Sea Ice Extents Continue to Set New Records: Arctic, Antarctic, and Global Results

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Abstract

The multi-channel satellite passive-microwave record of Earth's sea ice coverage, extending back to the late 1970s, has long revealed declining sea ice coverage in the Arctic but through 2015 revealed an overall increase rather than decrease in Antarctic sea ice coverage. Following major decreases in Antarctic sea ice since 2015, the 42-year 1979-2020 satellite dataset now shows losses in sea ice coverage in both hemispheres, and this is convincingly demonstrated by the enumeration of monthly and yearly record high and record low sea ice extents experienced over the course of the 42 years. In fact, one of the most convincing statistics on the declining Arctic sea ice cover is the fact that since 1986 the Arctic has not experienced a single monthly record high sea ice extent in any month but has experienced 93 monthly record lows. In contrast, all 12 calendar months have their 42-year Antarctic monthly record high sea ice extents in the period 2007-2015, while 8 of the 12 calendar months have had Antarctic record lows since 2015. Globally, every calendar month has registered a new monthly record low within the past 5 years. These results are complemented (and somewhat tempered) by quantification of the range of monthly and yearly sea ice extent values over the 42 years. For instance, although the Arctic's lowest September monthly average sea ice extent (in 2012) is 53% lower than its highest September monthly average sea ice extent (in 1980), the other months have far smaller percent differences between their lowest and highest Arctic values. For yearly average sea ice extents, the Arctic's lowest value (in 2020) is 18% lower than its highest value (in 1982), the Antarctic's lowest value (in 2017) is 16% lower than its highest value (in 2014), and the global lowest value (in 2019) is only 12% lower than its highest value (in 1982).

Keywords: Sea ice, Arctic sea ice, Antarctic sea ice, global sea ice, sea ice record highs and lows, satellite remote sensing, climate change.

1. Introduction

Sea ice distributions and extents since late 1978 have been well documented from a series of multi-channel satellite passive-microwave instruments. The satellite datasets reveal a predominantly decreasing Arctic sea ice coverage that was apparent by the mid-1990s (Johannessen *et al*., 1995; Parkinson *et al*., 1999) and has accelerated since then (Comiso *et al*., 2008; Stroeve and Notz, 2018). The satellite data also reveal changes in the Antarctic, although with trends through 2014 being predominantly toward increased rather than decreased sea ice coverage (Simmonds, 2015; Turner *et al*., 2015), followed by major decreases after 2014 (Parkinson, 2019).

The Arctic sea ice decreases have many significant impacts on Arctic climate and ecosystems (Meier *et al*., 2014; Walsh, 2013) and could also be impacting much lower latitudes (Cohen *et al*., 2021; Luo *et al*., 2019; Rind *et al*., 1995; Vihma, 2014), although the extent of the lower-latitude impact is controversial (Blackport and Screen, 2021; Blackport *et al.* 2019; Voosen, 2021; Warner *et al*., 2020). While decreases in Arctic sea ice were expected, in light of a warming climate, the changes undergone by the Antarctic sea ice cover were generally not expected and consequently have generated attempted explanations, both for the increases in Antarctic sea ice coverage through 2014 (e.g., Hobbs *et al*., 2016; Meehl *et al*., 2016) and for the rapidity of the subsequent decreases (e.g., Eayrs *et al*., 2021; Z. Wang *et al*., 2019).

While much of the satellite-based work reporting changes in the Arctic and Antarctic sea ice coverages has focused on trends in the time series of sea ice extents, a different but complementary view of the contrasting hemispheric sea ice changes was introduced in 2016 with new visualizations and the identification, month by month, of all record monthly highs and record monthly lows in each polar region over the period 1979-2015 (Parkinson and DiGirolamo, 2016; hereafter referred to as P&D 2016). The tally of monthly records starkly highlighted the contrast between the hemispheres: In the 1979-2015 dataset, the Arctic sea ice extents had not experienced any monthly record highs since 1986 but 75 monthly record lows, while the record highs since 1986 for the Antarctic sea ice extents totaled 45 and the record lows only 6 (P&D 2016).

In this paper, we incorporate the five additional years of data since 2015, including the sharp reversal from increasing to decreasing sea ice coverage in the Antarctic, into the framework of the P&D 2016 visualizations and monthly record highs and lows, plus we add yearly record highs and lows to the P&D 2016 framework and we additionally depict and discuss the range of monthly sea ice extents throughout the annual cycle, for the Arctic, Antarctic, and global results, over the full 1979-2020 period.

2. Methodology

As in P&D 2016, we use data from a sequence of National Aeronautics and Space Administration (NASA) and Department of Defense (DOD) satellite passive-microwave instruments, specifically NASA's Scanning Multichannel Microwave Radiometer (SMMR) and DOD's Special Sensor Microwave Imager (SSMI) and SSMI/Sounder (SSMIS), to calculate sea ice concentrations (percent areal coverages of sea ice), gridded onto polar stereographic projections with grid cell areas of approximately 625 km^2 (25 km x 25 km) at 70° latitude, ranging up to approximately 665 km^2 at the poles (the full north and south polar area matrices are available at https://nsidc.org/data/polar-stereo/tools_geo_pixel.html#pixel_area), and then calculate sea ice extents in each polar region as the total area of all grid cells in the region that have sea ice concentrations of at least 15%. Following P&D 2016 and other studies, we use ice concentrations generated with the NASA Team Algorithm, described in Gloersen *et al*. (1992).

Other algorithms are also available. Comparative ice-algorithm studies show broadscale similarities in the calculated ice concentration fields, some quantifiable differences, and no clear-cut 'best' algorithm (e.g., Comiso *et al*., 1997; Ivanova *et al*., 2015); ice-extent comparisons suggest a likelihood that use of a different algorithm would yield results quite similar to those presented here (e.g., Comiso and Parkinson, 2008; Parkinson and Comiso, 2008).

Because of the satellite orbits and the scanning characteristics of the instruments, the SMMR data do not extend poleward of 84.6° latitude, the SSMI data do not extend poleward of 87.6° latitude, and the SSMIS data do not extend poleward of 89.2° latitude. This is not relevant for the Antarctic sea ice calculations, because no sea ice is at those latitudes, but it is relevant for the Arctic calculations. To handle these missing data in the vicinity of the North Pole, we assume that each affected grid cell has an ice concentration of at least 15%, hence including it in our calculation of ice extent. This assumption might cease to be valid in the future, if the ice cover continues to decline, but it appears valid for 1979-2020. Being able to make such an assumption is a major advantage of our using the ice extent metric rather than basing our calculations on ice area (calculated as the sum of the products of area times ice concentration for each grid cell with ice concentration exceeding 15%). Ice area calculations would require estimating ice concentrations within the Pole-centered region of missing data; such estimations would entail far greater uncertainty than the assumption that the near-Pole concentrations are at least 15%.

For both the Arctic and Antarctic, daily sea ice extents were calculated and then averaged to obtain monthly average sea ice extents for each month in the 42-year period 1979-2020 and yearly averages for each of the 42 years. The 42 Januarys were then ranked from 1 for the year with the lowest January sea ice extent to 42 for the year with the highest January sea ice extent, with corresponding rankings also done for each of the other 11 calendar months and for the yearly averages. The rankings were then used to identify each time (based on the data from 1979 up until that time) a new monthly or yearly record high sea ice extent or a new monthly or yearly record low sea ice extent was reached within the 1979-2020 period. Global rankings and record highs and lows were obtained similarly, after adding the Arctic and Antarctic monthly and yearly average sea ice extents to obtain the corresponding global datasets.

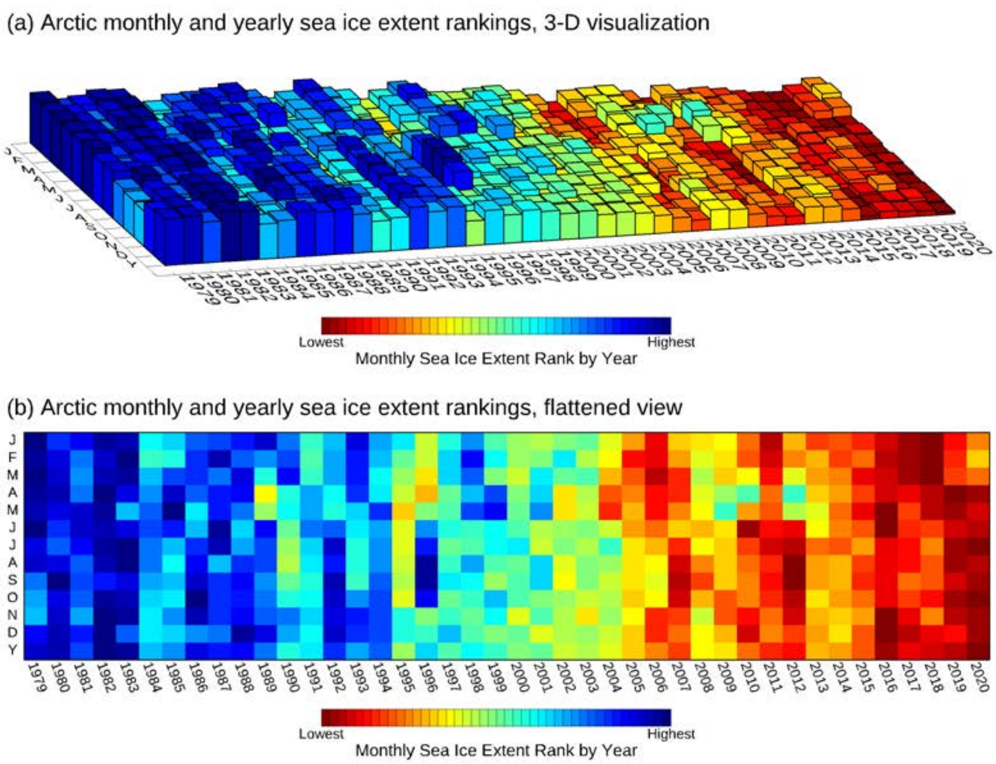
The data used in this study are available at the United States' National Snow and Ice Data Center (NSIDC) website, https://nsidc.org (Cavalieri *et al.*,1996).

3. Results

Results are presented for the Arctic, Antarctic, and global datasets through 3-D and flat visualizations, tabulations of the monthly and yearly rankings, and graphics of the occurrence of each record high and each record low (Figures 1-3).

3.1. Arctic

The addition of five years to the 1979-2015 P&D 2016 dataset reveals an Arctic sea ice cover in continued decline (Figure 1). Moreover, each of the 60 months in 2016-2020 have ice extents that rank (for the month) in the bottom third of the 42-year observation period (Figure 1a-c). Not only does the fact of no new monthly record highs since 1986 continue to hold, but now 18 new monthly record lows have occurred (Figure 1d), so that, for the 1979-2020 period, there have been no new monthly record highs since 1986 but 93 new monthly record lows. Only August and September have not experienced new record lows in the past five years. For August and September, the year of the record lows for the full dataset, now 1979-2020, remains 2012 (Figure 1d). The last record high for Arctic yearly average ice extents was back in 1982, in sharp contrast to the 12 new record low yearly average ice extents since that time (11 since 1986), the



(c) Arctic monthly and yearly sea ice extent rankings, tabulated

J	42	35	37	41	40	26	28	33	34	36	39	32	24	29	38	30	27	18	25	31	23	20	19	21	22	17	12	05	14	15	16	10	03	13	08	09	07	04	02	01	06	11
F	41	38	32	39	42	24	25	35	40	33	31	34	23	30	36	29	22	18	28	37	26	20	21	27	19	16	06	05	12	17	15	09	04	11	13	08	10	03	02	01	07	14
M	42	39	31	40	41	29	34	35	32	38	25	37	24	30	36	26	20	15	28	33	21	18	27	22	23	13	09	03	07	19	14	16	06	17	12	11	05	04	02	01	08	10
A	41	40	32	42	38	31	39	33	36	37	16	25	30	26	35	27	18	13	22	29	34	21	28	15	19	09	11	06	07	17	20	23	10	24	14	12	08	04	05	03	01	02
M	40	38	39	41	29	33	42	27	36	32	20	26	30	25	28	35	14	21	23	34	37	22	31	15	18	07	13	06	11	16	24	12	09	19	17	10	05	01	08	03	02	04
J	42	35	39	40	38	34	36	29	41	28	37	22	32	33	27	30	17	31	25	24	26	23	19	20	21	18	12	10	14	13	15	02	06	05	16	11	09	01	07	08	04	03
J	38	33	37	41	42	32	29	35	40	30	34	20	28	39	25	31	17	36	22	23	26	27	18	21	19	24	15	13	07	16	14	08	04	03	10	09	12	05	06	11	02	01
A	39	38	33	40	42	32	26	37	29	35	34	19	27	36	25	31	18	41	24	30	23	22	28	17	21	20	15	16	04	11	14	10	07	01	12	13	08	05	06	09	02	03
S	32	42	34	36	38	30	29	39	35	37	31	22	25	40	24	33	19	41	27	26	20	23	28	16	21	18	15	17	03	08	14	11	06	01	12	13	07	05	10	09	04	02
O	30	38	33	41	40	28	27	42	35	36	32	25	26	39	31	34	17	37	22	24	29	23	21	20	18	19	14	16	04	13	09	11	07	03	15	12	10	05	08	06	02	01
N	29	39	30	42	41	27	31	40	35	37	33	32	28	38	36	34	25	21	24	22	26	17	23	19	15	20	16	07	08	18	09	06	10	04	13	14	12	01	05	11	03	02
D	37	40	36	42	33	27	28	31	32	41	38	30	26	39	35	34	25	24	29	23	21	22	17	19	20	18	14	07	10	16	13	04	11	08	12	15	09	01	03	05	06	02
Y	39	40	34	42	41	29	31	38	36	37	32	25	27	35	30	33	20	28	23	26	24	21	22	18	19	17	14	11	08	16	15	10	07	06	13	12	09	02	05	04	03	01
	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020

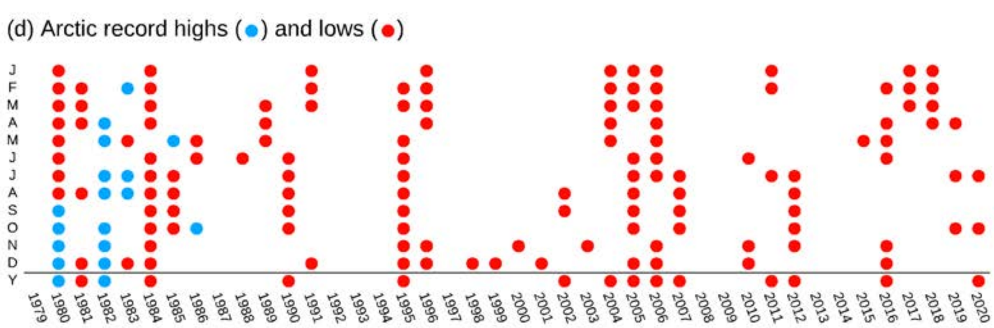


Figure 1. (a) Arctic sea ice extent rankings by year, for each calendar month and the yearly average, over the 42-year period 1979-2020. Rankings are from the month's (or yearly average's) lowest sea ice extent (deep red) to its highest sea ice extent (deep blue). (b) Flattened version of (a). (c) Numerical rankings, from 1 for the year with the lowest sea ice extent to 42 for the year with the highest sea ice extent, for each calendar month and the yearly average. (d) Identification of all monthly and yearly Arctic record high sea ice extents (blue dots) and all monthly and yearly Arctic record low sea ice extents (red dots).

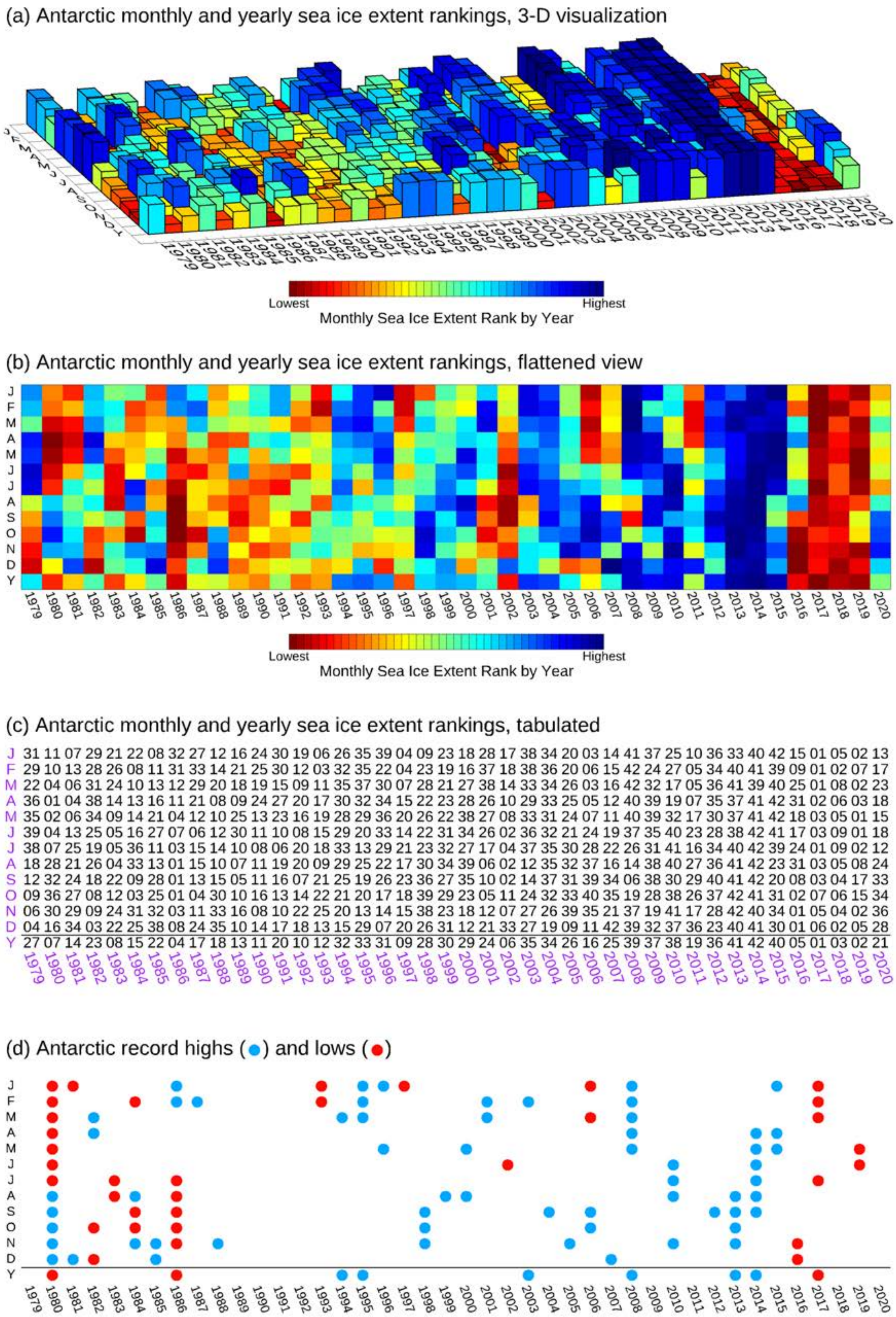
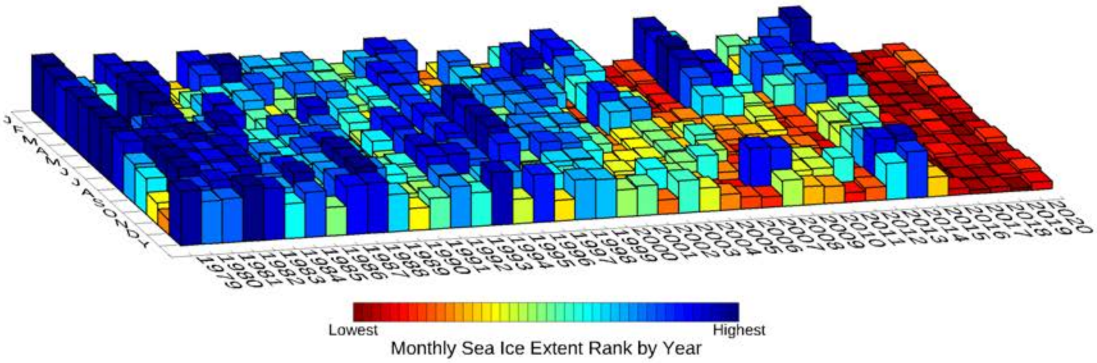
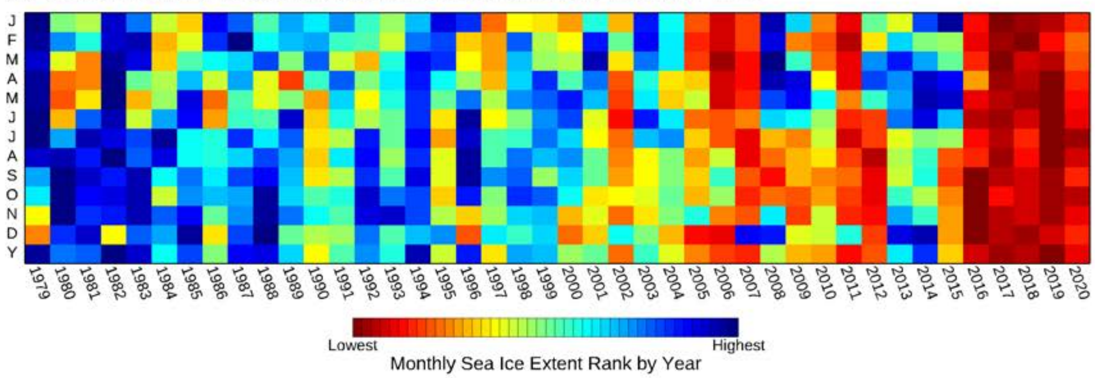


Figure 2. Same as Figure 1 but for the Antarctic sea ice cover.

(a) Global monthly and yearly sea ice extent rankings, 3-D visualization



(b) Global monthly and yearly sea ice extent rankings, flattened view



(c) Global monthly and yearly sea ice extent rankings, tabulated

	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
J	42	21	19	39	32	18	14	37	33	23	30	27	31	24	20	29	38	35	10	16	15
F	41	31	25	39	40	13	17	35	42	26	29	30	24	23	18	32	34	14	12	33	19
M	39	17	11	41	38	14	23	26	28	34	21	33	18	13	25	37	35	16	12	29	20
A	41	10	11	42	22	19	29	18	30	17	08	24	33	21	27	36	26	20	13	28	35
M	41	09	15	42	13	20	38	10	23	17	21	12	28	16	25	35	22	32	19	31	33
J	42	13	33	40	18	30	37	12	24	23	39	14	25	19	22	35	15	41	16	21	31
J	42	30	40	38	34	41	26	25	35	27	33	15	19	36	22	37	12	39	23	24	32
A	39	40	36	42	33	38	26	25	28	34	30	14	27	37	20	35	17	41	23	32	29
S	30	42	39	36	40	26	32	27	34	37	29	15	19	35	23	38	17	41	31	33	20
O	27	42	37	38	40	18	31	29	30	41	28	23	25	39	32	34	14	36	21	35	33
N	16	42	35	36	40	33	37	22	31	41	32	26	23	38	39	34	19	14	20	28	29
D	11	35	39	16	33	30	41	15	34	42	22	19	20	32	23	29	31	09	27	24	28
Y	41	32	33	42	39	26	34	21	37	38	28	16	23	31	25	40	18	36	15	30	29

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
J	12	25	13	36	26	09	04	08	40	28	11	05	22	17	34	41	06	01	02	03	07
F	16	36	22	37	27	07	04	08	38	11	09	03	15	28	21	20	05	02	01	06	10
M	19	40	15	32	27	08	02	06	42	24	10	05	31	36	30	22	07	01	04	03	09
A	23	32	09	25	15	14	04	06	40	38	16	05	34	31	39	37	12	02	03	01	07
M	36	29	08	27	14	18	04	07	34	37	26	11	24	30	40	39	05	03	02	01	06
J	34	17	06	36	27	10	09	11	28	26	20	07	08	32	38	29	03	02	04	01	05
J	28	16	10	29	31	14	09	05	13	11	18	04	08	17	21	20	06	03	07	01	02
A	31	22	11	16	21	12	18	05	10	13	15	08	03	19	24	09	07	02	06	01	04
S	28	22	12	16	21	14	24	09	06	13	11	10	05	18	25	08	01	03	04	02	07
O	26	15	16	17	22	13	20	07	10	09	12	08	05	24	19	11	01	06	04	02	03
N	13	17	10	15	21	25	11	09	27	08	18	07	06	30	24	12	01	03	04	02	05
D	10	14	26	21	13	06	05	37	36	17	18	25	08	38	40	12	01	03	02	04	07
Y	20	22	10	24	17	11	08	07	19	13	12	06	09	27	35	14	04	02	03	01	05

(d) Global record highs (●) and lows (●)

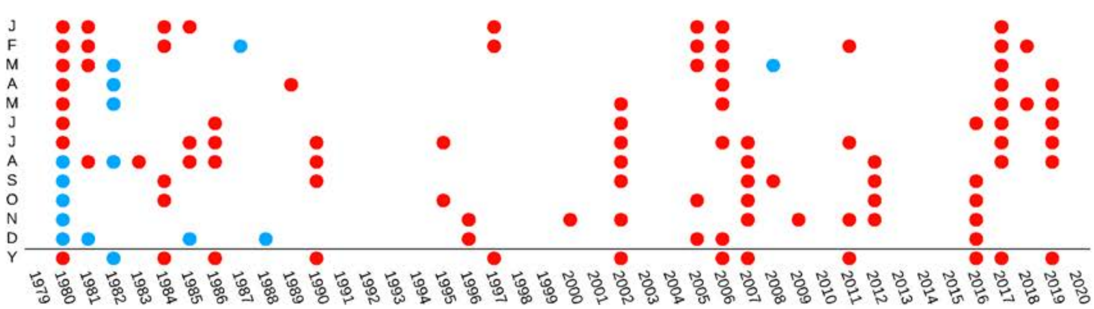


Figure 3. Same as Figure 1 but for the global sea ice cover.

final in 2020, the last year of the 42-year dataset, powerfully illustrating the reality of the declining Arctic sea ice cover (Figure 1d).

3.2 Antarctic

In sharp contrast to the situation for the Arctic, the addition of the five years 2016-2020 to the Antarctic dataset decidedly changes fundamental aspects of the results, as now the Antarctic record no longer shows a compelling trend toward increasing ice extents, instead dipping to unusually low values in 2016-2019, then rebounding somewhat in 2020 (Figure 2a-c). In fact, the additional five years show no new Antarctic monthly record highs and eight new Antarctic monthly record lows, for totals through 2020 of 45 record highs and 14 record lows since 1986. Eight of the 12 calendar months experienced new record lows in the five years 2016-2020, as did the yearly average ice extents, which went from their 42-year highest value in 2014 to their 42-year lowest value in 2017 (Figure 2d).

3.3 Global

With the Arctic continuing its sea ice extent declines (Figure 1) and the Antarctic reversing from increasing sea ice extents to a conspicuous decrease in ice extents after 2015 (Figure 2), the global results now show the last five years of the record, 2016-2020, to be dominated by unusually low values (Figure 3a-b). In fact, each of the 60 months in the five years 2016-2020 has a global sea ice extent that ranks (for the month) in the bottom 29% of the 42-year record, and all months except April 2016 rank in the bottom 25% (Figure 3c). Additionally, every calendar month registered at least one new global record low ice extent in these last five years, with four months registering two new record lows and two months registering three new record lows, for a total of 20 new monthly record lows over the period 2016-2020 (Figure 3d). Not only did the period 2016-2020 have no new global monthly record high sea ice extents, but there has been only one new monthly record high in global sea ice extents since 1988, that one coming in March 2008 (Figure 3d). Altogether, the global sea ice cover has experienced 3 monthly record highs and 63 monthly record lows since 1986 (Figure 3d). On a yearly average basis, the last global record high ice extent was in 1982, with 11 global record lows since that time, the last of the 42-year 1979-2020 dataset coming in 2019 (Figure 3d).

3.4 42-Year Sea Ice Extent Record Highs and Lows

The monthly and yearly record high Arctic, Antarctic, and global sea ice extents over the 1979-2020 period of the multi-channel satellite passive-microwave record are listed in Table 1, and the corresponding record lows are listed in Table 2. Both sets of monthly values are plotted in Figure 4, where the ranges of the monthly ice extents are highlighted.

In the Arctic case, the 42-year monthly record highs all occurred in 1986 or earlier, whereas the 42-year monthly record lows all occurred in 2012 or later (Tables 1-2), illustrating well the downward trend in Arctic sea ice coverage. In the Antarctic case, the 42-year monthly record highs were all in the period 2007-2015 (Table 1), reflecting the upward trend in Antarctic sea ice coverage until 2014/2015. The decreases in Antarctic ice extents after 2014 led to 42-year Antarctic record lows in 2016-2019 for eight calendar months although did not yield new lows in the other four months, which instead have their 42-year record lows in 1980 and 1986. Globally, all months have their 42-year record highs in 1979-1988 except March, for which the record high is in 2008, whereas all twelve 42-year record lows are in 2016-2019, again illustrating the decline in global sea ice coverage (Tables 1-2).

Despite the definitive downward trend in Arctic sea ice coverage, for seven of the 12 calendar months the record low ice extent is no more than 17.5% lower than the record high ice

Table 1. Monthly and Yearly Average Sea Ice Extent 42-Year (1979-2020) Record Highs.

Month	Arctic Record Highs		Antarctic Record Highs		Global Record Highs	
	Year	Ice Extent (x 10^6 km^2)	Year	Ice Extent (x 10^6 km^2)	Year	Ice Extent (x 10^6 km^2)
January	1979	15.2	2015	6.9	1979	20.6
February	1983	15.8	2008	3.9	1987	19.0
March	1979	16.1	2008	5.3	2008	20.4
April	1982	15.3	2015	8.4	1982	23.0
May	1985	14.0	2015	11.7	1982	24.7
June	1979	12.6	2014	14.7	1979	26.8
July	1983	10.6	2014	17.1	1979	26.8
August	1983	8.2	2014	18.9	1982	25.9
September	1980	7.7	2014	19.8	1980	26.6
October	1986	9.6	2013	19.0	1980	27.8
November	1982	11.7	2013	16.9	1980	27.6
December	1982	13.6	2007	12.0	1988	24.6
Year	1982	12.4	2014	12.8	1982	24.0

Table 2. Monthly and Yearly Average Sea Ice Extent 42-Year (1979-2020) Record Lows.

Month	Arctic Record Lows		Antarctic Record Lows		Global Record Lows	
	Year	Ice Extent (x 10^6 km^2)	Year	Ice Extent (x 10^6 km^2)	Year	Ice Extent (x 10^6 km^2)
January	2018	13.0	2017	3.8	2017	16.9
February	2018	13.8	2017	2.3	2018	16.1
March	2018	14.1	2017	2.7	2017	16.9
April	2019	13.4	1980	5.4	2019	19.1
May	2016	11.9	2019	8.9	2019	21.1
June	2016	10.4	2019	12.3	2019	22.9
July	2020	7.3	2017	15.3	2019	22.9
August	2012	4.7	1986	17.0	2019	22.5
September	2012	3.6	1986	17.7	2016	22.7
October	2020	5.4	1986	17.2	2016	23.6
November	2016	8.7	2016	14.2	2016	22.9
December	2016	11.4	2016	8.3	2016	19.7
Year	2020	10.1	2017	10.7	2019	21.1

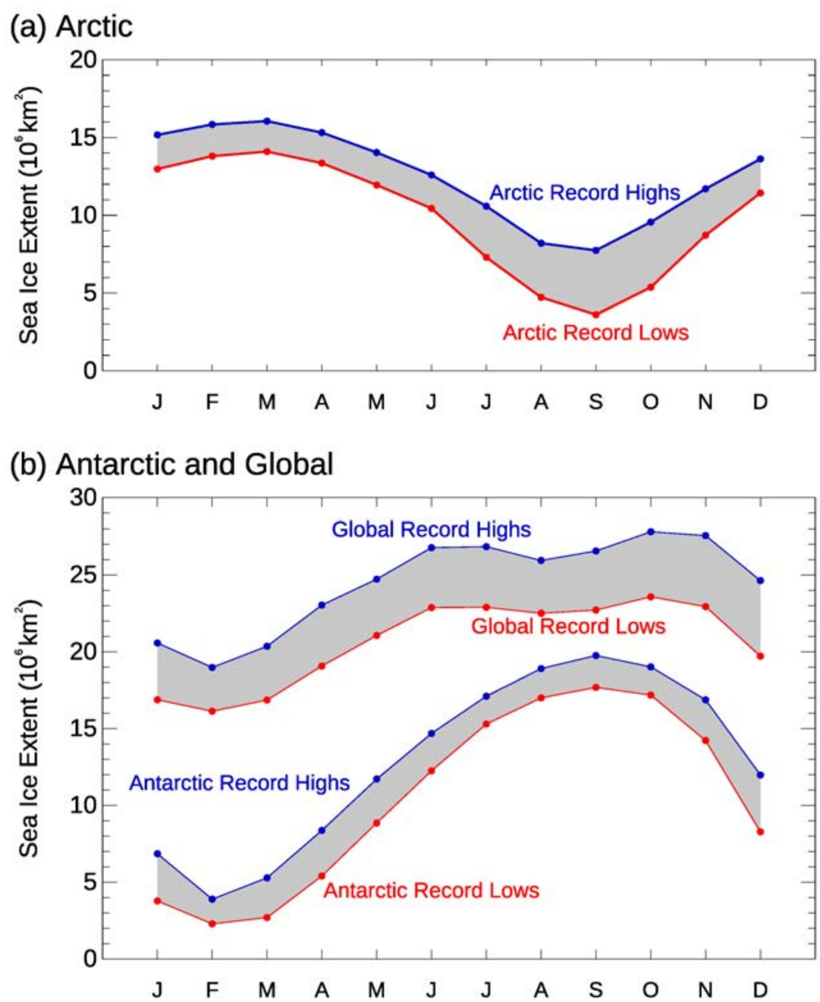


Figure 4. Annual cycles of the 42-year monthly record highs and record lows for (a) the Arctic and (b) the Antarctic and global sea ice extents. The spacing on the y-axis scales is identical for parts (a) and (b), to allow direct comparison, at the same scales, of the Arctic, Antarctic, and global results.

extent (Table 3). The much greater percent contrasts in the Arctic monthly sea ice extents come in summer and fall, with the largest being 53% for September, the month with the least sea ice coverage and hence the lowest baseline for the percentage calculation (Table 3 and Figure 4a). The Antarctic also has its highest percent contrasts in its summer and early fall (January – April), but in contrast to the Arctic, these are not also consistently the months of greatest areal range in ice extents (Table 3 and Figure 4b). Globally, the range in monthly ice extents exceeds the range in the corresponding ice extents for each hemisphere by a substantial margin in all months except

August-October, when the Arctic range equals or exceeds the global range. However, in view of the much greater global versus hemispheric ice extents, the higher global ranges do not yield correspondingly higher % contrasts. In fact, for the global results, no month has its record low more than 20% lower than its record high, and the lowest yearly-average ice extent is only 12% lower than the highest yearly-average ice extent (Table 3).

Table 3. Range of Monthly and Yearly Average Sea Ice Extents (Record High – Record Low), for each calendar month and the year, and Percent Contrast (Range/Record High, abbreviated Range/H), for the 1979-2020 period. [Ice extents in Tables 1 and 2 and ranges in Table 3 were calculated to more decimal places before being rounded in each case to the nearest 0.1 x 10^6 km^2, hence accounting for the occasional 0.1 mismatch between the range listed in Table 3 versus the Table 1 – Table 2 difference and the occasional 1-percentage-point mismatch between the Range/H values in Table 3 and the rounded Ranges and Record Highs in Tables 1 and 3.]

Month	Arctic High vs Low		Antarctic High vs Low		Global High vs Low	
	Range (x 10^6 km^2)	Range/H (%)	Range (x 10^6 km^2)	Range/H (%)	Range (x 10^6 km^2)	Range/H (%)
January	2.2	14	3.1	45	3.7	18
February	2.0	13	1.6	41	2.9	15
March	2.0	12	2.6	49	3.5	17
April	2.0	13	3.0	35	4.0	17
May	2.1	15	2.9	24	3.7	15
June	2.1	17	2.4	17	3.9	15
July	3.3	31	1.8	11	3.9	15
August	3.5	42	1.9	10	3.4	13
September	4.1	53	2.1	10	3.8	14
October	4.2	44	1.8	10	4.2	15
November	3.0	26	2.6	16	4.6	17
December	2.2	16	3.7	31	4.9	20
Year	2.3	18	2.0	16	3.0	12

4. Discussion

Sea ice is an integral component of the climate system, with numerous impacts on the polar environment and ecosystems. It contributes to keeping the polar regions colder than they otherwise would be by reflecting solar radiation back to space; it limits exchanges of heat, mass, and momentum between the ocean and the atmosphere; it affects the salinity and thereby density structure of the underlying ocean by releasing salt as it forms and ages and releasing relatively fresh water as it melts; it offers protection against coastal erosion by limiting wave action; and it houses a variety of microorganisms and provides a platform for larger animals to rest, wander, and breed. Consequently, as the sea ice cover changes substantially, this has numerous ramifications.

Satellite technology has provided a means of viewing the entire polar sea ice cover and recording changes in its extent over time since the start of the multi-channel satellite passive-microwave record in late 1978. This record reveals a strong long-term trend toward decreasing sea ice coverage in the Arctic (Figure 1a) and a more mixed pattern of increases and decreases in the Antarctic and global sea ice coverages, with conspicuous decreases in the last five years of the 1979-2020 dataset (Figures 2a and 3a). The Arctic decreases are in line with the expectations from global warming, but the more mixed sequence of Antarctic changes has been much more puzzling.

Following decades of an overall upward trend in Antarctic sea ice extents, these extents declined so rapidly from 2014 to 2017 that, on a yearly average basis, the Antarctic lost an ice extent in that 3-year period that was as great as the Arctic had lost in the previous three decades (Parkinson, 2019). Attempted explanations of why the Antarctic sea ice extents increased overall from the late 1970s until well into the twenty-first century include ties to the ozone hole (Thompson and Solomon, 2002; Turner *et al*., 2009; rejected in Sigmond and Fyfe 2010 and in Bitz and Polvani 2012), the El Nino-Southern Oscillation (ENSO) (Stammerjohn *et al*., 2008), the Interdecadal Pacific Oscillation (Meehl *et al*., 2016), the Amundsen Sea Low pressure system

(Meehl *et al*., 2016; Turner *et al*., 2009; Turner *et al*., 2015), and meltwater from ice shelves (Bintanja *et al*., 2013; rejected in Swart and Fyfe 2013); and attempted explanations of why the ice extents decreased so rapidly after 2014 include ties to ocean warming (Eayrs *et al*., 2021; Meehl *et al*., 2019; Stuecker *et al*., 2017), the Interdecadal Pacific Oscillation (Meehl *et al*., 2019), the Southern Annular Mode (SAM) (Meehl *et al*., 2019; Schlosser *et al*., 2018; Stuecker *et al*., 2017; Turner *et al*., 2017), an atmospheric zonal wave 3 circulation pattern (Schlosser *et al*., 2018; G. Wang *et al*., 2019), the ENSO (Stuecker *et al*., 2017), a weakening of the polar stratospheric vortex (G. Wang *et al*., 2019), and wind-driven northward sea ice drift (Z. Wang *et al*., 2019). Proxy records of Antarctic sea ice extending back thousands of years also have revealed the possibility of connections with ENSO and SAM (Crosta *et al*., 2021). However, so far there is no consensus explanation for either the increases in Antarctic sea ice coverage from the late 1970s to 2015 or the rapidity of the decreases in Antarctic sea ice coverage after 2014. These remain topics of active research and illustrate that, despite the considerable progress made in the past several decades, there is still further progress to be made before scientists have a complete understanding of the Earth's highly interconnected atmosphere-ocean-land-ice climate system.

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