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A Regime Shift in Seasonal Total Antarctic Sea Ice Extent in the 20th Century

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Abstract

In stark contrast to the Arctic, there have been statistically significant positive trends in total Antarctic sea ice extent since 1979, despite a sudden decline in sea ice in 2016¹⁻⁵ and increasing greenhouse gas concentrations. Attributing Antarctic sea ice trends is complicated by the fact that most coupled climate models show negative trends in sea ice extent since 1979, opposite of that observed⁶⁻⁸. Additionally, the short record of sea ice extent (beginning in 1979), coupled with the high degree of interannual variability, make the record too short to fully understand the historical context of these recent changes⁹. Here we show, using new robust observation-based reconstructions, that 1) these observed recent increases in Antarctic sea ice extent are unique in the context of the 20th century and 2) the observed trends are juxtaposed against statistically significant decreases in sea ice extent throughout much of the early and middle 20th century. These reconstructions are the first to provide reliable estimates of total sea ice extent surrounding the continent; previous proxy-based reconstructions are limited¹⁰. Importantly, the reconstructions continue to show the high degree of interannual Antarctic sea ice extent variability that is marked with frequent sudden changes, such as observed in 2016, which stress the importance of a longer historical context when assessing and attributing observed trends in Antarctic climate⁹. Our reconstructions are skillful enough to be used in climate models to allow better understanding of the interconnected nature of the Antarctic climate system and to improve predictions of the future state of Antarctic climate.

Main

Sea ice is a critically important component of the very complex Antarctic climate system. Ecologically, sea ice is habitat¹¹. Physically, it modulates the ocean-atmosphere exchange of fluxes, helps maintain the equator-pole temperature gradient and its formation maintains the global overturning circulation¹²⁻¹⁵. Sea ice is also one of the most challenging essential climate

variables to understand. Its variability is driven by changes in the atmosphere and ocean, which interact with each other, and operate on different timescales¹⁶. The remote nature of Antarctica means that there are very few *in situ* measurements of the atmosphere or ocean surrounding Antarctica where the sea ice forms, and our understanding of its variability depends largely upon satellite observations^{17,18}. Satellite measurements of Antarctic sea ice extent indicate weak, but statistically significant increases in total sea ice around Antarctica from 1979-2016, followed by a sharp decline to below average values in 2016 and a record low in summer 2017, before returning to average by austral summer 2020. While the total Antarctic sea ice extent exhibits a positive trend² (contrary to Arctic sea ice extent¹⁹), there is a strong regionality¹ and seasonality⁴ to the trends and they can be of opposite sign. Analyses of the temporal and spatial variability in Antarctic sea ice have been attempted^{20–23,23,24} but a thorough understanding is limited because the sparsity of *in situ* observations and the brevity of the satellite record mean that their temporal uniqueness cannot be easily assessed⁹. Their future change is also uncertain, since coupled climate models used in both the Intergovernmental Panel on Climate Change (IPCC) 5th and the most recent 6th assessment reports fail to reproduce the observed increases in Antarctic sea ice and instead most show widespread decreases around Antarctica^{6–8}.

To improve the scientific understanding of Antarctic sea ice variability, several reconstructions of Antarctic sea ice have been completed^{10,25,26}. These are primarily based on one of two types of proxy data: ice cores from the Antarctic ice sheet, or ocean sediments from the ocean floor below where the ice forms. While these reconstructions substantially extend the short observational record, they have their own limitations. Their main challenges are that they only represent sea ice conditions in a certain area (or sometimes, at a certain point along the ice edge), and they often can only resolve annual mean sea ice conditions or the sea ice extent during

a specific season¹⁰. Even model-based simulations of past sea ice that assimilate proxy records for sea ice are not able to provide more detail on the temporal variability of Antarctic sea ice, as these are similarly limited by the resolution of the proxy data incorporated into the model²⁷.

Total Antarctic Sea Ice Extent in the 20th Century

In this study, we present new seasonal reconstructions of Antarctic sea ice that avoid the shortcomings of existing estimates outlined above. In addition to the total sea ice extent, we use the ensemble approach to separately reconstruct seasonal Antarctic sea ice for five sectors that partition the Antarctic region²⁸. This reconstruction ensemble provides, to our knowledge, the first estimates of seasonally resolved Antarctic total sea ice extent during the 20th century (Fig. 1). The ensemble mean (blue line in Fig. 1), taken as the average of the more than 200,000 sums of sector reconstructions, is well-correlated with the observations ($r > 0.79$). Further, the large number of ensembles for the total sea ice extent reconstruction allows for a time-varying assessment of reconstruction uncertainty (gray shading in Fig. 1). Our reconstruction clearly captures the positive trend in observations prior to 2016², and the sudden decline in 2016^{5,23,29} lies within the reconstruction uncertainty. Notably, our total sea ice reconstructions outperform (based on correlations with observations and their ability to reproduce trends) other proxy-based reconstructions^{10,25–27}, better resolving interannual Antarctic sea ice variability, trends, and changes than other existing estimates which only provide information for specific sectors, the annual mean, or a certain season.

Our ensemble reconstructions are based on a principal component regression model, successfully employed in previous Antarctic climate reconstructions^{30–33}. At the heart of this model is the strong connection sea ice shares with regional and large-scale climate variability,

captured through a network of 30 long-term stations across the Southern Hemisphere (SH) and indices of climate variability extending back to 1905 (Supplementary Fig. S1). Of particular note is the station Orcadas, situated near the Antarctic Peninsula, which is the longest continuous atmospheric record poleward of 60°S³⁴. We verify our reconstructions with an independent leave-one-out cross validation procedure (see Methods). To indirectly account for the comparatively slower role of the ocean (compared to the atmosphere) on driving Antarctic sea ice changes, we also allow for the predictor data to lead the Antarctic sea ice by up to one season, at one-month increments (see Methods). To further evaluate the reconstruction performance, we also use four different skill metrics: correlations of the reconstruction and verification reconstruction with the observed sea ice extent (hereafter, $cal\ r$ and $val\ r$, respectively) as well as the reduction of error and coefficient of efficiency (RE and CE, respectively; see Methods).

Since the Antarctic sea ice extent is reconstructed separately for five sectors as well as the total, we can further examine the reconstruction performance and provide more detail than previous studies on the historical total Antarctic sea ice extent variability. Figure 2 displays the total seasonal Antarctic sea ice extent represented by three additional reconstructions (see Fig. 2 caption for details) along with the ensemble mean from Fig. 1. Correlations with the observed total Antarctic sea ice extent exceed 0.69 for all seasons for each configuration. Except for SON, the reconstructions for the sum of the sectors are more highly correlated with the observed than for the reconstruction specifically calibrated to the observed total Antarctic sea ice (red line). This fact also validates the skill of the sector reconstructions, as their sum was not calibrated to the observed total sea ice extent during the reconstruction model. Further, the correlations of each reconstruction with the ensemble mean from Fig. 1 (given at the bottom of each panel in

Fig. 2) are above 0.56 (comparable to and often exceeding the correlation of existing proxy-based reconstructions with observations)^{10,25–27}. These high correlations between the various reconstructions of the total sea ice extent demonstrate that the reconstructions are fairly stationary across the large ensemble and not overly sensitive to particular predictor data. Collectively, the larger variance inherent in the three individual total sea ice reconstructions (compared to the ensemble mean) in Fig. 2 allow us to conclude that sudden changes in the total Antarctic sea ice extent as observed in 2016 have occurred numerous times in the past century, including large increases from one year to the next.

The overall skill across all sectors and ensemble members further indicate that the reconstructions are robust (Fig. 3); perfect reconstructions will reach 1.0 for all skill metrics, and positive values for the RE and CE indicate superior performance of the reconstruction and validation reconstruction compared to the climatological mean³⁵. The boxplots for all ensemble reconstructions (with the number of ensembles given for each season) are in blue, while the reconstructions with the best fit to the observed sea ice, a subset of only 6 reconstructions (1 for each sector, and the total) are given in red. Here, the best fit reconstruction is chosen as the reconstruction with the highest CE since this is the hardest skill metric to pass, unless this reconstruction indicates potential model overfitting. Overfitting was determined using an F-test of the variances of the reconstruction compared to observations. If the variances of the reconstruction with highest CE were determined unequal ($p < 0.01$) in the reconstruction during 1905-1978 (the reconstruction period) compared to the observed variance, an alternate reconstruction with the next highest CE that maintained similar variances as observed (where possible) was selected as the best fit reconstruction.

The median reconstruction skill for all four metrics is highest in SON, with similar performance in the remaining seasons. Only a few reconstruction ensemble members have skill metrics below zero in DJF and SON, otherwise across the large ensemble meaningful reconstructions are produced for all sectors and seasons. The best fit reconstructions have skill metrics at or above 0.60; indeed the total sea ice extent reconstructions in Figs. 1 and 2 are often the least skillful reconstructions we produce. The lower skill for total Antarctic sea ice extent, compared to performance at the regional or sector level, relates to the fact that the total Antarctic sea ice extent is influenced by many regional processes that often offset and or cancel each other, as seen in sea ice extent trends in the Ross Sea compared to the Amundsen and Bellingshausen Seas^{2,16,20}. Similar to the reconstructions, sea ice forecasts perform much better for individual sectors than they do for the total Antarctic-wide sea ice³⁶. These sectoral differences are also why a circum-Antarctic proxy-based reconstruction has not been possible, to date^{10,26}.

A Regime Shift in 20th Century Antarctic Sea Ice Extent

The most dramatic new finding from the reconstructions is the changes in the trends throughout time (Fig. 4). By now nearly tripling the length of the observed data timeseries, the reconstructions provide a clear, consistent story of the historical importance of the observed Antarctic sea ice extent trends. The comparatively short observational period (Fig. 4, left column) shows strong positive trends in Antarctic sea ice, especially for periods ending in 2014 (when Antarctic sea ice extent reached its record maximum based on satellite measurements²) to 2016, prior to the marked decline. The increase in total Antarctic sea ice extent over the satellite record is in stark contrast to rapid, widespread declines in Arctic sea ice over the same time period¹⁹. As discussed earlier, the Antarctic sea ice extent trends weaken considerably for ending

years after 2016, and are only statistically significant ($p < 0.10$) in JJA if the ending year of the trends is after 2016 and the starting year is before the mid-1980s (Fig. 4, left panel of third row). Indeed, the positive trends seen before 2016 switch to negative (albeit, not statistically significant) trends for ending years after 2016 in DJF (first plot in top row). However, these trends are only based on a little over 40 years of observed satellite data, making it a challenge to resolve decadal-scale variability and assess their historical significance from observations alone⁹.

The short duration of the observed trends in the context of variability since the start of the 20th century is visualized as the relatively small box in the upper right panels of the remaining three columns of Fig. 4, which show trends from the reconstructions for various time periods throughout the 20th century. The positive trends since 1979 in both observations and reconstructions are unique in the context of Antarctic sea ice variability over the last century. Given that our reconstructions are the first to fully resolve variations across the seasons, it is now shown that these are the only statistically significant ($p < 0.10$) increases in Antarctic sea ice extent across for any time period simultaneously in all four seasons since 1905.

Moreover, in most seasons, the positive trends in the observational period stand in marked contrast to statistically significant ($p < 0.10$) negative trends in the early to mid-20th century, especially prevalent in the ensemble mean (Fig. 4, rightmost column, and Fig. 1). The negative trends in the early to mid 20th century reach high levels of statistical significance ($p < 0.05$, stippled in Fig. 4) in all but SON, where they are weaker and there is more variation in the sign and magnitude of the sea ice trends among the various estimates of total Antarctic sea ice extent. It should be noted that the insignificant positive trends for the best fit reconstruction in MAM (second column, second row) is an outlier for this season – it is the only ensemble member for the total sea ice reconstruction in MAM to display weakly positive trends in

Antarctic sea ice (not shown). Combined with the short observations timeseries, the reconstructions strongly suggest a regime shift in Antarctic sea ice extent in the middle of the 20th century, where long-term declines in Antarctic sea ice extent prior to 1960 are juxtaposed by strong increases in the late 20th century which encompass the satellite observations (left column of Fig. 4 and boxes in other columns). These trends also suggest that the observed period, in addition to being too short to fully capture the range of true historical variability of Antarctic sea ice extent⁹, started at a time of relatively low sea ice extent in the context of the last century, giving rise to a strong positive trend that is part of multidecadal scale variability (Figs. 1 and 2).

Although difficult to compare (due to the aforementioned limitations of other existing reconstructions), many other proxy-based reconstructions of Antarctic sea ice extent outside of the Amundsen-Bellingshausen Seas hint at a similar, but weaker, reversal of sea ice changes from the early to late 20th century, especially in the Ross and Weddell Seas^{10,25,27}. Although the observed trends are not produced as well as our reconstructions, the most recently published set of Antarctic sea ice extent reconstructions²⁶ based on six proxies similarly confirm the idea of a mid-20th century regime shift in Antarctic sea ice, with widespread decreases in annual mean Antarctic sea ice in many sectors in the early to mid 20th century that switch to increases in Antarctic sea ice extent during the observed satellite period.

Since the regime shift in the total sea ice extent reconstruction is most prominent in austral winter (JJA, Fig. 4), our reconstruction approach allows us to further examine this spatially by looking at the changes across the sectors (Fig. 5). Notably, the low-frequency versions of the sector reconstructions and observations are also highly correlated ($r > 0.8$, bottom correlation numbers in each timeseries in Fig. 5), further validating the reconstruction approach as the reconstruction model was calibrated explicitly for interannual variations. The high skill in

reproducing these variations translates into similar high skill in the low-frequency decadal scale variations. Across the sectors, it is clear that the regime shift is not equally pronounced in all sectors (Fig. 5), highlighting the known independent nature of Antarctic sea ice in various sectors around the continent²⁸. The differences among the sectors also show that the mid-20th century Antarctic sea ice extent regime shift is not an artifact of the reconstruction or a gross error in the data employed to estimate pre-satellite Antarctic sea ice conditions (as this would likely be seen across all sectors). Indeed, the regime shift from early to mid 20th century ice loss to late 20th century ice gains is most pronounced in the King Hakon VII and Ross Sea sectors (Figs. 5b,d). For the Ross Sea, our best fit reconstruction indicates the austral winter sea ice decreased - 0.187 ± 0.104 standard deviations per decade ($p < 0.01$) during 1905-1978, followed by an increase of 0.236 ± 0.207 standard deviations per decade ($p < 0.05$) from 1979-2020; the Ross Sea sector is the only sector to display a statistically significant ($p < 0.05$) increase in Antarctic sea ice extent during 1979-2020 in our reconstructions and observations. Furthermore, the significant observed increase in Antarctic sea ice extent during 1979-2020 for the Ross Sea sector (0.268 ± 0.239 standard deviations per decade) is also comparable to the trend in our reconstruction. Similarly supporting a regime shift, the 1905-1978 trend (-0.144 ± 0.097 standard deviations per decade, $p < 0.01$) and the 1979-2020 trend (0.116 ± 0.245 standard deviations per decade, $p > 0.10$) in the best fit reconstruction for the King Hakon sector are statistically different from each other at $p < 0.05$.

Similar to patterns in sea ice trends during the satellite era^{22,24,37}, our sector reconstructions also clearly indicate an offsetting behavior between the Ross (Fig. 4d) and Bellingshausen-Amundsen Seas (Fig. 5c) throughout the 20th century. In the Bellingshausen-Amundsen Seas, the best fit reconstruction demonstrates that ice was increasing during 1905-

1978 (0.138 ± 0.109 standard deviations per decade, $p < 0.05$), in opposition to the decreases in the Ross Sector in the same time period (Fig. 5d). The trend switched to a weakly and statistically insignificant negative trend after 1979 in the Bellingshausen-Amundsen Seas, similar to observed, and again in opposition to the change in the Ross Sea (Figs. 4c,d). The opposing behavior of sea ice in this sector, at least in observations, can largely be linked to changes in the atmospheric circulation related to the Amundsen Sea Low (ASL), a semipermanent region of low pressure. When particularly strong, the winds associated with the ASL act to push sea ice toward the Antarctic coast and Peninsula in the Bellingshausen Sea, while pushing it equatorward in the adjacent Ross Sea^{1,22,38,39}. We note that our finding supporting the persistence in the 20th century of the observed opposing relationship between the Ross and Bellingshausen-Amundsen Seas was not found in another Antarctic sea ice extent reconstruction study²⁷, which may be due to their lower reconstruction skill, especially in the Bellingshausen Sea (only our Ross Sea reconstruction is positively correlated with theirs during the 20th century). We also note that the increase in sea ice extent in the early portion of the 20th century in our reconstruction for the Bellingshausen-Amundsen seas is inconsistent with other proxy-based reconstructions, which suggest a persistent decrease of sea ice in this sector throughout the 20th century^{25,27}. These differences may arise from limitations of both our reconstruction and existing proxy-based reconstructions, which capture various processes that are related to Antarctic sea ice extent; however, we note that our reconstructions preserve known physical relationships throughout the 20th century between the Ross and Bellingshausen-Seas and are better calibrated to observations. Regardless, we urge caution in using a specific time period to investigate a trend, as Fig. 4 indicates the trends (both in magnitude and statistical significance) are sensitive to the starting

and ending dates, and the regime shift does not begin simultaneously across the sectors nor the various ensemble members in the reconstruction.

Given the complexities of the Antarctic sea ice trends (both spatially and temporally), interpreting the causality of this pronounced regime shift remains a challenge. Observational records near Antarctica generally only reach back to the International Geophysical Year (1957-1958)⁴⁰, and because the trends that stand in contrast to the observed period originated in the early 20th century and continued only into the middle 20th century, there is not a pronounced signal in many of the closest meteorological measurements^{41,42}. Attribution studies are further complicated since climate models generally produce widespread Antarctic ice loss since 1979, opposite that of observations⁶⁻⁸. Yet, the regional and time-sensitive character of the reversal strongly hints at the important role of pronounced decadal scale variability in both the atmosphere and ocean. Observations of the ocean are even more sparse near Antarctica, but previous work suggests that convection in the Southern Ocean contributes strongly to observed trends in temperature and sea ice near Antarctica, especially on longer timescales^{16,43,44}. From the atmospheric perspective, earlier work examining trends in the midlatitude pressure observations used as predictors in this study show patterns of decadal-varying trends with synchronous, but opposing variability between the mid and high latitudes of the Southern Hemisphere⁴⁵. This study connected a considerable portion of the broad changes in atmospheric pressure (circulation) across the entire Southern Hemisphere to the Southern Annular Mode (SAM), with negative pressure trends in many seasons in the early 20th century that became positive in the late 20th century. The SAM has also been suggested to influence mid 20th century Antarctic sea ice regime shifts in other work²⁶, although it is necessary to note that the SAM index used by ref. 26 (based on gridded atmospheric reanalysis products spanning the entire 20th

century) is known to have artificial trends throughout the 20th century due to changes in data availability in the underlying products used to create the index^{46,47}. Perhaps more importantly due to the regional variations in the trends, Fogt and Connolly (2021) also note that regional changes in the atmospheric circulation were often associated with multi-decadal tropical variability. In particular, significant ($p < 0.05$) shifts in the Interdecadal Pacific Oscillation (negative trends in early and late 20th century, to positive trends in the mid 20th century), a pattern known to especially impact Antarctic sea ice variations from the Ross to Weddell Seas^{23,24,37}, likely also plays an important role. Given that all the JJA best fit reconstructions from the Ross to Weddell Seas in Fig. 4 employ many different subsets of tropical SST indices, including the IPO, the importance of decadal scale tropical variability cannot be overstated. Analysis of these contributions is part of future work, yet hopefully the newly generated reconstructions presented here will promote an increase in research from many disciplines aimed at further interpreting and unlocking historical variations in Antarctic sea ice extent during the 20th century.

Discussion and Summary

The brevity of the timeseries of satellite-observed Antarctic sea ice, combined with its large interannual variability make it very challenging to understand its behavior and to predict its future. To improve the understanding, we have created and present here, an initial analysis of seasonally-resolved reconstructions of the Antarctic sea ice extent back until 1905. These reconstructions are based on strong relationships the sea ice shares with midlatitude climate (pressure and temperature) and the role that modes of large-scale atmospheric variability play in influencing Antarctic sea ice extent. They are verified using an independently produced

validation reconstruction as well as through an ensemble of reconstructions that vary the predictor data used.

Importantly the reconstructions demonstrate high skill, far exceeding that of previous proxy-based reconstructions of Antarctic sea ice extent, and the simple use of the climatological mean from gridded products like the Hadley Center Sea Ice and Sea Surface Temperature data set⁴⁸ that is often used in historical climate model simulations spanning the entire 20th century. Moreover, the reconstructions are the first to provide a seasonally-resolved picture of Antarctic sea ice. We also produce robust reconstructions for five sectors partitioning the ocean around Antarctica.

Our reconstructions highlight the large interannual variability observed in Antarctic sea ice extents throughout the early 20th century, with a pronounced regime shift occurring in the middle of the 20th century. This regime shift is characterized by changes in total Antarctic sea ice extent trends, from decreases in seasonal total Antarctic sea ice extent in the early to mid 20th century, to the increases in Antarctic sea ice extent seen in observations prior to 2016. Such dramatic changes continue to highlight the importance of having longer records of Antarctic climate to fully encompass the range of historical variability, and the need for historical data rescue to uncover yet unpublished records of Antarctic climate to help place recent changes in a longer context. As these reconstructions are highly skillful, they are also appropriate to use in further research on evaluating climate models and interpreting the precise causes of the regime shifts depicted in these reconstructions.

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Figure 1. Seasonal total Antarctic sea ice extent in the 20th century, with observations depicted in black. The blue line is the ensemble mean reconstruction acquired from the average of over 200,000 possible sums of seasonal sector-based sea ice extent reconstructions, and the gray shading approximates the reconstruction uncertainty as the greater of the two standard deviation spread of the ensemble members or the two standard deviation range of the residuals of an individual best fit reconstruction ensemble member. a) December – February, DJF; b) March-May, MAM; c) June – August, JJA; d) September-November, SON.

Total Sea Ice Extent (Reconstruction vs. Reconstruction Sum), 1905-2020

Figure 2. Seasonal timeseries plots of various ways of representing the total Antarctic sea ice extent reconstruction, along with various reconstruction skill metrics for the best-fit reconstruction (red line); cal r = calibration correlation, val r = validation correlation, RE = reduction of error; CE = coefficient of efficiency. The best fit reconstruction (red line) was the highest performing ensemble member calibrated specifically to the observed total sea ice extent. The best fit summed sector reconstruction (green line) is the ensemble member from all possible sums of the individual sector ensemble members, while the ensemble mean (blue line) is the average of all these possible sector reconstruction sums. The sum of the best fit sector reconstructions (purple) is the sum of the highest performing sector reconstruction ensemble members that have been specifically calibrated to the observed sector sea ice extent. The correlation of all reconstructions with observations ('correl w/ obs') as well as the correlation of the reconstruction with the ensemble mean ('correl w/ ensmean') is given at the bottom, with the colors representing the various reconstructions labeled in the legend below the figure. The number of ensemble members (# ens) is also given for the best fit reconstruction (red line, number in red) as well as for the ensemble mean (blue number).

Reconstruction Seasonal Skill Performance across All Ensembles

Figure 3. Boxplots of reconstruction performance across all ensembles (blue) and the best fit reconstruction for each sector, including total (red).

Total Sea Ice Extent Seasonal Time-Varying Trends

Figure 4. Time-varying linear trends of standardized seasonal total Antarctic sea ice extent. The y-axis identifies the starting year for a trend, and the x-axis the ending year for a trend, making the shorter time periods in the upper-left, with longer periods in the lower right of each panel. The diagonal line is exactly 30 years, and trends are only given for periods longer than 30 years. The observations are in the far left column (with different start / end periods), and the remaining columns represent an estimate of the total Antarctic sea ice as described in Fig. 2. Cross-hatching and stippling represent trends that are significantly different from zero at $p<0.10$ and $p<0.05$, respectively.

JJA Sea Ice Extent Sector Reconstructions, 1905-2020

Figure 5. Austral winter (JJA) timeseries of the sector reconstructions with a map showing the boundaries of each sector. The thick lines are smoothed versions (with an 11-year running mean) of each timeseries. Given in each panel are the reconstruction skill metrics (detailed in Fig. 1) for the best fit reconstruction (red line), as well as the correlation between the ensemble mean and best fit reconstruction during 1905-2020 (“correl”). The number of ensemble reconstructions produced is given in the upper right, and the correlations of the 11-year smoothed versions with the observed smoothed data are given in the bottom, with the colors representing the best fit (red) or ensemble mean (blue) reconstructions. The gray shading in each panel represents the reconstruction uncertainty, taken as the larger of 1.96 times the standard deviations of the best fit reconstruction compared to the observed, or 1.96 times the standard deviation of the reconstruction ensembles for a given year.

Methods

Data

The seasonal sea ice extent reconstructions are primarily based on monthly mean pressure and temperature records across the Southern Hemisphere extratropics and midlatitudes from 1905-2020. These records were used in previous research^{1,2} and obtained from the University Corporation for Atmospheric Research research data archive dataset ds570.0³. A few stations were patched with nearby stations using a monthly mean offset, as discussed in earlier work². Data for the stations in South Africa (Cape Town, Durban, and Port Elizabeth) were updated through 2020 by creating monthly means from the daily data in the National Centers for Environmental Information Global Summary of the Day dataset⁴. Beyond the direct observations of temperature and pressure, indices of modes of climate variability were also used as potential predictors of Antarctic sea ice extent. These include the Interdecadal Pacific Oscillation (IPO)⁵, which is calculated using the difference of sea surface temperature (SST) anomalies averaged in the central equatorial Pacific, the northwest Pacific, and the southwest Pacific from the NOAA Extended Reconstructed Sea Surface Temperature dataset, version 5 (ERSSTv5)⁶. We also calculate the Niño sea surface temperature indices from ERSSTv5, namely the Niño 1+2 SSTs (averaged over 0°-10°S, 270°-280°E), the Niño 3 SSTs (5°N – 5°S, 210°-270°E), Niño 3.4 SSTs (5°N – 5°S, 190°-240°E), and the Niño 4 SSTs (5°N – 5°S, 160°-210°E). In addition to these SSTs to monitor the variability associated with these SSTs to monitor the El Niño-Southern Oscillation, we also use the Southern Oscillation Index (SOI), the difference in standardized pressure from Tahiti, French Polynesia, and Darwin, Australia from the Australian Bureau of Meteorology as it does not have any gaps in the 20th century (<http://www.bom.gov.au/climate/current/soihtm1.shtml>). We also use the index for the Atlantic Multidecadal Oscillation (AMO)⁷. For the Southern Annular Mode (SAM) index⁸, we merge the

‘Fogt’ seasonal SAM index reconstructions^{9,10}, which extend back to at least 1905, with the observationally-based SAM index¹¹ after 1957. In contrast to the other indices, the SAM indices are only available seasonally; all other predictor data are available for each month.

We computed sea ice extent (SIE) using satellite-observed sea ice data from Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) and Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager - Special Sensor Microwave Imager/Sounder (SSM/I-SSMIS). We used the Climate Data Record (CDR) daily concentration fields from the National Oceanic and Atmospheric Administration / National Snow and Ice Data Center (NOAA/NSIDC) Climate Data Record of Passive Microwave Sea Ice Concentration, Version 4¹². The CDR algorithm output combines of ice concentration estimates from the National Aeronautics and Space Administration (NASA) Team algorithm¹³ and the NASA Bootstrap algorithm¹⁴. The data span the period 25 October 1978 to 31 December 2020 and are daily except prior to July 1987 when they are given every other day. Data are gridded on the SSM/I polar stereographic grid (25 km × 25 km). The SIE used in our analysis is calculated using the equatorward limit of the 15% sea ice concentration (SIC) isoline. Thus, it is the sum of the area of every grid cell that is 15% or more covered with sea ice. The monthly SIE was calculated as the average of the SIE for days in that month. In addition to the alternate day observations from 1978 to 1987, there are a number of days and segments of days with no observations. In particular, there are no data between 3 December 1987 and 12 January 1988. For these days we fit a stochastically imputed the daily SIE using the following procedure: We constructed anomalies by subtracting off the invariant annual cycle, estimated using the methods of recent work¹⁵. We then fit a Bayesian AutoRegressive Integrated Moving Average (ARIMA) model to the observed daily SIE. We then stochastically imputed the missing days by drawing

for their posterior distribution. The monthly SIE values were computed by averaging of all days in the month. We note that, except for the period from 3 December 1987 and 12 January 1988 the impact of this stochastic multiple imputation scheme is small. The sectoral SIE was computed as the sum of the area within the sector of every grid cell that is above 15% or more covered with sea ice (most cells are completely within a single sector). Although contiguous, the sectors are defined based on their spatial decorrelation scale as discussed in earlier work¹⁶. The longitude bounds for the sectors are as follows: Bellingshausen-Amundsen Seas (250°-290°E), Weddell Sea (250°-346°E), King Hakon VII (346°-71°E), East Antarctica (71°-162°E) and Ross Sea (162°-250°E); the total Antarctic sea ice extent represents the area of all sea ice surrounding Antarctica, and is precisely equal to the sum of the areas in the five sectors.

Reconstruction Methodology

The seasonal sea ice extent reconstructions follow previous work on early Antarctic climate using a proven principal component regression technique^{1,17-19}. We first compute seasonal means of the various predictor data, and correlate these with the sea ice extent time-series that is being reconstructed; all data are linearly detrended prior to correlation. To indirectly account for the slower response of the sea ice to the atmosphere and the role of the ocean in this relationship, we also correlate predictor data which lead the Antarctic sea ice extent data for up to one season, at increments of one month. For example, if reconstructing sea ice extent for June-August (JJA), correlations of predictors with JJA sea ice extent are computed for predictor data averaged in JJA (no lag), May – July (MJJ, 1 month lead), April – June (AMJ, two months lead), and March-May (MAM, 3 months or one season lead). We perform one separate ensemble reconstruction using all temperature and pressure observations (regardless of correlation magnitude), and smaller networks of predictor data, including indices of climate

variability (see Fig. S1), that are significantly correlated at $p<0.10$, $p<0.05$, $p<0.025$, and $p<0.01$. These increasing smaller sets of predictor data comprise our predictor data networks (5 total). We then subsequently add on beyond the temperature and pressure observations any indices of climate variability correlated at the various thresholds for each data network; these additions comprise our data layers. The climate index layers (in order of layering) are: The IPO, AMO, PDO, SOI, Niño 1+2 SSTs, Niño 3.4 SSTs, Niño 3 SSTs, Niño 4 SSTs, and the SAM index. Altogether, the combination of data predictor networks (based on the significance of the correlation between predictors and sea ice extent time-series we are reconstructing) and the data layers (adding on significantly correlated climate indices) constitutes a possibility of up to 41 ensemble members for each reconstruction (4 data networks times 10 data layers plus 1 ensemble member which employs all observations regardless of correlation magnitude).

Once the predictor data are selected using the above procedure, principal component analysis is performed using the retained standardized predictor data (each variable is standardized over the time period 1905-2020), including predictor data which lead the sea ice by up to one season. We limit the number of factors calculated in the principal component analysis to a maximum of 35 to expedite the computations. A subset of these principal components (PCs), sorted by the absolute magnitude of their correlation with the sea ice extent time-series being reconstructed, is then regressed onto the sea ice extent time series during 1979-2020 (our calibration period) to fit the reconstruction model. The reconstruction can then be obtained using the relationships the PCs share with the sea ice extent time-series (the regression coefficients) and the relationships the PCs share with the individual predictor data (PC expansion weights). Combining the regression and PC weights through matrix multiplications yields a value for each predictor variable, sometimes called the beta weights. These beta weights can then be used on

the full length of the observed predictor data to obtain the reconstruction back until 1905. Alternatively, the PCs can similarly be extended back to 1905 using the predictor data and used with the regression coefficients to perform the reconstruction.

The ideal number of PCs to retain for the regression model is based on an independent validation procedure (leave-one-out cross validation) employed in previous work^{1,17,19}. Here, we repeat the PC regression model one time for each year in the observed record (calibration period) from 1979-2020 (42 times), each time leaving an individual year and its two neighboring years before and after (a total of up to 5 years) out. The center year is thus assumed to be independent of the remaining retained years and is predicted using the weights generated in the reconstruction model described above. Predicting each year independently and concatenating the predicted values yields an entirely predicted and independent timeseries we call the validation reconstruction. This reconstruction is correlated to the observed sea ice extent data (giving the skill metric we call validation correlation, or $val\ r$), and used separately to compute the coefficient of efficiency (CE) as discussed in earlier work²⁰. After the CE is determined, the entire validation procedure is repeated by adding one more PC at a time to the regression model. The reconstruction that yields the highest CE is selected as the best performing and retained ensemble reconstruction for that particular data network and data layer. Selecting the highest CE aids in limiting model overfitting, as the CE will reach a peak and sharply decline and often go very negative as more PCs are added to the regression; this sudden decline is a key indicator of model overfitting despite the overall calibration correlation continuing to increase. Furthermore, only retaining a subset of the PCs makes this regression approach superior to multiple linear regression, as we effectively filter out unwanted noise by only retaining the most strongly correlated PCs. The entire procedure is then reproduced for each data network and data layer to

yield at least 5 ensemble reconstruction members for each season and sector. The number of ensembles for a given sea ice extent reconstruction is dependent on the number of additional data layers employed beyond the temperature and pressure observations.

Once all ensemble reconstructions are produced, the best fit ensemble member (red lines in the main paper, one for each season / sector of Antarctic sea ice extent) is first selected by extracting the reconstruction with the highest CE across all the ensemble reconstructions. To perform an additional check for model overfitting, the variance of the reconstruction in the period 1905-1978 is compared with the reconstruction variance in 1979-2020 and the observed variance in 1979-2020. If the reconstruction variance is significantly ($p < 0.01$) larger than the observed reconstruction, there is a possibility of overfitting occurring. In these few cases, the best fit reconstruction was selected as the next highest CE where the variances were not statistically significantly different from the observed variance during 1979-2020, if possible. In some cases there were no alternative reconstruction ensemble members with equal variances, and the highest CE was still selected as the best fit reconstruction. This procedure was repeated for each season and sector to create the full array of ensemble and best-fit sector reconstructions.

The total reconstruction was produced separately following the above principal component regression model, as was done for each sector. It was also estimated using the sum of the sector best fit reconstructions, since the observed sea ice extent for all sectors sum up to the total sea ice extent. Since each sector had multiple ensemble reconstructions, it is important to check to see how the sum of all possible ensemble member combinations across the sector compare. These combinations constitute more than 200,000 possible combinations for each season (there are over 1 million possible combinations in JJA). We therefore also provide an additional estimate from these combinations by selecting the combination which is most

correlated with the observed sea ice extent timeseries (green line in Fig. 2 in main paper). We use this and the full ensemble spread to further estimate reconstruction uncertainty.

Statistical Methods

Statistical significance of correlation coefficients and regression coefficients (for linear trends of Antarctic sea ice extent) is calculated using a Student's *t*-test, with $n-2$ degrees of freedom. In making these calculations, we assume each year is independent from every other year.

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Code Availability

The reconstruction as well as all figures were generated using the NCAR Command Language. All code used to perform the reconstructions and generate the plots are available from the corresponding author upon request, and will be hosted, along with the ensemble reconstructions, on a public data repository and the National Snow and Ice Data Center soon after publication.

Contributions

R.L.F., M.N.R. and M.S.H conceived the study. R.L.F. and A.M.S. performed the reconstructions. R.L.F. led the writing of the manuscript and produced all the figures in the paper. All authors analyzed the results and assisted in writing and editing the manuscript.

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703 **Competing Interests**

704 The authors declare no competing financial and non-financial interests.

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