BAMS Article

The Role of the Weather in the Fate of Shackleton's *Endurance*

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Climate variability;
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ABSTRACT: *Endurance*, one of the main vessels of the Imperial Trans-Antarctic Expedition of 1914–17, became stuck and eventually was crushed by sea ice, sinking to the bottom of the Weddell Sea; yet, miraculously, every member of the expedition returned safely home. Nonetheless, it still is not clear what role the weather of 1914–15 may have played in the ship becoming beset and destroyed by the ice conditions, forcing the need for a heroic survival. Through examining the weather observations from *Endurance* in a climatological perspective, two key elements emerge that may have compromised the expedition. First, the austral summer of 1914–15 was marked with more extensive sea ice in the Weddell Sea both in the context of satellite observations and estimates from the twentieth century, consistent with an ongoing El Niño event. Once the ship became beset in the ice, persistent near-record minimum daily mean temperatures lasted through the remainder of the summer of 1914–15, offering little opportunity before winter to become dislodged. Second, the austral spring season of 1915 was marked by persistent high pressure anomalies in the Weddell Sea, confirmed by nearby observations and reconstructions. These extensive, persistent high pressure conditions delayed ice breakup in the Weddell Sea and moved the ship into heavier multiyear ice, ultimately limiting opportunities for an early escape from the ice. While it is impossible to conclusively prove that these exceptional conditions sealed the fate of *Endurance*, neighboring years do not show such extreme conditions, which may have led to a different outcome altogether.

SIGNIFICANCE STATEMENT: The Imperial Trans-Antarctic Expedition is one of the greatest tales of Antarctic history. Here, we analyze the conditions recorded by the crew during the journey of *Endurance* from a climatological perspective. Importantly, these comparisons suggest that the ship likely encountered one of the most extensive years of ice coverage and persistent near-record cold temperatures in the early twentieth century, leading to it becoming beset much earlier than expected with no opportunity to escape prior to winter. Additionally, a dominant high pressure in the austral spring also likely hindered their ability to achieve an early escape. If the expedition was completed in a different year, a very different outcome may have resulted, making this tale of heroism and survival even more impressive.

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1. Introduction

Of all the legends of Antarctic heroism and discovery, the 1914–17 Imperial Trans-Antarctic Expedition, led by Sir Ernest Shackleton, is arguably one of the most well-known and powerful. The primary goal of the component of this expedition led by Shackleton was to sail south into the Weddell Sea, land on the Antarctic continent as far south as possible, traverse the continent on foot to the South Pole, and rendezvous with other members who had landed on the continent via the Ross Sea for their return northward. It was a very ambitious journey from the start but plans quickly changed as the ship *Endurance* became lodged in thick pack ice early on in their voyage south in the Weddell Sea, never to be freed, and eventually was crushed and sank in November 1915. In small lifeboats, the crew managed to land on nearby Elephant Island on 14 April 1916, until a small rescue effort led by Shackleton and expert navigator Frank Worsley miraculously guided the lifeboat *James Caird* across the perilous Drake Passage and South Atlantic to South Georgia (Fig. 1a) later that month. A few members of this rescue team then were the first to ever cross South Georgia on foot to the whaling station at Stromness, and, after a number of failed efforts, a Chilean ship rescued the remaining expedition members from Elephant Island at the end of August 1916. Amazingly, against all odds, no one perished during this journey, and Shackleton, although unsuccessful at his original goals, emerged as one of the greatest leaders of the heroic age of Antarctic exploration. Impressively, much of the remains of *Endurance* was recently discovered at the bottom of the Weddell Sea in March 2022, bringing this story of heroism and survival back into public attention.

Few could argue that in such challenging conditions, Shackleton was not an effective leader. However, it is not yet clear if the expedition was compromised or made even more difficult because of the (uncontrollable) weather conditions the crew faced during this particular time. Despite being in survival mode and facing the harsh conditions in the Weddell Sea, Shackleton and his crew, especially expedition meteorologist Leonard Hussey, continued to record the meteorological conditions (temperature and pressure) until April 1916. Remarkably these observations were preserved during the perilous journey to Elephant Island on small lifeboats. Moreover, due primarily to the commercial activity from hunting seals and whales, the proximity to South America and several islands, the Weddell Sea region already had a relative abundance of nearby observations (Fig. 1b) that can further detail the conditions experienced by the crew, now in a much longer climatological context. Indeed, similar comparisons with more modern-day longer historical records have demonstrated some of the unique aspects of weather that may have led to different outcomes of the first successful expeditions to the South Pole led by Robert F. Scott and Roald Amundsen (Solomon and Stearns 1999; Solomon 2001; Fogt et al. 2017). More recently, and similar to this study, the ice conditions experienced by *Belgica*, which also became lodged in the ice for a year in 1898 in the Bellingshausen and Amundsen Seas, but successfully broke free, were recently placed into the context of modern satellite observations to help document potential long-term change elsewhere around Antarctica (Doddridge et al. 2024).

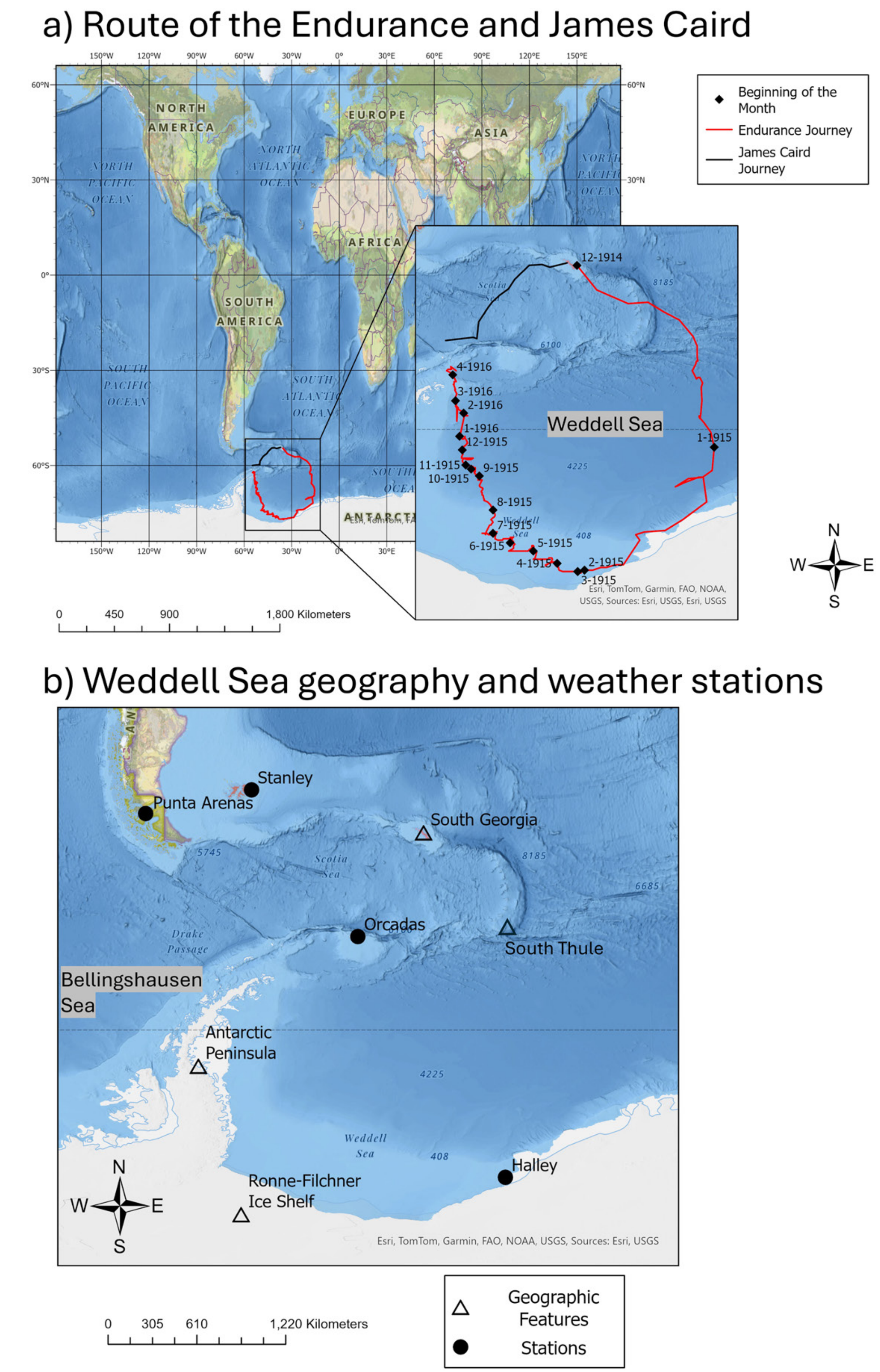

Fig. 1. (a) Map of the routes of *Endurance* and *James Caird*, with relevant dates for the voyage of *Endurance* given in the map subset. (b) Locations of local weather station data and geographic features. Note: Only pressure data from Punta Arenas, Stanley, and South Georgia were assimilated into various twentieth century reanalyses in 1914–17; observations from *Endurance* were only assimilated into 20CRv3.

Even in the Weddell Sea, a few years prior to *Endurance*, Filchner's *Deutschland* was beset in pack ice in 1912, but eventually drifted northward and was dislodged without suffering damage. Earlier, in 1902, the Scottish National Antarctic Expedition ship *Scotia* sailed south into the Weddell Sea and frequently encountered the pack ice and regions of open water in February near 60°–70°S, but ultimately did not sail as far south as either *Endurance* or *Deutschland* and was only stuck in the ice while anchored for winter over along the South Orkney Islands (near present-day Orcadas Station, Fig. 1). Nonetheless, both of these early voyages highlight that regional ice conditions can vary greatly from year to year in the early twentieth century, and that even if *Endurance* were to get stuck, Shackleton had reason to believe it might get free without any damage.

Here, we investigate the meteorological conditions recorded by the crew of *Endurance* in light of contemporary reanalysis data (Hersbach et al. 2020), twentieth-century reanalysis data (Slivinski et al. 2019; Laloyaux et al. 2018; Poli et al. 2016; Fogt and Connolly 2021), and nearby observations spanning a century from Orcadas Station on the South Orkney Islands (Zazulie et al. 2010), supplemented by recent reconstructions of Antarctic pressure and sea ice extent (SIE) (Fogt et al. 2016a,b, 2022). By employing a longer historical context, it is possible to determine how the weather of this particular year may have added unexpected and additional challenges that altered the main goals of the expedition and forced the heroic outcome.

2. The unique weather during 1914–15

Using the daily latitude and longitude coordinates provided in *Endurance* logbooks (Fig. 1a), Fig. 2 enables a comparison of the weather and ice conditions the ship and crew encountered throughout the Weddell Sea from December 1914 to 1915 with more recent climatological data. The fifth generation European Centre for Medium-Range Weather Forecasts atmospheric reanalysis (ERA5) data (1959–2021) are used after the onset of the International Geophysical Year, when more Antarctic data were assimilated into ERA5, especially around the Antarctic Peninsula (Marshall et al. 2022), to provide a longer-term perspective (represented here as anomalies, differences from the 1959–2021 mean) for both daily mean temperature (Fig. 2a) and pressure (Fig. 2b); satellite observations of sea ice concentration (1979–2022) from the National Snow and Ice Data Center (NSIDC) are used to provide a climatology of sea ice conditions along the journey (see the appendix for technical details on the data and methods). While many of *Endurance's* daily mean temperature and pressure anomalies oscillate around the ERA5 climatological mean, there are a few key exceptions that stand out in Fig. 2: The crew encountered much colder-than-average conditions and an early approach to dense pack ice in December 1914–February 1915 (Figs. 2a,c) and persistent high pressure anomalies in September–November 1915. These periods correspond to the time when *Endurance* was first stuck in the ice (19 January 1915) and the ultimate sinking of *Endurance* (21 November 1915) and are therefore the focus of this study.

a. An unusually cold start. Within a week of its departure from South Georgia (Fig. 1b), *Endurance* first encountered ice on 8 December 1914 and ventured into it 11 December 1914. Compared to the climatology from satellite observations (Fig. 2c), the latitude of the pack ice edge at this time appears to be much northward of its average position in the 1979–2022 satellite sea ice record. In the satellite sea ice record, the average observed sea ice concentration (SIC) is still <5% at this location and time, less than the 15% threshold typically used to mark the sea ice edge (Meier et al. 2021), with only a few years of observed ice, with the maximum near 50% SIC. The ship therefore encountered ice earlier than would be common over the last 40 years. Shackleton made note of this, saying, "This was disconcerting. . . I had not expected to find pack-ice nearly so far north, though the whalers had reported pack

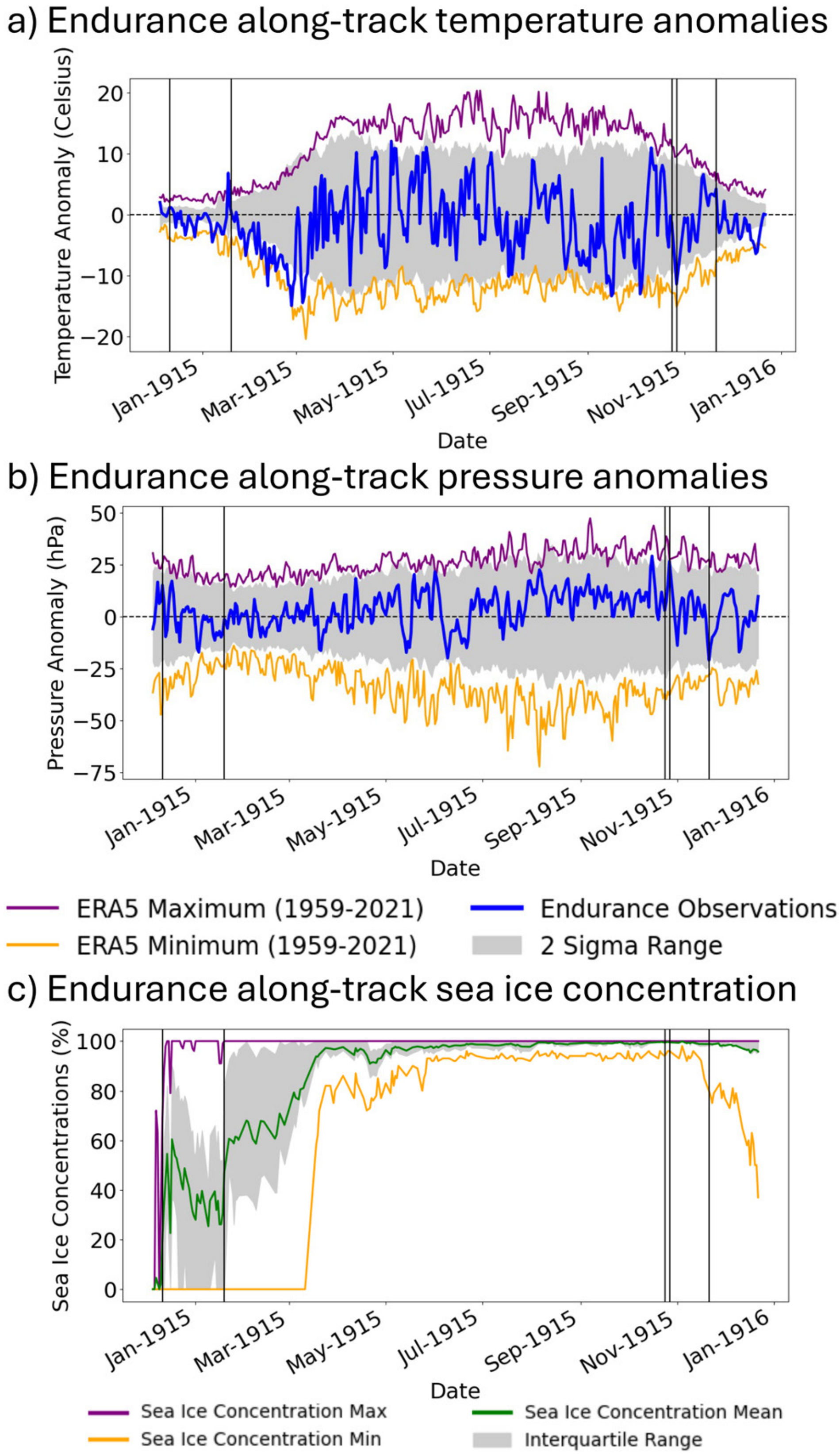

Fig. 2. ***Endurance*** **along-track daily mean observations, represented as anomalies from the along-track daily mean ERA5 data (which include the maximum–minimum anomaly) during 1959–2021 for (a) temperature and (b) mean sea level pressure. (c) NSIDC daily mean along-track sea ice concentration (minimum, mean, maximum, and interquartile range, 1979–2022). The vertical lines mark specific dates for** ***Endurance*****, respectively: ship first entered pack ice (11 Dec 1914), ship became stuck in the ice (19 Jan 1915), ship cracked and began to fill with water (24 Oct 1915), ship was abandoned (27 Oct 1915), and ship sank (21 Nov 1915).**

right up to South Thule" (Shackleton 1998, p. 5) (Fig. 1b for location). While the sea ice concentrations varied in Shackleton's words from "loose" (interpreted as much less than 50% SIC) to "heavy" (interpreted as >50% SIC) pack ice as they sailed south, the observed mean ice concentration is typically around 40%–50% (Fig. 2c). Shackleton noted that during this portion of the journey, the ship only once left the pack into the open ocean again for about a 36-h period spanning 8–10 January 1915. Even at the point when the ship became stuck in the ice (second vertical line in Fig. 2), the mean ice concentrations are normally around 60%, with less than 25% of the time having observed sea ice concentrations as much as 100%. Thus, not only did *Endurance* encounter ice much earlier than typically observed from satellite measurements, but it also became stuck in dense pack ice much earlier than expected based on over 40 years of satellite observations.

From Fig. 2a, the crew also encountered much colder-than-average conditions at the beginning of the expedition, with temperatures for much of December 1914–February 1915 approaching the record minimum daily mean temperatures from ERA5. From Fig. 2a, a short-lived warm temperature anomaly preceded the persistent cold spell, likely indicating a storm. During the warmest temperature anomaly on 16–17 January 1915, Shackleton and his crew sought shelter near a large iceberg from the winds, noting, "A blizzard from the east-north-east prevented us leaving the shelter of the berg on the following day (Sunday, 17 January). The weather was clear, but the gale drove dense clouds of snow off the land and obscured the coast-line most of the time" (Shackleton 1998, p. 28). When the crew did finally leave on the 18th, they ventured into the pack ice again, and in his retelling of the story, Lansing notes, "Almost immediately they realized that this was a different sort of ice from anything they encountered before. The floes were thick but very soft, and consisted mostly of snow" (Lansing 2014, p. 34). The blizzard-like conditions a few days prior likely altered the ice conditions, and, unfortunately, in a short time, on 19 January, the ship was lodged and trapped into the pack ice as it closed around it. Although the crew made some attempts to dislodge the ship, Fig. 2a indicates they encountered nearly a month of persistent, near-record cold extreme temperature anomalies (well below two standard deviations from the along-track ERA5 data). While the Weddell Sea is generally the region of the Antarctic with the most summer sea ice from satellite observations (Parkinson 2019), it is very likely that this persistent cold would result in an even more extensive-than-normal Weddell Sea ice coverage in the late summer through early fall, with the small possibility of sufficient breakups in the ice to allow the ship to safely escape from the thick pack. Sea ice extent reconstructions based on paleoclimatological data (Abram et al. 2010; Dalaiden et al. 2021; Fogt et al. 2024) and estimates from ship logbook data (Edinburgh and Day 2016; Teleti et al. 2019) point to the possibility of generally increased Weddell Sea sea ice extent in the early twentieth century, which would support the likelihood of increased ice coverage during 1915 that beset *Endurance*. However, these estimates with coarse spatial and temporal resolution (only for a few locations and times of year in the Weddell Sea) do not yet set it apart from *Deutschland*, which was able to break free from the Weddell Sea pack ice just a few years prior.

To check the possibility of increased sea ice coverage for the specific years of *Endurance*, Figs. 3a and 3b examine other sources of early twentieth-century sea ice estimates (Fogt et al. 2022; Murphy et al. 1995, 2014). In Fig. 3a, boxplots of the seasonal sea ice extent distributions from reconstructions (1905–2020) for the Weddell Sea indicate that sea ice extent in December 1914–February 1915 was in the upper quartile (reconstructions also indicate a record high for circumpolar total Antarctic extent at this time, not shown). Sea ice remained continuously high throughout the year from the reconstructions for the Weddell Sea (Fig. 3a), supporting the dense ice conditions that *Endurance* encountered. Although this represents only an estimate of all the ice coverage in the Weddell Sea (and not at the specific location of

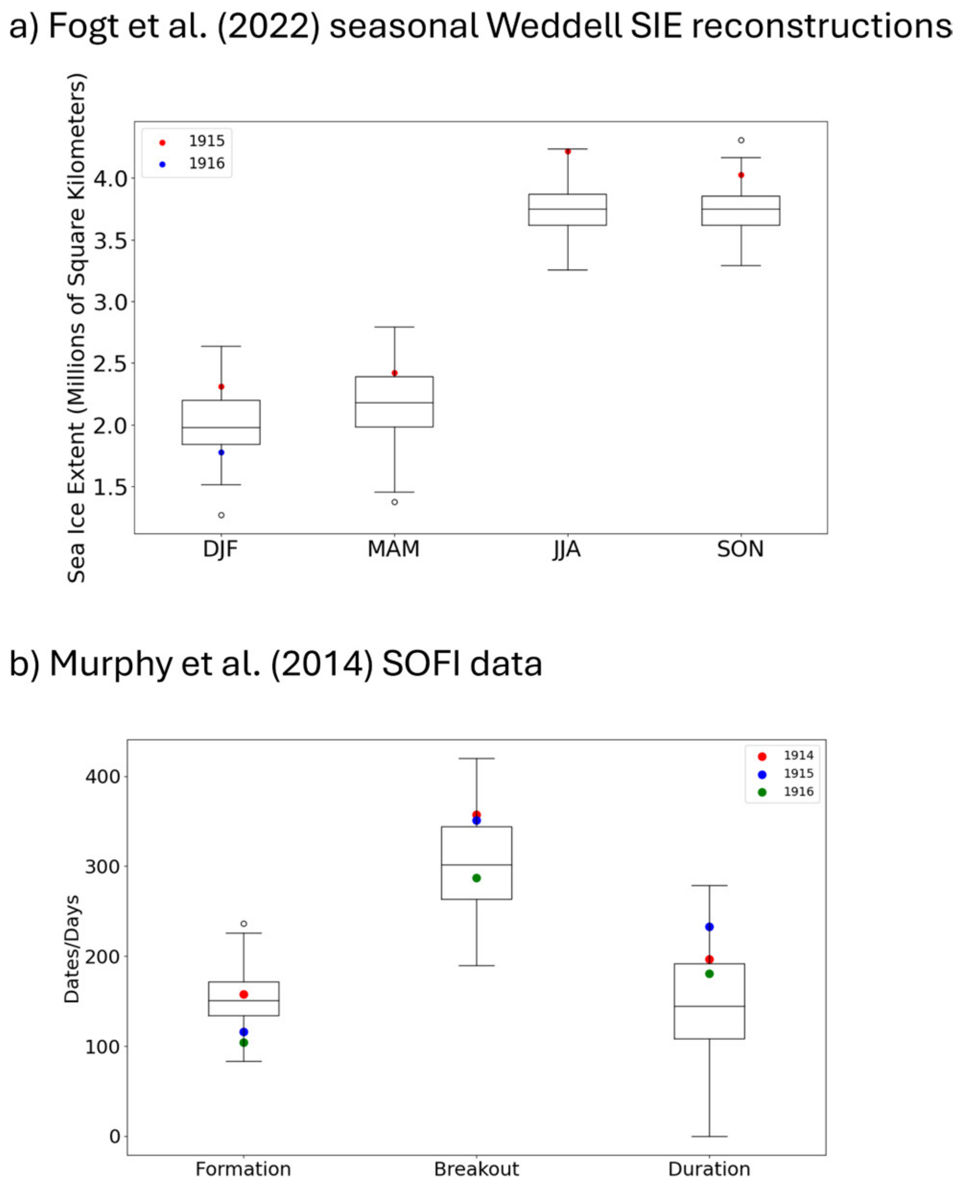

Fig. 3. Climatological aspects of the increased SIC for the beginning of *Endurance's* journey. (a) Boxplots of seasonal SIE distributions from the Fogt et al. (2022) reconstructions for the Weddell Sea, with the 1915 and 1916 seasonal values plotted separately with colored markers; (b) the SOFI from Murphy et al. (2014) boxplots for formation, breakout (both given as Julian days), and duration (given as a number of days). The whiskers on the boxplots extend to inner fences, 1.5 × IQR above and below the upper and lower quartiles, respectively. Outliers outside the inner fences are marked individually with open circles.

Endurance), these reconstructions continue to suggest that ice coverage during the period of very cold temperatures at the start of *Endurance* voyage into the Weddell Sea was much higher than normal, even in the context of the early twentieth century. This is further supported by the South Orkney fast ice (SOFI) observation-based data (Murphy et al. 1995, 2014) of dates (in Julian day, Fig. 3b) of formation and breakout of the fast (land trapped) ice on the South Orkney Islands (where Orcadas is located, Fig. 1b). In both 1915 and the year after, fast ice formation at the South Orkney Islands was in the earliest 25% of years, which was followed by a much later (top 25%) breakout date in both 1914 and 1915. Indeed, 1915, when *Endurance* was stuck in Weddell Sea sea ice, was the year with the 8th longest fast ice duration at the South Orkney Islands (out of 106 years, in the top 10%).

Altogether, the SOFI observations support the evidence from reconstructions and paleoclimatological data that during the time *Endurance* entered the Weddell Sea, it was encountering much heavier ice coverage than normal (even for the early twentieth century), which inevitably caused it to encounter ice earlier than typical and ultimately to become beset in February 1915. The persistent cold reflects the higher coverage of ice and kept the ship stuck in the ice throughout the summer. As ice began to advance, the ship was doomed to remain into the ice throughout the winter, when the ice concentrations are near 100% on average (Fig. 2c). The only hope would have been an earlier retreat of ice in austral spring that would have lessened the stress on the ship and possibly given it a break to escape.

b. Dominant high pressure during the normal ice retreat. The austral autumn and winter were marked by frequent swings in temperature and pressure along the track of *Endurance* (Figs. 2a,b), likely associated with typical synoptic weather patterns and the passage of storms followed by lulls. While these may have altered the conditions near the ice edge, by this time the ship was located near the Ronne–Filchner Ice Shelf (Fig. 1), far from the ice edge. To break free, *Endurance* needed to encounter warmer temperatures or persistent strong winds to help substantially break up and retreat the ice early in the Weddell Sea. Shackleton writes, "The vital question for us was whether or not the ice would open sufficiently to release us, or at least give us a chance of release, before the drift carried us into the most dangerous area. There was no answer to be got from the silent bergs and the grinding floes, and we faced the month of October with anxious hearts" (Shackleton 1998, p. 66). Unfortunately, fate was not on their side again, as nearly the opposite happened. During most of August–November 1915, pressures were persistently above average, associated with the dominance of high pressure (Fig. 2b) and lighter winds (not shown).

Since pressure anomalies tend to be more spatially uniform on monthly and longer time scales than temperature, we can use nearby weather data (Zazulie et al. 2010; Turner et al. 2004) to investigate the extent and magnitude of this high pressure anomaly pattern. Figure 2a demonstrates that although the pressure anomalies were not near record high values on any given day, this period in austral spring [August–October (ASO), or using traditional seasons, September–November (SON) 1915] was the only sustained period where daily pressure was nearly continuously above the long-term mean, with a few exceptions on days when cyclones passed nearby. The monthly mean observed pressure data from Orcadas (Fig. 4a) align well overall with *Endurance* data, despite the ship being over 1000 km south of the station at this time (Fig. 1), indicating spatially widespread pressure anomalies. Further, the Orcadas data also similarly reflect the persistent above-average pressure anomalies from September to November 1915 (red line, Fig. 4a), with October 1915 monthly mean pressures nearly two standard deviations above the 1903–2020 average. Seasonal pressure reconstructions for Halley Station, located around 860 km further southeast of *Endurance* at this time (Fig. 1), still show similar agreement with seasonal mean pressures from *Endurance* (Fig. 4b, left). In particular, both indicate that the pressures during SON 1915 were record high based on the 1905–2013 period covered by the Halley pressure reconstruction (Fig. 4b); this season is the best agreement between these two measurements and further indicates the exceptional nature of the persistent positive pressure anomaly during SON that ultimately did not favor an earlier retreat of sea ice. Notably, during austral spring 1915, *Endurance* barely moved (Fig. 1a), also consistent with the strong high pressure anomaly: The wind-driven ice motion (counterclockwise around a high pressure, driving the ship southeastward) would oppose the underlying oceanic clockwise circulation of the Weddell gyre (Eayrs et al. 2019), stalling its motion and making the ship stay in dense pack ice and eventually become crushed and sinking in November 1915.

c. Analog events. To place the anomalous events that likely played a role in its fate in a wider spatial context than specific to the location of *Endurance*, we examine composite

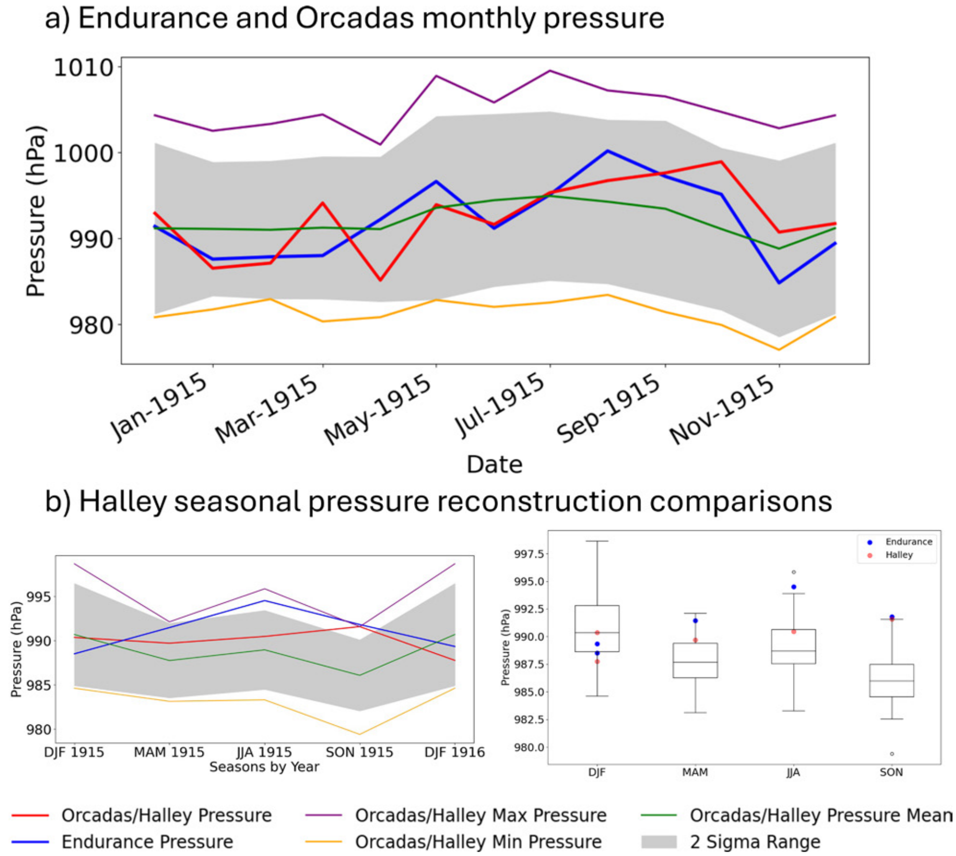

Fig. 4. Climatological aspects of the persistent high pressure during the normal time of ice retreat in the Weddell Sea. (a) Monthly pressure comparisons between *Endurance* and Orcadas observations (1903–2021); (b) seasonal comparisons of *Endurance* data with the Halley station pressure reconstructions (1905–2013) from Fogt et al. (2016a), with the boxplots constructed as in Fig. 3.

averages of ERA5 anomaly data for years where ERA5 most closely matched the 1915 *Endurance* observations at critical times of the year. Further, since April 1914–May 1915 was marked with El Niño conditions in the tropical Pacific, which has known influences on the south polar atmosphere (Turner 2004; Karoly 1989; Li et al. 2021) and sea ice (Yuan 2004; Yuan and Martinson 2001; Yuan and Li 2008) in the Weddell Sea, we also investigate the potential connections to average El Niño circulation anomalies. First, we examine composite averages of years where ERA5 temperatures were more than one standard deviation below the long-term mean in January and February, which provide an analog for the cold extremes at the start of *Endurance's* journey into the Weddell Sea (January–February 1915, Fig. 5a, left column), along with average circulation composites for January and February El Niño years (Fig. 5a, middle column). During similar cold months in January and February (Fig. 5a, left), 10-m winds flow off the Antarctic continent, which dynamically favors increased sea ice concentration anomalies at the ice edge by pushing ice equatorward and favoring increased ice production in the colder air. In January, these conditions are also associated with significantly ($p < 0.05$) higher-than-normal pressure in the South Pacific (north of the Bellingshausen Sea), while in February, they are associated with significantly ($p < 0.05$) lower pressure in the Bellingshausen Sea (west of the Antarctic Peninsula, Fig. 1b) and higher-than-normal pressure in the South Atlantic. The analog case aligns very well with the average January composite for El Niño years, but it is less consistent with the February composite (Fig. 5a, middle column). Nonetheless, the 10-m winds near the *Endurance* location, both moving equatorward toward the Peninsula, are consistent with significantly ($p < 0.05$) below-normal temperatures throughout much of the Weddell Sea.

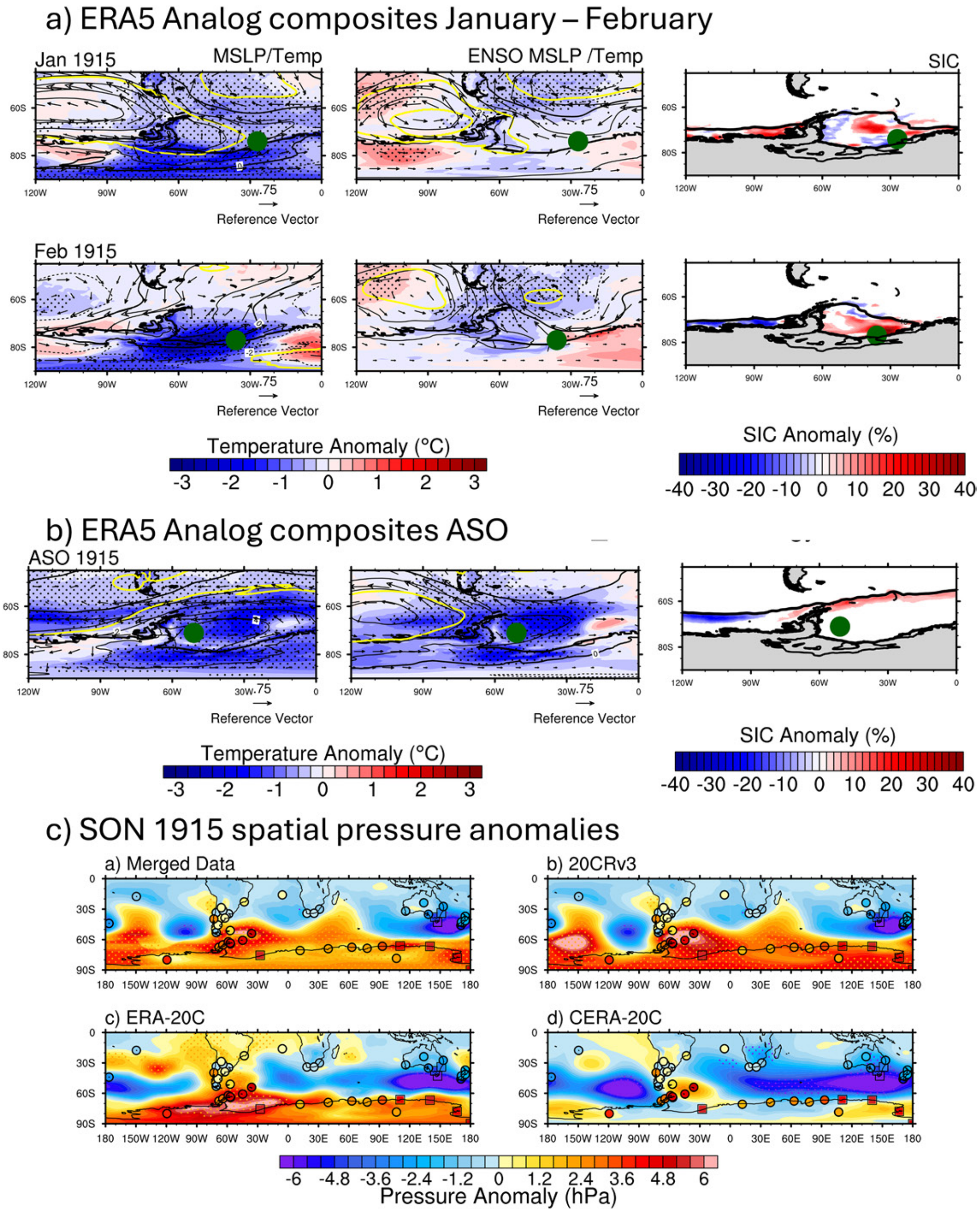

Fig. 5. **Spatial comparison of atmospheric and ice conditions. (a) ERA5 and NSIDC analog anomaly composites (i.e., group average minus climatology) based on months with similar temperature anomalies (exceeding one standard deviation below normal) as experienced by *Endurance* in (top) January 1915 and (middle) February 1915. (left) Temperature anomalies are shaded (indicated by the label bar), with stippling indicating anomalies significantly different from zero at $p < 0.05$, pressure anomalies contoured (with the yellow line indicated pressure anomalies significantly different from zero at $p < 0.05$), and 10-m wind vector anomalies with a reference vector noted. (center) The same near-surface conditions averaged during El Niño years. (right) SIC anomalies (as indicated by the label bar) composited for the cold months (as in left column), with the thick contour line indicating the climatological 15% SIC ice edge. (b) As in (a), but for (bottom) seasonal pressure anomalies above one standard deviation as experienced by *Endurance* for El Niño events in ASO 1915, based on the U.S. Climate Prediction Center definition of the ASO oceanic Niño index above 0.5°C. (c) Pressure anomalies for SON 1915 for four different datasets: the merged data from Fogt and Connolly (2021), 20CRv3, ERA-20C, and CERA-20C. Also plotted are individual station anomalies away from the Antarctic continent and reconstruction anomalies from Fogt et al. (2016a) on the Antarctic continent. Stippling indicates pressure anomalies significantly different from zero at $p < 0.05$, while boxes indicate individual station/reconstruction pressure anomalies significantly different from zero at $p < 0.05$.**

The increased concentration at the ice edge in January confirms that the ship would have encountered the ice edge further north (and hence earlier) than normal and likely reached a thick enough pack ice to trap the ship much farther northward as well. In February, the SIC anomalies localize around the ship, confirming that the persistent cold would be associated with increased ice concentrations that would continue to keep the ship trapped in late summer without an opportunity for escape like *Deutschland*, keeping it beset as ice advanced in fall throughout winter. It is noted that the positive sea ice concentration anomalies in Fig. 5a may have originated several months prior to the beginning of 1915, due to the persistence of sea ice anomalies from coupled ocean–ice processes (Holland et al. 2013); however, the causality of these anomalies apart from the near-term dynamic and thermodynamic effects of January–February temperature and wind patterns in Fig. 5a is difficult without any ocean observations and is therefore beyond the scope of this paper.

Second, we examine composite averages of years for which the ASO ERA5 mean pressure was more than one standard deviation above the long-term mean. The mean pressure experienced by *Endurance* during ASO 1915 (997.60 hPa) was close to the highest value found in the ERA5 data (998.72 hPa in 1972). ERA5 composite fields for ASO (Fig. 5b) show that 10-m winds are very weak, with a cold-core high pressure anomaly everywhere south of 60°S (both pressure and temperature anomalies are statistically different from zero at $p < 0.05$ in much of the Weddell Sea) in similar years based on ERA5 data (left panel, Fig. 5b). As postulated earlier, this persistent cold-core strong high pressure anomaly (with a slight northward component to the flow) thermodynamically favors increased SIC at the ice edge during winter along the entire edge of the Weddell Sea in ASO, including the South Orkney Islands, consistent with the long duration of fast ice there in 1915 (right panel, Fig. 5b). Despite the El Niño event in 1915 ended before August, there are still some similarities with the El Niño composite for these months (Fig. 5b, middle), although the region just west of the Antarctic Peninsula is marked with a stronger high pressure anomaly typical for El Niño events in that region (Turner 2004; Yuan 2004; Li et al. 2021). This high pressure anomaly creates more pronounced northerly flow near the Antarctic Peninsula (cf. left and middle columns of Fig. 5b), which increases SIC more along the tip of the Antarctic Peninsula in El Niño years (not shown), rather than along much of the Weddell Sea ice edge likely experienced in ASO 1915 (Fig. 5b, right column). The overall lighter winds from the broad, persistent high pressure in Fig. 5b would also reduce sea ice motion throughout the Weddell Sea and the likelihood of any leads forming that may allow a navigable path through the ice. In turn, the ice would continue to remain dense and thick around the ship, not only keeping it stuck, but eventually crushing the ship under its continuing pressure.

For a larger spatial context of the austral spring higher pressure anomaly that inhibited an early sea ice retreat, a full Southern Hemisphere perspective is provided in Fig. 5c using various gridded datasets as well as additional station (or over Antarctica, reconstruction) data for this specific year and season (SON, to utilize seasonal reconstruction data). Most data sources agree on widespread high pressure during SON 1915 over Antarctica (supported by individual station reconstructions), locally strong in the Weddell Sea. In particular, 20CRv3 (panel b in Fig. 5c) directly assimilates *Endurance* observations, giving further credibility to the strong and broad high pressure anomaly in the Weddell Sea. In all products, the pressures are significantly ($p < 0.05$) below average south of Australia (further supported by both Australian and New Zealand stations), loosely reflecting a negative phase of the Southern Annular Mode (SAM, a pattern which represents the strength of the meridional pressure gradient across the Southern Hemisphere extratropics and the resulting strength of the westerly winds around Antarctica) (Fogt and Marshall 2020); SAM index reconstructions also indicate a negative phase of the SAM in SON 1915 (Jones et al. 2009). Consistent with this idea, station temperatures are usually colder than average near the Antarctic Peninsula (near where *Endurance* was located in SON 1915, Fig. 1a) in a negative SAM phase, which themselves are also common during El Niño years (Fogt et al. 2011; Stammerjohn et al. 2008). The colder-than-normal air temperatures would have (thermodynamically) favored increased ice in this region and delayed any earlier retreat. This pattern of increased ice concentrations and delayed retreat is consistent with the observed lengthy fast ice duration at the South Orkney Islands in 1915, mirrored by ERA5 and SIC analog composites for similar years in ASO (Fig. 5b).

3. Discussion

While Shackleton's leadership successfully safeguarded against any loss of life during the Imperial Trans-Antarctic Expedition of 1914–16, neither he nor the crew could have fully prepared for the role the weather during these particular years may have played in the fate of their ship, *Endurance*. Using several data sources to place the routine measurements made from or near the ship, we have shown that the crew encountered two periods of extreme weather that likely challenged the expedition's goals from early on. First, the ship encountered ice much farther north than normal, and, following a storm, soon became stuck in the ice in January 1915; the anomalous northward extent of the sea ice edge was consistent with an ongoing El Niño event. From there, persistent cold ensued that kept sea ice concentrations above average around the ship, not allowing it any time to break free. As the ship endured several storms, as is common during the winter, its hope for survival now hinged on the possibility of an early sea ice retreat that could free it from the increasing pressure and strain of the persistent ice coverage in the Weddell Sea. Unfortunately, during austral spring, when Antarctic sea ice starts its annual retreat, there was a strong and persistent high pressure anomaly centered over the Weddell Sea. This high pressure anomaly favored light winds (their motion stalled), cold conditions, and increased sea ice concentrations at the sea ice edge. As such, this persistently strong high pressure anomaly (and associated light winds and cold temperatures) reduced opportunities for ice breakup and instead kept the ship rather stationary, prolonged the period of fast ice surrounding the ship, and expanded the sea ice further north throughout the Weddell Sea. Eventually, the strain on the ship was too much, and it succumbed to the pressure around it, first forcing the crew to abandon it, and then ultimately to the ice crushing it and sinking it in November 1915.

The climatological comparisons here add another new element to this exciting story—that the fate of the expedition was partly determined by the unusual weather conditions in these particular years. Both the cold in late summer and the high pressure during austral spring were suggested originally as early as 1921(Mossman 1921), but here we place them in a historical context over 100 years. The cold and heavy ice conditions were near-record breaking at the start of their journey, even in the context of the full twentieth century; a similar story emerges for the spring high pressure anomaly. While it is not possible to prove conclusively that these specific weather and ice conditions were the main reason that the ship became stuck and was eventually destroyed, given the statistical significance of the anomalies, it is likely that they set the expedition up for challenges already from the first few weeks. Had the expedition happened in a different year—even 1 year later or earlier—the outcome may have been different, much like that experienced by *Deutschland* only a few years prior. Nonetheless, historical climatological data recovery and digitization, especially in data sparse areas like Antarctica in the early twentieth century, can help to provide valuable insight into historical expeditions like this one, as well as to ongoing changes by providing new, longer-term measurements to place current events in a longer historical perspective. Indeed, since the early twentieth century shows a notable global temperature dip that is more pronounced across the Southern Hemisphere (Hegerl et al. 2018), studies like this one help us to understand historical climate variations in a relatively data sparse area that could have global importance.

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Data availability statement. All data used in this paper are publicly available online. The digitized measurements from *Endurance* are from Phil Brohan, available online (https://oldweather.github.io/Expeditions/voyages/Antarctic.html). ERA5 reanalysis data can be downloaded from the Copernicus climate data store (https://cds.climate.copernicus.eu/datasets). Antarctic and sub-Antarctic island surface observations can be accessed from the READER project (https://legacy.bas.ac.uk/met/READER/). The Antarctic pressure reconstructions are available on Figshare (https://figshare.com/collections/Antarctic_Seasonal_Pressure_Reconstructions/6765447/1), as well as the sea ice extent reconstructions (https://figshare.com/collections/Antarctic_Sea_Ice_Reconstructions/5709767). Satellite observations of Antarctic sea ice concentration can be downloaded from NSIDC (https://nsidc.org/data/g02202/versions/4). The fast ice record at the South Orkney Islands can be obtained from the British Antarctic Survey (https://data.bas.ac.uk/full-record.php?id=GB/NERC/BAS/PDC/00802).

APPENDIX
Detailed Data and Methods

Pressure observations on *Endurance* were made using a standard Kew-pattern mercury barometer until the ship was abandoned, after which readings were made using an aneroid barometer. Temperature measurements were made using standard thermometers in a screen on the ship's deck. The ship's daily position was determined by sun or star sights where possible and, otherwise, estimated by dead reckoning. A brief account of *Endurance* observations is given by Mossman (1921). On most days, six observations by the *Endurance* crew were taken approximately every 4 h, starting near 0100–0300 local time (LT); in particular, we make use of temperature, pressure, and wind speed (approximately converted from the Beaufort scale to m s^{-1}). From these observations, daily mean data (and average position) were constructed by averaging all available data. The observations from the *Endurance* expedition, including those made after the ship was abandoned, have been transcribed and incorporated into the International Comprehensive Ocean–Atmosphere Data Set (ICOADS) (Freeman et al. 2017), although, for this project, we obtained *Endurance* data directly from Dr. Philip Brohan as part of the Old Weather citizen-science-based data recovery project (https://oldweather.github.io/Expeditions/voyages/Antarctic.html).

To construct a climatology, data from the fifth generation European Centre for Medium-Range Weather Forecasts atmospheric reanalysis (ERA5) (Hersbach et al. 2020) were employed—specifically, 6-hourly data (0000, 0600, 1200, 1800 UTC), 2-m temperature and sea level pressure, and monthly mean 2-m temperature, 10-m zonal (u) and meridional (v) components of the wind. Comparison of temperature and pressure measurements from drifting buoys in the Weddell Sea pack ice with collocated ERA5 data has shown that ERA5 provides an accurate representation of surface meteorological conditions in this region (King et al. 2022). For the along *Endurance* track data, we used ERA5 data from 1959 to 2021; using the ERA5 data only after 1979, when additional satellite data were assimilated into the reanalysis did not impact the representation of the mean or maximum/minimum values. We thus used the post-IGY period to provide the longest climatology possible. Daily means from the ERA5 data were constructed from the 6-hourly surface data, and the climatology of minimum, maximum, and the two sigma range was calculated for the values across all years at each nearest grid point from ERA5 using the daily mean latitude and longitude values from *Endurance* logbooks. The daily climatological mean was calculated for each day using ERA5 data during 1959–2021, and *Endurance* anomalies were calculated in reference to these ERA5 daily means. For the analog composites, we used the 1980–2020 monthly mean climatology.

We also make use of nearby monthly mean temperature and pressure observations from Orcadas (60.7°S, 44.7°W), obtained from the Reference Antarctic Data for Environmental Research (READER) online archive (Turner et al. 2004). We make use of the Halley seasonal pressure reconstructions (Fogt et al. 2016a), based on statistical pressure relationships shared between Antarctica and the Southern Hemisphere midlatitudes, which cover the period 1905–2013. Other observations across the Southern Hemisphere were obtained from the National Center for Atmospheric Research (NCAR) research data archive dataset 570.0 (NCAR 1981) to provide a hemispheric-wide perspective of pressure anomalies in 1915.

For sea ice comparisons, we use daily mean sea ice concentrations along the track of *Endurance* from the National Oceanic and Atmospheric Administration (NOAA)/National Snow and Ice Data Center (NSIDC) Climate Data Record from passive microwave satellite data, version 4 (Meier et al. 2021), from 1979 to 2022. The daily minimum, maximum, and interquartile range (IQR), as well as the climatological mean, were calculated for the full 1979–2022 period. For a longer perspective, we also make use of seasonal sea ice extent reconstructions for the Weddell Sea and the total Antarctic (Fogt et al. 2022), as well as the South Orkney fast ice record (1903–2008) formation, breakup, and duration dates (Murphy et al. 2014, 1995).

Gridded pressure datasets that extend into the early twentieth century (mostly historical reanalyses) are also examined to provide a large-scale pattern of atmospheric circulation anomalies during 1915. These consist of the NOAA/Cooperative Institute for Research in Environmental Sciences Department of Energy 20th century reanalysis, version 3 (20CRv3) (Slivinski et al. 2019), the European Centre for Medium-Range Weather Forecasts (ECMWF) 20th-century reanalysis (ERA-20C) (Poli et al. 2016), and ECMWF's coupled ocean–atmosphere reanalysis of the 20th century (CERA-20C) (Laloyaux et al. 2018). All of these twentieth century reanalyses primarily assimilate only surface pressure observations; ERA-20C and CERA-20 also assimilate marine surface winds, and CERA-20 further assimilates ocean temperature and salinity measurements. Since most of these twentieth century reanalysis products have shown artificial trends in the high southern latitudes prior to 1958 (Schneider and Fogt 2018; Fogt et al. 2021), we also make use of the "merged" pressure data (Fogt and Connolly 2021), which are a blend of 20CRv3 north of 60°S and seasonal spatial Antarctic pressure reconstructions (Fogt et al. 2019) poleward of 60°S as another estimate of early twentieth century Southern Hemisphere pressure. It is noted that 20CRv3, based on the fourth version of the International Surface Pressure Databank (ISPD), does assimilate observations from *Endurance*, while the other two reanalyses based on ISPDv3 do not.

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