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Ice core evidence for a 20th century decline of sea ice in the Bellingshausen Sea, Antarctica

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[1] This study uses ice core methanesulphonic acid (MSA) records from the Antarctic Peninsula, where temperatures have been warming faster than anywhere else in the Southern Hemisphere, to reconstruct the 20th century history of sea ice change in the adjacent Bellingshausen Sea. Using satellite-derived sea ice and meteorological data, we show that ice core MSA records from this region are a reliable proxy for regional sea ice change, with years of increased winter sea ice extent recorded by increased ice core MSA concentrations. Our reconstruction suggests that the satellite-observed sea ice decline in the Bellingshausen Sea during recent decades is part of a long-term regional trend that has occurred throughout the 20th century. The long-term perspective on sea ice in the Bellingshausen Sea is consistent with evidence of 20th century warming on the Antarctic Peninsula and may reflect a progressive deepening of the Amundsen Sea Low due to increasing greenhouse gas concentrations and, more recently, stratospheric ozone depletion. As a first-order estimate, our MSA-based reconstruction suggests that sea ice in the Bellingshausen Sea has retreated southward by ~0.7° during the 20th century. Comparison with other 20th century sea ice observations, reconstructions, and model simulations provides a coherent picture of Antarctic sea ice decline during the 20th century, although with regional-scale differences evident in the timing and magnitude of this sea ice decline. This longer-term perspective contrasts with the small overall increase in Antarctic sea ice that is observed in post-1979 satellite data.

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1. Introduction

[2] Sea ice around Antarctica plays a crucial role in modulating ecosystems and climate; however, it remains a poorly constrained component in model projections of past and ongoing climate change. This is largely because routine satellite monitoring of sea ice only began in the 1970s and its strong interannual variability has meant that long-term trends over this short interval have been difficult to discern [*Zwally et al.*, 2002; *Cavalieri and Parkinson*, 2008]. Over the 1978–2007 interval, satellite observations show that sea ice extent around Antarctica has increased by a small amount (increasing at a rate of 1.0% decade^{-1}; $p < 0.05$). Although this increasing trend is statistically significant, a long control run of a coupled climate model suggests that this recent increase in Antarctic sea ice extent may still be within the bounds of natural climate variability [*Turner et al.*, 2009]. When examined at a regional scale, the strongest trends in the satellite record of Antarctic sea ice are an increase in annual sea ice extent in the Ross Sea (4.6% decade^{-1}; $p < 0.05$) and a decrease in annual sea ice extent in the Amundsen-Bellingshausen Seas (−6.6% decade^{-1}; $p < 0.01$). This dipole pattern of increasing and decreasing sea ice extent in the Ross and Amundsen-Bellingshausen seas is thought to be driven by strengthening of the cyclonic atmospheric flow over the Amundsen Sea (i.e., the Amundsen Sea Low). Model studies suggest that much of the increase in cyclonic flow since ~1980 may be attributed to circulation changes caused by stratospheric ozone depletion [*Turner et al.*, 2009].

[3] Prior to satellite monitoring, direct information about Antarctic sea ice is extremely sparse, and this has prompted attempts to produce reconstructions of 20th century sea ice change using historical information from whaling ships and the chemistry of ice cores. Records of the position of whale catches, which are assumed to have occurred near the ice edge, have been used to estimate that Antarctic-average summer sea ice extent retreated southward by 2.8° during the mid-20th century [*de la Mare*, 1997]. However, the use of this whaling data as a sea ice indicator has been challenged

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Table 1. Details of the Antarctic Peninsula Ice Cores Used in This Study[a]

Site	Location	Elevation (MASL)	Accumulation Rate (MWE)	Annual Temperature (°C)	Collection Year
James Ross Island	64.2°S, 57.0°W	1600	0.4	−14	1997–1998
Dyer Plateau	70.6°S, 65.0°W	1940	0.5	−22	1988–1989 2004–2005
Beethoven Peninsula	71.9°S, 74.6°W	580	1.2	−17	1991–1992

[a] MASL, elevation in meters above sea level; MWE, annual average accumulation in meters of water equivalent.

due to potential biases caused by changes in the species of whales caught, spatial and temporal heterogeneities in the coverage of the whaling data, and offsets between satellite and chart records of sea ice extent [*Vaughan*, 2000; *Ackley et al.*, 2003]. A recent re-examination of the whaling catch records alongside early ship charts of Antarctic sea ice extent has suggested a revised regionally weighted sea ice retreat of ~1.7° from the early (1930 to mid-1950s) to the late (1971–1987) 20th century [*de la Mare*, 2009]. Regional analysis also suggests that the magnitude of sea ice retreat has differed markedly around Antarctica [*Cotte and Guinet*, 2007; *de la Mare*, 2009], although the regional changes produced using direct chart observations do still differ in detail from those derived from whaling records.

[4] The chemistry of Antarctic ice cores provides an alternate way to reconstruct past sea ice changes on a range of time scales [*Curran et al.*, 2003; *Wolff et al.*, 2003; *Dixon et al.*, 2005; *Rothlisberger et al.*, 2010]. For high accumulation sites around coastal Antarctica, it has been proposed that changes in the methanesulphonic acid (MSA; CH_3SO_3H) concentration of ice cores may provide a proxy for examining past sea ice changes, potentially going back thousands of years. The only source of MSA in Antarctic ice cores comes from the atmospheric oxidation of dimethylsulphide, which is derived from marine phytoplankton that live in the sea ice zone [*Welch et al.*, 1993; *Curran and Jones*, 2000]. The seasonal melting of sea ice promotes blooms of these sea ice algae, leading to increased emissions of dimethylsulphide to the atmosphere. For this reason, it has been proposed that years of enhanced winter sea ice extent, and subsequently enhanced sea ice algae blooms during seasonal sea ice melting, can lead to increased MSA being transported to near coastal ice cores in the following summer. This proxy was utilized in the Law Dome ice core to infer a 1.5° retreat in winter sea ice extent since the 1950s [*Curran et al.*, 2003].

[5] Similar positive relationships between ice core MSA records and Antarctic sea ice variability have now been identified at a number of other near-coastal sites in the Ross Sea/Indian Ocean sector of east Antarctica [*Welch et al.*, 1993; *Foster et al.*, 2006; *Becagli et al.*, 2009]. However, in some locations, increased ice core MSA is not a reliable proxy for enhanced winter sea ice extent [*Sun et al.*, 2002; *Abram et al.*, 2007; *Rhodes et al.*, 2009]. In the Weddell Sea and Dronning Maud Land region, it appears that transport strength and direction have an important influence on the concentration of ice core MSA [*Fundel et al.*, 2006; *Abram et al.*, 2007], while the presence of a summer open water polynya in the Ross Sea is thought to dominate the interannual variability of MSA in the nearby Mount Erebus Saddle ice core [*Rhodes et al.*, 2009]. Atmospheric chemistry measurements also indicate that ice core MSA records from inland Antarctic Plateau sites may not be representative of sea ice-associated emissions of dimethylsulphide due to long transport distances and oxidation processes [*Preunkert et al.*, 2008] and the influence of postdepositional losses [*Weller et al.*, 2004]. The potential for various factors to influence the MSA signal preserved in ice cores highlights the need for detailed site-specific assessments of the suitability of MSA as a sea ice proxy.

[6] In this study we use a set of ice core records from three sites along the western Antarctic Peninsula to investigate the reliability of MSA records from this region as sea ice proxies. We are then able to use these ice core records to examine the history of 20th century changes in winter sea ice extent in the Bellingshausen Sea, and how these compare to other 20th century climate records from the Antarctic Peninsula region and to sea ice reconstructions from other regions around the Antarctic continent.

2. Methods

[7] We use ice core MSA records from three sites extending along the western and northern Antarctic Peninsula (Table 1). The Beethoven Peninsula and Dyer Plateau cores were collected by the British Antarctic Survey [*Mulvaney et al.*, 2002; *Thomas et al.*, 2008]. The core from James Ross Island was drilled by an Argentinian/French team [*Aristarain et al.*, 2004; *McConnell et al.*, 2007]. Chronologies for each of these high-resolution cores have been established by counting the clear annual cycles in water isotopes and trace chemistry and are verified by known volcanic eruption events.

[8] Measurements of MSA were made in a class-100 clean laboratory at the British Antarctic Survey using Dionex ion chromatographs [*Littot et al.*, 2002; *Abram et al.*, 2008]. The experimental setup used a DX2000 anion instrument, using an AS17 4 mm column and KOH eluent that was run using a gradient method ranging from 0.3 to 60 mmol L^{-1} concentration that optimized MSA separation. The MSA measurements were made at subannual resolution (approximately 28 samples/year for Beethoven, 12 samples/year for Dyer, and 2 samples/year for James Ross Island), and the results were interpolated and averaged to produce annual resolution records of MSA centered about the MSA maximum that occurs in the Austral summer (i.e., ~July–June annual averages).

[9] It has been shown that MSA can be lost from archived ice cores during storage at −20°C [*Smith et al.*, 2004; *Abram et al.*, 2008] due to a relatively high diffusion coefficient for MSA in ice [*Roberts et al.*, 2009] that can result in a decrease in the mean amount of MSA retained in the

archived core. However, this mean loss does not destroy the relative variability of the original MSA record if all samples have a similar storage time and geometry [*Abram et al.*, 2008; *Roberts et al.*, 2009], and if detailed storage and ice geometry information are available then the effects should be able to be corrected using a 2-D diffusion model [*Roberts et al.*, 2009]. The MSA measurements from the Beethoven Peninsula and early Dyer Plateau cores were made on archived ice samples refrozen in discrete bottles, a storage method that has been shown to prevent MSA loss [*Abram et al.*, 2008]. The MSA measurements on the more recent Dyer Plateau core were completed within 18 months of core collection, so postcollection MSA loss should also be negligible in this core. It is likely that the James Ross Island core will have experienced some loss in the absolute amount of MSA, as it was analyzed for MSA after 9 years of frozen storage. As this study uses only the normalized MSA records to look at relative variability of MSA, rather than absolute MSA concentrations, any postcollection loss of MSA should not affect the results of this study [*Abram et al.*, 2008; *Roberts et al.*, 2009]. This is confirmed by earlier discrete measurements of MSA on a short section of the James Ross Island core (13.8–29.5 m analyzed 3 years after collection), which show a similar temporal variability to the more recent MSA measurements used in this study.

[10] The statistical significance of the reported linear correlation results in this study are computed based on a 2-sided *t* test. To take into account autocorrelation effects, these tests use effective sample sizes that were estimated using the correction of: $N^{\mathrm{eff}} = N\,(1 - r_a r_b)/(1 + r_a r_b)$, where r_a and r_b are the lag-1 autocorrelation values for the two series [*Bretherton et al.*, 1999; *van Ommen and Morgan*, 2010]. In order to assess the approximate magnitude of sea ice extent change from the regional-scale proxy records, a geometric mean regression technique was used (also known as reduced major axis regression) [*Smith*, 2009]. This method avoids the assumption applied in ordinary least squares regression that there is no error in the independent variable (in this case, satellite sea ice extent records). The geometric mean regression method allows for error in both parameters by calculating the line of best fit that minimizes the error in both the *x* and *y* dimensions.

3. Results

[11] The James Ross Island, Dyer Plateau, and Beethoven Peninsula ice core MSA records each display similar patterns of MSA variability through their overlapping intervals (Figure 1a). In order to maximize this common environmental signal, the three records were normalized and averaged to produce a stacked MSA record for the Antarctic Peninsula. Following the method applied in previous studies [*Curran et al.*, 2003; *Abram et al.*, 2007], the stacked MSA record was correlated with a compilation of the latitude of maximum winter (August–October average) sea ice extent averaged across 10° sectors around Antarctica from the Joint Ice Center (JIC) data set that begins in 1973 [*Jacka*, 1990]. After taking into account autocorrelation of the MSA and sea ice time series, the western Antarctic Peninsula stacked MSA record is found to have a significant (>90% confidence) positive correlation with winter sea ice extent over a 30° sector of the adjacent Bellingshausen Sea that spans from 70°W to 100°W (Figure 1b). This provides an initial indication that in this region ice core records of MSA may be a good proxy for reconstructing past changes in sea ice, with years of increased (decreased) sea ice extent in the Bellingshausen Sea marked by increased (decreased) MSA deposition at the western Antarctic Peninsula ice core sites.

[12] These findings were verified using the NASA bootstrap satellite sea ice data set [*Cavalieri and Parkinson*, 2008; *Turner et al.*, 2009] that begins in 1979 and is known to be more reliable than the JIC sea ice data set. Similar positive correlations are found between our stacked Antarctic Peninsula MSA record and the NASA data for winter sea ice extent in the Bellingshausen Sea, although the later start year of the NASA data set reduces the interval available for establishing the significance of these positive correlations. A comparison of the JIC sea ice extent record with an equivalent compilation of the NASA sea ice extent data in 10° longitude sectors further confirms the reliability of the JIC data across the 70°W–100°W region where significant correlations exist with ice core MSA; here winter sea ice extent correlates strongly ($r = 0.90$) between the JIC and NASA sea ice data sets (see also section 4 and Figure 4a in section 4.2).

[13] To further test the reliability of our ice core MSA records as a proxy for sea ice changes in the Bellingshausen Sea, we next examined the meteorological conditions associated with MSA variability at our Antarctic Peninsula ice core sites. Using the European Centre for Medium-Range Weather Forecasts Re-Analysis data (ERA-40) [*Uppala et al.*, 2005] for the interval after 1979 that is reliable for high southern latitudes [*Marshall*, 2003], we first plotted density maps for the 5 day back trajectories of precipitation events at each of the ice core sites (Figure 1c) [*Thomas and Bracegirdle*, 2009]. At each ice core site, it is seen that the greatest density of precipitation-bearing air parcels arrive from the adjacent Bellingshausen Sea region. This precipitation source region occurs over the same geographical area where positive correlations are observed with sea ice extent (Figure 1b). This strongly supports the notion that MSA preserved in our ice core records is derived primarily from the sea ice margin in the Bellingshausen Sea.

[14] Correlation of the western Antarctic Peninsula MSA record with the meteorological data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis fields since 1979 [*Kalnay et al.*, 1996] provides further evidence that MSA is a reliable sea ice proxy in the Bellingshausen Sea region. Data from the NCEP/NCAR reanalysis were averaged over annual increments spanning July–June that match the Austral summer-centered annual averages of the ice core MSA data. Negative correlations with surface air temperature in the Bellingshausen Sea indicate that increased MSA at our ice core sites corresponds with cooler Bellingshausen Sea air temperatures (Figure 2a). Again, the location of these air temperature anomalies in the Bellingshausen Sea (which would be expected to also reflect changes in sea ice cover) coincides with the region of maximum positive correlations between sea ice extent and the ice core MSA stack (Figure 1b).

[15] Additional correlation maps for sea level pressure and wind fields show that the physical processes driving the connection between cool Bellingshausen Sea air tempera-

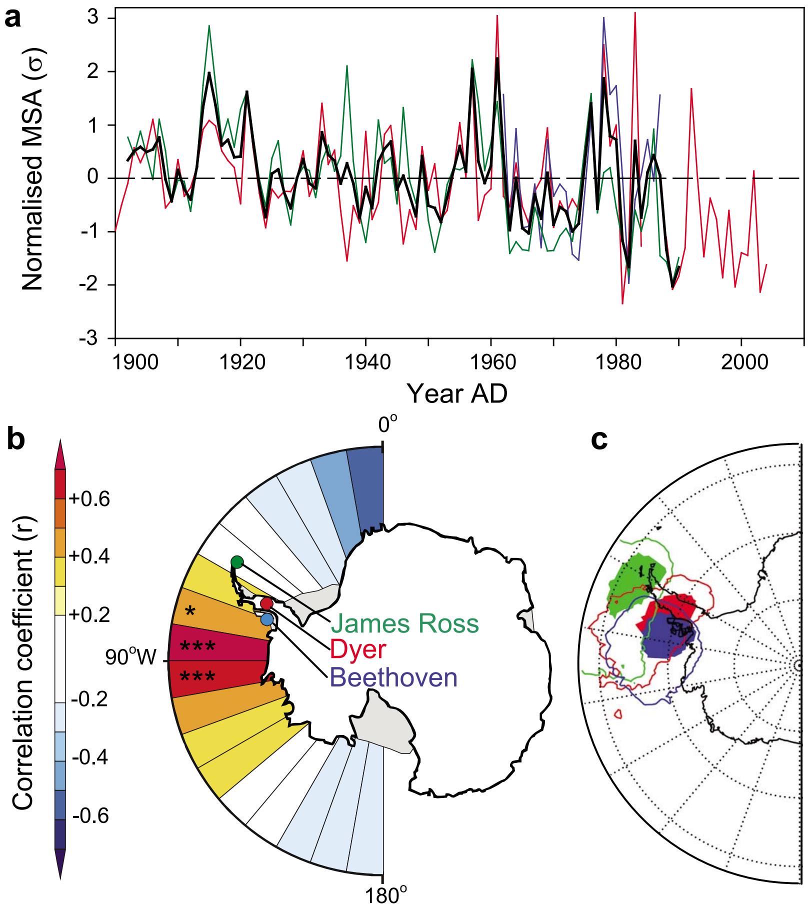

Figure 1. (a) Ice core MSA records from James Ross Island (green), Dyer Plateau (red), and Beethoven Peninsula (blue) normalized relative to the 1901–1990 interval and the stacked MSA record (black) produced from these three sites. (b) Correlation of the stacked MSA record with the winter (August–October) maximum sea ice extent in 10° sectors around Antarctica (1973–1990 [*Jacka*, 1990]). Increased ice core MSA is significantly correlated with increased winter sea ice in the Bellingshausen Sea between 70°W–100°W (*>90% and ***>99% confidence; 2-sided *t* test using autocorrelation-adjusted effective data sizes). (c) Density maps of ERA-40 [*Uppala et al.*, 2005] 5 day back trajectories for precipitation events at the James Ross Island (green), Dyer (red), and Beethoven (blue) ice core sites. Shading and contour line show the 20% and 10% densities, respectively, for each site. All sites show a Bellingshausen Sea-dominated source for precipitation events, which corresponds with the region of maximum correlation in with sea ice extent.

tures and increased ice core MSA are linked with a high surface air pressure anomaly centered in the Amundsen Sea (Figure 2b). The wind fields associated with the high pressure anomaly over the Amundsen Sea involve westerly wind anomalies that travel along the West Antarctic coast (Figure 2c) and continue northward along the Antarctic Peninsula (Figure 2d). This wind configuration brings cold Antarctic air over the Bellingshausen Sea, resulting in the prominent cool anomaly in the surface air temperature fields from the reanalysis data that corresponds with years of high MSA at our ice core sites. These wind fields are also favorable for transporting MSA from high sea ice anomalies in the Bellingshausen Sea onshore to the ice core sites.

[16] Together this analysis of our ice core MSA records alongside a variety of sea ice and meteorological data provides strong evidence that MSA is a reliable proxy for changes in sea ice in the adjacent Bellingshausen Sea. Using the stacked ice core MSA as a proxy for changes in sea ice since 1901 suggests that the Bellingshausen Sea has experienced a marked loss of sea ice during the 20th century (Figure 3). A linear trend analysis calculated across the whole 1901–1990 interval identifies a significant decreasing trend of $-0.10 \pm 0.03\sigma$ decade^{-1} in the stacked MSA record. When this analysis is repeated over 50 year intervals, similar significant trends are found for the early ($-0.12 \pm 0.06\sigma$ decade^{-1}, 1901–1950) and late ($-0.13 \pm 0.09\sigma$ decade^{-1}, 1941–1990) halves of the 20th century. A prominent episode of high MSA in the late 1950s means that the trend of decreasing MSA is maximized when calculated over the 1958–1990 interval ($-0.34 \pm 0.18\sigma$ decade^{-1}). The sustained trends of decreasing MSA imply that the recent decline in sea ice in the Bellingshausen Sea observed using

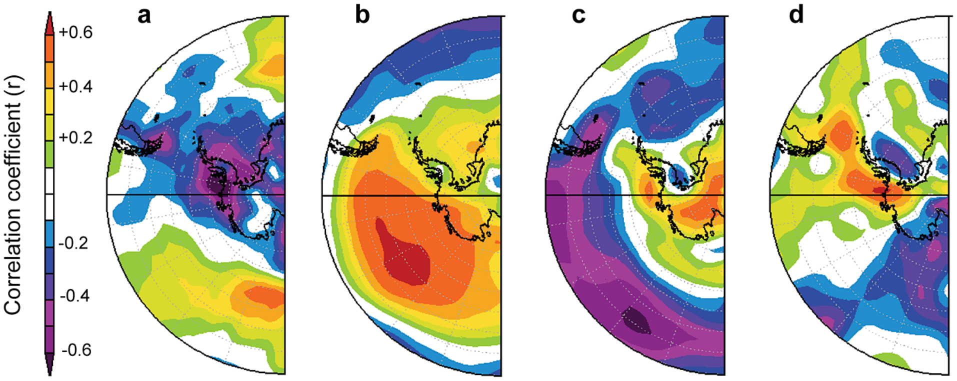

Figure 2. Correlation of the stacked Antarctic Peninsula MSA record with NCEP reanalysis July–June annual averages of (a) surface air temperature, (b) mean sea level pressure, (c) 850 mbar zonal wind, and (d) 850 mbar meridional wind (1979–2004 [*Kalnay et al.*, 1996]). Correlation fields show that increased (decreased) ice core MSA is associated with years of cool (warm) air temperature in the Bellingshausen Sea that are caused by a high- (low-) pressure anomaly in the Amundsen Sea that has accompanying southwesterly (northeasterly) wind anomalies that form along the western side of the Antarctic Peninsula and extend across the Bellingshausen Sea.

satellite observations is part of a long-term trend that has occurred throughout the 20th century.

4. Discussion

4.1. Comparison With Records of 20th Century Climate Change on the Antarctic Peninsula

[17] Our reconstruction of 20th century sea ice decline in the Bellingshausen Sea is consistent with evidence of warming along the adjacent Antarctic Peninsula. A statistically significant correlation ($r = -0.37$, $p = 0.01$) is observed between warming July–June annual mean air temperatures at Faraday/Vernadsky station and decreasing ice core MSA, and this is particularly evident at decadal time scales (Figure 3). The documented warming at Faraday station has been suggested to be part of a continued warming trend since at least the 1900s based on early exploration data [*Jones*, 1990]. Our stacked ice core record supports this notion that warming of the Antarctic Peninsula has occurred throughout the 20th century, although perhaps with increased strength since ~1958. A similar pattern of 20th century climate change has been reported for the Gomez ice core from the southern end of the Antarctic Peninsula. At the Gomez site, the statistically significant isotope-derived warming trend began around 1900 [*Thomas et al.*, 2009], with particularly strong increases in temperature and snow accumulation observed since ~1960 [*Thomas et al.*, 2008; *Thomas et al.*, 2009].

[18] Previous studies using satellite data and model simulations have highlighted the deepening of the Amundsen Sea Low as a likely driver of the observed warming of the

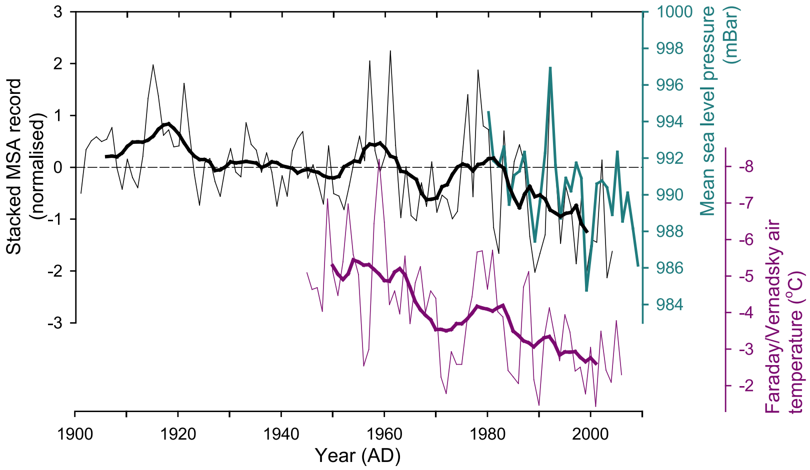

Figure 3. The MSA record (thin black curve) derived from the three Antarctic Peninsula ice cores correlates significantly with decreasing mean sea level pressure over the Amundsen Sea (green curve; NCEP reanalysis data for region 100°W–140°W, 55°S–70°S, July–June averages) [*Kalnay et al.*, 1996] and with the historical record of rising air temperature measured at Faraday/Vernadsky station (thin purple curve; inverted; July–June averages). Thick black and purple curves are 11 year running means, and dashed black line shows the mean of the stacked MSA record over the 1901–1990 normalization interval.

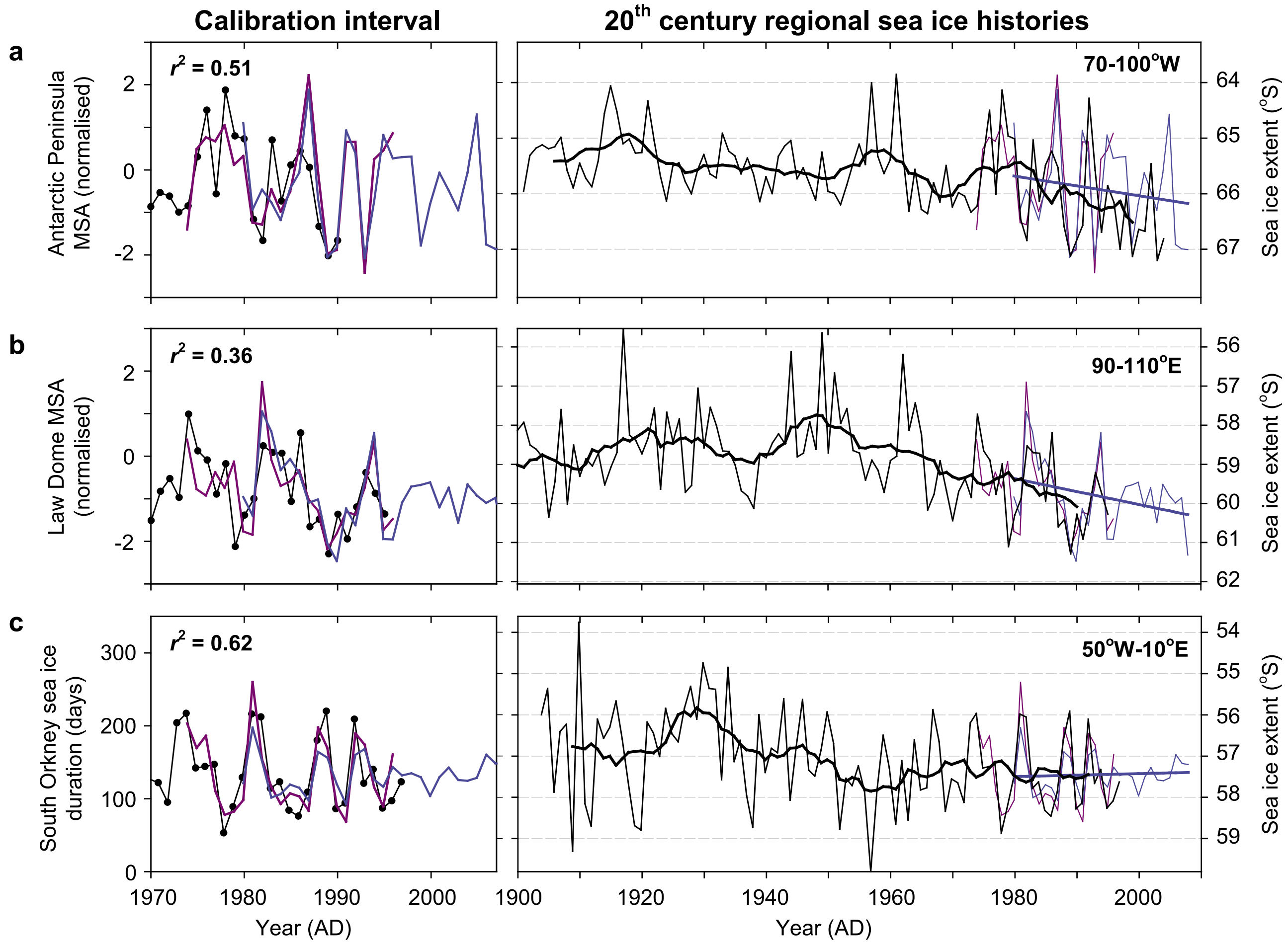

Figure 4. Regional sea ice reconstructions from (a) the Antarctic Peninsula stacked MSA record (this study), (b) the Law Dome ice core MSA record [*Curran et al.*, 2003], and (c) the South Orkney historical sea ice duration record [*Murphy et al.*, 1995]. Left column plots for the calibration interval show the ice core MSA and historical sea ice duration records (black curves) with the JIC sea ice extent (purple curves) [*Jacka*, 1990] and NASA bootstrap sea ice extent (blue curves) [*Cavalieri and Parkinson*, 2008] data for the region where significant correlations exist between the proxy and satellite records. Estimates of past sea ice extent from the proxy records are based on calibration with the JIC sea ice extent data set, and r^2 values for the calibration intervals are given. All are significant at greater than 99% confidence level. Right column plots show the 20th century regional sea ice reconstructions (thin black curves) with their 11 year running means (thick black curves). Corresponding regional sea ice extent data from the JIC (purple curves) and NASA bootstrap (blue curves) sources are also shown, and thick blue lines show the 1979–2007 linear trends for the regional NASA sea ice extent data.

Antarctic Peninsula and sea ice decline in the Bellingshausen Sea [*Lefebvre et al.*, 2004; *Harangozo*, 2006; *Stammerjohn et al.*, 2008; *Goosse et al.*, 2009; *Turner et al.*, 2009]. This is because strengthening of the Amundsen Sea Low brings warm southerly wind anomalies to the western Antarctic Peninsula and Bellingshausen Sea region. To examine this link further, we compared our ice core MSA time series with the NCEP/NCAR reanalysis record since 1979 of July–June annual mean sea level pressure averaged over the region of the Amundsen Sea spanning 100°W–140°W and 55°S–70°S (Figure 3). A highly significant (r = 0.63, p = 0.01) relationship exists between decreasing sea level pressure in this region and decreasing MSA in the ice core records. Visual examination of the records suggests that this relationship is relevant both for the overall decreasing trends in Amundsen mean sea level pressure and Bellingshausen sea ice, as well as for interannual scale variability of these climate features (Figure 3). The inference that is gained from the MSA sea ice reconstruction is that the recent deepening of the Amundsen Sea Low may also be part of a long-term trend that has occurred over the whole of the 20th century.

[19] The strength of the Amundsen Sea Low is known to be influenced by the Southern Annular Mode (SAM) that describes variability in the strength of the westerly winds that circle the Antarctic continent [*Marshall*, 2003]. This is due to the blocking effect of the mountainous Antarctic Peninsula that encourages the development of low-pressure storm system over the Amundsen Sea region when the circumpolar westerlies are strong. A reconstruction of the SAM index back to 1958 based on station observations

identified a significant increase in the SAM that has been most pronounced since the mid-1970s [*Marshall*, 2003]. Model-based assessments of the cause of the increase in the SAM index suggest that both the increase in greenhouse gas concentrations and stratospheric ozone depletion have contributed to the increase in the SAM [*Goosse et al.*, 2009], with changes in stratospheric zone being likely the largest contributor [*Turner et al.*, 2009]. Our ice core record of decreasing MSA (and Bellingshausen sea ice) shows a weak correlation with the strengthening of the annual average SAM index since 1957. The correlations that exist between July–June annual mean warming at Faraday and the SAM index are also below significance when calculated over the annual mean scale of the ice core record. This may be due to the large seasonal differences in trends and variability of the SAM [*Marshall*, 2003]. The correlations of the Faraday temperature and ice core MSA records with the SAM are observed to be more robust after ~1980, which may also suggest that the influence of the SAM on climate variability in this region has been enhanced in recent decades by the influence of stratospheric ozone depletion on circulation.

4.2. Comparison With Other Records 20th Century Sea Ice Change

[20] To make a first-order estimate of the amount of sea ice decline that has occurred in the Bellingshausen Sea associated with 20th century deepening of the Amundsen Sea Low and warming of the Antarctic Peninsula, the stacked MSA record was calibrated to the JIC data for mean winter sea ice extent [*Jacka*, 1990] in the 70°W–100°W region where a significant correlation occurs (Figure 4). This calibration was carried out over the 1973–1990 interval; defined by the start of the JIC data and the last year where our stacked MSA record is composed of data from at least two ice core sites. To extend the sea ice history as far as possible into the present, the NASA bootstrap [*Cavalieri and Parkinson*, 2008] winter sea ice extent data (1979–2007) is also presented for the 70°W–100°W region. To allow for a direct comparison, the gridded bootstrap sea ice extent data were first compiled into the same 10° longitude sectors as for the JIC data and were then calibrated from a square kilometer scale onto the equivalent latitude South scale used for the JIC data. The excellent agreement ($r = 0.90$) between the JIC and NASA bootstrap sea ice data sets is clearly evident in Figure 4.

[21] Comparing the difference between mean MSA-derived sea ice extent values from the 1900–1920 interval, with those from the 1979–2007 NASA bootstrap satellite sea ice data, we estimate that the Bellingshausen Sea has experienced a mean retreat in winter sea ice extent of ~0.7° since the start of the 20th century. The significant trend of decreasing MSA over the whole 1901–1990 interval equates to a winter sea ice decline of ~0.08° ± 0.02° per decade and when maximized over the 1958–1990 interval to 0.26° ± 0.14° retreat per decade. For comparison, the linear trend in the NASA sea ice data for 1979–2007 equates to a winter sea ice retreat of 0.18° ± 0.19° per decade.

[22] We applied this same calibration technique to two other records that previously have been used to infer Antarctic sea ice changes during the 20th century (Figure 4). The first is the coastal Law Dome ice core MSA record [*Curran et al.*, 2003]. Repeating the correlation analysis with winter sea ice extent we find a significant positive correlation in the 90°E–110°E sector that lies offshore of Law Dome. Using a geometric mean regression with sea ice extent, we suggest that this sector has experienced a mean sea ice retreat of ~1.2° during the 20th century (1900–1920 mean ice core proxy data compared with the 1979–2007 mean NASA satellite sea ice data).

[23] The other record used for comparison is the measure of winter sea ice duration at the South Orkney Islands that began in 1903 [*Murphy et al.*, 1995]. This local sea ice duration index correlates significantly with winter sea ice extent across a broad region of the Weddell Sea between 50°W and 10°E. Calibration of the sea ice duration index suggests that during the 20th century the mean winter sea ice extent in the Weddell Sea has retreated by ~0.5° (equivalent to a local decrease in sea ice duration of ~30 days at the South Orkney Islands; 1903–1920 mean historical data compared with the 1979–2007 mean NASA satellite sea ice data).

[24] Each of the reconstructions show that winter sea ice around Antarctica has retreated during the 20th century. This longer-term perspective differs from observations based only on the satellite era when Antarctic sea ice has undergone a small increase in extent [*Cavalieri and Parkinson*, 2008]. This pattern of an overall 20th century decline in Antarctic sea ice (despite the small increases during the satellite observation era) is consistent with modelling studies performed over the past half century that are forced by observed surface temperature variations. These model simulations produce a clear decrease in Antarctic sea ice extent during the early 1960s to the early 1980s most likely driven by increasing greenhouse gas concentrations [*Goosse et al.*, 2009], followed by a slight increase in sea ice area over the 1980–2000 period due to regional-scale sea ice changes driven by stratospheric ozone depletion that have strengthened the Amundsen Sea Low [*Goosse et al.*, 2009; *Turner et al.*, 2009].

[25] The regional sea ice reconstructions from the Antarctic Peninsula, Law Dome, and South Orkney sites indicate that the timing of 20th century sea ice decline has been markedly different between the three regions examined here (Figure 4). Our stacked MSA record for the Bellingshausen Sea suggests that sea ice decreased progressively through the 20th century, with the fastest retreat occurring since ~1958. Offshore of Law Dome, it appears that sea ice retreat began in ~1950, whereas the South Orkney index shows a pronounced decline in sea ice extent in the Weddell Sea between ~1930–1960. These regional differences in 20th century sea ice decline around Antarctica suggest that multiple regional reconstructions are needed to better understand the dynamics and drivers of past Antarctic sea ice change, and the likely regional-specific responses to ongoing climate change.

[26] It is useful to further compare these 20th century Antarctic sea ice reconstructions with sea ice change estimates derived from early ship charts and whale catch positions to gain a better understanding of the range of different estimates for regional changes in Antarctic sea ice extent. Recently, a revised regional-scale assessment has been carried out using direct and whaling-based historical sea ice observations, where sea ice changes were determined from the differences between early (1930 to mid-1950s) to late (1971–1987) sea ice position information [*de la Mare*, 2009]. In the eastern Indian Ocean region (90°E–170°E),

historical records suggest that a mean regional sea ice retreat of ~1.3° occurred between the early and late intervals. Using these same time intervals, a similar sea ice retreat of ~1.0° in the 90°E–110°E sector is inferred from the Law Dome MSA record [*Curran et al.*, 2003].

[27] Historical whaling/ship data are too sparse in the Bellingshausen Sea to produce an estimate for this region alone, but across the broader South Pacific Ocean region (70–150°W), sea ice retreat between the early and late intervals is estimated at ~0.3° [*de la Mare*, 2009]. It is worth noting, however, that in this region, different historical sources give very different sea ice change estimates; direct ship observations indicate an early-to-late sea ice retreat of ~2.1°, whereas whale catch records suggest an early-to-late sea ice advance of ~0.6°. Our MSA-based reconstruction for the 70°W–100°W sector of the Bellingshausen Sea documents no mean change (0.0°) in sea ice extent between these specific early and late intervals. This is due to the timing of the early and late intervals with respect to decadal variability in the Bellingshausen sea ice reconstruction.

[28] In the Weddell Sea region, significantly different magnitudes of sea ice retreat are produced using the whaling/ship chart information compared with the inferences from the sea ice duration record from the South Orkney Islands. The South Orkney record [*Murphy et al.*, 1995] suggests a mean sea ice retreat in the Weddell Sea region of ~0.4° between the early and late intervals, whereas whaling/ship records from this region suggest that sea ice retreat may have exceeded 4° [*de la Mare*, 2009]. This exceptionally large sea ice retreat indicated by the historical ship-based records has been hypothesized to reflect, at least in part, the dynamic position of the eastern tongue of the Weddell Sea ice pack that in some years delayed or prevented the early whaling vessels from reaching the true sea ice edge [*de la Mare*, 2009]. It is also possible that a more prominent and sustained Weddell ice tongue during the early 20th century resulted in a strong seasonal difference in sea ice retreat in this region, with the whaling records documenting a strong retreat of the summer ice pack, and the South Orkney sea ice duration record representing a more moderate retreat of winter sea ice.

5. Implications

[29] Our study using ice cores from three sites along the western and northern Antarctic Peninsula has found that in this region the MSA concentration in ice is a reliable proxy for regional-scale changes in winter sea ice extent. The ice core MSA-based reconstruction indicates that the Bellingshausen Sea has experienced a progressive decline in sea ice throughout the 20th century, with a particularly strong retreat in sea ice since ~1958. This supports theories that recent warming along the Antarctic Peninsula has been part of a continued trend since the early 1900s. Climate simulation studies may be able to further test the relationship that these 20th century changes in Bellingshausen sea ice and Antarctic Peninsula temperatures have to circulation processes associated with the Amundsen Sea Low and the SAM, and the implications that greenhouse gas concentrations and stratospheric ozone changes have for future changes in Antarctic sea ice extent. The recent collection of a deep ice core from James Ross Island will also allow for a more complete understanding of the natural range and drivers of past sea ice variability in the Bellingshausen Sea spanning the whole of the Holocene.

[30] The sea ice reconstruction, presented here, for the Bellingshausen Sea builds on previous evidence for a 20th century decline in Antarctic sea ice. Although all presatellite records demonstrate evidence for a decline in Antarctic sea ice during the 20th century, the details of these reconstructed sea ice declines are quite varied. Differences in the magnitude of sea ice decline that is reconstructed by different methods within the same region highlight the need for improved methods of quantification for the historical and proxy record data sets. Geographical differences in the timing of sea ice decline demonstrate the need for multiple regional-scale reconstructions. For the future, ice core MSA records from the Amundsen Sea coast and around coastal east Antarctica will be particularly useful for developing a more comprehensive understanding of the geographical differences in interannual to centennial-scale changes in Antarctic sea ice. The combination of ice core MSA records with numerical modeling assessments of MSA production, transport, and deposition pathways will also help to improve the quantification of these sea ice reconstructions so that the drivers of past and future sea ice change around Antarctica may be better understood.

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