for the surface response to small
 592 amplitude perturbations in boundary data in the shallow-ice-stream
 593 approximation. *The Cryosphere*, 2(2), 77-93.



- 594 Gudmundsson, G. H. (2013). Ice-shelf buttressing and the stability of marine ice sheets.
 595 The Cryosphere, 7(2), 647-655.
- 596 Gudmundsson, G. H., Krug, J., Durand, G., Favier, L., & Gagliardini, O. (2012). The
 597 stability of grounding lines on retrograde slopes. The Cryosphere, 6(6), 1497-
 598 1505.
- 599 Han, H., Lee S., Kim, J.-I., Kim, S. H., & Kim H.C. (2019). Changes in a giant iceberg
 600 created from the collapse of the Larsen c ice shelf, Antarctic Peninsula, derived
 601 from Sentinel-1 and CryoSat-2 data." Remote Sensing 11, no. 4: 404.
- 602 Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horanyi, A., Muñoz-Sabater, J., ... &
 603 Thepaut, J. N. (2020). The ERA5 global reanalysis. Quarterly Journal of the
 604 Royal Meteorological Society, 146(730), 1999-2049.
- 605 Hogg, A.E., & Gudmundsson, G.H. (2017). Impacts of the Larsen-C Ice Shelf calving
 606 event. Nature Climate Change 7, no. 8 (2017): 540-542.
- 607 Holland, P. R., Corr, H. F., Pritchard, H. D., Vaughan, D. G., Arthern, R. J., Jenkins, A.,
 608 & Tedesco, M. (2011). The air content of Larsen ice shelf. Geophysical Research
 609 Letters, 38(10).
- 610 Huth, A., Adcroft, A., Sergienko, O., & Khan, N. (2022). Ocean currents break up a
 611 tabular iceberg. Science Advances, 8(42), eabq6974.
- 612 Jansen, D., Sandhäger, H., & Rack, W., (2005). Model experiments on large tabular
 613 iceberg evolution: ablation and strain thinning. Journal of glaciology, 51(174),
 614 pp.363-372.
- 615 Jansen, D., Schodlok, M., & Rack, W., (2007). Basal melting of A-38B: A physical model
 616 constrained by satellite observations. Remote sensing of environment, 111(2-3),
 617 pp.195-203.
- 618 Joughin, I., & MacAyeal, D.R., (2005). Calving of large tabular icebergs from ice shelf
 619 rift systems. Geophysical research letters, 32(2).
- 620 Kooyman, G.L., Ainley, D.G., Ballard, G., & Ponganis, P.J., (2007). Effects of giant
 621 icebergs on two emperor penguin colonies in the Ross Sea, Antarctica. Antarctic
 622 Science, 19(1), p.31.
- 623 Lazzara, M.A., Jezek, K.C., Scambos, T.A., MacAyeal, D.R. & Van der Veen, C.J.,
 624 (1999). On the recent calving of icebergs from the Ross Ice Shelf. Polar
 625 Geography, 23(3), pp.201-212.
- 626 Long, D. G., Ballantyn, J., & Bertoia, C. (2002). Is the number of Antarctic icebergs
 627 really increasing? EOS, Transactions American Geophysical Union, 83(42), 469-
 628 474.
- 629 MacAyeal, D.R., et al, (2006). Transoceanic wave propagation links iceberg calving
 630 margins of Antarctica with storms in tropics and Northern Hemisphere.
 631 Geophysical Research Letters 33, no. 17.
- 632 McMillan, M., Shepherd, A., Sundal, A., Briggs, K., Muir, A., Ridout, A., & Wingham, D.
 633 (2014). Increased ice losses from Antarctica detected by CryoSat-2. Geophysical
 634 Research Letters, 41(11), 3899-3905.
- 635 Massom, R. A., Hill, K.L., Lytle, V.I., Worby, A.P. Paget, M.J., & Allison, I. (2001).
 636 Effects of regional fast-ice and iceberg distributions on the behaviour of the Mertz
 637 Glacier polynya, East Antarctica." Annals of Glaciology 33: 391-398.



- 638 Massom, R.A., Scambos, T.A., Bennetts, L.G., Reid, P., Squire, V.A. & Stammerjohn,
 639 S.E., (2018). Antarctic ice shelf disintegration triggered by sea ice loss and ocean
 640 swell. *Nature*, 558(7710), pp. 383-389.
- 641 McGrath, D., Steffen, K., Rajaram, H., Scambos, T., Abdalati, W. & Rignot, E., (2012).
 642 Basal crevasses on the Larsen C Ice Shelf, Antarctica: Implications for meltwater
 643 ponding and hydrofracture. *Geophysical research letters*, 39(16).
- 644 Merino, N., Le Sommer, J., Durand, G., Jourdain, N.C., Madec, G., Mathiot, P., &
 645 Tournadre, J., (2016). Antarctic icebergs melt over the Southern Ocean:
 646 Climatology and impact on sea ice. *Ocean Modelling*, 104, pp.99-110.
- 647 Nielsen, K., Stenseng, L., Andersen, O.B., & Knudsen, P. (2017). The performance &
 648 potentials of the CryoSat-2 SAR and SARIn modes for lake level estimation.
 649 *Water*, 9(6), 374.
- 650 Padman, L., Fricker, H. A., Coleman, R., Howard, S., & Erofeeva, L. (2002). A new tide
 651 model for the Antarctic ice shelves and seas. *Annals of Glaciology*, 34, 247-254.
- 652 Price, J.F., Weller, R.A., & Schudlich, R.R. (1987). Wind-driven ocean currents and
 653 Ekman transport. *Science*, 238(4833), 1534-1538.
- 654 Rignot, E., Casassa, G., Gogineni, P., Krabill, W., Rivera, A.U. & Thomas, R., (2004).
 655 Accelerated ice discharge from the Antarctic Peninsula following the collapse of
 656 Larsen B ice shelf. *Geophysical research letters*, 31(18).
- 657 Rignot, E., Jacobs, S., Mouginot, J. & Scheuchl, B., (2013). Ice-shelf melting around
 658 Antarctica. *Science*, 341(6143), pp.266-270.
- 659 Robinson, N.J., & Williams, M.J.M., (2012). Iceberg-induced changes to polynya
 660 operation and regional oceanography in the southern Ross Sea, Antarctica, from
 661 in situ observations. *Antarctic Science*, 24(5), p.514.
- 662 Russell-Head, D.S., (1980). The melting of free-drifting icebergs. *Annals of glaciology*,
 663 1, pp.119-122.
- 664 Scambos, T.A., Bohlander, J.A., Shuman, C.A. & Skvarca, P., (2004). Glacier
 665 acceleration and thinning after ice shelf collapse in the Larsen B embayment,
 666 Antarctica. *Geophysical Research Letters*, 31(18).
- 667 Scambos, T., Sergienko, O., Sargent, A., MacAyeal, D. & Fastook, J., 2005. ICESat
 668 profiles of tabular iceberg margins and iceberg breakup at low latitudes.
 669 *Geophysical Research Letters*, 32(23).
- 670 Silva, T.A.M., Bigg, G.R., & Nicholls, K.W., 2006. Contribution of giant icebergs to the
 671 Southern Ocean freshwater flux. *Journal of Geophysical Research: Oceans*,
 672 111(C3).
- 673 Smith, R. M., & Bigg, G. R. (2023). Impact of giant iceberg A68A on the physical
 674 conditions of the surface South Atlantic, derived using remote sensing.
 675 *Geophysical Research Letters*, 50(18), e2023GL104028.
- 676 Stern, A.A., Adcroft, A., & Sergienko, O. (2016). The effects of Antarctic iceberg calving-
 677 size distribution in a global climate model. *Journal of Geophysical Research:*
 678 *Oceans*, 121(8), 5773-5788.
- 679 Stuart, K.M., & Long, D.G., (2011). Tracking large tabular icebergs using the SeaWinds
 680 Ku-band microwave scatterometer. *Deep Sea Research Part II: Topical Studies*
 681 *in Oceanography* 58.11-12: 1285-1300.
- 682 Tarling, G. A., Thorpe, S. E., Henley, S. F., Burson, A., Liszka, C. M., Manno, C., ... &
 683 Abrahamsen, E. P. (2024). Collapse of a giant iceberg in a dynamic Southern



- 684 Ocean marine ecosystem: in situ observations of A-68A at South Georgia.
 685 Progress in Oceanography, 103297.
- 686 Wagner, T.J., Wadhams, P., Bates, R., Elosegui, P., Stern, A., Vella, D., Abrahamsen,
 687 E.P., Crawford, A., & Nicholls, K.W., (2014). The “footloose” mechanism: Iceberg
 688 decay from hydrostatic stresses. Geophysical Research Letters, 41(15), pp.5522-
 689 5529.
- 690 Wagner, T.J., Dell, R.W. & Eisenman, I., (2017). An analytical model of iceberg drift.
 691 Journal of Physical Oceanography, 47(7), pp.1605-1616.
- 692 Wang, X., Cheng, X., Gong, P., Shum, C.K., Holland, D.M., & Li, X., (2014). Freeboard
 693 and mass extraction of the disintegrated Mertz Ice Tongue with remote sensing
 694 and altimetry data. Remote sensing of environment 144: 1-10.
- 695 Wang, X., Holland, D.M., Cheng, X., & Gong, P., (2016). Grounding and calving cycle of
 696 Mertz Ice Tongue revealed by shallow Mertz Bank. Cryosphere 10, no. 5: 2043-
 697 2056.
- 698 Williams, G.D., Aoki, S., Jacobs, S.S., Rintoul, S.R., Tamura, T. & Bindoff, N.L., (2010).
 699 Antarctic bottom water from the Adélie and George V Land coast, East Antarctica
 700 (140–149 E). Journal of Geophysical Research: Oceans, 115(C4).
- 701 Wunsch, C., Heimbach, P., Ponte, R. M., Fukumori, I., & ECCO-GODAE
 702 CONSORTIUM MEMBERS. (2009). The global general circulation of the ocean
 703 estimated by the ECCO-Consortium. Oceanography, 22(2), 88-103.
 704



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

Parameters	Setting
Iceberg Density (Considering firm layer thickness)	857 kg/m ³
Ocean Density	1028 kg/m ³
Iceberg Freeboard	32.5 m
Iceberg Draft	163.0 m
Iceberg Temperature	-20 °C
A-Glen Law	2.9377×10^{-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 °/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.

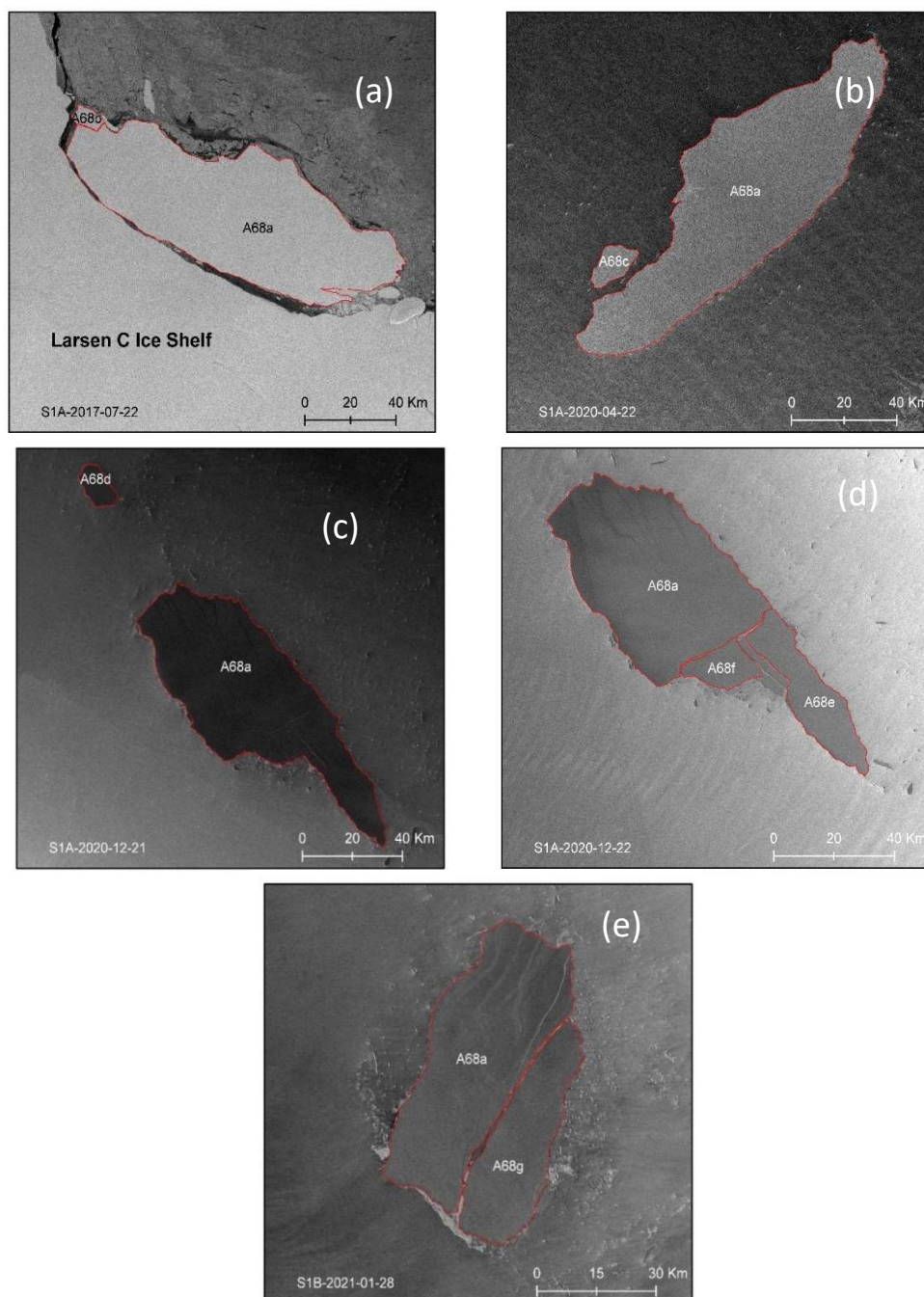




Figure 2. (a) to (d) shows sequential locations, outlines, breakup, and vanishing of A68a during 2021. The exact observation date of each of the MODIS images is marked in the lower left. (e) Location of A68a at 12:45 UTC on December 16, 2020, (MODIS). The outline of A68a is indicated with red polygon.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

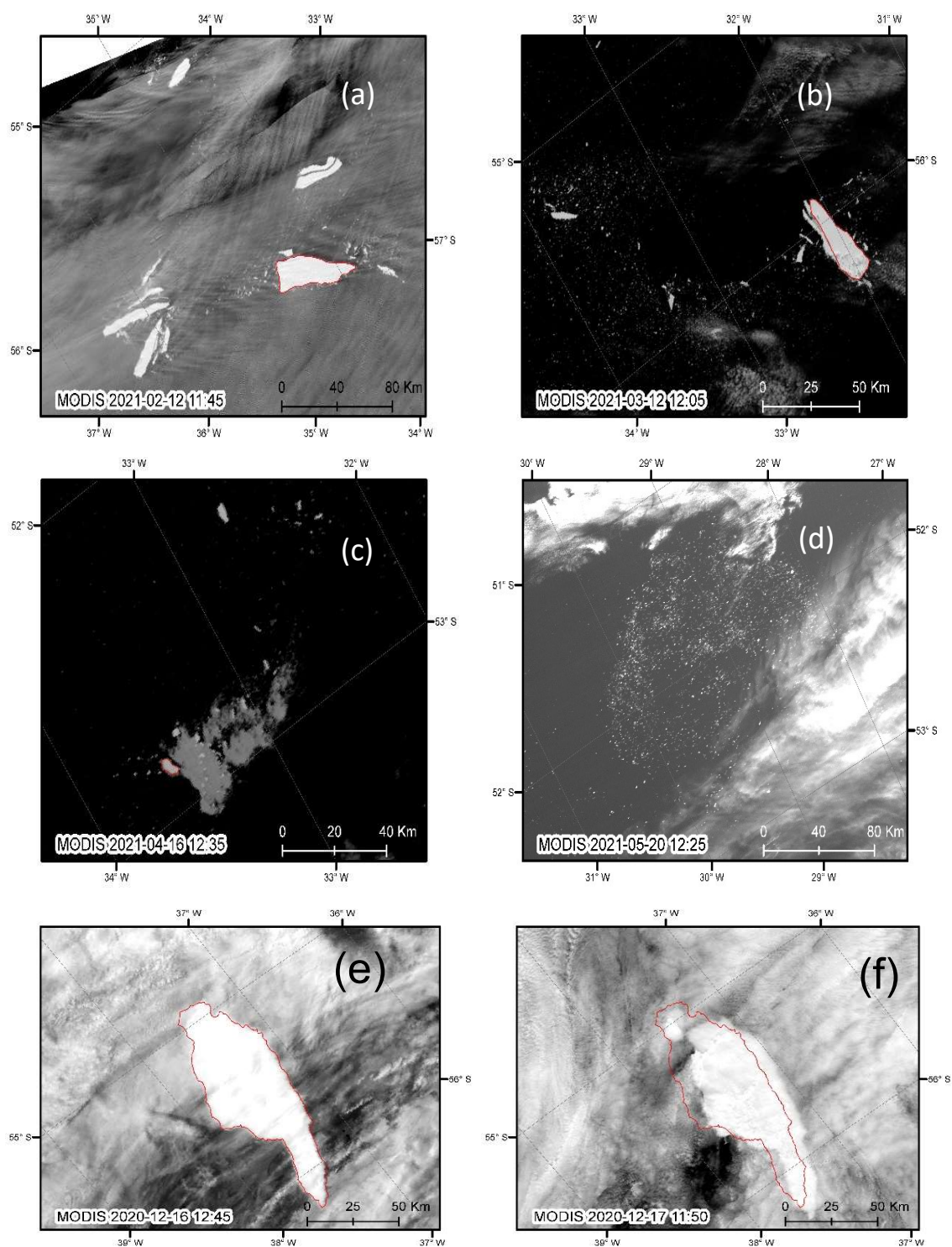




Figure 3. Drifting trajectory, areal changes, the major breakup, the appearance of rift lines, and the vanishing of iceberg A68a. **(a)** Drifting trajectory of A68a following its calving from Larsen C Ice Shelf in July 2017. **(b)** Outline and location of A68a before and after a breakup event in mid-December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

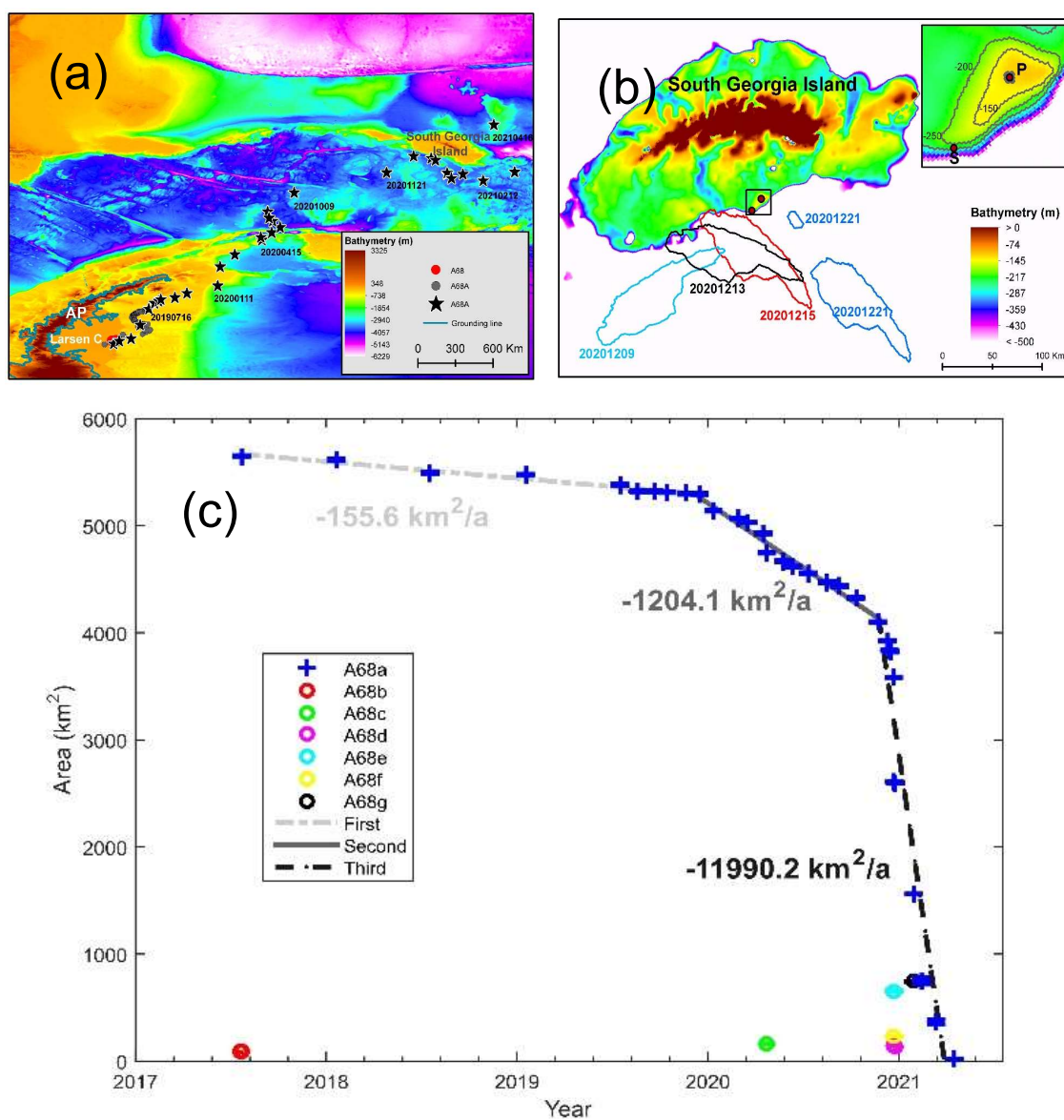




Figure 4. **(a)** ground tracks of Cryosat-2 from November 1 to December 16, 2020, in the vicinity of South Georgia Island used to extract the freeboard of iceberg A68a. The freeboard height distribution ranging from 40 m to 55 m (relative to a geoid) is indicated by blue to yellow. Yellow dots in the 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.

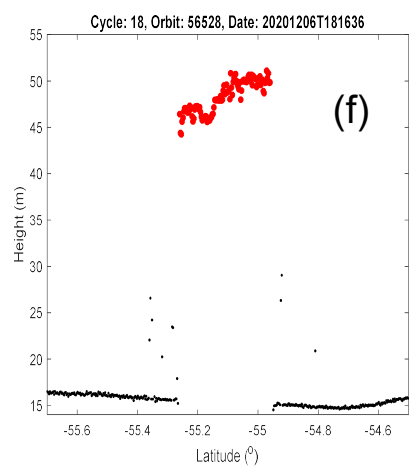
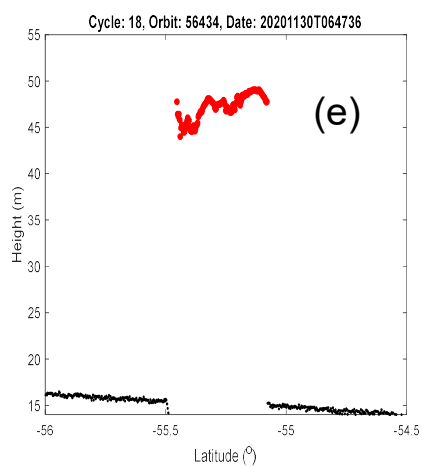
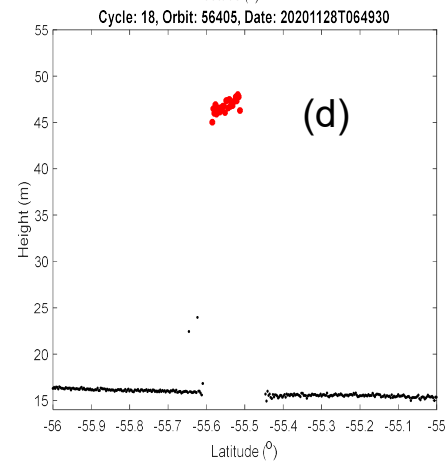
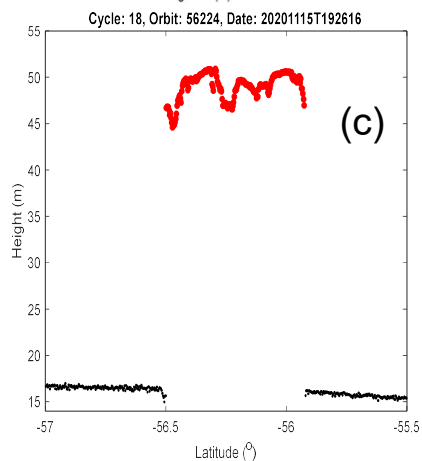
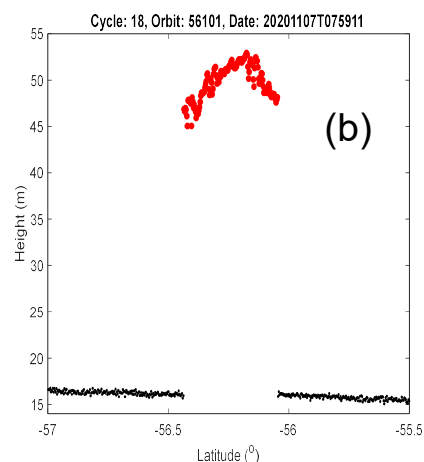
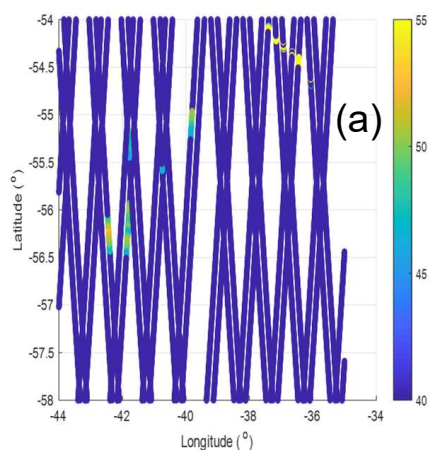




Figure 5. Breakup line extraction procedure. **(a)** Sentinel-1A observation on December 15, 2020, and an outline of iceberg A68a from MODIS on December 16 (red polygon). **(b)** to **(d)** show the georeferencing of Sentinel-1A observations on December 15, 21, and again 21 to the A68a location on December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

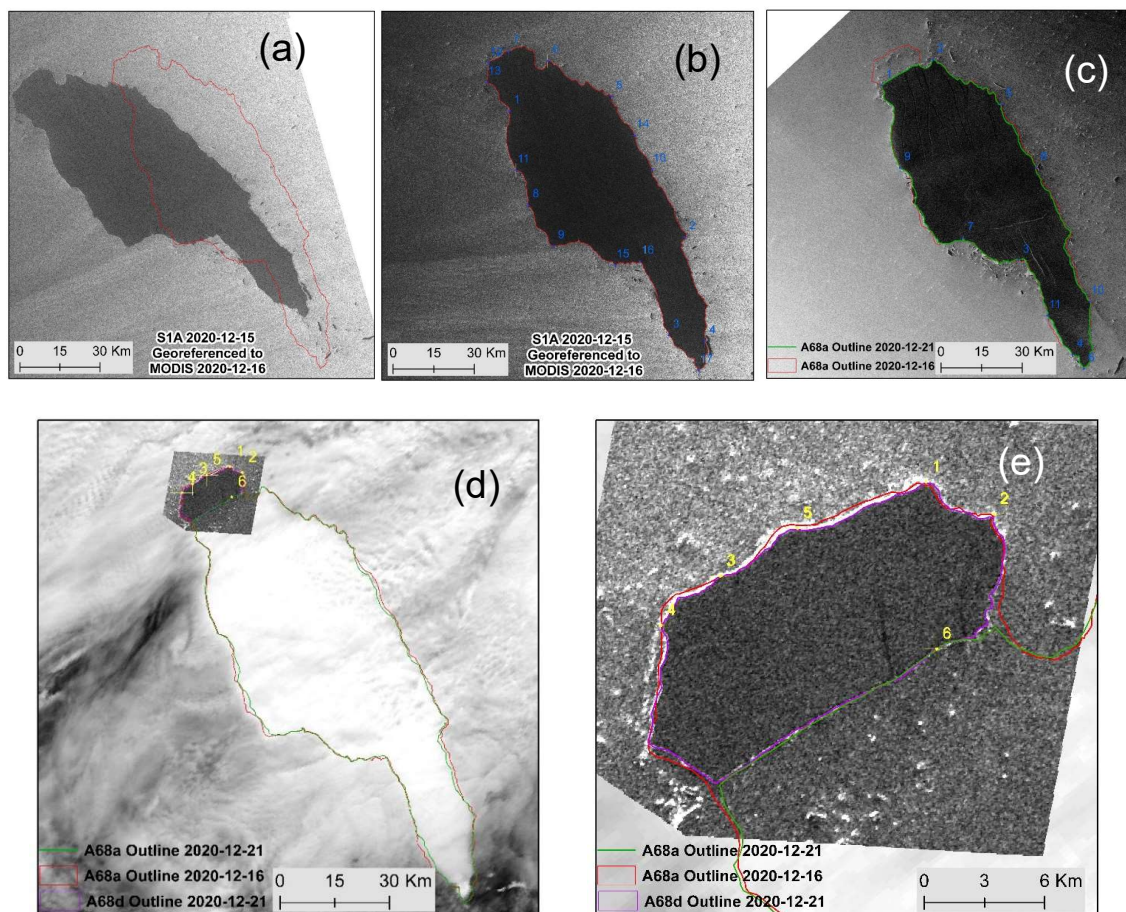




Figure 6. Grounding of A68a on seamount of the South Georgia Island. **(a)** Two rifts seen on December 16, 2020 (MODIS). The rift contour is extracted from Figure 5. **(b)** Grounding detection of A68a at 12:45 UTC on December 16, 2020 (MODIS). Negative values indicate grounded regions of A68a. **(c)**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

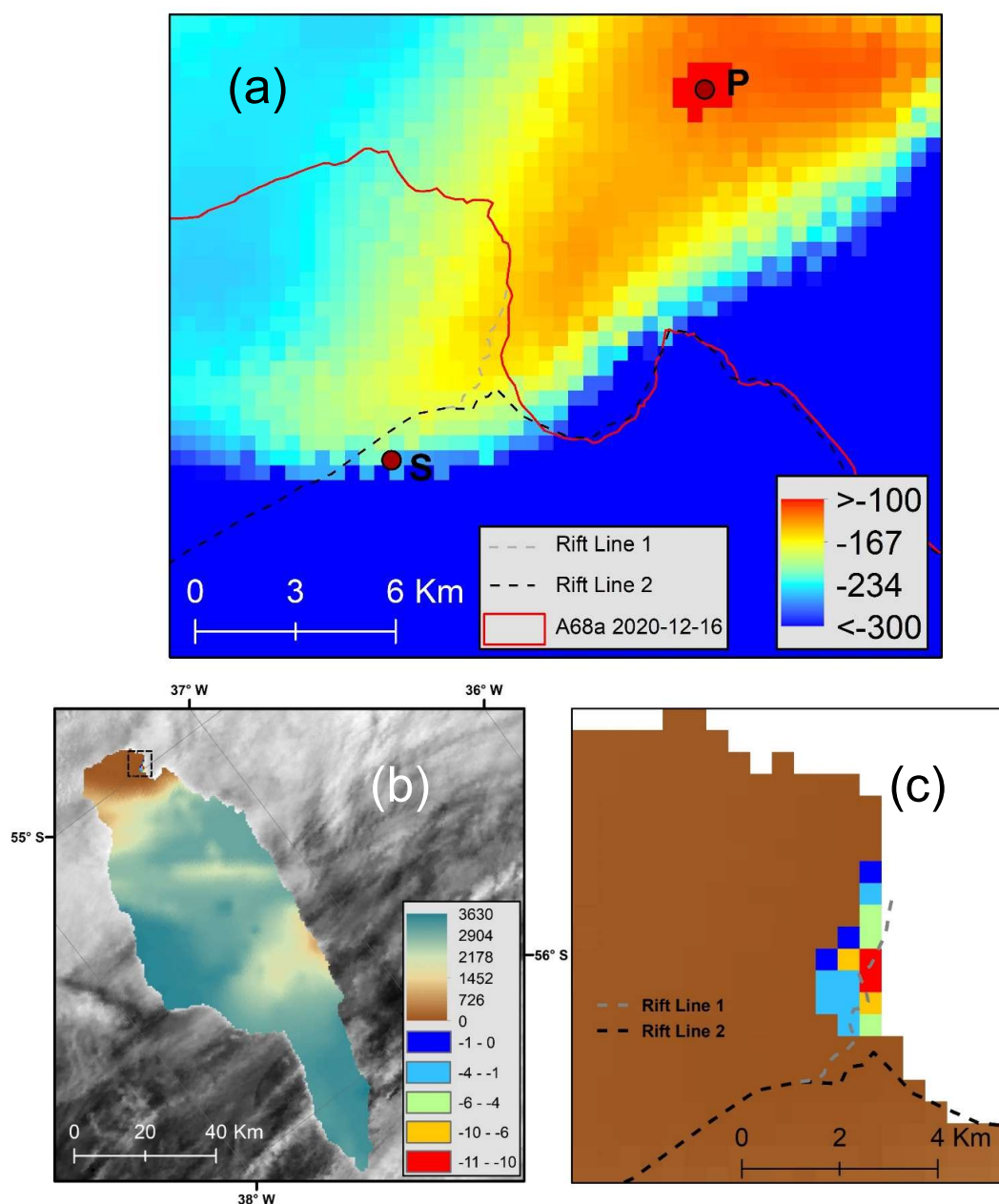




Figure 7. Modeling the interaction of iceberg A68a and the seafloor using U_a . **(a)** Basal ice velocity of A68a inverted from U_a , **(b)** Deviatoric stresses of A68a inverted from U_a . Red vectors are tensile; blue vectors are compressive. The maximum tensile stress is indicated with a green dot. **(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.

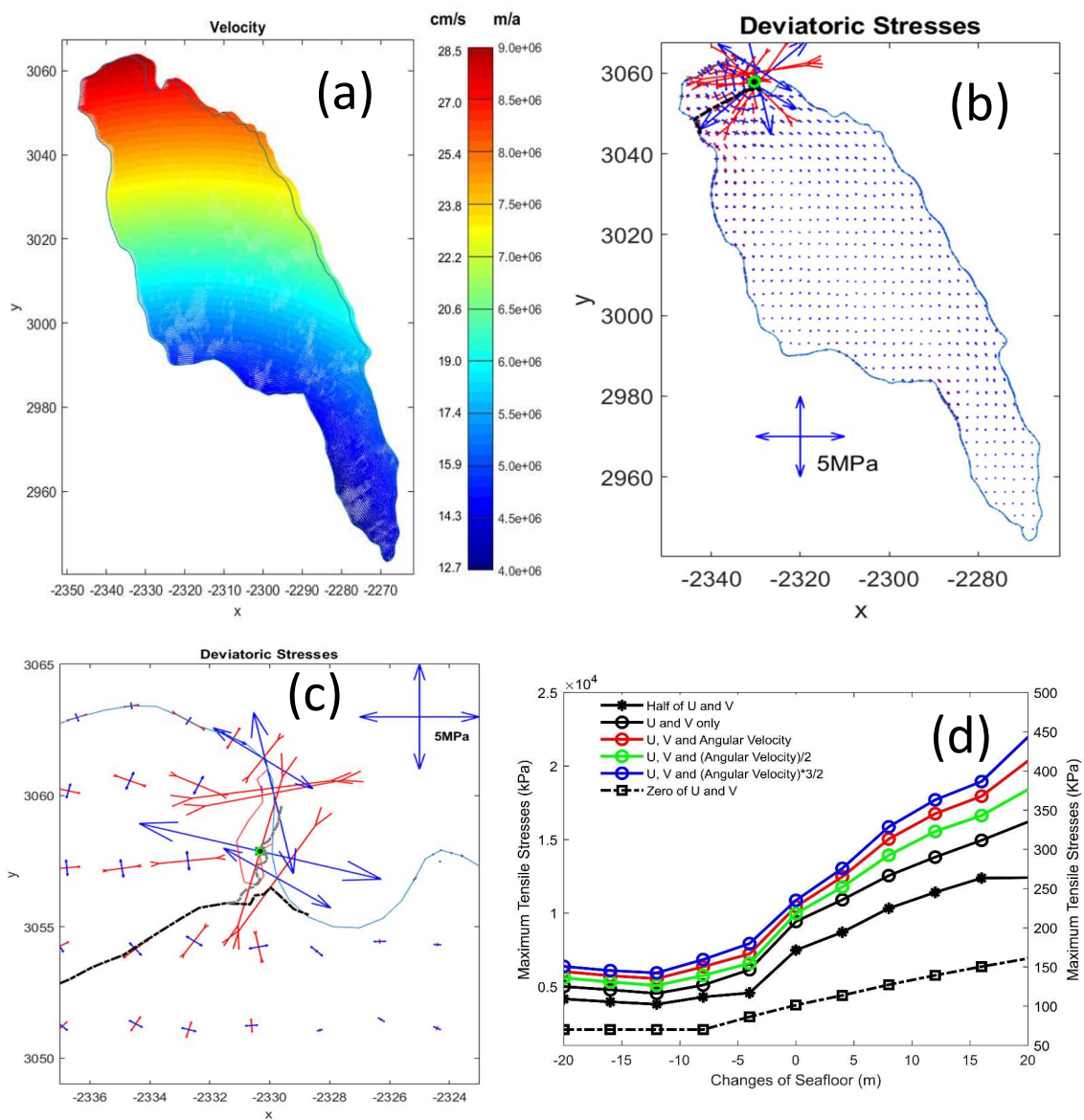




Figure 8. (a) to (d) basal ice velocity of A68a inverted from U_a when setting ocean-ice coefficient of drag C_o as $0.4e5$, $0.4e4$, $0.4e3$, and 0.4 , respectively (motionless ocean). (e) to (h) corresponding deviatoric stresses of A68a inverted from U_a when setting C_o as $0.4e5$, $0.4e4$, $0.4e3$, 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.

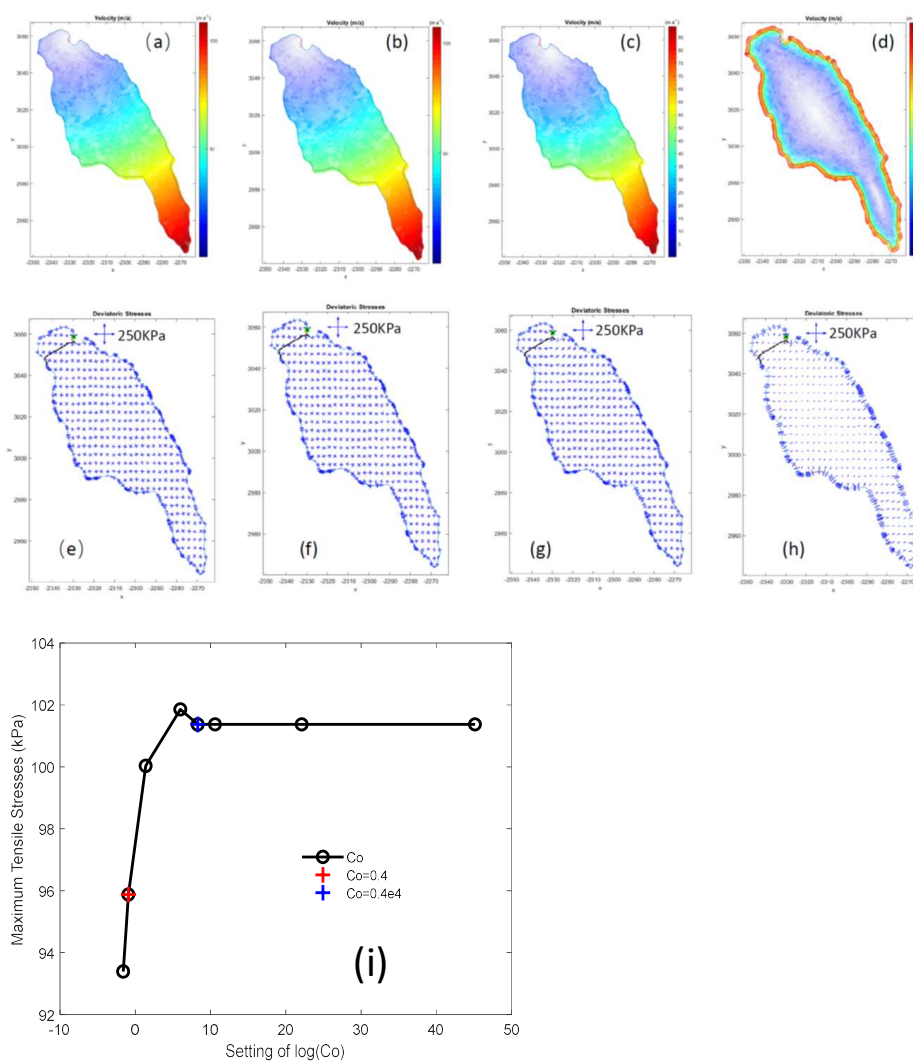




Figure 9. Sensitivity experiment in which the seafloor is lowered by 50 m, but other parameter settings are the same as in Extended Table 1c. **(a)** mesh grid of iceberg A68a as used in *Ua* modeling. **(b)** basal ice velocity of A68a inverted from *Ua*. **(c)** deviatoric stresses of A68a with the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

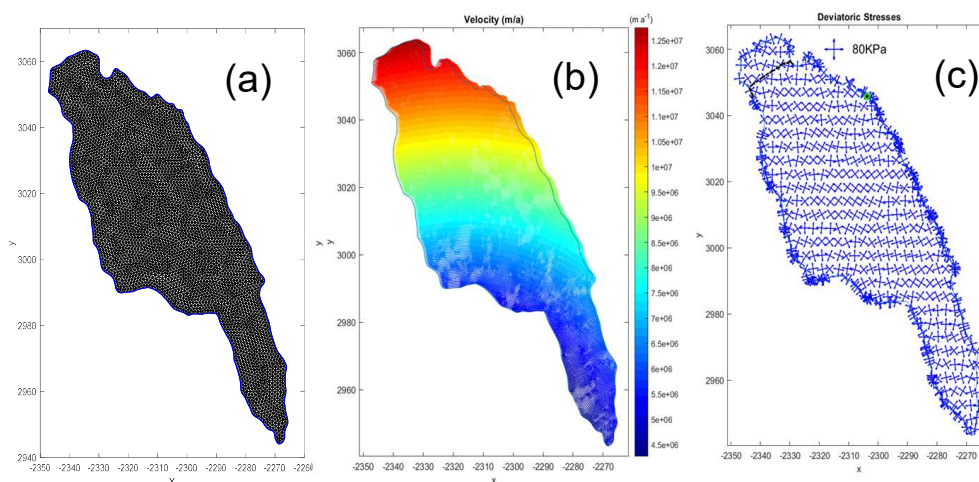
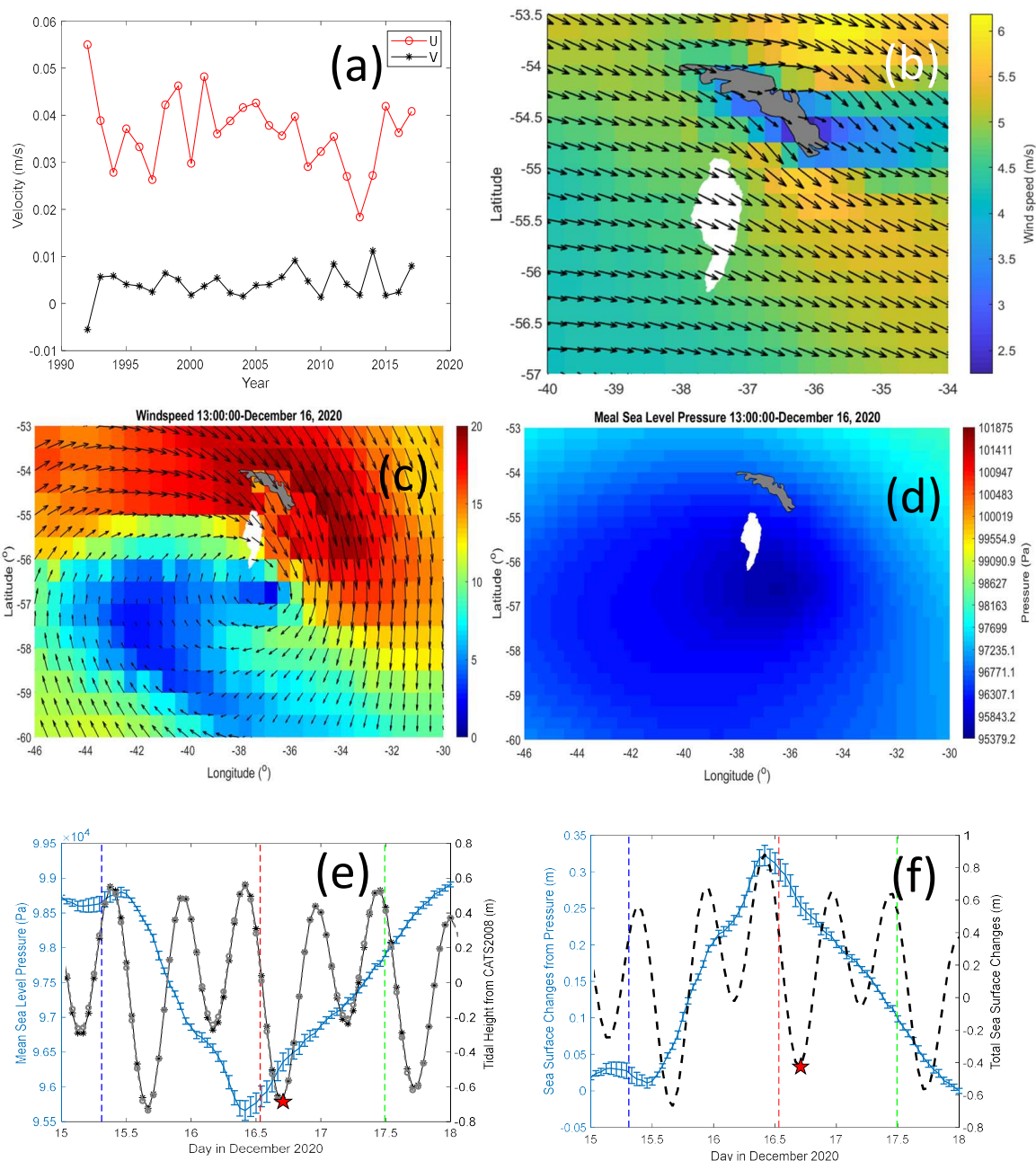




Figure 10. Ocean and atmosphere influences near A68a. **(a)** Historical ocean current patterns (m/s) from 1992 to 2017. **(b)** Hourly-averaged wind speed (m/s) around South Georgia Island (grey polygon). **(c)** Wind speed and direction at 13:00 UTC on December 16, 2020, during an intense polar cyclone 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.