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Author for correspondence:
Seelye Martin, E-mail: seelye@uw.edu

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Comparison of Antarctic iceberg observations by Cook in 1772–75, Halley in 1700, Bouvet in 1739 and Riou in 1789 with modern data

Seelye Martin[1], David G. Long[2] and Michael P. Schodlok[3]

[1]School of Oceanography, University of Washington, Seattle WA 98195, USA; [2]Department of Electrical and Computer Engineering, Brigham Young University, 450 EB, Provo UT 84602, USA and [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

Abstract

During Cook's 1772–75 Antarctic circumnavigation on the *HMS Resolution*, he recorded the positions of hundreds of icebergs. This paper compares Cook's observations and those of Halley in 1700, Bouvet in 1739 and Riou in 1789, with the Brigham Young University/National Ice Center (BYU/NIC) and the Alfred Wegener Institute datasets. Cook's description of the iceberg plume east of the Amery Ice Shelf and the iceberg distributions in the Weddell, Ross and Amundsen Seas agree with modern data. In January 1774, Cook reached his farthest south on the shelf of the Amundsen Sea Embayment, the site of the current International Thwaites Glacier Collaboration field study. Cook's largest iceberg had a 2.5 km diameter, where power-law models show that icebergs of this size or smaller comprise 92% of their total number. In the eastern Weddell, Cook's observation of a sea-ice tongue with a much greater extent than in satellite imagery remains unexplained. Although Riou's icebergs lie 1000 km east of the BYU/NIC trajectories, application of the England and others (2020) fracture and drift model to the trajectories removes the discrepancy and means that all the ship observations are consistent with modern observations and theory.

1. Introduction

The British Admiralty and Royal Society jointly sponsored James Cook's 1772–1775 circumpolar Antarctic cruise on the *HMS Resolution*. Although the cruise began with two ships, with Tobias Furneaux commanding the *Adventure*, on 30 October 1773, they became permanently separated. During the austral spring and summers, the *Resolution* made five traverses into the sea ice and iceberg-covered regions of the Antarctic Ocean, then spent its austral winters in more temperate latitudes. On these traverses, Cook observed hundreds of icebergs.

One of the Admiralty's instructions to Cook was to investigate an earlier discovery. On 1 January 1739, Lozier Bouvet on the ships *Aigle* and *Marie* (*Eagle* and *Mary*) of the French East India Company observed what he thought was land in the South Atlantic at 54.0°S, 11.3°E. Bouvet named this feature Cape Circumcision, after the 1 January date of the Feast of the Circumcision. Although Bouvet may have seen what is now Cape Circumcision on Bouvet Island at 54.0°S, 3.3°E or 530 km west of his recorded position, Cook was to search the region around 11.3°E and investigate whether this observation was part of a much larger land mass (Cook, 1777a, 1777b, 24, 52).

On the *Resolution*, Cook used the new Larcum Kendall K1 watch. This was an exact copy of the Harrison H4 watch that in combination with sextant observations of the sun elevation, allowed longitude to be determined with an accuracy of 6–19 km (3–10 nm), or at 60°S, to an accuracy of 0.1–0.3 degrees (Sobel, 2005; Skullern, 2016). Cook took great care of the K1. When it was removed from storage to be used or wound, the commander, first lieutenant and astronomer, or their designated alternates, had to be present. Other methods for longitude determination included measurement of the apparent size of the moon, for which purpose the crew included an astronomer, William Wales.

Determination of position from either the K1 or astronomical observations required clear skies, so that during bad weather, gaps occurred in their cruise track. Otherwise, Cook and Wales determined the ship's position at ∼24 h intervals, where the interval between positions could be as large as 250 km. At these positions, Cook recorded the number of icebergs he saw, and in some cases the size, which he gave as the iceberg circuit-length or circumference. On 24 January 1774, Cook recorded his largest iceberg, which he described as 'a very large ice-island…not less than three to four miles [6 to 8 km] in circuit (Cook, 1777a, 267)'.

Cook rewrote his journal for publication in terms of 'civil time', where days run midnight to midnight, instead of the Royal Navy 'nautical time', where days run noon to noon (Cook, 1777a, xxxv). Wales kept his journal in nautical time and recorded all navigational data with additional observations of ice conditions (Wales, 1775). His handwritten logbook is available on-line from the Greenwich Observatory. Because of their different definitions of a day, Wales's morning of 29 January corresponds to Cook's morning of 30 January.

Part of Cook's success came from his discovery that the icebergs could supply sufficient fresh water for his long traverses into the ice. On 14 December 1772, at the beginning of

Fig. 1. Watercolor by William Hodges, dated 4 January 1773, with the caption *The Resolution and Adventure, taking on ice for water, Latitude 61 S*. The illustration corresponds to the ice recovery described in Cook's log on 8 January 1773 at 61.2°S, 31.8°W. For scale, the *Resolution* measures 100 m at the waterline. The image is out of copyright and courtesy of the Mitchell Library, State Library of New South Wales (Mitchell Library, 2022).

his first traverse in the Weddell Sea, Cook recovered small pieces of glacier ice from the sea and found that they yielded fresh water (54.8°S, 21.5°E). On 8 January 1773, Cook deployed three boats, and in ~6 h, recovered enough ice from an iceberg to yield 'fifteen tons of good fresh water'. Cook realized that icebergs could supply his fresh water needs, and that 'I did not doubt of getting more whenever we were in want. I therefore, without hesitation, directed our course more to the south… (Cook, 1777a, 88)'. Figure 1 shows a watercolor of the two ships and the ice recovery by the artist on the *Resolution*, William Hodges.

This study discusses observations of Antarctic icebergs from Cook on the *HMS Resolution*, Halley on the *HMS Paramore* and Riou on the *HMS Guardian*, and includes Bouvet's observation of Cape Circumcision on the *Aigle* and *Marie* that helped inspire Cook's voyage. Cook's observations make up 95% of the total. Comparison of their size distribution with modern data, and their spatial distribution with the trajectories of contemporary satellite-tracked icebergs from the Alfred Wegener Institute (AWI) and the Brigham Young University/National Ice Center (BYU/NIC) shows that except for the location of the *Guardian* icebergs, the modern and historic datasets agree. The study then describes Cook's five traverses into the eastern Weddell Sea, the Indian Ocean, the Ross Sea, the Amundsen Sea and the western Weddell Sea. For the *Guardian* outliers, the application of a drift and fracture model to the BYU/NIC trajectories extends them to the positions of the *Guardian* icebergs, so that modern observations and theory explain all the historic ship observations. In the conclusions, notable results include Cook's transect in the Indian Ocean through the iceberg plume that exits the coast to the east of the Amery Ice Shelf, and his attainment in the Amundsen Sea of his furthest south, where the *Resolution* was the first ship to reach the continental shelf of the Amundsen Sea Embayment (ASE) which contains the terminuses of the Pine Island and Thwaites Glaciers. This achievement is a remarkable precursor to the International Thwaites Glacier Collaboration (ITGC) that in the same location in 2018, began its fieldwork 244 years later.

2. Datasets

2.1 HMS Resolution

The lead author extracted Cook's observations of the number of icebergs versus position and date along his five traverses from a line-by-line search of a downloadable version of Cook (1777a, 1777b). Whenever possible, Cook (1777a, 1777b) recorded his position plus his observations of icebergs, which he referred to in terms such as 'ice islands', 'ice isles' and 'hills of ice'. This paper supplements Cook's observations by inclusion of one observation from Wales's (1775) handwritten logbook. For the subsequent data display (see Fig. 2 below), Cook's and Wales's observations were divided into three categories: no icebergs, one to three icebergs and many icebergs. These were transcribed into the spreadsheet in the Supplementary material that contains the date, position, the iceberg categories and Cook's or Wales's description of each observation. The latitude and longitude are given to 0.1 degrees, which as the previous section discusses, is

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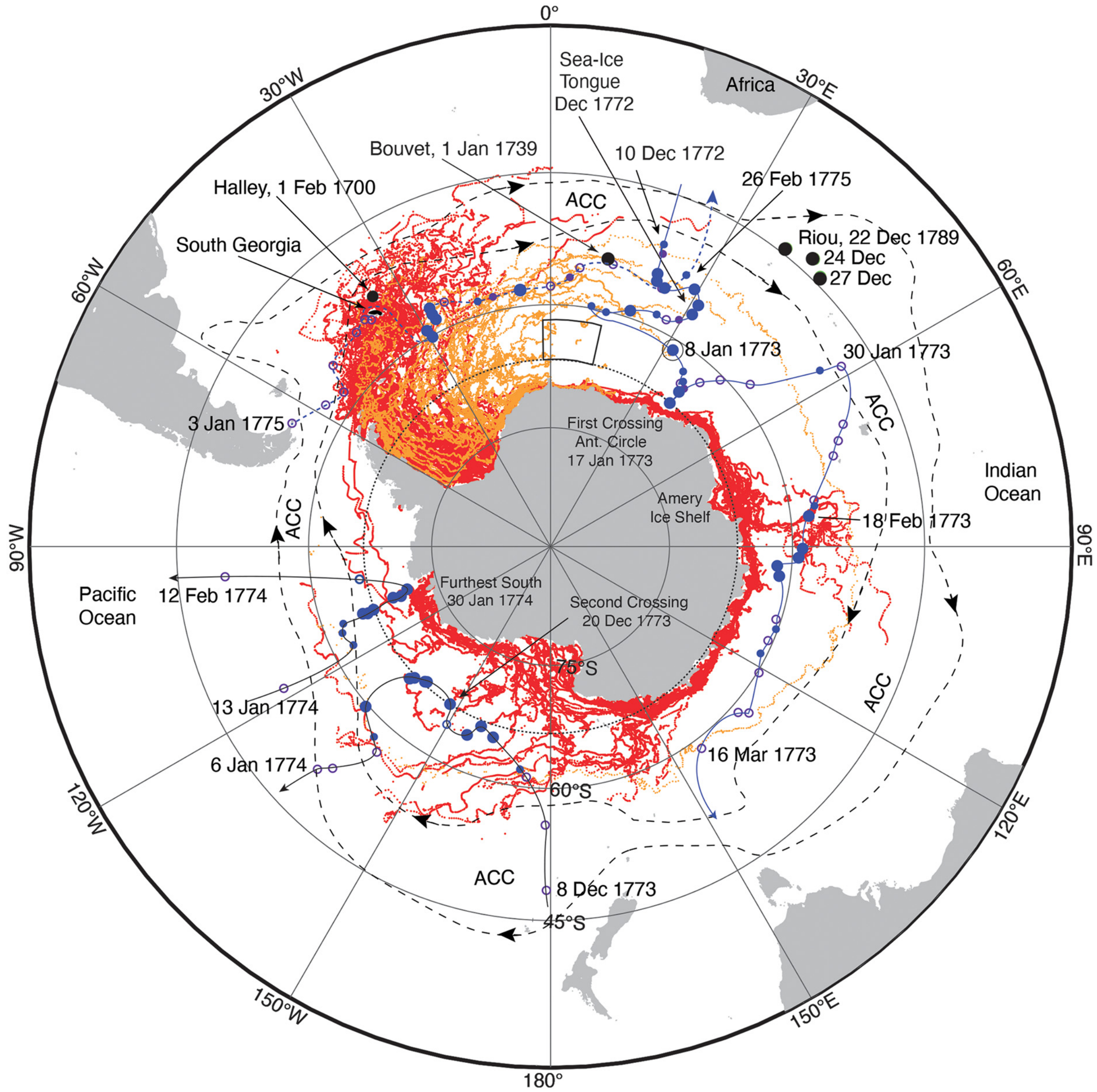

Fig. 2. Comparison of the datasets: BYU/NIC in red, AWI in orange, Halley, Bouvet and Riou observations in black and Cook's cruise tracks and data points in blue. His first traverse of the Weddell Sea is a solid line; his second is dotted. For Cook, open circles mean no icebergs; small closed circles, one to three icebergs; larger closed circles, many icebergs. The circled point on 8 January 1773 marks where Cook collected fresh water from an iceberg and of Hodges's watercolor. Also marked are Cook's three crossings of the Antarctic circle, his farthest south and the sea-ice and iceberg tongue in the Weddell Sea. The dashed lines between 45°S and 60°S show the boundaries of the Antarctic Circumpolar Current (ACC). The dotted circle is the Antarctic Circle. The latitude–longitude box (62°S–68°S, 3°W–12°E) in the Weddell Sea shows the location of the Maud Rise Polynya.

the best longitude accuracy associated with the Kendall chronometer. Since positions were taken at local noon, and the ship could travel as much as 200 km d^{-1} with the iceberg observations occurring at any time, the actual iceberg positions were less accurate. The final spreadsheet includes 93 observations from Cook and one from Wales. For quality control, the first draft of these points was plotted on a polar projection, then compared with Cook's cruise plot (Cook, 1777a, Plate I), following which outliers were removed, revised and reentered. The entire file was then rechecked against the original texts.

2.2. Other historic ship observations

During 1700–1799, and in addition to Lozier Bouvet's discovery on the *Aigle* and *Marie* of Cape Circumcision, Edmond Halley on the *HMS Paramore* and Edward Riou on the *HMS Guardian* provided five more iceberg observations that the spreadsheet includes. Although these ships recorded few icebergs, Halley observed the largest, the Bouvet discovery was an inspiration for Cook's voyage and Riou's encounters show the importance of fractures in the determination of iceberg trajectories.

2.2.1 HMS Paramore

On 1 February 1700, Edmond Halley, who determined his longitude from dead reckoning, reached a point just north of the undiscovered South Georgia Island. At this position, Halley encountered three tabular icebergs and provided what may be their first sketches and written descriptions (Thrower, 1981). The largest of these icebergs which Halley named 'B' had a 60 m freeboard and a 9 km waterline length. He then sailed north, encountering a few smaller icebergs in fog. For all the ships, his iceberg 'B' was the largest observed.

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2.2.2 HMS Guardian

Between 21 and 27 December 1789, Captain Edward Riou of the *HMS Guardian*, a supply ship en route to the new Australian colony, was surprised to see several icebergs 2100 km southeast of Cape Town at about 44°S, or well north of Cook's observations (Riou, 1790; Dickson, 2012). On 22 December, Riou observed two icebergs, where the first was saddle-shaped and measured ∼10 m high and 300 m long at the waterline, with a similarly sized iceberg observed from the masthead (Riou, 1790, 4–5). On this day, Riou reported that the air temperature remained between 50° and 60°F (10–15°C), suggesting that the seawater surface temperature was above freezing.

On Christmas Eve 1789, Riou observed a third iceberg with a waterline length of ∼200 m and hummocks at each end, the larger 60 m high, the smaller 15 m high (Riou, 1790, 7–13). In the late afternoon, Riou deployed small boats to this iceberg to recover ice for fresh water. From Riou (1790, 9), as the boats approached, tonnes of ice fell from the large hummock, providing 'convincing proof of [its] rapid decay…'. About an hour after completing this task, in the early evening and heavy fog, the *Guardian* collided with a fourth iceberg, which Riou describes as 'a body of ice full twice as high as our masthead, showing itself through the thickest fog I ever witnessed (Dickson, 2012, 23)'. Given a mast height of ∼30 m, this implies an ice height of ∼60 m. Because of the fog, no additional information exists on the size of this iceberg.

The sailing master of the ship, Thomas Clements, stated that while the ship turned away from the iceberg, it collided stern-first with 'a piece of ice, which projected out from the main body underwater… (Dickson, 2012, 31)'. The incident ocean swell drove the *Guardian* onto the underwater projection with sufficient force that its rudder was torn off and bottom severely damaged, following which it ran aground.

As Wagner and others (2014) show, this underwater ice foot results from wave melting. If the ocean is above freezing, the waves carry heat toward the iceberg, cutting a notch at the waterline. After the notch grows in a few meters, the ice above the waterline sloughs off, while the underwater foot remains. If this foot grows large enough, its buoyant torque will fracture the iceberg, a process called the 'footloose' mechanism (Wagner and others, 2014). For 5 or 6 min, the *Guardian* remained grounded on the foot, during which time Riou and Clements feared that the overhanging ice would fall and destroy the ship. The ship then broke free and moved clear of the iceberg (Riou, 1790, 19; Dickson, 2012, 23, 31).

Following the collision, about half of the 124 crew, passengers and convicts abandoned ship, while the rest remained onboard with Riou. On 27 December 1789, at 43.2°S, 45°W, Riou observed his last iceberg. Because Riou's chronometers were stolen in the chaos surrounding the collision, the longitude given here and in the spreadsheet is from dead reckoning. Then in an amazing feat and despite the severe damage, Riou sailed the hulk on an irregular course 2500 km back to Cape Town, arriving 60 d after the collision on 22 February 1790 (Dickson, 2012).

2.3 Modern iceberg observations

2.3.1 Brigham Young University/National Ice Center (BYU/NIC)

The BYU/NIC dataset began in July 1978 and continues through the present, with most of its data collection occurring since 1992 (Stuart and Long, 2011; Budge and Long, 2018). The BYU part of the dataset uses low-resolution satellite scatterometer radars to track icebergs. Volume scattering from the radar signal penetrating into the firn makes the icebergs much brighter than either the ocean surface or sea ice. During the austral summer, when meltwater forms on the iceberg surface, the contrast disappears, leading to gaps in the trajectories. The backscatter measurements are processed onto polar stereographic grids with 8.9, 4.2 or 2.2 km pixels, depending on the sensor. Since it takes several pixels to unambiguously identify an iceberg, the smallest iceberg that can be tracked has a length of 5–10 km. The NIC part of the data consists of iceberg positions derived from visible, infrared and radar satellite observations. These are used to check the scatterometer positions or occasionally to fill in missing data (Budge and Long, 2018). Since Cook's largest iceberg had a circumference of ∼8 km, corresponding to a 3 km diameter, it would have been too small for the scatterometer to observe.

2.3.2 Alfred Wegener Institute (AWI)

The AWI dataset contains the results from the January 1999 to January 2003 deployment of satellite transponders from the R/V *Polarstern* onto 52 icebergs in the Weddell Sea. These buoys reported GPS positions at daily intervals via ARGOS. Most of these icebergs had lengths between 100 and 1500 m, and freeboards between 10 and 70 m, with a few much larger (Schodlok and others, 2006). Their deployments used two types of buoys. In the first year, the transponders were mounted in sealed tubes that were 2 m tall with a 20 cm diameter, with additional floatation attached. Because of their large number of batteries, the German environmental protection agency (Umwelt Bundesamt) required that if these buoys melted free, they would be able to float out of the Antarctic treaty zone. The second type was 1.8 m tall with a 20 cm diameter and had a positive buoyancy without an additional float. All buoys were buried halfway into the iceberg with an attached meter-square wooden panel at the surface to avoid tilting (Schodlok and others, 2006).

3. Results

3.1 Comparison of ship and modern observations

3.1.1 Iceberg sizes

Cook recorded his largest iceberg on 24 January 1774, when he observed 'a very large ice-island…not less than three to four miles [6 to 7 km] in circuit (Cook, 1777a, 267)'. Cook's larger estimate of circumference is equivalent to a 2.4 km diameter iceberg with a 4.4 km^2 area. He does not describe encounters with the 100 km scale icebergs, such as icebergs B-15A, C-19A or A-68 that occur within the BYU/NIC dataset.

In their Figure 2 and Table S2, England and others (2020) show the size distribution of icebergs based on their interpretation of the −1.5 power-law dependence of iceberg frequency on area (Tournadre and others, 2016). Their table gives this dependence in terms of eight area categories that range from 0.3 to 1000 km^2. The four categories with areas ≤10 km^2, corresponding to a 3.2 km diameter, account for 92% of the total icebergs. While Halley's iceberg 'B' had a 9 km length at its waterline, such that it was the largest iceberg observed from any of the ships and would have been visible in the scatterometer data, Halley provided no estimate of its area. Assuming that the *Resolution* encountered 1000 icebergs, their Table S2 shows that only seven of these would have areas >1000 km^2. The low probability of these giant icebergs is one reason that they were not observed from the ships.

3.2.1 Iceberg trajectories and positions

Figure 2 shows Cook's cruise tracks and iceberg observations in blue, the BYU/NIC trajectories in red, the AWI trajectories in orange, and the Halley, Bouvet and Riou observations in black, where these colors were chosen to make the figure color-blind accessible. An unusual feature of the display is that many of the orange trajectories occur southeast of the red trajectories. Wagner and others (2017) provide an explanation. As their

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analysis and their Figure 7 show, large icebergs, which they define as having length scales >15 km, drift with the ocean currents. Smaller icebergs, which they define as having length scales <1.5 km, continue to drift with the currents but are more strongly driven by the winds. This size difference roughly corresponds to different iceberg sizes of the two satellite datasets.

Stern and others (2016, Figs 3a–3c) similarly show that as the iceberg length scale increases from 60 m to 1.7 km, the trajectories of the Weddell icebergs shift from the winds carrying them into the central Weddell to the currents keeping them adjacent to the coast. For Halley's iceberg 'B', its location north of South Georgia places it within the stream of large icebergs carried by the currents. All this strongly suggests that the red trajectories tend to follow the currents, while most of the orange trajectories follow the winds.

The red BYU/NIC trajectories show there is a dense counterclockwise coastal flow of icebergs around the continent to the Weddell Sea, where the Antarctic Peninsula diverts them to the northeast into a region of the South Atlantic nicknamed 'Iceberg Alley'. About 90% of the icebergs exit the Antarctic region through this outflow (Stuart and Long, 2011). Of the remainder, 8% exit the Ross Sea, and ∼2% leave the coast east of the Amery Ice Shelf at about 90°E. Since the neglect of small icebergs biases these percentages, the actual outflow from the region may be much larger.

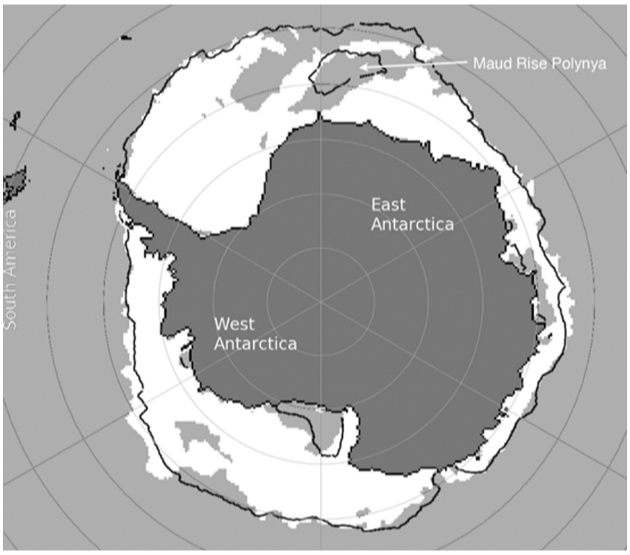

Fig. 3. Passive satellite image of the Antarctic sea-ice extent for 14 December 2018. Sea ice is white, water is light gray, the continent is dark gray. For the same date and the thirty-year period 1981–2010, the black lines show the median ice extent. The open water associated with the Maud Rise Polynya (indicated with arrow) is visible in both the daily and median image (Image courtesy NSIDC).

3.2 Cook's five traverses

3.2.1 First traverse: Eastern Weddell Sea

After leaving Cape Town, Cook's first traverse began in the Weddell Sea when on 10 December 1772, he saw his first iceberg. Cook 'judged it to be about 50 feet (15 m) high and half a mile (800 m) in circuit. It was flat at top, and its sides rose in a perpendicular direction (Cook, 1777a, 22)'.

On 14 December 1772, Cook encountered a tongue of sea ice and icebergs that blocked his advance south. From Cook's description, '…we were stopped by an immense field of low ice; to which we could see no end, either to the east, west, or south. In different parts… were islands, or hills of ice, like those we found floating in the sea… (Cook, 1777a, 24)'. The ship sailed east until on 21 December, it reached the tip of this sea-ice tongue, '…having never less than ten or twelve islands in sight (Cook, 1777a, 29)'. The *Resolution* then sailed south until it reached the southern edge of the tongue, turning west on Christmas Day with the goal of reaching the longitude of Cape Circumcision (12.5°E).

The position of this sea-ice tongue is in part determined by the Maud Rise Polynya, which frequently occurs in the austral autumn within the 62°S–68°S, 3°W–12°E box in Figure 2 (Mchedlishvili and others, 2022). The combination of the winds and ocean circulation drives the warm water upwelling within the polynya, which in late autumn melts the surface ice. From the numerical model of Beckmann and others (1999), the polynya is at one of the two centers of the double-cell Weddell gyre, with the other at ∼15°W.

From daily passive microwave sea-ice images from National Snow and Ice Data Center (NSIDC), Figure 3 shows that for 14 December 2018, the sea-ice tongue also occurs (NSIDC, 2022). On the figure, the black line is the median ice extent for the same day averaged over 1981–2010. This median line shows the ice extent and the Maud Rise Polynya. The tongue is a transient feature, with its northern boundary determined by the melting ice edge, and its southern boundary by a combination of the receding ice edge and the growing open-water area of the polynya. Relative to Cook's sea-ice tongue, the NSIDC tongue occurs a week to 10 days earlier, with its northern boundary ∼500 km south, and its eastern tip ∼250 km east.

Given the sea-ice tongue as evidence for a greater ice extent during 1772 in the eastern Weddell Sea, Parkinson (1990) examined Cook's other observations of the sea-ice edge, which occurred during his three crossings of the Antarctic Circle. She found that these were either consistent with or even slightly less than the 1970s satellite observations. As Parkinson (1990, 7) concludes, given the lack of enhanced sea-ice extents from other regions, the enhanced ice cover that Cook observed is 'of interest, but …remains unexplained'.

On 8 January 1773, after leaving the tongue, Cook made his critical recovery of fresh water at the position circled in Figure 2, then on 17 January 1773, the *Resolution* crossed the Antarctic Circle for the first time, where compact sea ice stopped its farther southward movement. The ship was 175 km from land, its closest distance to the continent. It then sailed north on this traverse until on 30 January 1773, Cook reported his last iceberg.

3.2.2 Second traverse: Indian Ocean

On 16 February 1773, the *Resolution* sailed southeast in the Indian Ocean to encounter a region of enhanced iceberg density. Between 81°E and 97°E, Cook and Wales observed many icebergs in approximately the same location as the BYU/NIC iceberg plume around 90°E in Figure 2. Tournadre and others (2008, Fig. 6b), from an analysis of altimeter data for November 2004 to December 2005, also found a large concentration of icebergs south of 60°S between 70°E and 120°E.

For this region, Wales (1775) provides a valuable supplement to Cook's description. For 18 February, as marked on Figure 2, when Cook only reported position, Wales (1775, 64) reported 'many very large islands of ice'. Cook also provides no position or iceberg observations for 19 February, yielding a gap in his observations between 18 and 20 February, corresponding to longitudes 83°E and 91°E, for a separation of 465 km. Although Wales (1775, 64) does not give position data for 19 February, in the morning he reports 'eight exceedingly large islands of ice', and in the afternoon, 'many large islands of ice'. His observation fills the gap in Cook's data and shows that the iceberg coverage remains dense across the plume.

For 20 February 1773 at 91°E, Cook wrote 'nothing was to be seen but ice islands'. On 23 February at 95°E, Cook said

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'[daylight] only served to increase our apprehensions, by exhibiting to our view those huge islands of ice, which in the night, we had passed without seeing (both quotes from Cook, 1777a, 55–56)'. After sailing through the plume, the *Resolution* encountered few icebergs as it continued east, until 16 March 1773, when it turned north.

3.2.3 Third traverse: Ross Sea

On 8 December 1773, during the next austral summer, the *Resolution* sailed south along 180° to reach the western Ross Sea, then transited east. As Figure 2 shows, some of the icebergs within this region originated from the vicinity of the Ninnis/Mertz Ice Tongue at about 150°E, others originated directly from the Ross Sea. On 20 December 1773, the ship crossed the Antarctic Circle for the second time. The next morning, Cook wrote 'The ice islands …were high and rugged, forming at their tops many peaks…many of them were between two and three hundred feet (60–90 m) in height and between two and three miles (4–6 km) in circuit, with perpendicular cliffs or sides, astonishing to behold'. On 24 December at 138°W, Cook wrote 'we could see near 100 around us', and on 26 December at 134°E, he saw '200 large ice islands (all quotes from Cook, 1777a, 254–256)'. On 31 December 1773 at 131°E, the ship turned north, leaving the region on 6 January 1774.

3.2.4 Fourth traverse: Amundsen Sea

On 13 January 1774, the *Resolution* sailed into the Amundsen Sea. It crossed the Antarctic Circle for the third time, then on 30 January 1774 achieved its farthest south (71.2°S, 106.9°W) on the shelf of the ASE, into which the Pine Island and Thwaites Glaciers discharge. At this position, the water depth was 480 m, and the ship was 10 km south of the shelf break and 400 km north of the present position of the Pine Island Glacier (depth and locations from ETOPO1, Amante and Eakins, 2009).

A solid wall of pack ice and icebergs confronted the ship, which Cook described as follows: '…at eight o'clock [in the morning], we were close to its edge. It extended east and west, far beyond the reach of our sight…Ninety-seven ice-hills were distinctly seen within the field, besides those on the outside, many of them very large, and looking like a ridge of mountains, rising one above another till they were lost in the clouds…(Cook, 1777a, 267)'. Wales (1775, 181) helps interpret Cook's description. Wales stated that the morning was foggy and '…within this field, which we could not see over, there seemed to run a long ridge of prodigious high mountainous ice, which was probably only a fog-bank'.

Taken together, Cook's and Wales's observations suggest that the apparent rise of the ice into the clouds was an illusion generated by the fog, and not a view of an ice shelf or glacier. In support of this interpretation, Larter and others (2014) show from marine geophysical data that 10 000 years ago, the ice shelves in the embayment were close to their present positions. Also, Graham and others (2022), in their examination of the retreat of the Thwaites Glacier, cite evidence that shows over the past millennia, its retreat rate was 0.01–0.02 km per year, while their work on the Thwaites response to a grounding ridge shows that short periods of rapid retreat of ∼2 km per year punctuate this long-term rate. For the last two centuries, they estimate overall rates of 0.3–0.8 km a^{-1}. Both studies suggest that during Cook's visit, the ice shelves in the embayment were at least 200 km south of the *Resolution*, so that Cook and Wales could not have seen the glaciers. The large number of icebergs that Cook and Wales observed probably originated from calving of the Thwaites and Pine Island Glaciers. After this achievement, the ship turned north, and Cook ceased to record icebergs.

Because of its potentially large contribution to sea-level rise, the Thwaites Glacier is a topic of urgent scientific study. In 2015, the US National Academy of Sciences and the UK Royal Society endorsed a joint 5-year program, the ITGC, that began its fieldwork in 2018 (Scambos and others, 2017; NSIDC, 2018; ITGC, 2022). Thus, for the ASE, the Royal Society endorsed both Cook's expedition and the ITGC, two projects separated by 244 years.

3.2.5 Fifth traverse: Western Weddell Sea

Eleven months later on 3 January 1775, the *Resolution* left a protected anchorage on Isla de los Estados (Staten Island) in the vicinity of Cape Horn and sailed east into the Weddell Sea. In iceberg-free waters, Cook discovered South Georgia Island, then sailed southeast to discover the South Sandwich Islands. On 28 January 1775 at 60.0°S, 29.3°W, Cook observed his first icebergs on this traverse. Cook stated they were 'surrounded with a vast number of large ice-islands…[These] were nearly all the same height, and showed a flat even surface…some being two or three miles [4–6 km] in circuit'. From their circumference, these icebergs had diameters of ∼2 km. Two days later at 59.5°S, 29.4°W, they '…passed one of the largest ice-islands we had seen…' without recording its size (Cook, 1777b, both quotes p. 204).

Figure 2 shows that although the icebergs from Cook's second Weddell traverse lie within the envelope of the BYU/NIC and AWI trajectories, they are displaced to the east. This displacement may be due to Cook's course, where he sailed northeast along the edge of BYU/NIC trajectory envelope, then southeast along the South Sandwich Island arc. It may also result from natural variability, since Cook's traverse provides only a 1-month sample of the iceberg distribution, while the BYU/NIC trajectories provide a multi-decadal sample. Despite this eastern displacement, Cook's icebergs lie within the satellite trajectories.

On 14 February 1775, they crossed the prime meridian and sailed through Bouvet's position for Cape Circumcision, after which Cook concluded that what Bouvet 'had seen could be nothing but an island of ice, for if it had been land, it is hardly possible we could have missed it (Cook, 1777b, 319)'. Finally on 26 February near 30°E, they saw their last iceberg before returning to Cape Town.

4. Reconciliation of the Guardian observations with modern data

The iceberg observations by Halley, Bouvet and Cook agree with modern data. For Cook, this includes the plume of icebergs from east of the Amery Ice Shelf and the iceberg distributions in the Weddell, Ross and Amundsen Seas. Riou's icebergs, however, lie ∼1000 km east of the nearest BYU/NIC trajectories. As England and others (2020) show, these can be brought into agreement by extension of the BYU/NIC trajectories by application of a drift model and the footloose mechanism (Wagner and others, 2014).

As Section 2.2.2 describes, the footloose fracture mechanism depends on ocean waves and above-freezing seawater. Under these conditions, the waves cut notches into the sides of the icebergs, where their penetration depths grow at speeds of meters-per-day. When the notch becomes deep enough, the overburden collapses, leaving an underwater foot, identical to that on which the *Guardian* collided and ran aground. The foot exerts a torque on the iceberg, which as the foot grows in length, fractures the iceberg. In support of this mechanism applying to the *Guardian* icebergs, the warm air temperatures between 10 and 15°C imply warm seawater, the collision is direct evidence of an underwater foot, and the iceberg sizes, with the possible exception of the one involved in the collision, were smaller than the scatterometer resolution.

When Wagner and others (2014) apply their model to the BYU/NIC icebergs, they find that even as the iceberg size falls below the scatterometer resolution, the icebergs continue to drift as they shed smaller icebergs. Examination of their Figure 4c shows that two of BYU/NIC trajectories, when enhanced by the footloose model, continue to drift east in the ACC to the longitudes and approximate latitude of Riou's icebergs. This means that all the ship observations of icebergs are consistent with modern observations and theory.

5. Conclusions

This paper examines the distribution and properties of the icebergs observed during Cook's 1772–75 circumnavigation of Antarctica, Halley's 1700 traverse into the South Atlantic, Bouvet's 1739 discovery of Cape Circumcision and Riou's 1789 disastrous iceberg encounter in the Antarctic Circumpolar Current. Because the application of an ice drift and the footloose mechanism to the BYU/NIC trajectory data by England and others (2020) explains the outliers observed by Riou, the distribution of all the ship-observed icebergs agrees with modern observations and theory. The largest iceberg Cook records had a 5 km^2 area, and while Halley's largest iceberg had a 9 km waterline length, he provided no estimate of its area. Based on the power-law curve of Tournadre and others (2016), England and others (2020) show that the size of Cook's largest iceberg is equal to or greater than at least 92% of the Antarctic icebergs. The fact that none of the ships observed giant icebergs is explained by their low probability of occurrence.

The areas of agreement between Cook's icebergs and modern data include their distribution in the Weddell Sea, the plume to the east of the Amery Ice Shelf and the results of his traverses in the Ross and Amundsen Seas. For sea ice, although Cook's sea-ice edge in regions other than the eastern Weddell Sea agrees with satellite observations, the large differences between his and satellite imagery of the sea-ice tongue remain unexplained (Parkinson, 1990). Cook's transect onto the shelf of the ASE, where the ship attained its farthest south and Cook and Wales observed at least a hundred icebergs that probably calved from the Pine Island and Thwaites Glaciers, provides a remarkable precursor to the ITGC that began its fieldwork in 2018.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/jog.2022.111

Data. The BYU/NIC data can be downloaded at www.scp.byu.edu/iceberg. Cook's and other shipboard iceberg positions are available in the Supplementary material. The AWI dataset is available from MPS at michael.p.schodlok@jpl.nasa.gov.

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References

Amante C and Eakins BW (2009) ETOPO1 1 Arc-Minute Global Relief Model: procedures, data sources and analysis. NOAA Technical Memorandum NESDIS NGDC-24, National Geophysical Data Center, NOAA. doi: 10.7289/V5C8276M

Beckmann A, Hellmer HH and Timmerman R (1999) A numerical model of the Weddell Sea: large-scale circulation and water mass distribution. *Journal of Geophysical Research Oceans* **104**(C10), 23375–23391. doi: 10.1029/1999JC900194

Budge JS and Long DG (2018) A comprehensive database for Antarctic iceberg tracking using scatterometer data. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* **11**(2), 434–442. doi: 10.1109/JSTARS.2017.2784186

Cook J (1777a) A voyage towards the South Pole and round the world. Performed in His Majesty's ships the *Resolution* and *Adventure* in the years 1772, 1773, 1774, and 1775 (Volume 1). Strahan and Cadell, London. Available at https://open.library.ubc.ca/viewer/chungpub/1.0129127 (Project Gutenberg has a downloadable version of this book in The three voyages of Captain Cook around the world, volume 3, at https://www.gutenberg.org/ebooks/author/2644?sort_order=title, last viewed April 2022).

Cook J (1777b) A voyage towards the South Pole and round the world. Performed in His Majesty's ships the *Resolution* and *Adventure*, in the years 1772, 1773, and 1775 (Volume 2), Strahan and Cadell. Available at https://open.library.ubc.ca/viewer/chungpub/1.0129126 (Project Gutenberg has a downloadable version in The three voyages of Captain Cook around the world, volume 4, at https://www.gutenberg.org/ebooks/author/2644?sort_order=title, last viewed June 2022).

Dickson R (ed.) (2012) *HMS Guardian and the island of ice: the lost ship of the first fleet and Lieutenant Edward Riou*, 1789-1790. Carlisle, Australia: Hesperian Press, 128 pp.

England MR, Wagner TJW and Eisenman I (2020) Modeling the breakup of tabular icebergs. *Science Advances* **6**(51), eabd1273. doi: 10.1126/sciadv.abd1273

Graham AGC and 11 others (2022) Rapid retreat of Thwaites Glacier in the pre-satellite era. *Nature Geosciences* **15**, 706–713. doi: 10.1038/s41561-022-01019-9

ITGC (2022) International Thwaites Glacier Collaboration, British Antarctic Survey. Available at https://www.bas.ac.uk/project/international-thwaites-glacier-collaboration/ (last viewed August 2022).

Larter RD and 17 others (2014) Reconstruction of changes in the Amundsen Sea and Bellingshausen Sea sector of the West Antarctic Ice Sheet since the Last Glacial Maximum. *Quaternary Science Reviews* **100**, 55–86. doi: 10.1016/j.quascirev.2013.10.016

Mchedlishvili A, Spreen G, Melsheimer C and Huntemann M (2022) Weddell Sea polynya analysis using SMOS–SMAP apparent sea ice thickness retrieval. *The Cryosphere* **16**, 471–487. doi: 10.5194/tc-16-471-2022

Mitchell Library (2022) Painting by Hodges, William – The Resolution and Adventure, 4 Jan 1773, taking in ice for water, lat. 61.S. From original sketches, drawings, maps etc collected by Admiral Isaac Smith/drawings and watercolours, mainly of Captain Cooks second voyage (1772–1775), call number SAFE/PXD 11, State Library of New South Wales. Available at https://collection.sl.nsw.gov.au/digital/gwZBwlom6gybk (last viewed September 2022).

NSIDC (2018) UK and US polar scientists team up to study Antarctica's 'wild card,' NSIDC press release, 30 April 2018. Available at https://nsidc.org/news/newsroom/archive/all (last viewed July 2022).

NSIDC (2022) Southern hemisphere daily and monthly sea ice files. Available at https://masie_web.apps.nsidc.org/pub//DATASETS/NOAA/G02135/south/ (Last viewed May 2022).

Parkinson CL (1990) Search for the little ice age in Southern Ocean sea-ice records. *Annals of Glaciology* **14**, 221–225. doi: 10.3189/S0260305500008624

Riou E (1790) Volume 02: Riou's narrative of the wreck of the Guardian, 8 September-25 December 1789, probably written 1790, State Library of New South Wales, Manuscripts Oral History and Pictures Catalogue, Call Number SAFE/MLMSS 4711/2 (Safe 1/223b). Available at https://archival.sl.nsw.gov.au/Details/archive/110336566, transcription at acms.sl.nsw.gov.au/_transcript/2012/D01277/a2686.htm (last viewed July 2022).

Scambos TA and 22 others (2017) How much, how fast? A science review and outlook for research on the instability of Antarctica's Thwaites Glacier in the 21st century. *Global and Planetary Change* **153**, 16–34. doi: 10.1016/j.gloplacha.2017.04.008

Schodlok MP, Hellmer HH, Rohardt G and Fahrbach E (2006) Weddell Sea iceberg drift: five years of observations. *Journal of Geophysical Research Oceans* **11**, C06018. doi: 10.1029/2004JC002661

Skullern I (2016) Larcum Kendall and K1: the greatest watchmaker and watch you have (probably) never heard of, Quill and Pad. Available at https://quill-landpad.com/2016/06/08/larcum-kendall-k1-greatest-watchmaker-watch-probably-never-heard/ (last viewed May 2022).

Sobel D (2005) *Longitude*, 10th Edn. London: Walker and Company, 191 pp.

Stern AA, Adcroft A and Sergienko O (2016) The effects of Antarctic iceberg calving-size distribution in a global climate model. *Journal of Geophysical Research Oceans* **121**, 5773–5788. doi: 10.1002/2016JC011835

Stuart KM and Long DG (2011) Tracking large tabular icebergs using the SeaWinds Ku-band microwave scatterometer. *Deep-Sea Research II: Topical Studies in Oceanography* **58**(11–12), 1285–1300. doi: 10.1016/j.dsr2.2010.11.004

Thrower NJW (ed.) (1981) The three voyages of Edmond Halley in the Paramore, 1698–1701, Second Series No. 156, The Hakluyt Society, London, 392 pp., pp. 162–163.

Tournadre J, Bouhier N, Girard-Ardhuin F and Rémy F (2016) Antarctic iceberg distributions 1992–2014. *Journal of Geophysical Research Oceans* **121**, 327–349. doi: 10.1002/2015JC011178

Tournadre J, Whitmer K and Girard-Ardhuin F (2008) Iceberg detection in open water by altimeter waveform analysis. *Journal of Geophysical Research Oceans* **113**, C08040. doi: 10.1029/2007JC004587

Wagner TJW and 8 others (2014) The 'footloose' mechanism: iceberg decay from hydrostatic stresses. *Geophysical Research Letters* **41**, 5522–5529. doi: 10.1002/2014GL060832

Wagner TJW, Dell RW and Eisenman I (2017) An analytical model of iceberg drift. *Journal of Physical Oceanography* **47**(7), 1605–1616. doi: 10.1175/JPO-D-16-0262.1

Wales W (1775) Log book of HMS Resolution, 1772–1775, compiled by William Wales, Royal Greenwich Observatory Archives, Papers of the Board of Longitude (RGO 14/58). Available at https://cudl.lib.cam.ac.uk/view/MS-RGO-00014-00058/ (last viewed August 2022).