2023's Antarctic sea ice extent is the lowest on record

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Introduction

2023 was a year of record-breaking weather and climate events across the world, with extreme heat in North America, South America, Southern Europe and China; a North Atlantic marine heatwave; and wildfires in Eastern Canada that turned the skies of cities like New York City an apocalyptic red – as captured in *Weather*'s August front cover (e.g. ECMWF, 2023; Hausfather, 2023; Ripple *et al*., 2023). Concurrent with these conditions, remarkable Antarctic sea ice conditions were developing: an unprecedented slow winter freeze-up followed a record-breaking minimum extent, which was succeeded by the lowest winter maximum (NSIDC, 2023a). The 'missing' area of sea ice for the month of July (when negative anomalies reached their peak) relative to the 1981–2010 mean was, at 2.47 million (mn) km^2, larger than Algeria, the world's tenth largest country (Gilbert and Holmes, 2023).

In this article, we examine some of the historical context of this record low sea ice extent to demonstrate that the conditions of 2023 are entirely unprecedented within the observational period and comment on the potential links to human-caused climate change and natural variability.

Longer-term context of Antarctic sea ice

Antarctic sea ice plays a pivotal role in governing the regional and global climate. It helps to maintain stable global temperatures by reflecting incoming solar radiation from its bright, white surface (the sea ice albedo effect), contributes to ocean circulation via its impact on ocean bottom water formation (Abernathey *et al*., 2016), and influences atmospheric patterns that impact weather much further afield (Hobbs *et al*., 2016). Sea ice has the potential to limit Antarctica's contribution to sea level rise by acting as a buffer that protects marine-terminating glaciers and floating ice shelves from destructive wave action (Massom *et al*., 2018), while changes in sea ice also impact precipitation, evaporation and temperature changes in the Antarctic region with potential impacts on the ice sheet surface mass balance (Bracegirdle *et al*., 2015). Furthermore, the sea ice-covered Southern Ocean is vitally important for marine life, for example as a breeding habitat for emperor penguins (Fretwell *et al*., 2023) and with considerable impacts on the globally significant ecosystems of the Southern Ocean (Hobbs *et al*., 2016). The loss of Antarctic sea ice, therefore, has profound implications for global climate, ocean heat and carbon uptake, sea level change and ecosystems.

Accurate knowledge of Antarctic sea ice cover comes from satellite-derived measurements of sea ice concentration. Although intermittent monitoring began in the 1960s, for example via the Nimbus satellite (Gallaher *et al*., 2013), the temporally consistent record began in late 1978. We use the National Snow and Ice Data Center's Sea Ice Index version 3 (Fetterer *et al*., 2017). These data are at 25 km gridded resolution, and with variable temporal frequency: data were collected on alternate days prior to 1987, and daily since 1987. Measurements are spatially aggregated to calculate daily sea ice extent, which is the sum of the area of all grid pixels with more than 15% concentration. We also use OSI-450-a v3.0 data (OSI SAF, 2022a; 2022b) to assess anomalies in atmospheric and sea ice conditions.

These data show that the annual mean Antarctic sea ice extent increased slightly but by a statistically significant amount between 1979 and 2015 (Eayrs *et al*., 2019; Maksym, 2019; Parkinson, 2019). This trend contrasted with the large losses observed in the Arctic (e.g. Jones *et al*., 2019) and with predictions from climate models, leaving scientists scrambling to understand the complex drivers behind these perplexing patterns (Turner and Comiso, 2017). Then, after reaching a record high in 2014, the annual mean Antarctic sea ice extent plummeted to a record low in 2017. Successive low years followed, with year-to-year losses even exceeding rates seen in the rapidly changing Arctic (Parkinson, 2019). Record low sea ice was recorded in 2022, linked to atmospheric and oceanic drivers (Clem and Raphael, 2023).

Antarctic sea ice is intimately related to variability in atmospheric circulation patterns like the Amundsen Sea Low (ASL), a climatological but highly variable low-pressure system located off West Antarctica (Hosking *et al*., 2013). For instance, Turner *et al*. (2016) showed that the slightly positive trend observed from 1979 to 2015 was consistent with natural variability in the ASL over the same time period. The decline in extent in 2016–17 has similarly been attributed to changes in large-scale modes of variability like the Southern Annular Mode (SAM) and El Niño Southern Oscillation (ENSO) (Schlosser *et al*., 2017; Stuecker *et al*., 2017; Turner *et al*., 2017), while the long-term trend and maintenance of low extents has also been linked to changes in the ocean such as convection (Zhang *et al*., 2019, 2022). To complicate this picture, the particular phases of SAM and ENSO can interact to either intensify or suppress sea ice anomalies by affecting sea ice dynamical and thermodynamical processes (Wang *et al*., 2023).

Annual cycle of sea ice

Antarctic sea ice extent varies enormously throughout the year. Figure 1 shows its annual cycle from 1979 to 2023, with individual years shown as thin green/turquoise lines, the 1981–2010 climatology shown in bold, and 2023 (up to 31 August) highlighted in pink. The climatological minimum and maximum extents are 2.88 mn km^2 and 18.57 mn km^2, typically reached in late February and mid-September, respectively. This seasonal expansion increases the area of the Southern Ocean covered by sea ice sixfold, as shown in Figure 1.

Evolution of 2023 anomalies

It is apparent from Figure 1 that 2023 was an exceptional year in the satellite record, remaining below the climatological fifth percentile for nearly the entire year. The year began with a record-breaking minimum extent in February 2023, reaching a minimum of 1.79 mn km^2 that was 10% lower than the previous, already record-breaking, year in which annual minimum extent dropped below 2 mn km^2 for the first time (Liu *et al*., 2023). After an initial near-average freeze-up, from April 2023 the seasonal expansion of sea ice was particularly sluggish. By July, the monthly average total sea ice extent was 13.49 mn km^2, 15.2% below the climatological average for the month (Figure 1).

As well as total sea ice extent, sea ice extent can be calculated for five smaller subregions around the Antarctic coast, as indicated in Figure 2. Until recently, these

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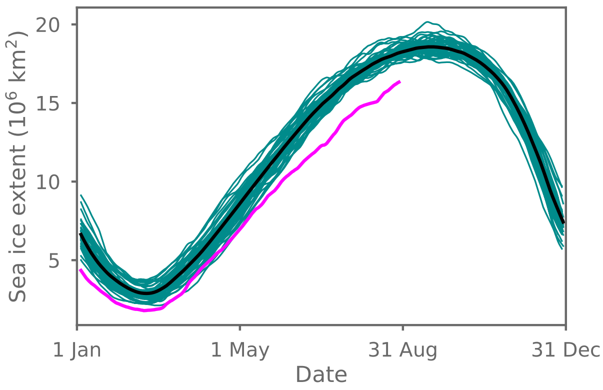

Figure 1. Annual five-day running mean Antarctic sea ice extent in millions of square kilometres between 1979 and 2023 as observed by satellites. The 1981–2010 climatological mean is shown by the thick black line and the thin turquoise coloured lines are individual years. Antarctic sea ice extent for 2023 (up to 31 August 2023) is shown by the pink line. Data are obtained from NSIDC (2023b). Five-day mean data are used as standard due to pre-1987 data being only available on every other day, and to smooth out weather-driven artefacts in the satellite retrievals.

sectors have been observed to have contrasting anomalies and trends due to regionally distinct drivers (e.g. Schroeter *et al*., 2023).

However, as shown in Figure 2, anomalies in 2023 were evident all around the Antarctic. At the climatological minimum (the black line in Figure 2a), sea ice is typically confined to areas very close to the coast around East Antarctica, while it expands a little further in West Antarctica and is comparably expansive in the Weddell Sea. In February 2023, sea ice was near average in the Weddell Sea but anomalously low elsewhere. Since April, there was below-average sea ice extent everywhere except the Amundsen Sea (102°20′ – 126°W); the situation in July 2023 (Figure 2b) is representative of these months. This recent transition from regionally compensating anomalies to regionally coherent ones contributes to the emergence of the strong hemisphere-wide anomalies and represents a departure from patterns observed during low sea ice years in earlier decades (Schroeter *et al*., 2023).

Drivers of low sea ice conditions

Although the causes of the sea ice low are likely numerous, recent publications have pointed to the important role of subsurface ocean heat in maintaining low sea ice extents since 2016 (Zhang *et al*., 2022; Purich and Doddridge, 2023). Sea surface temperatures in the Southern Ocean were also anomalously warm throughout the first half of 2023, which could partly explain both the record minimum extent in February and the slow freeze-up afterwards (Purich and Doddridge, 2023).

Indeed, Purich and Doddridge (2023) suggest that seasonal persistence in Antarctic sea ice has changed since 2015, implying that 'memory' in the system linked to the ocean may have allowed the unusually low-extent summertime state to persist.

In West Antarctica, the recent behaviour of the ASL is very consistent with the distinct anomaly pattern in sea ice. For much of 2023 it had been anomalously deep and at times far to the east (Figure 2c). This setup favours northerly winds west of the Antarctic Peninsula (Figure 2e) that drive warm air advection and push ice back to the coast, thereby limiting growth in the subsequent freeze-up season. Meanwhile, west of the ASL, cold southerly winds favour cold conditions and export sea ice, opening cold ocean areas, explaining the positive anomalies here (Hosking *et al*., 2013). However, by July the ASL had decayed and there were positive mean sea level pressure anomalies (Figure 2d) so a region of largely westerly flow dominated (Figure 2f). This would have favoured eastward advection of ice into the Bellingshausen Sea and so is consistent with the recovery of sea ice in this region by the winter maximum in September (not shown).

However, the role of other atmospheric patterns in the unusual circumpolar sea ice conditions of 2023 is less clear. Strong westerly winds associated with a positive SAM have, in past years, favoured high sea ice (Schroeter *et al*., 2023), due to SAM impacts on ocean currents and therefore ocean temperatures, but this year's conditions have happened despite a positive SAM (Purich and Doddridge, 2023).

Relative magnitude and rarity of winter 2023 anomalies

2023 stands out within the time series of annual and winter (June, July and August; JJA) sea ice extent shown in Figure 3. The pattern described above – of a slightly increasing trend in annual Antarctic sea ice extent from 1979 to 2015, followed by a precipitous decline in the intervening years – is evident in Figure 3a. Antarctic JJA sea ice extent from 1979 to 2022, shown in Figure 3b, followed the same approximate pattern as the annual mean, with a general increase until 2015 followed by successive years of dramatic losses.

As shown in Figure 3b and Table 1, the negative anomaly in JJA 2023 with respect to the 1981–2010 climatology was twice as large as any other JJA on record. JJA 2023 clocked in at 13.34 mn km^2 (an anomaly of 2.34 mn km^2) compared with 14.75 mn km^2 (0.93 mn km^2) in JJA 2022. The lowest five JJA periods are shown in Table 1.

We may also compare 2023 against pre-1979 sea ice extents. For instance, very low winter sea ice extents were noted from the reconstructed Nimbus record in JJA 1966 (15.5 mn km^2) (Gallaher *et al*., 2013). However, JJA 1966 would now be ranked an unremarkable 16th in the lowest sea ice years. Further, the low 1966 JJA average is dominated by the August values (June: 14.3 mn km^2, July: 16.4 mn km^2, August: 15.9 mn km^2 quoted in Gallaher *et al*., 2013) whereas in 2023 sea ice was low throughout JJA (June: 11.0 mn km^2, July: 13.5 mn km^2, August: 15.5 mn km^2). Lastly, as noted by Gallaher *et al*. (2013), the Nimbus record has large uncertainties, which reduce the reliability of these estimates, and the measured 1966 July–August drop is 'physically unlikely'.

The remarkable magnitude of the anomalies recorded in 2023 has spurred attempts to quantify exactly how rare this year's conditions have been. They are clearly far outside the bounds of normality, but can we say exactly how far?

Attempts to estimate this rely on estimating the variability of the system in a world without climate change, that is, what is 'normal'. These have pivoted upon the calculation of the standardised anomaly. This is the anomaly in units of standard deviation (sigma, σ), referred to as 'n-sigma' for some n, for any given period (e.g. a five-day mean), the number of standard deviations below the climatological average the anomalies fall. The standardised anomaly is calculated as:

$$\frac{SI - SI_{clim}}{\sigma} \quad (1)$$

where ($SI - Si_{clim}$) is the sea ice extent anomaly for any given period (here we use five-day running means) and σ is the climatological standard deviation for the same period. We use a 1981–2010 climatology.

The mean value of the standardised anomaly for JJA 2023 when compared against the 1981–2010 JJA climatology was −5.86 ('−5.86 sigma'), with a minimum value of −7.15 reached on 25 July 2023. This translates 2023's anomalies into a once-in-a-multi-million-year event without human-

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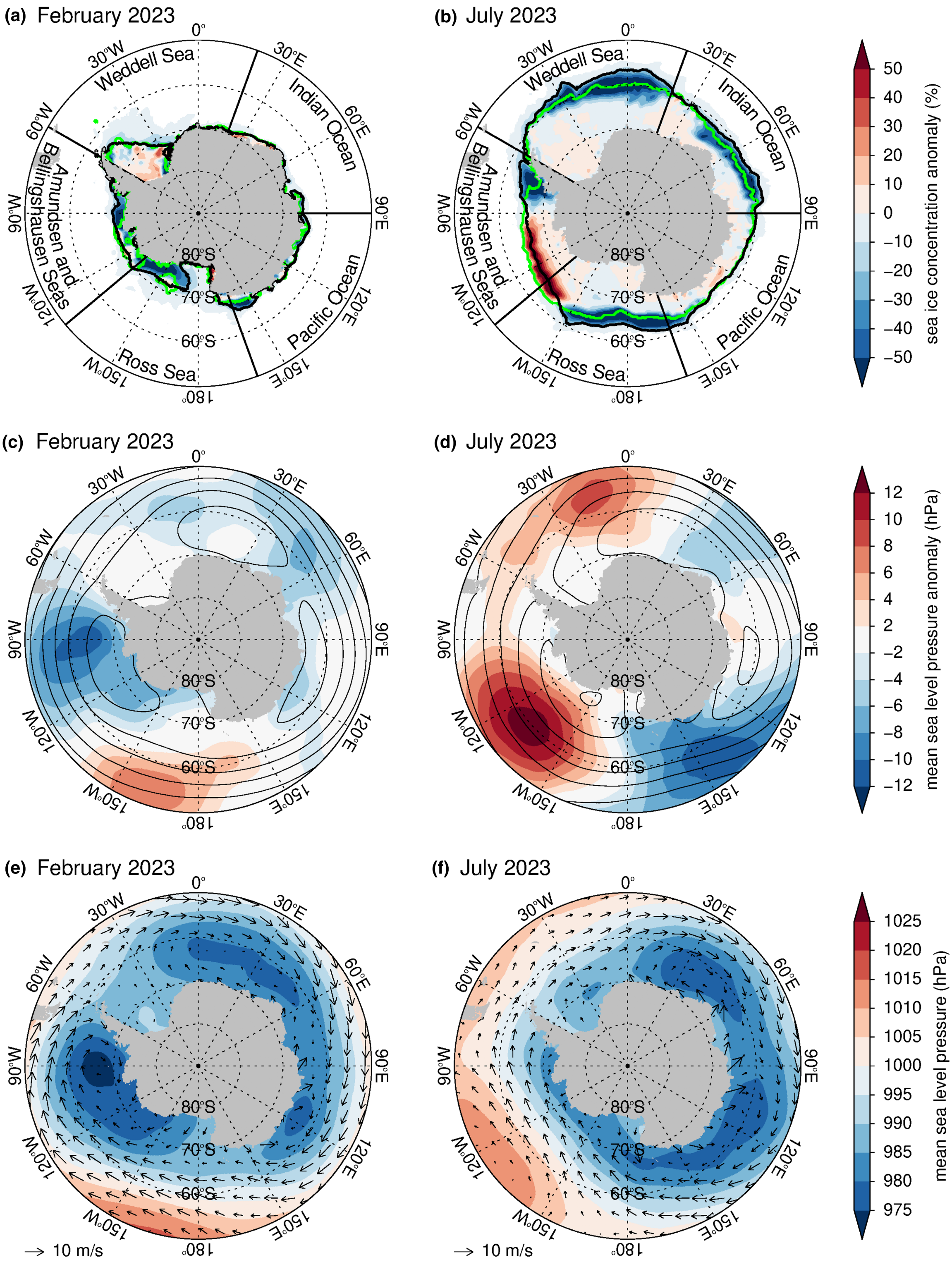

Figure 2. Sea ice and atmospheric conditions over ocean grid points in February 2023 (left) and July 2023 (right). Panels (a) and (b): Sea ice concentration anomalies from the climate data records OSI-450-a (v3.0, 2022; 1978–2020) and OSI-430-a (v3.0, 2022; 2021–2023). The black line indicates the climatological median monthly sea ice edge (>15% concentration), the green line shows the monthly mean ice edge in 2023, and red and blue colours indicate negative and positive anomalies, respectively, compared to climatology for 1981–2010. Panels (c) and (d): Mean sea level pressure (MSLP) anomalies (shading) and 1981–2010 monthly MSLP climatology (black contours, contour interval 5 hPa). Panels (e) and (f): winds at 10 m (arrows) and absolute MSLP fields (shading). MSLP and winds are from the ERA5 analysis (Hersbach et al., 2019).

caused climate change; that is, extremely rare.

However, both to calculate the standardised anomaly and to estimate the event's rarity, one must assume that the observations from which we estimate it are representative of a much longer time period, and to convert it into a probability, we must further assume that the values fall into a normal (Gaussian) distribution. These may not be sound assumptions. For example, Fogt *et al.* (2022) use a multi-decadal sea ice reconstruction to show that the 30-year increasing trend prior to 2016 was in fact highly unusual over the period 1905–2020, while Sardeshmukh *et al.* (2015) emphasise that probabilistic estimates of how unusual a particular event is can be misleading in non-Gaussian systems. Moreover, the observed trends in sea ice have occurred in a rapidly changing environment, meaning

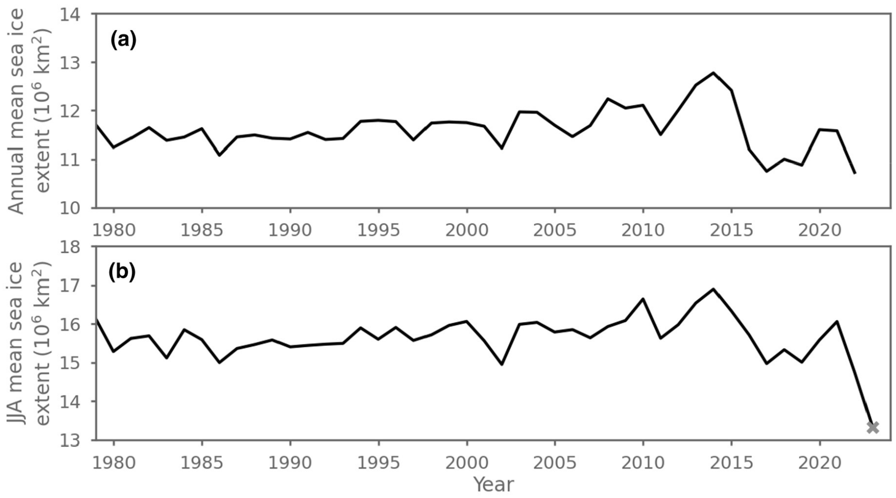

Figure 3. Time series of (a) mean Antarctic annual sea ice extent from 1979 to 2022 and (b) mean winter (June–August, JJA) sea ice extent from 1979 to 2023 as observed by satellites. JJA 2023 is highlighted by a cross. Data are obtained from NSIDC (2023b), and missing data (particularly in the early satellite record) are in-filled with piecewise linear interpolation.

Table 1

Top five years with largest negative JJA sea ice extent anomalies with respect to the 1981–2010 climatology, ranked from lowest sea ice extent to highest. All extents and anomalies are shown in millions of square kilometres (mn km^2).

Year	*JJA mean extent (mn km^2)*	*JJA anomaly (mn km^2)*
2023	13.34	−2.34
2022	14.75	−0.93
2002	14.95	−0.73
2017	14.97	−0.71
1986	15.00	−0.69

Table 2

Standardised anomaly calculated (according to Equation 1) using different baseline periods. For all baseline periods except the NSIDC climatology, climatological mean extent and standard deviation are calculated from the 5-day running mean observed sea ice extent. NSIDC climatology is available from Fetterer et al. (2017).

Baseline period	*Standardised anomaly*	*Standard deviation*
NSIDC climatology (1981–2010)	−5.86	0.41
1981–2010	−6.01	0.40
1991–2020	−4.99	0.50
1979–2022	−4.77	0.51

that climate change (and potentially other factors) is already shaping the calculation of the standardised anomaly and that estimations of this type are not useful for quantifying the rarity of such events.

Further, the baseline period from which the climatology SI_{clim} is calculated can alter this estimation. As shown in Table 2, using baselines that include more recent years increases the standard deviation of the baseline and so reduces the calculated standardised anomaly, and therefore, the estimated rarity (return period) of the event. This reflects the changes in sea ice that have occurred due to climate change and/or changes in natural variability over time.

In other words, while we can definitely say that 2023's sea ice conditions were exceptional, it is difficult to say with any certainty exactly *how* exceptional. That is because our satellite record is relatively short (45 years), and the system is – as we have seen – highly variable, such that those 45 years are probably not fully capturing natural variability, and that climate change is already impacting the Southern Ocean in complex ways, making an estimation of what is 'normal' impossible.

Links with climate change

The sheer magnitude and rarity of the anomalies observed hints that something unusual is happening in the Antarctic and that climate change may be involved. Unlike the decline of Arctic sea ice, which can be robustly linked to rising temperatures (Meredith *et al.*, 2019), the impact of climate change on Antarctic sea ice has proven more complex because of geographical and environmental factors. Antarctic sea ice trends vary by region and season and are strongly impacted by modes of variability like the SAM and ENSO, which are themselves influenced by climate change and may have competing influences (Yu *et al.*, 2023).

Climate models project a decline in Antarctic sea ice in response to greenhouse gas forcing and rising temperatures. However, as previously discussed, until 2015 this prediction was largely at odds with observed trends. Observed sea ice patterns suggest that the influence of climate change is not as straightforward as models assume, and natural variability is known to exert an important control on sea ice extent (Turner *et al.*, 2016; Maksym, 2019).

The complexity of atmosphere-ice-ocean interactions and the processes governing these makes them challenging to represent in models, especially at the relatively coarse grid scales (50–100 km) used in most long-term simulations. Particularly, models do not adequately capture key features of Antarctic sea ice such as regional trends, interannual variability and drivers of change like the ASL (Maksym, 2019) as well as factors that are likely to become increasingly important in future. For example, an increase in ice sheet melt, and therefore freshwater input, could increase ocean stratification, producing a colder, fresher layer and making it easier for ice to form, but the relative magnitude of this effect is very uncertain.

Despite the limitations of model projections, it seems inescapable that Antarctic sea ice will begin to decline in response to anthropogenic climate change. In fact, several studies have hinted that recent record low sea ice years may be less unusual in the near future (Eayrs *et al.*, 2021; Liu *et al.*, 2023; Purich and Doddridge, 2023). Southern Ocean warming has been robustly linked to rising anthropogenic greenhouse gas emissions (Swart *et al.*, 2018; Hobbs *et al.*, 2021) and the direct connection between recent low sea ice conditions and the buildup of ocean heat suggests a causal link to human-caused climate change (Purich and Doddridge, 2023). However, although we certainly could be seeing the beginning of a regime shift in Antarctic sea ice it is too early to say conclusively whether the past seven years are the beginning of a longer-term drop in sea ice extent.

Conclusions

Antarctic sea ice extent in JJA 2023 was exceptionally low and followed multiple years of low values. This record low extent was unprecedented in the satellite record, with seasonal mean anomalies reaching large negative standardised anomaly values. However, the brevity of the observational record precludes a conclusive examination of how rare this event is, because the calculation of the return period makes several key assumptions about the natural variability of sea ice over much longer time scales that may not be valid. Regardless, we know that the events of 2023 were entirely remarkable and unlike anything we have seen in the satellite record. It is too early to tell whether this is the emergence of a declining trend, or – as some have put it – a regime shift, but physical arguments and climate models do imply that Antarctic sea ice is almost certain to decline to some extent over the 21st century (Holmes *et al*., 2022) as human-caused climate change continues to transform the polar environment.

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Author contributions

Ella Gilbert: Conceptualization; writing – original draft; writing – review and editing; visualization; formal analysis; data curation. **Caroline Holmes:** Writing – original draft; writing – review and editing; visualization; formal analysis; data curation.

Conflict of interest

EG declares that she is the climate science editor of *Weather*. CH has no conflicts of interest to declare.

Data availability statement

The data that support the findings of this study are openly available. ERA5 data (Hersbach *et al*., 2019) were downloaded from the Copernicus Climate Change Service (C3S) (2023) at https://doi.org/10.24381/cds.adbb2d47 and sea ice index data are available from the National Snow and Ice Data Center (NSIDC) at https://nsidc.org/data/g02135/versions/3. OSI SAF data are available at https://doi.org/10.15770/EUM_SAF_OSI_0013 and https://doi.org/10.15770/EUM_SAF_OSI_0014.

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