Observational Evidence for a Regime Shift in Summer Antarctic Sea Ice

Will Hobbs,[a,b] Paul Spence,[a,c,d,e] Amelie Meyer,[b,d] Serena Schroeter,[f] Alexander D. Fraser,[a] Philip Reid,[a,g] Tian R. Tian,[a,d] Zhaohui Wang,[d,f] Guillaume Liniger,[b,d,h] Edward W. Doddridge,[a] and Philip W. Boyd[a,c]

[a] *Australian Antarctic Program Partnership (AAPP), Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia*
[b] *ARC Centre of Excellence for Climate Extremes (CLEX), University of Tasmania, Hobart, Tasmania, Australia*
[c] *Australian Centre for Excellence in Antarctic Science (ACEAS), University of Tasmania, Hobart, Tasmania, Australia*
[d] *Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia*
[e] *ARC Centre of Excellence for 21st Century Weather, University of Tasmania, Hobart, Tasmania, Australia*
[f] *CSIRO Environment, Castray Esplanade, Battery Point, Tasmania, Australia*
[g] *Australian Bureau of Meteorology, Hobart, Tasmania, Australia*
[h] *Monterey Bay Aquarium Research Institute, Moss Landing, California*

(Manuscript received 11 August 2023, in final form 17 December 2023, accepted 27 January 2024)

ABSTRACT: In recent years, the Southern Ocean has experienced extremely low sea ice cover in multiple summers. These low events were preceded by a multidecadal positive trend that culminated in record high ice coverage in 2014. This abrupt transition has led some authors to suggest that Antarctic sea ice has undergone a regime shift. In this study we analyze the satellite sea ice record and atmospheric reanalyses to assess the evidence for such a shift. We find that the standard deviation of the summer sea ice record has doubled from 0.31 million km^2 in 1979–2006 to 0.76 million km^2 for 2007–22. This increased variance is accompanied by a longer season-to-season sea ice memory. The atmosphere is the primary driver of Antarctic sea ice variability, but using a linear predictive model we show that sea ice changes cannot be explained by the atmosphere alone. Identifying whether a regime shift has occurred is difficult without a complete understanding of the physical mechanism of change. However, the statistical changes that we demonstrate (i.e., increased variance and autocorrelation, and a changed response to atmospheric forcing), as well as the increased spatial coherence noted by previous research, are indicators based on dynamical systems theory of an abrupt critical transition. Thus, our analysis is further evidence in support of a changed Antarctic sea ice system.

SIGNIFICANCE STATEMENT: In recent years, there have been several summers with extremely low Antarctic sea ice cover, including consecutive record lows in February 2022 and February 2023. Since then, the 2023 winter has seen a remarkably low sea ice growth with an anomaly far below expected climatology. This has led researchers to question whether there has been a regime shift, and we assess the observational evidence for such a shift. In the last decade or so, the variability of summer sea ice has almost doubled, accompanied by a much longer sea ice memory from season to season. These statistical changes, as well an increased spatial coherence noted by other researchers, are consistent with theoretical indicators of a critical transition, or regime shift.

KEYWORDS: Southern Ocean; Ice loss/growth; Climate variability

1. Introduction

Antarctic sea ice area increased over the period of reliable satellite records starting in 1979, resulting in record high anomalies in 2014 and 2015 (Parkinson 2019; Parkinson and DiGirolamo 2021). That four-decade increase ended abruptly and unexpectedly with sustained low sea ice cover in the years since, and three extreme ice loss events in the past seven summers, occurring in 2016, 2022, and 2023 (Turner et al. 2017; Parkinson 2019; Parkinson and DiGirolamo 2021; Raphael and Handcock 2022; Wang et al. 2022; Liu et al. 2023). Summer extremes were punctuated in the 2023 austral winter by a remarkably low winter sea ice growth, leading to a winter maximum that was 1 million km^2 below the previous low record. These recent events, with record highs followed by record lows (Fig. 1) has led to suggestions that the Antarctic ocean–sea ice system may have fundamentally changed in the last decade or so (Eayrs et al. 2021; Raphael and Handcock 2022; Purich and Doddridge 2023). In this study, we explore the evidence for that hypothesis.

Conceptually, Antarctic sea ice can be considered as part of the ocean's mixed layer (Schroeter 2020), due to its strong coupling with the ocean through heat and salinity (Marchi et al. 2019; Ordoñez et al. 2018). Its external drivers are the atmosphere and the sub–mixed layer deep ocean. At shorter time

Denotes content that is immediately available upon publication as open access.

Supplemental information related to this paper is available at the Journals Online website: https://doi.org/10.1175/JCLI-D-23-0479.s1.

Corresponding author: Will Hobbs, will.hobbs@utas.edu.au

DOI: 10.1175/JCLI-D-23-0479.1

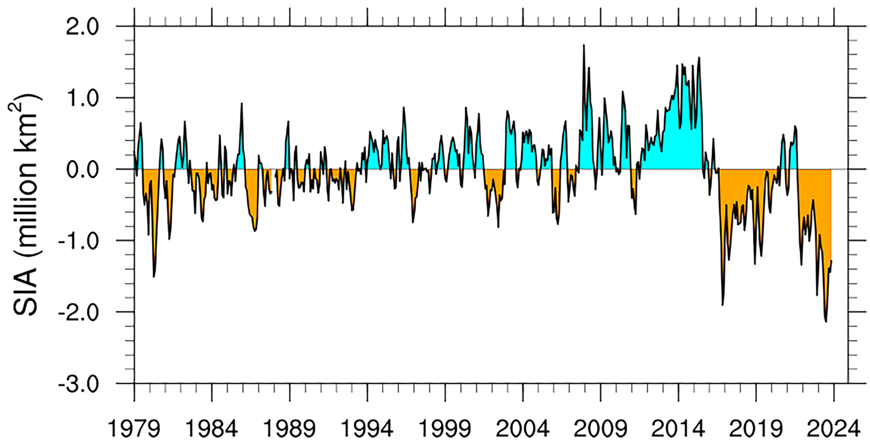

FIG. 1. Observed monthly total Antarctic sea ice area (SIA) anomalies (million km^2) with respect to 1979–2018 climatology from NSIDC climate data record (CDR) data (Meier et al. 2021a,b).

scales (i.e., seasonal and shorter), the dominant driver by far is the atmosphere. Wind is the main driver of sea ice motion, especially in the outer pack where sea ice concentration (SIC) is most variable (Kimura 2004). Winds cause both atmospheric thermal advection, which affects freeze and melt rates, and mechanical redistribution of the ice (Raphael 2007), with the latter thought to be the dominant effect (Hobbs and Raphael 2010). Northerly winds drive sea ice toward the Antarctic coast, which reduces sea ice extent but potentially produces very thick ridged ice (Massom et al. 2008). In contrast, southerly winds push the ice edge farther north. Since the presence of ice cover impedes both ocean cooling (in winter) and surface warming (in summer), the dynamic effect is also strongly related to thermodynamic freeze and melt. In winter, divergence caused by northward sea ice transport allows more freezing by creating open water leads; in summer the same open water absorbs solar radiation to help drive spring–summer melt (Nihashi and Ohshima 2001; Eayrs et al. 2019).

Given the dominant role of the atmosphere, it is unsurprising that both the multidecadal positive sea ice area trend from 1979 to 2015 (Holland and Kwok 2012; Hobbs et al. 2016, and references therein) and the low 2016/17 summer anomalies have been attributed to atmospheric anomalies (Turner et al. 2017; Schlosser et al. 2018; G. Wang et al. 2019; Z. Wang et al. 2019; Turner et al. 2020). More specifically, the 2016/17 event has been linked to the following:

- an unusually strong atmospheric zonal wave 3 (ZW3), which is related to stronger than usual meridional winds (Raphael 2007; Schlosser et al. 2018);
- a negative Southern Annular Mode (SAM) in spring 2016 (Stuecker et al. 2017; G. Wang et al. 2019);
- a deep Amundsen Sea low (ASL; Turner et al. 2017); and
- teleconnections to the tropical Pacific (Stuecker et al. 2017; Meehl et al. 2019; Purich and England 2019).

While the anomalies in these atmospheric indices were certainly key drivers, it is important to note that they were not individually nearly as extreme as the precipitous decline in sea ice cover between 2015 and 2016. This raises the question of whether the atmosphere—while unquestionably the major driver of sea ice variability—can alone explain the extreme sea ice fluctuations of the last decade. Multiple atmospheric drivers may have acted in concert to drive the observed sea ice loss (Stuecker et al. 2017; Schlosser et al. 2018; G. Wang et al. 2019), but to date the relative impact of these individual modes has not been quantified.

In addition to atmospheric drivers, upwelling warm deep water has been suggested as a driver of the 2016 event. The polar Southern Ocean is characterized by a cold, relatively fresh mixed layer atop relatively warm Circumpolar Deep Water (CDW: Martinson 1990; Orsi and Whitworth 2005). The latter upwells, regionally and on occasion, primarily due to the strong zonal winds over the Southern Ocean. Meehl et al. (2019) suggested that increased upwelling warm water played a part in the 2016 event. This warm deep water is also integral to understanding a theoretical “two-phase” response to the observed positive trend in the SAM (Ferreira et al. 2015), a response that is simulated by many coupled climate models, albeit with large uncertainty in timing (Kostov et al. 2017). This response is characterized by a period of increased sea ice extent under sustained positive SAM conditions, driven by increased zonal winds and the associated northward Ekman sea ice transport. Eventually, however, the Ekman pumping would bring up warm, deep water resulting in a sudden switch to sea ice decline. Despite the congruence of this hypothesis with observed sea ice variability in the last decade (i.e., a long-term increase followed by a sudden and sustained reduction), the SAM *trend* (as opposed to variability) has not been clearly connected to recent Antarctic sea ice changes (Polvani et al. 2021). What, if any, role the ocean has played remains an open question, which is difficult to address due to the lack of sustained under-ice observations in the polar Southern Ocean, and the complexity of modeling mixed layer processes.

Recent extreme sea ice events have challenged our understanding of Antarctic sea ice variability. In this work, we use sea ice observations and atmospheric reanalysis data to test the suggestion that there may have been a regime shift. We

TABLE 1. Summary of indices used to fit the empirical DJF SIA regression model.

Mode	Index description	Citation
Southern Annular Mode (SAM)	Difference between 40° and 65°S standardized ERA5 monthly zonal mean sea level pressure (MSLP)	Gong and Wang (1999)
Amundsen Sea low (ASL)	ERA5 monthly MSLP areal mean for 60°–75°S, 170°E–75°W	Turner et al. (2016)
Zonal wave-3 amplitude (ZW3amp) and phase (ZW3phs)	Derived from the leading two PCs of ERA5 monthly 500-hPa meridional wind anomalies	Goyal et al. (2022)
Southern Oscillation Index (SOI)	Standardized MSLP differences between Tahiti and Darwin	NOAA (2022)
Indian Ocean dipole (IOD)	SST difference between 10°S–10°N, 50°–70°E and 10°S–0°N, 90°–110°E	Saji and Yamagata (2003)
Sea ice area (SIAlead)	Total SIA from March to November preceding summer	–

follow the definition proposed by Lenton et al. (2023) of a *regime shift* as an abrupt change in the state of a system, which may or may not be associated with an irreversible change (i.e., *tipping point*). We do not consider whether the latter has occurred. Specifically, we consider whether there has been a significant change in sea ice variability that has led to the prevalence of extreme sea ice events (both positive and negative) during the last decade or so, and whether such a change indicates a changed response to the atmosphere, which is the primary external driver of sea ice variability.

2. Methods

a. Data

The primary observational data are version 4 of the monthly-mean National Snow and Ice Date Center Climate Data Record (CDR) of sea ice concentration (Meier et al. 2021b). At the time of writing these data run to the end of 2022, so for 2023 records we use the equivalent Near Real Time CDR product (Meier et al. 2021a). Sea ice area (SIA) is calculated as the spatial integral of SIC. Due to instrument issues, there are no data for December 1987–January 1988, so we exclude that summer from the record of December–February (DJF) means. Atmospheric variability is characterized by version 5 of the European Centre for Medium-Range Weather Forecasts reanalysis (ERA5; Hersbach et al. 2018). ERA5 has a proven high-quality representation of the atmosphere over the polar Southern Ocean, and although it has a slight spurious cooling trend over the Bellingshausen Sea (Hobbs et al. 2020), compared to other reanalyses, it has a superior representation of near-Antarctic atmospheric variability (Caton Harrison et al. 2022). Additionally, we use several indices of tropical variability that are derived from historical station records, or sea surface temperature; these indices and their source data are summarized in Table 1.

b. Statistical analysis

We use an F test to assess whether the summer (i.e., DJF) total SIA variance has changed over the satellite record, with degrees of freedom adjusted to account for autocorrelation in the data. Previous research indicates that the summertime series is not autocorrelated, since the separation time between each summer is longer than the typical decorrelation time scale of Antarctic sea ice, and each summer is separated by a midwinter "predictability barrier" (e.g., Ordoñez et al. 2018; Libera et al. 2022). Calculation of the lag-1 autocorrelation verified that this was true up to 2006, but for the latter analysis period there is some correlation between one summer and the next. We therefore adjust the degrees of freedom for each time period to account for autocorrelation at lags of up to 12 months, using the method of Zwiers and von Storch (1995).

To test the changing relationship between large-scale climate modes and Antarctic sea ice, we use a regression model to predict summer SIA using six indices with well-established relationships to Antarctic sea ice (SAM, SOI, ASL, ZW3 amplitude and phase, and IOD; see Table 1). Additionally, we include SIA for preceding months (i.e., March–November) as a predictive variable (SIAlead). The indices are each separated into individual calendar months leading or overlapping the DJF sea ice period (e.g., the monthly SAM index is separated into a March SAM index, April index, and so on), so that there are 81 potential predictor indices (i.e., 6 atmosphere variables $\times$ 12 months, plus 9 months for SIAlead).

Using all these indices allows us to consider the established large-scale drivers of summer SIA variability, but it raises the issue of covariance between these indices (e.g., SAM and ASL are closely related, as is SAM from one month to the next). To overcome this problem, these 81 indices are transformed into 40 principal components (PCs), which are theoretically independent of each other, and therefore do not covary. These PCs capture almost all the variance of the indices (Fig. S1 in the online supplemental material), and so include every possible combination of the original indices. However, any regression model fit is sensitive to the number of predictors used (in this case too few PCs diminishes the model skill, i.e., underfitting, while too many leads to overfitting). We use a cross-validation method (Picard and Cook 1984) to objectively find the optimal balance between under- and overfitting (see the online supplemental material S2). This is achieved by using the 10 leading PCs, which between them explain 64% of the total variance of the input data (Fig. S1). The variance explained and associated eigenvector patterns of all 10 PCs are also shown in Fig. S3.

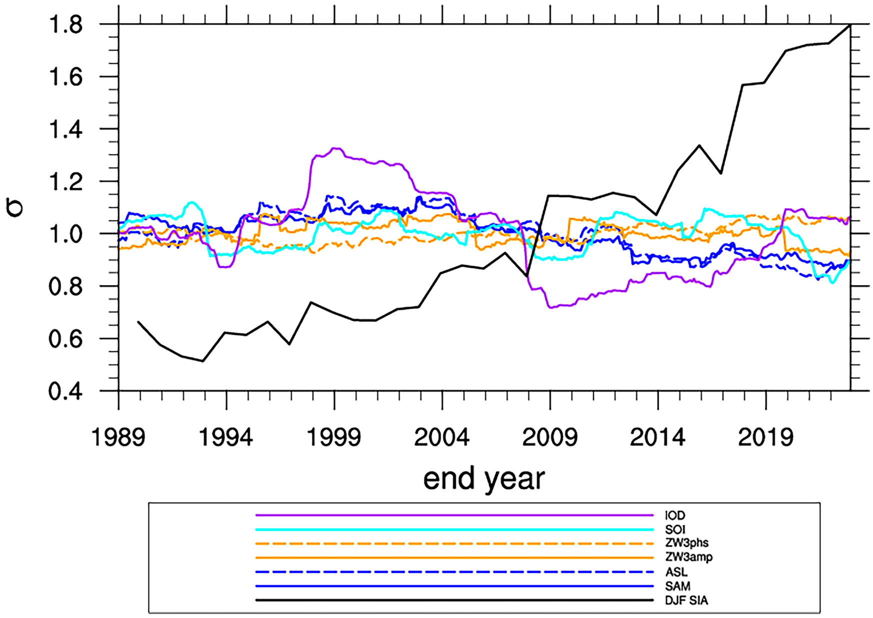

FIG. 2. Standard deviation (σ) of 120-month running windows for monthly atmospheric indices, and 10-yr running mean of summer (DJF) SIA. To account for the different units of each time series, each has been divided by its own 1979–2023 average (i.e., 1 on the y axis indicates a 120-month σ equal to the σ of the full period). The x-axis dates refer to the final date of each averaging period.

3. Results

a. Evidence for increased sea ice variability

Using a set of changepoint algorithms based on the Antarctic sea ice mean state, Purich and Doddridge (2023) identified two changepoints (2007 and 2016). These changepoints separate three periods in the satellite record: an early period spanning 1979–2006, a high sea ice cover from 2007 to 2016, and a low ice cover state from spring of 2016 to the present. Here we extend that changepoint analysis to explore shifts in the variability rather than the mean state of the sea ice record, where we term such behavior changes as a *regime shift*. The 2007 changepoint is also marked by an increased sea ice variability (Fig. 1) but the variability in the 2007–16 period and the 2016–present period are statistically indistinguishable (Purich and Doddridge 2023). Hence, we focus on the 2007 changepoint in this paper.

In terms of sea ice variability, austral summer (DJF) has generally shown the strongest signals, both in long-term trends (Hobbs et al. 2016) and for recent extremes (Turner et al. 2017; Raphael and Handcock 2022; Liu et al. 2023). We therefore focus our analysis on SIA anomalies during DJF. To test whether there has indeed been an increase in summer variance, we calculate the standard deviation of DJF SIA anomalies for running 10-yr periods (Fig. 2). This shows a clear, almost monotonic increase in SIA variance over the twenty-first century (black line, Fig. 2), and an accelerated ramping up since 2014. There is an increased standard deviation from 0.31 million km^2 in 1979–2006 to 0.76 million km^2 in 2007–22, an increased variance that is statistically significant at the 99% level based on an F test after accounting for temporal autocorrelation. Undoubtedly this increased variance is in part due to the extreme loss in 2016 (Fig. 1). To eliminate this, we calculate the standard deviation for 2007–15. There is still an increased variance (σ = 0.50 million km^2), although due to the smaller sample size it is only statistically significant at the 90% level. Regardless, it is clear that Antarctic sea ice summer variability has increased since the turn of the twenty-first century. In the subsequent sections we explore possible drivers for this apparent change in variability.

b. Possible drivers of recent sea ice variability

Figure 2 compares the changes in SIA variability with those of the atmospheric indices listed in Table 1. Most of the indices do not show systematic changes in their standard deviation over the period of satellite observations, with exception of the Indian Ocean dipole (IOD), which has variance changes broadly inverse to those of the sea ice record. While it is not immediately apparent how *increased* variance in the tropical Indian Ocean would *suppress* Antarctic sea ice variance (and vice versa), we note that the IOD may have contributed to the 2016 event (Purich and England 2019), so it is possible that a tropical teleconnection has some bearing on the nonstationary SIA variance. However, we also note that the magnitude of IOD variance change is small compared to that of the SIA record. Figure 2 suggests that despite the atmosphere's dominance in driving interannual sea ice variability, there is no immediate explanation from these indices which have a well-established relationship to Antarctic SIA. This implies three possibilities: 1) the sea ice response to atmospheric variability has altered/magnified; 2) the change in

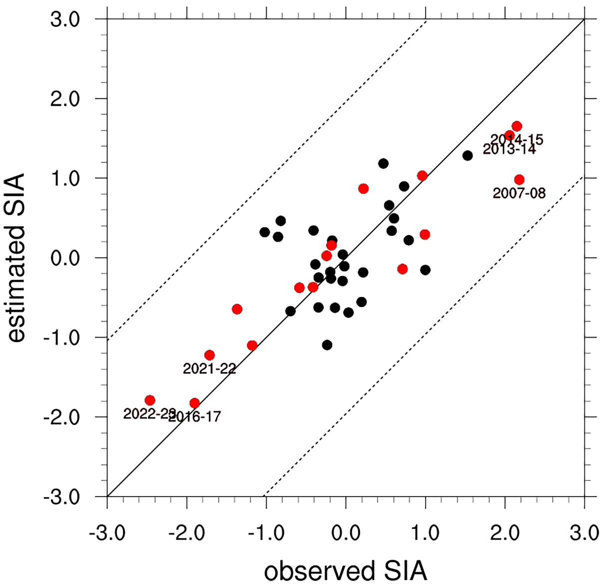

FIG. 3. Observed summer SIA (x axis), and SIA predicted by linear model (y axis), plotted as standardized anomalies (i.e., a value of 2 denotes a 2 standard deviation anomaly). Black dots are for 1979–2006 and red dots are for 2007–22. Solid line shows the 1-to-1 relationship and dashed lines show the 95% confidence intervals (defined as 2 times the calibration RMS error). Selected years that correspond to extreme sea ice events are annotated.

SIA variance is driven by some other factor (e.g., the ocean); 3) there is some nonlinear interaction between atmospheric modes that modulates the sea ice response. As an example, the sea ice response to ENSO events is affected by the background SAM state (Stammerjohn et al. 2008; Wang et al. 2023), and indeed both SAM and ENSO have been implicated in the 2016 event (Stuecker et al. 2017). Could the observed multidecadal positive SAM trend have changed the sea ice response to ENSO?

To test hypothesis 1), we fit a linear regression model using principal components of the climate indices that are related to Antarctic sea ice (SAM, SOI, ASL, ZW3, IOD, SIAlead; see Table 1) as described in section 2b. The empirical model shows reasonable skill at predicting summer SIA (Fig. 3), and interestingly shows rather more skill in the recent period (shown by red dots) compared to the earlier period, even though extreme values are often truncated in linear models. The predicted values have a similar increased variance as the observed time series, with σ = 0.30 million km^2 for 1979–2006 compared to 0.56 million km^2 for 2007–22. This gives us confidence that our relatively simple set of predictors captures most of the observed summer SIA variability, and we can explore this model further to isolate which predictors are essential for explaining the shift in SIA behavior. An important note is that this linear model is unable to capture nonlinear interactions suggested by hypothesis 3) above; the model's skill in reproducing summer sea ice suggests that such nonlinear interactions have not played a significant role in the variance changes.

We proceed by performing a simple "leave-one-out" analysis, whereby we refit the model but eliminating each of the 10 leading PCs used as predictors in turn; we can then compare the impact on model skill of each PC (Fig. 4). This analysis identifies that much of the model skill comes from the third and fourth PCs; the exclusion of any of the other PCs has a limited effect on the predictive skill, whereas model skill reduces when either PC3 or PC4 is excluded (Fig. 4a). The residuals over time shown in Fig. 4b indicate that no single PC has a consistently dominant influence on predictive skill over the entire time series. The importance of PCs 3 and 4 emerges only after 2010, and this effect predates the summer 2016/17 event. This result implies that the recent increased summer sea ice variance is explained by changes in these two principal components. (A confounding factor here is the period from 2005 to 2008, when the model skill is relatively poor for all PCs.)

An interesting point in the context of Fig. 2 is that the removal of PC2, which encompasses the IOD contribution (Fig. S2), does not change the skill, which confirms that the change in IOD variance is unlikely to have affected the sea ice variance. (An important note when interpreting Fig. 4 is to remember that the order of the PCs—i.e., PC1 explains greater variance than PC2, and so on—only applies to the input series in Table 1 from which the PCs are constructed, and not to the target variable of summer SIA. This means that the greater importance of PCs 3 and 4 over leading-order PCs for summer SIA is not necessarily inconsistent.)

The eigenvectors of PCs 3 and 4 are shown in Fig. 5. PC4 shows a relationship between June–July ZW3 and SAM/ASL throughout the March–September sea ice growth season, all indices which have been previously associated with the 2016/17 sea ice loss (Stuecker et al. 2017; Schlosser et al. 2018; G. Wang et al. 2019). Both PCs also show an important role for sea ice preconditioning, with winter SIA dominating PC3 and spring (September–November) SIA showing strongly in PC4. The eigenvalue time series of PCs 3 and 4 (Figs. 5c,d) both show a strong imprint of the 2016 and 2021 events. PC4 (related to SAM, ZW3, and spring sea ice) is indicative of a point process with importance for specific events (1980, 2016, 2021) but no evidence of a systematic change (Fig. 5d). PC3 on the other hand (related to winter sea ice preconditioning) shows an increased variance after 2000 that qualitatively matches the summer sea ice record.

The relationship between sea ice and the SAM, ASL, and ZW3 is long established, whereas the importance of winter sea ice preconditioning has only recently been noted (Purich and Doddridge 2023). To explore further which of the indices in PCs 3 and 4 are essential for predicting summer SIA, and also the temporal dependence of that predictive skill, we refit the model (including computing new PCs) excluding individually ZW3 (phase and amplitude), SAM/ASL, and SIAlead (Fig. 6). Prior to 2012 the model's residuals are reasonably stationary, and there is no evidence that the exclusion of any of the indices has a dominant effect, which would be indicated by a much larger residual for one of the lines in Fig. 6 compared to the others. (2002 is a notable exception and indeed was a rather unusual year, with the most negative winter SAM state on record coupled with El Niño conditions, and

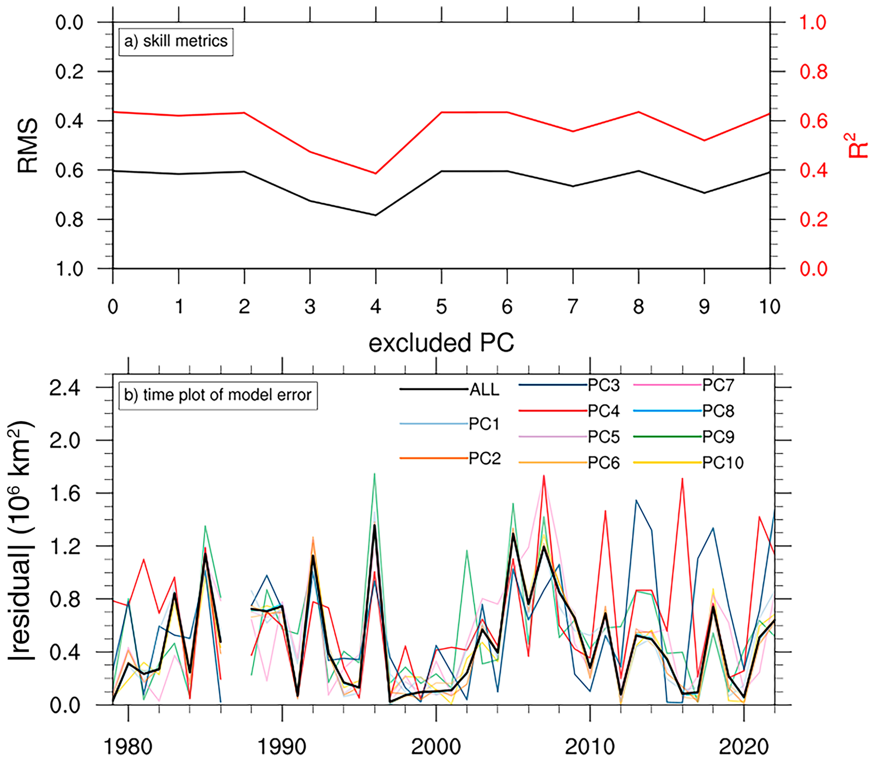

FIG. 4. Results of "leave-one-out" analysis, based on reconstructed 1979–2022 summer SIA after exclusion of a single PC. (a) Skill metrics based on predicted 1979–2022 summer SIA. The *x* axis refers to the excluded principal component (PC). The skill metrics are root-mean-square error (RMS; black line; note reversal of the *y* axis) and fraction of variance explained (R^2; red line; right *y* axis). For both metrics, a value close to the top of the plot indicates the greatest skill. (b) Absolute residuals (compared to observations) for each summer's predicted SIA. The reference case is "ALL"; i.e., no PC was excluded. A higher residual implies that that PC was important for explaining that particular summer.

the SAM's importance for that year's sea ice is clear in Fig. 6.) After 2012, however, the model predicts the summer sea ice if, and only if, winter/spring sea ice is included in the prediction model. In the context of increased sea ice variability, we can see from Fig. 6a that the atmosphere-only predictions produce the correct sign of the post-2012 anomalies, but not the magnitude of recent extreme anomalies. When SIA is excluded from the predictive model, the 2007–22 standard deviation is just 0.29 million km^2, compared to 0.56 when SIA is included, and 0.76 for the observations (section 3a). This result suggests that increased summer sea ice variance after 2006 can only be partially explained by atmosphere drivers, and is closely related to a significantly increased relationship between winter/spring sea ice and the subsequent summer. This change in sea ice memory across different seasons is in itself a change in the behavior of the sea ice system that we explore further in the next section.

c. Month-to-month sea ice relationships

In the previous section, we demonstrated that the increased summer Antarctic sea ice variability is not readily explained by atmospheric modes, and that SIA in winter and spring seems to have become a reliable predictor of the summer sea ice state. In this section we explore that relationship in more detail. Figure 7a shows the SIA record for each individual month. Up to 2006 there is little evidence of covariance between any of the months, indicated by the noisy "spread" between the months for any given year. Quantifying this, and with reference to the important PCs identified in the previous section, the 1979–2006 correlation between SON and the subsequent DJF SIA is very low (r = 0.14). However, from the late 2000s the different months begin to covary, and from 2010 onward they are remarkably coherent. This covariance includes the extreme 2016 loss but also clearly predates it, and includes both increases and decreases (i.e., the covariance is not merely due to a background trend common to all the months). From 2007, the SON to DJF correlation is statistically significant (r = 0.88, significant at the 95% confidence level).

This suggests that all seasons, not just those identified in the linear analysis in the previous section, have a stronger statistical relationship with summer SIA over the last decade or so. This is confirmed in Fig. S4, showing correlation coefficients by month with DJF SIA. Interestingly, even though the correlation with summer SIA is strong for all months, the predictive

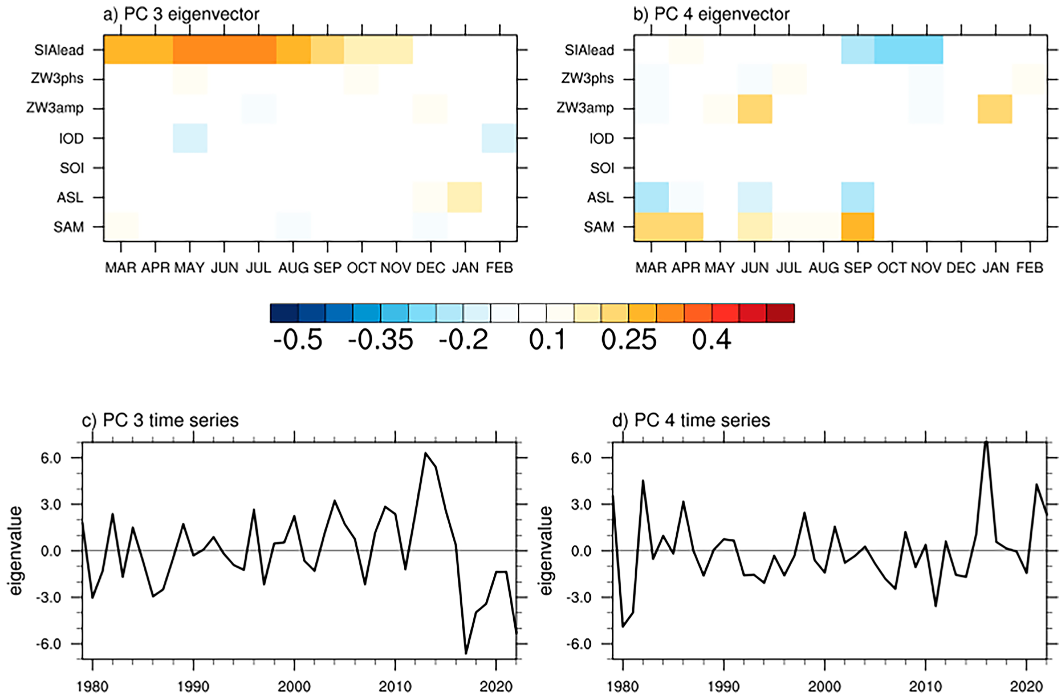

FIG. 5. (a),(b) Eigenvector pattern of the third and fourth principal components, respectively, calculated from correlation matrix of the seven input indices for each month outlined in Table 1. The sign of each loading pattern is arbitrary. (c),(d) Eigenvalue time series for the third and fourth principal components, respectively. (The eigenvector patterns of all 10 PCs are shown in Fig. S2.)

relationship (indicated by regression coefficients in Fig. S4b) is much more heterogenous and is particularly strong for June and September, broadly consistent with Fig. 5. (Note that the analysis in Fig. S4 does not account for covariance between the predictor months and should not be regarded as a reliable empirical model for summer SIA.)

While our focus has been on recent extreme summer events, Fig. 7a indicates that coherence in interannual variability is now happening for all months, not just for winter-to-summer correlations. We explore this further in Fig. 7b, which shows the autocorrelation of the monthly SIA record at different lags in running 10-yr periods. Unsurprisingly, like most ocean variables the SIA record has a high autocorrelation at 1-month lag throughout the satellite record. The recent increase becomes apparent at longer lags though, with autocorrelation of more than 0.7 for 6 months lag. At all lags the autocorrelation ramps up rapidly after 2006, consistent with Purich and Doddridge (2023).

This analysis shows that the increased SIA variance over the last decade or so has been accompanied by greater sea ice autocorrelation, indicating more capacity for sea ice anomalies to persist from one season to the next. Indeed, while atmosphere modes are essential drivers of month-to-month sea ice variability, our analysis shows that accounting for this sea ice memory is necessary to empirically predict summer sea ice. Previous studies describe how an increase in temporal autocorrelation accompanies an increase in variance, since anomalies accumulate over time rather than dissipate quickly (Scheffer et al. 2009; Lenton 2011). This can be formally proven mathematically, and is evident in historical climate records, hence our results have a sound theoretical underpinning. Intriguingly, these changes are considered as warning signs of a system approaching a critical transition, and paleoclimate records show that a sudden shift to very high autocorrelation—such as we show for Antarctic sea ice over the last decade—has been a precursor to several abrupt changes in Earth's history (Dakos et al. 2008). Our results therefore lend weight to suggestions that Antarctic sea ice has undergone a regime shift (Eayrs et al. 2021; Raphael and Handcock 2022; Purich and Doddridge 2023).

4. Discussion

We have shown that there has been a doubling of summer Antarctic sea ice variability over the period of satellite observations, consistent with Purich and Doddridge (2023). At the time scales considered in this study the primary driver of Antarctic sea ice is the atmosphere, but while large-scale atmospheric modes (e.g., SAM, ENSO, ZW3) are highly skillful in predicting summer sea ice, those modes alone are not enough to explain this recent increased variance. Instead, we show that since 2010 the sea ice state in preceding seasons is essential to skillfully predict summer sea ice. This is a departure from the earlier three decades of the satellite record, when winter and spring sea ice were not good predictors of the subsequent summer (Holland et al. 2013; Marchi et al. 2019; Ordoñez et al. 2018; Libera et al. 2022).

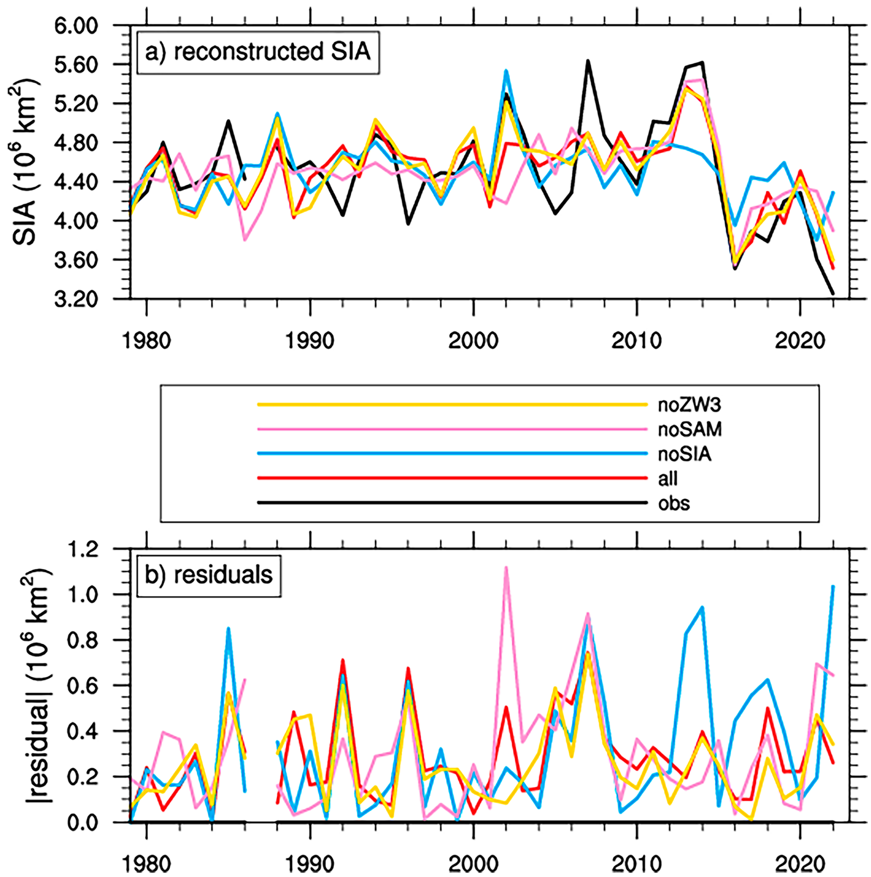

FIG. 6. Results from refitting the predictive model after excluding SIA, ZW3, and SAM/ASL as predictors, and using only SIA. (a) Observed and predicted summer SIA. (b) Absolute residuals with respect to the observations. Black line shows observations.

A dominant feature of the recent satellite record is the sudden decline from a record high in 2014 to record low in 2016, which contributes to the increase in variance. However, it is important to emphasize that the systemic changes are evident from 2010, and that an increased variance was statistically significant at the 90% level before 2016. As extraordinary as the summer 2016 event was, our results are not solely dependent on that.

The highly unusual sea ice state over recent years has led researchers to suggest that there may have been a regime shift in the Antarctic sea ice system (Eayrs et al. 2021; Raphael and Handcock 2022; Purich and Doddridge 2023). For the purposes of this paper, we have considered a *regime shift* as an abrupt change in the system's response to external drivers (Lenton et al. 2023), and in particular the sea ice response to atmospheric modes. Dynamical systems theory, proven in fields as broad as economics and ecology as well as climate science, shows that critical transitions in a system may be indicated by a state called "critical slowing down" (Wissel 1984; Dakos et al. 2008), which more specifically is indicated by an increased variance, an increased autocorrelation, and more spatially coherent system responses (Scheffer et al. 2009; Lenton 2011). Our analysis demonstrates the former two conditions, and it is important to note that they are related, since increased autocorrelation allows anomalies to accumulate rather than dissipate over time. We have not considered spatial changes in this study, but Schroeter et al. (2023) showed that since 2006, the sea ice anomalies have become more spatially homogenous, even though the wind forcing over the Southern Ocean has become more spatially heterogenous (and specifically more ZW3-like). This is something of a paradox since we would expect a more wavelike wind forcing to drive a more spatially heterogenous ice cover, but importantly it satisfies the third indicator of a critical change—spatial coherence—in a way that defies a simple attribution to atmospheric forcing.

Our study is limited by the relatively short satellite record of Antarctic sea ice, and by the fact that we do not yet have a physical mechanism to explain the observed changes. However, even with these *caveats*, the weight of statistical evidence is consistent with a regime shift. Indeed, we note that over recent months, winter 2023 sea ice cover has not just been a record low, but a striking seven standard deviations below the 1979–2008 climatology, and two standard deviations below the previous record (June 2022). This event has been remarkable not just for its magnitude but also its season, since winter sea ice variability is less than summer variability. While we

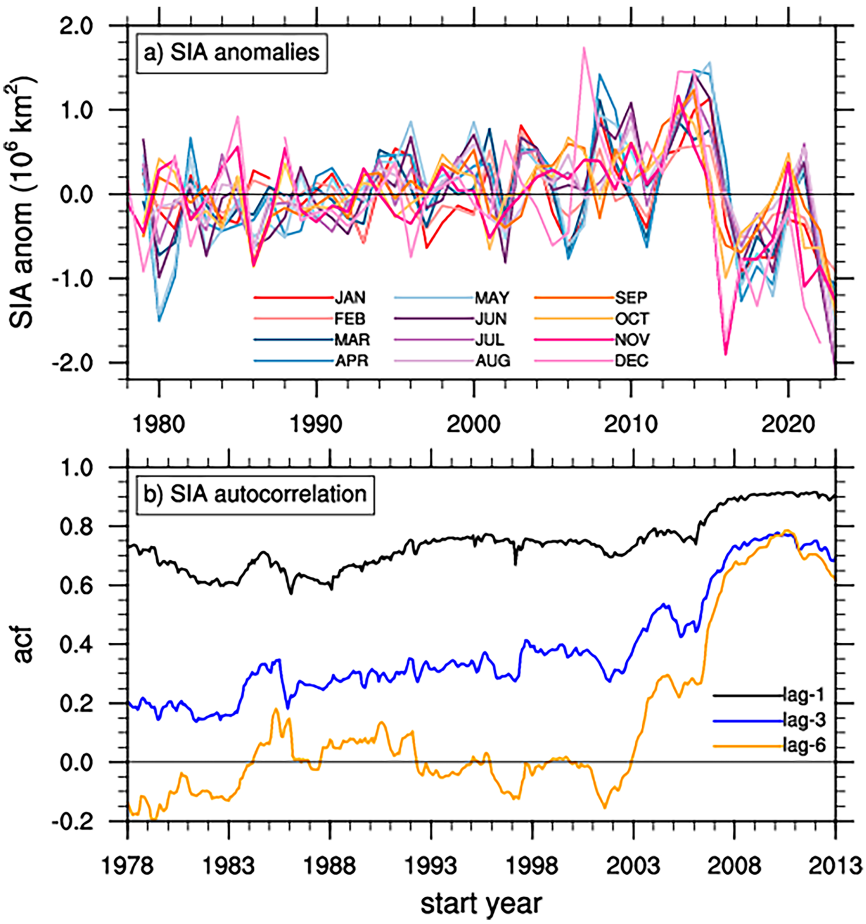

FIG. 7. (a) Time series of 1979–2023 SIA anomalies (million km^2) by month. (b) Autocorrelation function (acf) of monthly SIA record in running 120-month periods at lags of 1 month (black), 3 months (blue), and 6 months (orange). The x axis shows the first year of each 120-month period.

have focused on summer in this study, this austral winter is an important context for our results.

An intriguing result that merits future analysis is the 2005–08 period. This approximately coincides with the 2007 transition in Antarctic sea ice state found by Purich and Doddridge (2023), and Fig. 6 shows that none of our predictive variables (atmosphere or sea ice) have any real skill in capturing 2005–08 summer sea ice variability. This period coincides with a shift from a positive to negative phase of the interdecadal Pacific oscillation (IPO), a mode of decadal tropical Pacific variability that has been implicated in Antarctic sea ice variability (Meehl et al. 2016), but which is not included in our empirical model, since its long time scale means that it is difficult to train on a 45-yr dataset. The first decade of the twenty-first century is unique in our study period since the IPO was in a negative phase, which may have impacted observed sea ice trends (Meehl et al. 2016). Given the shortness of the observational record it is impossible to state whether this IPO transition could temporarily alter the sea ice–atmosphere relationship, but this merits further investigation.

As noted, this study presents a purely statistical analysis and does not consider the physical mechanism of the underlying change. However, the clear changes in the month-to-month memory are indicative of a change in sea ice–ocean mixed layer interactions. During the spring, an early retreat allows more solar energy to warm the ocean mixed layer, which is a source of predictability in subsequent seasons (Stammerjohn et al. 2012); however subsequent sea ice melt forms a well-stratified surface layer that separates the spring thermal anomalies from the ice pack, so that the spring memory does not influence the summer sea ice (Holland et al. 2013; Marchi et al. 2019; Libera et al. 2022). During winter, sea ice production entrains older, deep water with no memory of recent surface conditions into the mixed layer (Martinson and Iannuzzi 1998). This implies a negative sea ice–ocean feedback that would limit variability, and also reset the thermal state of the sea ice–mixed layer system and causes a winter predictability barrier (Libera et al. 2022). Our finding that spring (SON) SIA is now an important predictor of the summer state therefore indicates that the system may not be developing such a well-defined fresh summer layer. Moreover, we have shown that early winter anomalies now seem to cross the midwinter predictability barrier. Since sea ice–mixed layer interactions are the primary constraint on sea ice memory, our result of an increased correlation from winter to summer is a possible indicator that ocean processes could be driving the change in Antarctic sea ice behavior. While this is merely a hypothesis, given both the ocean's role as a source of memory and that even persistent atmospheric drivers (e.g., ENSO) cannot explain the increase in summer sea ice variance, it seems highly likely that the ocean is involved in some way.

It is also important to note that this study does not consider the impact or otherwise of anthropogenic climate forcings, an analysis that would require a formal detection and attribution study (Hegerl et al. 2009). While our statistical analysis suggests a possible regime change, it is possible that such shifts have happened unforced in the past, prior to the continuous satellite record. Changes in sea ice modes have been observed even within the satellite record, such as the Antarctic Circumpolar Wave (White and Peterson 1996), an eastward propagating mode of sea ice and ocean temperature anomalies that has waxed and waned over the satellite record (Cerrone et al. 2017). However, robustly detectable anthropogenic warming signals have emerged in multiple aspects of the Antarctic climate (Hobbs et al. 2021; Dalaiden et al. 2022; Holland et al. 2022), and it seems reasonable to consider the possibility of an anthropogenic change to the sea ice system. Formal detection and attribution studies rely on the comparison of observations with coupled climate model simulations, but a possible confounding factor is the low confidence that current coupled models adequately represent Southern Ocean processes (Meredith et al. 2019; Roach et al. 2020). Further climate-scale perspectives may also be gained from analysis of pre-satellite-era sea ice reconstructions (e.g., Fogt et al. 2022).

This analysis has several implications for seasonal predictability of summer sea ice, a topic that has seen increased interest since the start of a coordinated annual prediction comparison for Antarctica, the Sea Ice Prediction Network-South project (Lieser et al. 2020). Our results indicate a more predictable total circumpolar sea ice, although in practice, regional predictions are more relevant for operational users who need them for access and logistics (e.g., national Antarctic programs, Southern Ocean fisheries).

Sea ice is a critical component of the Antarctic ecosystem, and extreme low summer ice cover has significant impacts. A stark example is the reported 2022 catastrophic breeding failure of emperor penguin (*Aptenodytes forsteri*) colonies due to early sea ice loss (Fretwell et al. 2023). Sea ice loss could also have significant consequences for Southern Ocean biogeochemistry. Changes in sea ice behavior can affect the synchronicity between ice retreat and the onset of water column biological productivity, which have been well studied locally and at circumpolar scales (Vernet et al. 2008; Montes-Hugo et al. 2009; Taylor et al. 2013; Li et al. 2016; Liniger et al. 2020; von Berg et al. 2020). Based on our findings, understanding how the physical environment, biogeochemistry, and ecosystems could be affected by such changes in local sea ice is critical, noting considering that variability in sea ice extent has been shown to affect phytoplankton communities' diversity near the northern Antarctic Peninsula (Lin et al. 2021), with implications for the ocean carbon cycle. The ecosystem impacts of a sustained and repeated loss of Antarctic sea ice are complex and varied (Swadling et al. 2023), but the impacts of increased variability have not yet been systematically considered.

5. Conclusions

In the last 15 years, summer Antarctic sea ice variability has been significantly greater than the earlier satellite record. This increased variance is tied to a marked increase in month-to-month sea ice autocorrelation. These changes, along with changes in the spatial variance of Antarctic sea ice shown by Schroeter et al. (2023), are all consistent with theoretical precursors of a transition to a new sea ice state. Our model indicates that the increased sea ice variance and autocorrelation are not directly attributable to changes in atmospheric drivers of Antarctic sea ice variability. Although we have not considered a physical mechanism, we suggest that the changes in sea ice variability herald a shift in seasonal sea ice–ocean mixed layer interactions.

Acknowledgments. This project received grant funding from the Australian Government as part of the Antarctic Science Collaboration Initiative program and was supported under the Australian Research Council's Special Research Initiative for Antarctic Gateway Partnership (Project ID SR140300001). A. M. was supported by the Australian Research Council Discovery Early Career Research Award project DE200100414. Z. W. was supported by a postgraduate scholarship from the Australian Research Council's Special Research Initiative for the Antarctic Gateway Partnership SRI40300001. W. H. and E. D.'s contributions were supported the Australian Research Council Discovery DP230102994. W. H., A. M., and G. L. acknowledge support from the Australian Research Council Centre of Excellence in Climate Extremes (CE170100023). P. S. was supported by ARC grants FT190100413, DP190100494, LP200100406, CE230100012, DP240102358. The authors thank Dr. Rishav Goyal for supplying the updated zonal wave 3 index. The authors are indebted to Dr. Mark Handcock for his invaluable help, and thank the three anonymous reviewers whose comments greatly improved this paper.

Data availability statement. All sea ice concentration data used during this study are openly available from the National Snow and Ice Data Center (https://nsidc.org/data/g02202/versions/4/). ERA5 monthly data are openly available from the Copernicus Climate Data Service (https://doi.org/10.24381/cds.f17050d7).

REFERENCES

Caton Harrison, T., S. Biri, T. J. Bracegirdle, J. C. King, E. C. Kent, É. Vignon, and J. Turner, 2022: Reanalysis representation of low-level winds in the Antarctic near-coastal region. *Wea. Climate Dyn.*, **3**, 1415–1437, https://doi.org/10.5194/wcd-3-1415-2022.

Cerrone, D., G. Fusco, Y. Cotroneo, I. Simmonds, and G. Budillon, 2017: The Antarctic circumpolar wave: Its presence and interdecadal changes during the last 142 years. *J. Climate*, **30**, 6371–6389, https://doi.org/10.1175/JCLI-D-16-0646.1.

Dakos, V., M. Scheffer, E. H. van Nes, V. Brovkin, V. Petoukhov, and H. Held, 2008: Slowing down as an early warning signal for abrupt climate change. *Proc. Natl. Acad. Sci. USA*, **105**, 14 308–14 312, https://doi.org/10.1073/pnas.0802430105.

Dalaiden, Q., A. P. Schurer, M. C. Kirchmeier-Young, H. Goosse, and G. C. Hegerl, 2022: West Antarctic surface climate changes since the mid-20th century driven by anthropogenic forcing. *Geophys. Res. Lett.*, **49**, e2022GL099543, https://doi.org/10.1029/2022GL099543.

Eayrs, C., D. Holland, D. Francis, T. Wagner, R. Kumar, and X. Li, 2019: Understanding the seasonal cycle of Antarctic sea ice extent in the context of longer-term variability. *Rev. Geophys.*, **57**, 1037–1064, https://doi.org/10.1029/2018RG000631.

——, X. Li, M. N. Raphael, and D. M. Holland, 2021: Rapid decline in Antarctic sea ice in recent years hints at future change. *Nat. Geosci.*, **14**, 460–464, https://doi.org/10.1038/s41561-021-00768-3.

Ferreira, D., J. Marshall, C. M. Bitz, S. Solomon, and A. Plumb, 2015: Antarctic Ocean and sea ice response to ozone depletion: A two-time-scale problem. *J. Climate*, **28**, 1206–1226, https://doi.org/10.1175/JCLI-D-14-00313.1.

Fogt, R. L., A. M. Sleinkofer, M. N. Raphael, and M. S. Handcock, 2022: A regime shift in seasonal total Antarctic sea ice extent in the twentieth century. *Nat. Climate Change*, **12**, 54–62, https://doi.org/10.1038/s41558-021-01254-9.

Fretwell, P. T., A. Boutet, and N. Ratcliffe, 2023: Record low 2022 Antarctic sea ice led to catastrophic breeding failure of emperor penguins. *Commun. Earth Environ.*, **4**, 273, https://doi.org/10.1038/s43247-023-00927-x.

Gong, D., and S. Wang, 1999: Definition of Antarctic Oscillation Index. *Geophys. Res. Lett.*, **26**, 459–462, https://doi.org/10.1029/1999GL900003.

Goyal, R., M. Jucker, A. S. Gupta, and M. H. England, 2022: A new zonal wave 3 index for the Southern Hemisphere. *J. Climate*, **35**, 5137–5149, https://doi.org/10.1175/JCLI-D-21-0927.1.

Hegerl, G. C., O. Hoegh-Guldberg, G. Casassa, M. Hoerling, S. Kovats, C. Parmesan, D. Pierce, and P. Stott, 2009: Good practice guidance paper on detection and attribution related to anthropogenic climate change. *IPCC Expert Meeting on Detection and Attribution Related to Anthropogenic Climate Change*, T. F. Stocker et al., Eds., University of Bern, 1–9.

Hersbach, H., and Coauthors, 2018: Operational global reanalysis: Progress, future directions and synergies with NWP. ERA Rep. Series 27, 65 pp., https://doi.org/10.21957/tkic6g3wm.

Hobbs, W. R., and M. N. Raphael, 2010: The Pacific zonal asymmetry and its influence on Southern Hemisphere sea ice variability. *Antarct. Sci.*, **22**, 559–571, https://doi.org/10.1017/S0954102010000283.

——, R. Massom, S. Stammerjohn, P. Reid, G. Williams, and W. Meier, 2016: A review of recent changes in Southern Ocean sea ice, their drivers and forcings. *Global Planet. Change*, **143**, 228–250, https://doi.org/10.1016/j.gloplacha.2016.06.008.

——, A. R. Klekociuk, and Y. Pan, 2020: Validation of reanalysis Southern Ocean atmosphere trends using sea ice data. *Atmos. Chem. Phys.*, **20**, 14 757–14 768, https://doi.org/10.5194/acp-20-14757-2020.

——, C. Roach, T. Roy, J.-B. Sallee, and N. Bindoff, 2021: Anthropogenic temperature and salinity changes in the Southern Ocean. *J. Climate*, **34**, 215–228, https://doi.org/10.1175/JCLI-D-20-0454.1.

Holland, M. M., E. Blanchard-Wrigglesworth, J. Kay, and S. Vavrus, 2013: Initial-value predictability of Antarctic sea ice in the Community Climate System Model 3. *Geophys. Res. Lett.*, **40**, 2121–2124, https://doi.org/10.1002/grl.50410.

Holland, P. R., and R. Kwok, 2012: Wind-driven trends in Antarctic sea-ice drift. *Nat. Geosci.*, **5**, 872–875, https://doi.org/10.1038/ngeo1627.

——, and Coauthors, 2022: Anthropogenic and internal drivers of wind changes over the Amundsen Sea, West Antarctica, during the 20th and 21st centuries. *Cryosphere*, **16**, 5085–5105, https://doi.org/10.5194/tc-16-5085-2022.

Kimura, N., 2004: Sea ice motion in response to surface wind and ocean current in the Southern Ocean. *J. Meteor. Soc. Japan*, **82**, 1223–1231, https://doi.org/10.2151/jmsj.2004.1223.

Kostov, Y., J. Marshall, U. Hausmann, K. C. Armour, D. Ferreira, and M. M. Holland, 2017: Fast and slow responses of Southern Ocean sea surface temperature to SAM in coupled climate models. *Climate Dyn.*, **48**, 1595–1609, https://doi.org/10.1007/s00382-016-3162-z.

Lenton, T. M., 2011: Early warning of climate tipping points. *Nat. Climate Change*, **1**, 201–209, https://doi.org/10.1038/nclimate1143.

——, and Coauthors, 2023: The global tipping points report 2023. Accessed 15 December 2023, https://publications.pik-potsdam.de/pubman/item/item_29187.

Li, Y., R. Ji, S. Jenouvrier, M. Jin, and J. Stroeve, 2016: Synchronicity between ice retreat and phytoplankton bloom in circum-Antarctic polynyas. *Geophys. Res. Lett.*, **43**, 2086–2093, https://doi.org/10.1002/2016GL067937.

Libera, S., W. Hobbs, A. Klocker, A. Meyer, and R. Matear, 2022: Ocean-sea ice processes and their role in multi-month predictability of Antarctic sea ice. *Geophys. Res. Lett.*, **49**, e2021GL097047, https://doi.org/10.1029/2021GL097047.

Lieser, J., F. Massonnet, W. Hobbs, J. Fyfe, C. M. Bitz, and P. Reid, 2020: Sea ice prediction network-south: Coordinating seasonal predictions of sea ice for the Southern Ocean [in "State of the Climate in 2019"]. *Bull. Amer. Meteor. Soc.*, **101**, S313–S315, https://doi.org/10.1175/BAMS-D-20-0090.1.

Lin, Y., and Coauthors, 2021: Decline in plankton diversity and carbon flux with reduced sea ice extent along the western Antarctic Peninsula. *Nat. Commun.*, **12**, 4948, https://doi.org/10.1038/s41467-021-25235-w.

Liniger, G., P. G. Strutton, D. Lannuzel, and S. Moreau, 2020: Calving event led to changes in phytoplankton bloom phenology in the Mertz polynya, Antarctica. *J. Geophys. Res. Oceans*, **125**, e2020JC016387, https://doi.org/10.1029/2020JC016387.

Liu, J., Z. Zhu, and D. Chen, 2023: Lowest Antarctic sea ice record broken for the second year in a row. *Ocean-Land-Atmos. Res.*, **2**, 0007, https://doi.org/10.34133/olar.0007.

Marchi, S., T. Fichefet, H. Goosse, V. Zunz, S. Tietsche, J. J. Day, and E. Hawkins, 2019: Reemergence of Antarctic sea ice predictability and its link to deep ocean mixing in global climate models. *Climate Dyn.*, **52**, 2775–2797, https://doi.org/10.1007/s00382-018-4292-2.

Martinson, D. G., 1990: Evolution of the southern ocean winter mixed layer and sea ice: Open ocean deep-water formation and ventilation. *J. Geophys. Res.*, **95**, 11 641–11 654, https://doi.org/10.1029/JC095iC07p11641.

——, and R. A. Iannuzzi, 1998: Antarctic ocean-ice interaction: Implications from ocean bulk property distributions in the Weddell gyre. *Antarctic Sea Ice: Physical Processes, Interactions and*

Variability, Antarctic Research Series, Vol. 74, Amer. Geophys. Union, 243–271.

Massom, R. A., S. E. Stammerjohn, W. Lefebvre, S. A. Harangozo, N. Adams, T. A. Scambos, M. J. Pook, and C. Fowler, 2008: West Antarctic Peninsula sea ice in 2005: Extreme ice compaction and ice edge retreat due to strong anomaly with respect to climate. *J. Geophys. Res.*, **113**, C02S20, https://doi.org/10.1029/2007JC004239.

Meehl, G. A., J. M. Arblaster, C. M. Bitz, C. T. Y. Chung, and H. Teng, 2016: Antarctic sea ice expansion between 2000 and 2014 driven by tropical Pacific decadal climate variability. *Nat. Geosci.*, **9**, 590–595, https://doi.org/10.1038/ngeo2751.

——, ——, C. T. Y. Chung, M. M. Holland, A. DuVivier, L. Thompson, D. Yang, and C. M. Bitz, 2019: Sustained ocean changes contributed to sudden Antarctic sea ice retreat in late 2016. *Nat. Commun.*, **10**, 14, https://doi.org/10.1038/s41467-018-07865-9.

Meier, W. N., F. Fetterer, A. K. Windnagel, and J. S. Stewart, 2021a: Near-real-time NOAA/NSIDC climate data record of passive microwave sea ice concentration. NSIDC User Guide, 45 pp., https://nsidc.org/sites/default/files/g02202-v004-userguide_1_1.pdf.

——, ——, ——, and ——, 2021b: NOAA/NSIDC climate data record of passive microwave sea ice concentration, version 4. National Snow and Ice Data Center, accessed 1 February 2024, https://doi.org/10.7265/efmz-2t65.

Meredith, M. P., and Coauthors, 2019: Polar regions. *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, H.-O. Pörtner et al., Eds., Cambridge University Press, 203–320.

Montes-Hugo, M., S. C. Doney, H. W. Ducklow, W. Fraser, D. Martinson, S. E. Stammerjohn, and O. Schofield, 2009: Recent changes in phytoplankton communities associated with rapid regional climate change along the western Antarctic peninsula. *Science*, **323**, 1470–1473, https://doi.org/10.1126/science.1164533.

Nihashi, S., and K. I. Ohshima, 2001: Relationship between ice decay and solar heating through open water in the Antarctic sea ice zone. *J. Geophys. Res.*, **106**, 16 767–16 782, https://doi.org/10.1029/2000JC000399.

NOAA, 2022: Southern Oscillation Index (SOI). NOAA, accessed 14 April 2022, https://www.ncei.noaa.gov/access/monitoring/enso/soi.

Ordoñez, A. C., C. M. Bitz, and E. Blanchard-Wrigglesworth, 2018: Processes controlling Arctic and Antarctic sea ice predictability in the Community Earth System Model. *J. Climate*, **31**, 9771–9786, https://doi.org/10.1175/JCLI-D-18-0348.1.

Orsi, A. H., and T. Whitworth III, 2005: *Southern Ocean.* Vol. I, *Hydrographic Atlas of the World Ocean Circulation Experiment (WOCE)*, M. Sparrow, P. Chapman and J. Gould, Eds., International WOCE Project Office, Southampton, U.K., http://woceatlas.tamu.edu/printed/SOA_VOLUME1.html.

Parkinson, C. L., 2019: A 40-y record reveals gradual Antarctic sea ice increases followed by decreases at rates far exceeding the rates seen in the Arctic. *Proc. Natl. Acad. Sci. USA*, **116**, 14 414–14 423, https://doi.org/10.1073/pnas.1906556116.

——, and N. E. DiGirolamo, 2021: Sea ice extents continue to set new records: Arctic, Antarctic, and global results. *Remote Sens. Environ.*, **267**, 112753, https://doi.org/10.1016/j.rse.2021.112753.

Picard, R. R., and R. D. Cook, 1984: Cross-validation of regression models. *J. Amer. Stat. Assoc.*, **79**, 575–583, https://doi.org/10.1080/01621459.1984.10478083.

Polvani, L. M., and Coauthors, 2021: Interannual SAM modulation of Antarctic sea ice extent does not account for its long-term trends, pointing to a limited role for ozone depletion. *Geophys. Res. Lett.*, **48**, e2021GL094871, https://doi.org/10.1029/2021GL094871.

Purich, A., and M. H. England, 2019: Tropical teleconnections to Antarctic sea ice during austral spring 2016 in coupled pacemaker experiments. *Geophys. Res. Lett.*, **46**, 6848–6858, https://doi.org/10.1029/2019GL082671.

——, and E. W. Doddridge, 2023: Record low Antarctic sea ice coverage indicates a new sea ice state. *Commun. Earth Environ.*, **4**, 314, https://doi.org/10.1038/s43247-023-00961-9.

Raphael, M. N., 2007: The influence of atmospheric zonal wave three on Antarctic sea ice variability. *J. Geophys. Res.*, **112**, D12112, https://doi.org/10.1029/2006JD007852.

——, and M. S. Handcock, 2022: A new record minimum for Antarctic sea ice. *Nat. Rev. Earth Environ.*, **3**, 215–216, https://doi.org/10.1038/s43017-022-00281-0.

Roach, L. A., and Coauthors, 2020: Antarctic sea ice area in CMIP6. *Geophys. Res. Lett.*, **47**, e2019GL086729, https://doi.org/10.1029/2019GL086729.

Saji, N. H., and T. Yamagata, 2003: Possible impacts of Indian Ocean dipole mode events on global climate. *Climate Res.*, **25**, 151–169, https://doi.org/10.3354/cr025151.

Scheffer, M., and Coauthors, 2009: Early-warning signals for critical transitions. *Nature*, **461**, 53–59, https://doi.org/10.1038/nature08227.

Schlosser, E., F. A. Haumann, and M. N. Raphael, 2018: Atmospheric influences on the anomalous 2016 Antarctic sea ice decay. *Cryosphere*, **12**, 1103–1119, https://doi.org/10.5194/tc-12-1103-2018.

Schroeter, S., 2020: The response of Antarctic sea ice to anthropogenic climate change, from model and satellite observations. M.S. thesis, Dept. of Philosophy, University of Tasmania, 185 pp., https://doi.org/10.25959/100.00035266.

——, T. J. O'Kane, and P. A. Sandery, 2023: Antarctic sea ice regime shift associated with decreasing zonal symmetry in the Southern Annular Mode. *Cryosphere*, **17**, 701–717, https://doi.org/10.5194/tc-17-701-2023.

Stammerjohn, S., D. G. Martinson, R. C. Smith, X. Yuan, and D. Rind, 2008: Trends in Antarctic annual sea ice retreat and advance and their relation to El Niño–Southern Oscillation and Southern Annular Mode variability. *J. Geophys. Res.*, **113**, C03S90, https://doi.org/10.1029/2007JC004269.

——, R. Massom, D. Rind, and D. Martinson, 2012: Regions of rapid sea ice change: An inter-hemispheric seasonal comparison. *Geophys. Res. Lett.*, **39**, L06501, https://doi.org/10.1029/2012GL050874.

Stuecker, M. F., C. M. Bitz, and K. C. Armour, 2017: Conditions leading to the unprecedented low Antarctic sea ice extent during the 2016 austral spring season. *Geophys. Res. Lett.*, **44**, 9008–9019, https://doi.org/10.1002/2017GL074691.

Swadling, K. M., and Coauthors, 2023: Biological responses to change in Antarctic sea ice habitats. *Front. Ecol. Evol.*, **10**, 1073823, https://doi.org/10.3389/fevo.2022.1073823.

Taylor, M. H., M. Losch, and A. Bracher, 2013: On the drivers of phytoplankton blooms in the Antarctic marginal ice zone: A modeling approach. *J. Geophys. Res. Oceans*, **118**, 63–75, https://doi.org/10.1029/2012JC008418.

Turner, J., J. S. Hosking, G. J. Marshall, T. Phillips, and T. J. Bracegirdle, 2016: Antarctic sea ice increase consistent with intrinsic variability of the Amundsen Sea low. *Climate Dyn.*, **46**, 2391–2402, https://doi.org/10.1007/s00382-015-2708-9.

——, T. Phillips, G. J. Marshall, J. S. Hosking, J. O. Pope, T. J. Bracegirdle, and P. Deb, 2017: Unprecedented springtime retreat of Antarctic sea ice in 2016. *Geophys. Res. Lett.*, **44**, 6868–6875, https://doi.org/10.1002/2017GL073656.

——, and Coauthors, 2020: Recent decrease of summer sea ice in the Weddell Sea, Antarctica. *Geophys. Res. Lett.*, **47**, e2020GL087127, https://doi.org/10.1029/2020GL087127.

Vernet, M., D. Martinson, R. Iannuzzi, S. Stammerjohn, W. Kozlowski, K. Sines, R. Smith, and I. Garibotti, 2008: Primary production within the sea-ice zone west of the Antarctic Peninsula: I—Sea ice, summer mixed layer, and irradiance. *Deep-Sea Res. II*, **55**, 2068–2085, https://doi.org/10.1016/j.dsr2.2008.05.021.

von Berg, L., C. J. Prend, E. C. Campbell, M. R. Mazloff, L. D. Talley, and S. T. Gille, 2020: Weddell Sea phytoplankton blooms modulated by sea ice variability and polynya formation. *Geophys. Res. Lett.*, **47**, e2020GL087954, https://doi.org/10.1029/2020GL087954.

Wang, G., H. H. Hendon, J. M. Arblaster, E.-P. Lim, S. Abhik, and P. van Rensch, 2019: Compounding tropical and stratospheric forcing of the record low Antarctic sea-ice in 2016. *Nat. Commun.*, **10**, 13, https://doi.org/10.1038/s41467-018-07689-7.

Wang, J., H. Luo, Q. Yang, J. Liu, L. Yu, Q. Shi, and B. Han, 2022: An unprecedented record low Antarctic sea-ice extent during austral summer 2022. *Adv. Atmos. Sci.*, **39**, 1591–1597, https://doi.org/10.1007/s00376-022-2087-1.

——, ——, L. Yu, X. Li, P. R. Holland, and Q. Yang, 2023: The impacts of combined SAM and ENSO on seasonal Antarctic sea ice changes. *J. Climate*, **36**, 3553–3569, https://doi.org/10.1175/JCLI-D-22-0679.1.

Wang, Z., J. Turner, Y. Wu, and C. Liu, 2019: Rapid decline of total Antarctic sea ice extent during 2014–16 controlled by wind-driven sea ice drift. *J. Climate*, **32**, 5381–5395, https://doi.org/10.1175/JCLI-D-18-0635.1.

White, W. B., and R. G. Peterson, 1996: An Antarctic circumpolar wave in surface pressure, wind, temperature and sea-ice extent. *Nature*, **380**, 699–702, https://doi.org/10.1038/380699a0.

Wissel, C., 1984: A universal law of the characteristic return time near thresholds. *Oecologia*, **65**, 101–107, https://doi.org/10.1007/BF00384470.

Zwiers, F. W., and H. von Storch, 1995: Taking serial-correlation into account in tests of the mean. *J. Climate*, **8**, 336–351, https://doi.org/10.1175/1520-0442(1995)008<0336:TSCIAI>2.0.CO;2.