Characteristics of Antarctic Sea Ice Extent Change, 1978-2024

SARAH VILLHAUER,[1*] MARILYN RAPHAEL,[1]

[1] *University of California, Los Angeles*
[*] *svillhauer@g.ucla.edu*

Abstract: Antarctic sea ice extent has a distinct annual cycle, peaking around September and troughing around late February. While it is known that there is substantial spatial and temporal variability concerning the annual cycle of Antarctic sea ice extent, there is still uncertainty surrounding what this variability looks like. This paper uses passive microwave data to decompose the annual cycle of sea ice extent from 1978 to 2024 across the five Antarctic sectors (the Ross Sea, the Amundsen-Bellingshausen Seas, the Weddell Sea, the King Hakon Sea, and East Antarctic sectors) and the total Antarctic continent. Linear regression models are used to analyze the trends and behavior of six components: [1] annual minimum, [2] annual maximum, [3] time of advance, [4] time of retreat, [5] advance amplitude, and [6] retreat amplitude of sea ice extent. Advance amplitude is used as a measure of intra-annual variability, and retreat amplitude is used as a measure of inter-annual variability. Intra- and inter-annual variability are increasing in the Ross Sea and Amundsen-Bellingshausen Seas sectors, while intra- and inter-annual variability are decreasing in the Weddell Sea sector. Since there are no significant trends in annual maximum sea ice extent, these changes in intra- and inter-annual variability are dominated by change in annual minimum sea ice extent. Annual minimum sea ice extent is decreasing by around $0.0107(\pm 0.0060) \times 10^6\,\mathrm{km}^2/\mathrm{year}$ in the Ross Sea sector and $0.0056(\pm 0.0025) \times 10^6\,\mathrm{km}^2/\mathrm{year}$ in the Amundsen-Bellingshausen Seas sector, while it is increasing by around $0.0069(\pm 0.0057) \times 10^6\,\mathrm{km}^2/\mathrm{year}$ in the Weddell Sea sector.

1. Introduction

Sea ice forms through the freezing of seawater over large areas at the Southern and Northern poles, and plays various essential roles in the global climate system, such as acting as an insulator between the atmosphere and the ocean, affecting surface albedo, and influencing ocean circulation (Gloersen et al., 1992). Analyzing and understanding patterns in sea ice extent—the total area with at least 15 percent sea ice cover—can aid us in making better predictions of our future climate.

Annual Antarctic sea ice extent follows a positive trend of $17 \pm 1200\,\mathrm{km}^2/\mathrm{year}$ from the 32 year period spanning from November 1978 to December 2010. The causation of this increase has been difficult to attribute, with some explanations including but not limited to El Niño, Southern Oscillation, the Interdecadal Pacific Oscillation, the Amundsen Sea Low, and basal meltwater from ice shelves (Parkinson, 2019). However, starting in 2014, this decade-long trend of gradual sea ice extent increase was reversed. Yearly average Antarctic sea ice extent reached a record high of $12.8\,10^6\,\mathrm{km}^2$ in 2014, which was followed by a sharp decline so that sea ice extent reached a minimum low of $10.7\,10^6\mathrm{km}^2$ in 2017 (Parkinson, 2019). In fact, the drop from the record high in 2014 to the record low in 2017 equalled the 30-year observed decrease in Arctic sea ice extent (Eayrs et al., 2021). In addition, there is also regional variability in sea ice extent across the Antarctic continent, complicating prediction of future Antarctica sea ice extent trends even further. Previous studies have found that the Ross Sea and Weddell Sea sectors largely contribute to a positive annual trend, while the Bellinghausen-Amundsen Seas sector have overall negative annual sea ice extent trends (Parkinson, 2019).

In order to better understand trends in Antarctic sea ice extent, it is necessary to understand the annual cycle. Antarctic sea ice extent has a distinct annual cycle, peaking around September

Data Availability: The data that support the findings of this study are available on Github.

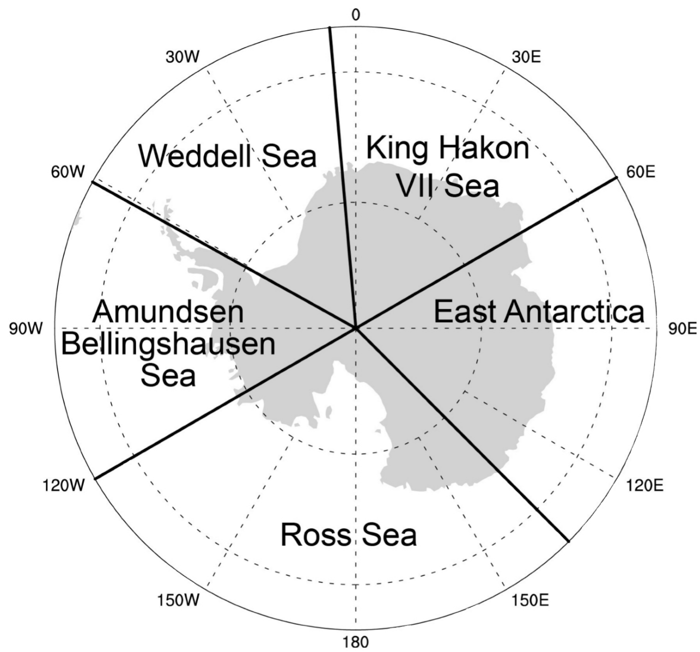

Fig. 1. Identification of the five sectors of Antarctica discussed in this paper: the Ross Sea, the Amundsen-Bellingshausen Seas, the Weddell Sea, the King Hakon Sea, and East Antarctica sectors (Parkinson, 2019).

and troughing in late February. Models of Antarctic sea ice extent that include amplitude and phase dilation better capture both intra- and inter-annual variability because they are not fixed to day of the year (Handcock and Raphael, 2020). While the traditional model of Antarctic sea ice extent—or the annual mean—represents sea ice extent as a fixed cyclical pattern, phase-and-amplitude adjustment of the cycle captures inter-annual variability and results in a 77.3% improvement in mean squared error (Handcock and Raphael, 2020).

This paper seeks to decompose the annual cycle of Antarctic sea ice extent into its key components: annual minimum, annual maximum, time of advance, time of retreat, advance amplitude, and retreat amplitude. These six components of the annual cycle are computed for all five Antarctic sectors (Figure 1) and on a continental basis, in order to provide a comprehensive summary of how they behave individually and how they relate across geographical sectors.

2. Methods

2.1. Data

This study uses satellite-based multichannel passive-microwave data of daily Antarctica sea ice extent, obtained from the National Snow and Ice Data Center. This data is derived from the Scanning Multichannel Microwave Radiometer (SMMR) instrument on the Nimbus-7 satellite, along with the Special Sensor Microwave/Imager (SSM/I) and the Special Sensor Microwave Imager/Sounder (SSMIS) on the Defense Meteorological Satellite Program's (DMSP) -F8, -F11, -F13, -F15, -F16, -F17, and -F18 satellites (NSIDC). The microwave data was converted into sea ice concentrations in each pixel of the gridded satellite data, and sea ice extents were calculated by summing up the area of 'ice-covered' pixels (Parkinson, 2019). Sea ice extent defines an

Data Availability: The data that support the findings of this study are available on Github.

area as ‘ice-covered’ or ‘not ice-covered’ based on a common threshold of 15 percent sea ice concentration; this means that if a data cell has a greater than 15 percent sea ice concentration, it is considered ‘ice-covered,’ elsewise it is considered ‘ice-free’ (NSIDC).

All analysis is performed individually for the five geographical sectors of Antarctica—the Ross sea, the Amundsen-Bellingshausen Seas, the Weddell Sea, the King Hakon Sea, and East Antarctica sectors—and for the total Antarctic continent (Figure 1). We perform linear regressions for all components: annual maximum, annual minimum, time of advance, time of retreat, advance amplitude, and retreat amplitude. A Pearson’s correlation is also calculated for all components across Antarctic sectors.

2.2. Annual Minimum and Maximum Sea Ice Extent

Annual minimum sea ice extent refers to the smallest magnitude of sea ice extent recorded for any given year. Annual maximum sea ice extent refers to the largest magnitude of sea ice extent recorded for any given year.

The annual minimum of sea ice extent was extracted from 1979 to 2024, and the annual maximum of sea ice extent was extracted from 1979 to 2023. Since passive-microwave satellite record began in late 1978, no available data captures the minimum and maximum of sea ice extent in 1978. Furthermore, the available data for 2024 does not yet contain the annual maximum of sea ice extent in 2024.

2.3. Time of Advance and Retreat

Time of advance and time of retreat were extracted for every year from 1979-2021 across the five Antarctic sectors. Time of advance refers to the decimal Julian day of the year at which sea ice extent starts increasing, or when sea ice extent reaches its annual minimum. Time of retreat refers to the decimal Julian day of the year at which sea ice extent starts decreasing, or when sea ice extent reaches its annual maximum.

2.4. Advance and Retreat Amplitudes

We define advance amplitude as the difference between maximum and minimum sea ice extent within any given year.

$$\text{Advance Amplitude} = \text{max·extent}_{\text{year}} - \text{min·extent}_{\text{year}} \tag{1}$$

We define retreat amplitude as the difference between maximum sea ice extent in any given year (e.g. 2023) and minimum sea ice extent in the proceeding year (e.g. 2024).

$$\text{Retreat Amplitude} = \text{max·extent}_{\text{year}} - \text{min·extent}_{\text{year+1}} \tag{2}$$

Given annual minimum data spans 1979-2024 and annual maximum data spans 1979-2023, both advance and retreat amplitudes are calculated from 1979-2023.

3. Results & Discussion

3.1. Annual Minimum Sea Ice Extent

Annual minimum sea ice extent in three Antarctic sectors—the Ross Sea, the Amundsen-Bellingshausen Seas, and the Weddell Sea sectors—shows significant linear trends (Figure 2; Table 1). Minimum sea ice extent in both the Ross Sea and Amundsen-Bellingshausen Seas sectors show negative linear trends, indicating that the annual minimum of sea ice extent in the Ross Sea and Amundsen-Bellingshausen Seas is growing smaller. Minimum sea ice extent in the Weddell Sea shows a positive linear trend, indicating that the annual minimum of sea ice extent in the Weddell Sea is growing larger.

Data Availability: The data that support the findings of this study are available on Github.

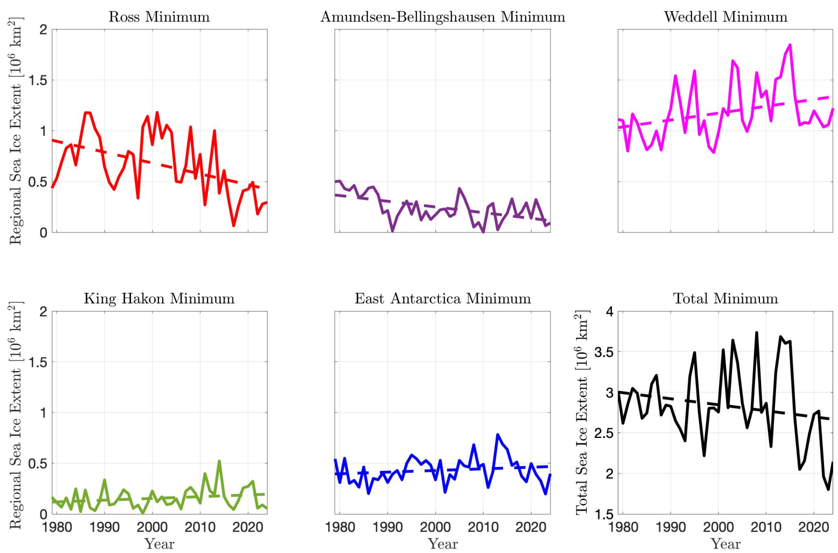

Fig. 2. Annual minimum extent of Antarctic sea ice extent for **[a]** the Ross Sea, **[b]** the Amundsen-Bellingshausen Seas, **[c]** the Weddell Sea, **[d]** the King Hakon Sea, **[e]** East Antarctica, and **[f]** the total continent from 1979-2024. Dashed lines are the linear regressions.

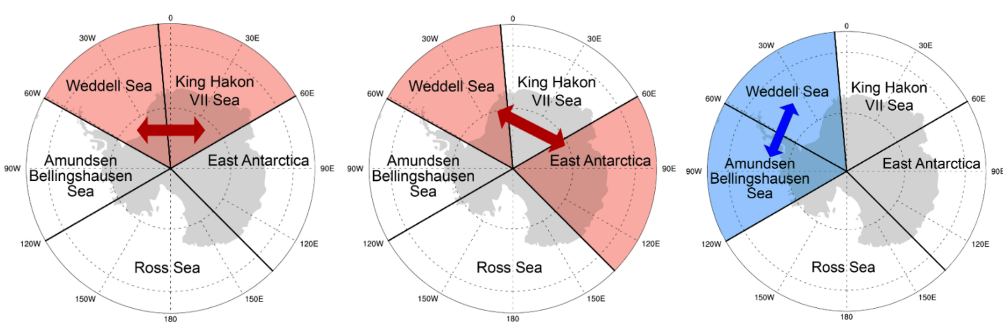

Fig. 3. The five Antarctic sectors, with red representing a positive correlation and blue representing a negative correlation in annual minimum sea ice extent between sectors. There is **[a]** a significant positive correlation in annual minimum between the Weddell Sea and King Hakon Sea sectors ($r = 0.3471$, $p = 0.0181$), **[b]** a significant positive correlation in annual minimum between the Weddell Sea and East Antarctica sectors ($r = 0.4215$, $p = 0.0035$), and **[c]** a significant negative correlation in annual minimum between the Weddell Sea and Amundsen-Bellingshausen Seas sectors ($r = -0.4767$, $p = 0.0008$).

Data Availability: The data that support the findings of this study are available on Github.

Sector	p	R^2	m [10^6 km^2/year]
Ross	7.9135e-04	0.2280	−0.0107 (±0.0060)
Amundsen-Bellingshausen	5.1596e-05	0.3138	−0.0056 (±0.0025)
Weddell	0.0209	0.1153	0.0068 (±0.0057)
King Hakon	0.1491	0.0467	0.0017 (±0.0024)
East Antarctica	0.2700	0.0276	0.0016 (±0.0029)
Total	0.1558	0.0452	−0.0074 (±0.0104)

Table 1. P-values (**p**), R-squared values ($\mathbf{R^2}$), and slopes (**m**) of linear regressions for annual minimum of sea ice extent. Values in parentheses indicate uncertainty of the slope based on 95% confidence intervals.

The Weddell Sea sector is involved in all significant correlations that occur in annual minimum sea ice extent between sectors. There are two positive correlations in annual minimum sea ice extent: between the [1] Weddell Sea and King Hakon Sea sectors and [2] the Weddell Sea and East Antarctica sectors (Figure 3). As the annual minimum of sea ice extent grows larger (smaller) in the Weddell Sea sector, the annual minimum of sea ice extent grows larger (smaller) in the King Hakon Sea and East Antarctica sectors. There is a negative correlation in annual minimum sea ice extent between the Weddell Sea and Amundsen-Bellingshausen Seas sectors (Figure 3). As the annual minimum of sea ice extent grows larger (smaller) in the Weddell Sea sector, the annual minimum of sea ice extent grows smaller (larger) in the Amundsen-Bellingshausen Seas sector.

Since the Weddell Sea and East Antarctica sectors are not geographically adjacent to one another, we should expect to find some large-scale atmospheric and/or oceanic mechanism driving that correlation. Since the Weddell Sea is geographically adjacent to the King Hakon Sea and Amundsen-Bellingshausen Seas sectors, we should expect to find some local-scale atmospheric and/or oceanic mechanism driving those two correlations. The inverse relationship in annual minimum between the Weddell Sea and Amundsen-Bellingshausen Seas sectors is also reflect in the slopes of the linear regressions (Table 1). The annual minimum of sea ice extent in the Weddell Sea sector is predicted to increase $0.0068(\pm 0.0057) \times 10^6$ km^2/year, while the annual minimum of sea ice extent in the Amundsen-Bellingshausen Seas sector is predicted to decrease $0.0056(\pm 0.0025) \times 10^6$ km^2/year.

3.2. Annual Maximum Sea Ice Extent

Annual maximum sea ice extent shows no significant linear trends for any of the Antarctic sectors (Figure 4; Table 2). Although there is variability in annual maximum from 1979-2023, this variability does not significantly trend in one direction or the other.

Sector	p-value	R^2	m [10^6 km^2/year]
Ross	0.1373	0.0506	0.0055 (±0.0073)
Amundsen-Bellingshausen	0.5298	0.0092	0.0012 (±0.0037)
Weddell	0.1766	0.0420	−0.0048 (±0.0071)
King Hakon	0.6038	0.0063	0.0021 (±0.0079)
East Antarctica	0.4393	0.0140	−0.0019 (±0.0050)
Total	0.8908	4.4305e-04	$8.0334e-04$ (±0.0117)

Table 2. P-values (**p**), R-squared values ($\mathbf{R^2}$), and slopes (**m**) of linear regressions for annual maximum of sea ice extent. Values in parentheses indicate uncertainty of the slope based on 95% confidence intervals.

There are three negative correlations in annual maximum sea ice extent: between [1] the Ross Sea and the Amundsen-Bellingshausen Seas sectors, [2] the Ross Sea and Weddell Sea sectors,

Data Availability: The data that support the findings of this study are available on Github.

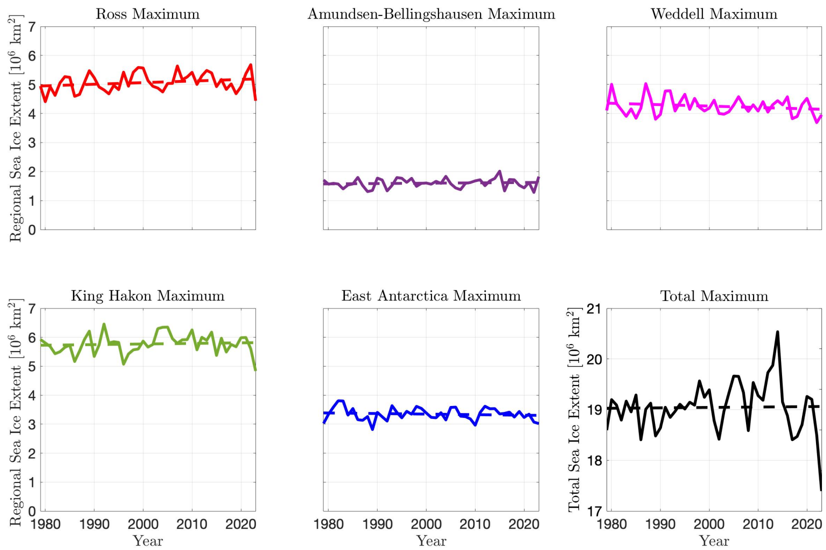

Fig. 4. Annual maximum extent of Antarctic sea ice extent for **[a]** the Ross Sea, **[b]** the Amundsen-Bellingshausen Seas, **[c]** the Weddell Sea, **[d]** the King Hakon Sea, **[e]** East Antarctica, and **[f]** the total continent from 1979-2023. Dashed lines show linear regressions.

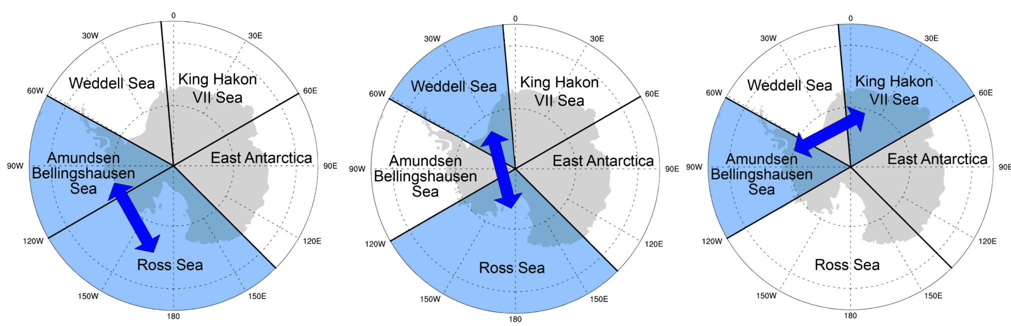

Fig. 5. The five Antarctic sectors, with red representing a positive correlation and blue representing a negative correlation in annual maximum sea ice extent between sectors. There is **[a]** a significant negative correlation in annual maximum between the Ross Sea and Amundsen-Bellingshausen Seas sectors ($r = -0.2950$, $p = 0.0491$), **[b]** a significant negative correlation in annual maximum between the Ross Sea and Weddell Sea sectors ($r = -0.3447$, $p = 0.0204$) and **[c]** a significant negative correlation in annual maximum between the Amundsen-Bellingshausen Seas and King Hakon Sea sectors ($r = -0.3059$, $p = 0.0410$) .

Data Availability: The data that support the findings of this study are available on Github.

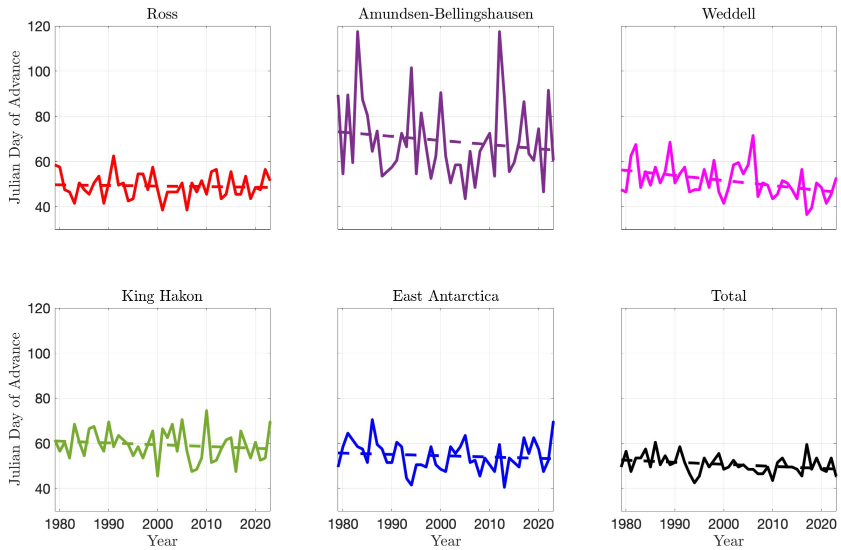

Fig. 6. Time of advance (decimal Julian days) of Antarctic sea ice extent for **[a]** the Ross Sea, **[b]** the Amundsen-Bellingshausen Seas, **[c]** the Weddell Sea, **[d]** the King Hakon Sea, **[e]** East Antarctica, and **[f]** the total continent from 1979-2024. Dashed lines show linear regressions.

and [3] the Amundsen-Bellingshausen Seas and King Hakon Sea sectors (Figure 5) . As the annual maximum of sea ice extent grows larger (smaller) in the Ross Sea sector, the annual maximum of sea ice extent grows smaller (larger) in the Amundsen-Bellingshausen Seas and Weddell Sea sectors. As the annual maximum of sea ice extent grows larger (smaller) in the Amundsen-Bellingshausen Seas sector, the annual maximum of sea ice extent grows smaller (larger) in the King Hakon Sea sector.

Since the Ross Sea and Amundsen-Bellingshausen Seas sectors are geographically adjacent to one another, we should expect to find some local-scale atmospheric and/or oceanic mechanism—like the Amundsen Sea Low (ASL)—driving this negative correlation. Since the other two significant correlations occur between non-adjacent sectors, we should expect to find some large-scale atmospheric and/or oceanic mechanism driving these correlations.

3.3. Time of Advance

Time of advance for the Weddell Sea sector and for the total Antarctic continent show significant negative linear trends (Figure 6; Table 3). Sea ice extent is reaching its annual minimum earlier in the year in the Weddell Sea sector. Despite there being no significant linear trends in time of advance within the other four Antarctic sectors, sea ice extent across the total Antarctic continent is still reaching its annual minimum earlier in the year.

All significant correlations in time of advance of sea ice extent occur between East Antarctica and other sectors. There are two positive correlations in the time of advance of sea ice extent: between [1] the King Hakon Sea and East Antarctica sectors and [2] the Weddell Sea and East Antarctica sectors (Figure 8). As the time of advance of sea ice extent occurs later (earlier) in the year in the East Antarctica sector, the time of advance of sea ice extent occurs later (earlier) in the year in the King Hakon Sea and Weddell Sea sectors.

Since the King Hakon Sea and East Antarctica sectors are geographically adjacent to one

Data Availability: The data that support the findings of this study are available on Github.

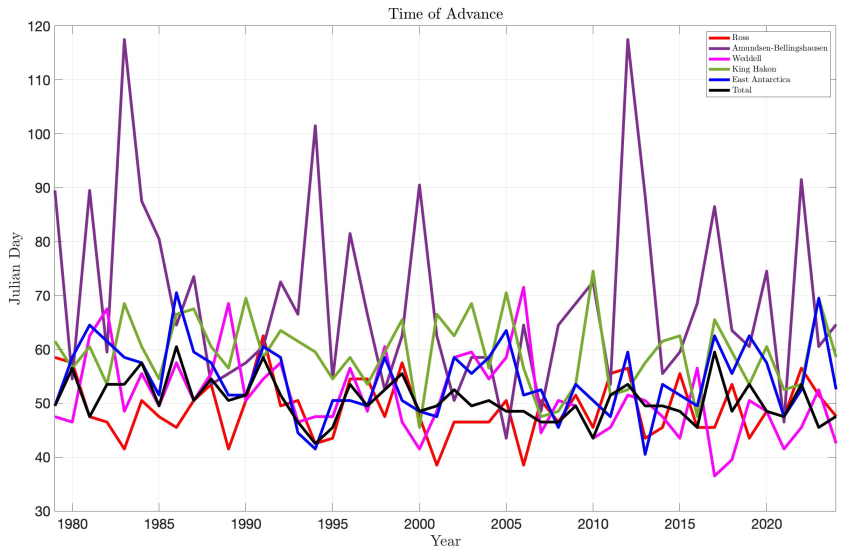

Fig. 7. Time of advance (decimal Julian days) of Antarctic sea ice extent for the five Antarctic sectors and the total continent, plotted together to showcase inter-regional variability.

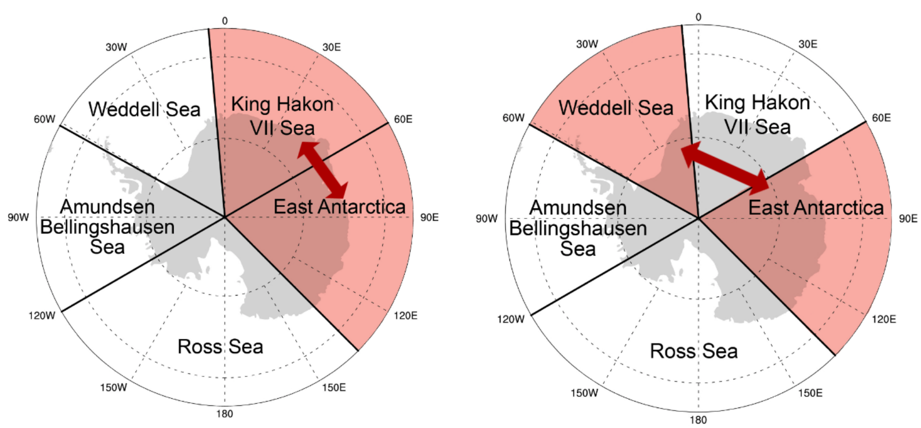

Fig. 8. The five Antarctic sectors, with red representing a positive correlation and blue representing a negative correlation in time of advance of sea ice extent between sectors. There is **[a]** a significant positive correlation in time of advance between the King Hakon Sea and East Antarctica sectors (r = 0.3436, p = 0.0194) and **[b]** a significant positive correlation in annual maximum between the Weddell Sea and East Antarctica sectors (r = 0.3138, p = 0.0337).

Data Availability: The data that support the findings of this study are available on Github.

Sector	p-value	R^2	m [days/year]
Ross	0.6693	0.0042	−0.0260 (±0.1220)
Amundsen-Bellingshausen	0.3441	0.0204	−0.1833 (±0.3863)
Weddell	0.0064	0.1570	−0.2229 (±0.1569)
King Hakon	0.2949	0.0249	−0.0790 (±0.1501)
East Antarctica	0.4441	0.0134	−0.0571 (±0.1490)
Total	0.0391	0.0932	−0.0916 (±0.0868)

Table 3. P-values (**p**), R-squared values ($\mathbf{R^2}$), and slopes (**m**) of linear regressions for time of advance of sea ice extent. Values in parentheses indicate uncertainty of the slope based on 95% confidence intervals.

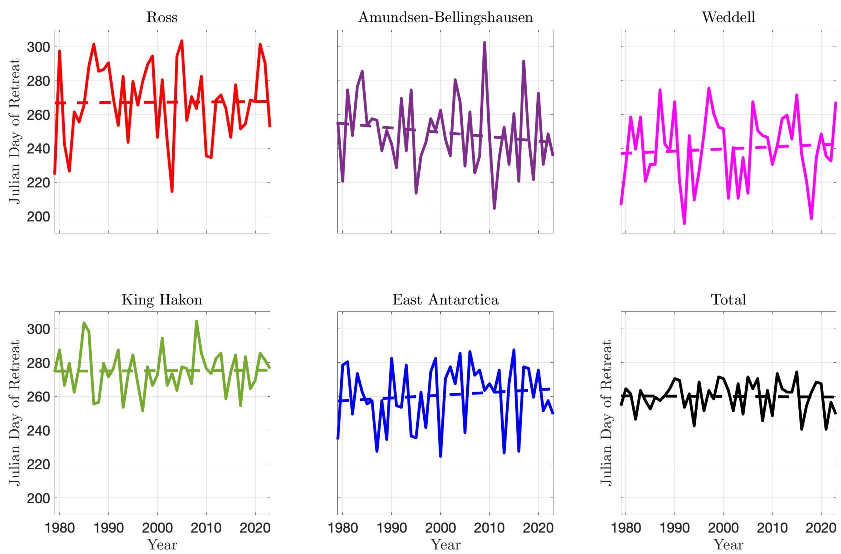

Fig. 9. Time of retreat (decimal Julian days) of Antarctic sea ice extent for **[a]** the Ross Sea, **[b]** the Amundsen-Bellingshausen Seas, **[c]** the Weddell Sea, **[d]** the King Hakon Sea, **[e]** East Antarctica, and **[f]** the total continent from 1979-2023. Dashed lines show linear regressions.

another, we expect this positive correlation to be driven by a local-scale atmospheric and/or oceanic mechanism. Since the Weddell Sea and East Antarctica sectors are not geographically adjacent to one another, we expect a large-scale atmospheric and/or oceanic mechanism to be driving this positive correlation. Since the linear trend of time of advance in the Weddell Sea sector is significant and negative, while the linear trend of time of advance in the East Antarctica sector is not significant, we could also expect to find some asymmetry regarding how this atmospheric and/or oceanic mechanism affects these two sectors.

3.4. Time of Retreat

Time of retreat of sea ice extent shows no significant linear trends for any of the Antarctic sectors (Figure 9; Table 4). Although there is variability in time of retreat from 1979-2023, this variability does not significantly trend in one direction or the other.

There is one negative correlation in time of retreat between the Weddell Sea and King Hakon Sea sectors (Figure 11). As time of retreat occurs later (earlier) in the year in the Weddell Sea

Data Availability: The data that support the findings of this study are available on Github.

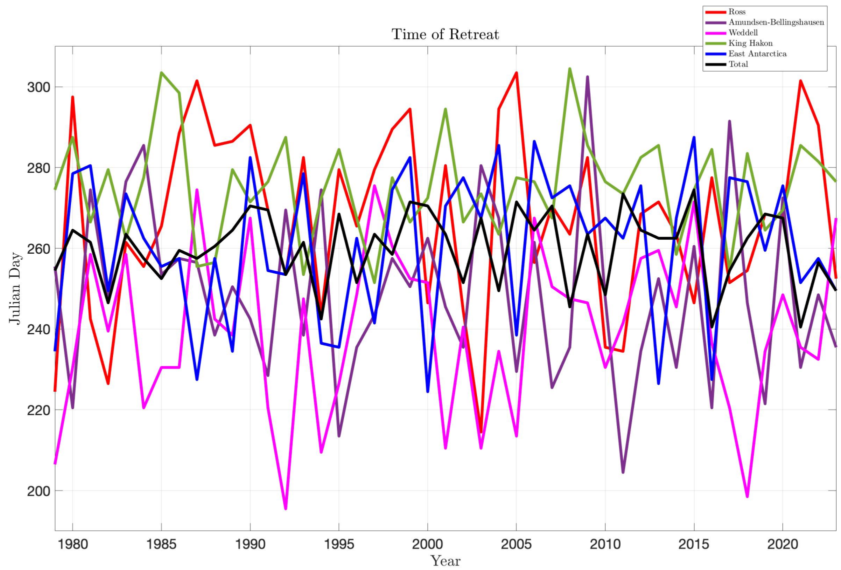

Fig. 10. Time of retreat (decimal Julian days) of Antarctic sea ice extent for the five Antarctic sectors and the total continent, plotted together to showcase inter-regional variability.

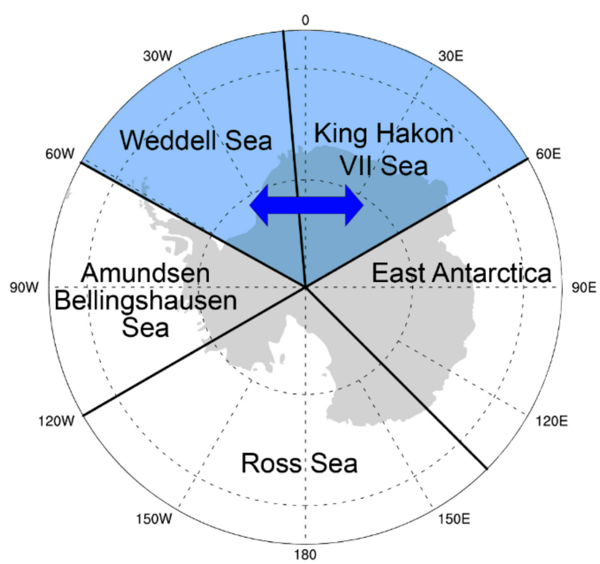

Fig. 11. The five Antarctic sectors, with red representing a positive correlation and blue representing a negative correlation in time of retreat of sea ice extent between sectors. There is a significant negative correlation in time of retreat between the Weddell Sea and King Hakon Sea sectors ($r = -0.3332$, $p = 0.0253$).

Data Availability: The data that support the findings of this study are available on Github.

Sector	p-value	R^2	**m** [days/year]
Ross	0.9404	1.3166e-04	0.0195 (±0.5226)
Amundsen-Bellingshausen	0.2972	0.0252	−0.2581 (±0.4932)
Weddell	0.5949	0.0066	0.1264 (±0.4756)
King Hakon	0.9275	1.9496e-04	0.0133 (±0.2931)
East Antarctica	0.4469	0.0135	0.1625 (±0.4268)
Total	0.8854	4.8824e-04	−0.0153 (±0.2127)

Table 4. P-values (**p**), R-squared values ($\mathbf{R^2}$), and slopes (**m**) of linear regressions for time of retreat of sea ice extent. Values in parentheses indicate uncertainty of the slope based on 95% confidence intervals.

sector, time of retreat occurs earlier (later) in the year in the King Hakon Sea sector.

Considering how this negative correlation occurs between two sectors that are geographically adjacent to one another, we can expect to find a local atmospheric and/or oceanic mechanism behind this relationship. While this atmospheric and/or oceanic mechanism does not drive any significant trend in time of retreat, it does drive an inverse relationship in time of retreat between the Weddell Sea and the King Hakon Sea sectors.

3.5. Advance Amplitude

Advance amplitude of sea ice extent shows significant trends in three Antarctic sectors: the Ross Sea, the Amundsen-Bellingshausen Seas, and the Weddell Sea sectors (Figure 12; Table 5). Advance amplitude shows a positive linear trend in the Ross Sea and the Amundsen-Bellingshausen Seas sectors, suggesting that the difference between annual maximum and minimum of sea ice extent is growing larger in these two sectors. Advance amplitude shows a negative trend in the Weddell Sea sector, suggesting that the difference between annual maximum and minimum of sea ice extent is growing smaller. Thus, intra-annual variability is increasing in the Ross Sea and the Amundsen-Bellingshausen Seas sectors, while intra-annual variability is decreasing in the Weddell Sea sector.

Sector	p-value	R^2	**m** [10^6 km^2/year]
Ross	4.2767e-04	0.2531	0.0158 (±0.0084)
Amundsen-Bellingshausen	0.0102	0.1438	0.0067 (±0.0050)
Weddell	0.0053	0.1674	−0.0119 (±0.0082)
King Hakon	0.9824	1.1480e-05	$-8.8677e-05$ (±0.0080)
East Antarctica	0.1630	0.0448	−0.0038 (±0.0053)
Total	0.2693	0.0283	0.0066 (±0.0120)

Table 5. P-values (**p**), R-squared values ($\mathbf{R^2}$), and slopes (**m**) of linear regressions for advance amplitude of sea ice extent. Values in parentheses indicate uncertainty of the slope based on 95% confidence intervals.

All significant correlations in advance amplitude of sea ice extent occur between the Amundsen-Bellingshausen Seas and other sectors. There are two negative correlations in advance amplitude of sea ice extent: between [1] the Amundsen-Bellingshausen Seas and East Antarctica sectors and [2] the Amundsen-Bellinshausen Seas and Weddell Sea sectors (Figure 13). As the advance amplitude grows larger (smaller) in the Amundsen-Bellingshausen Seas sector, the advance amplitude grows smaller (larger) in the East Antarctica and Weddell Sea sectors.

The inverse relationship in advance amplitude between the Amundsen-Bellingshausen Seas and Weddell Sea sectors is reflected in the slopes of the linear trends (Table 6). The advance amplitude of the Amundsen-Bellingshausen Seas sector is predicted to grow $0.0078(\pm 0.0050) \times 10^6$ km^2/year, while the advance amplitude of the Weddell Sea sector is predicted to decrease

Data Availability: The data that support the findings of this study are available on Github.

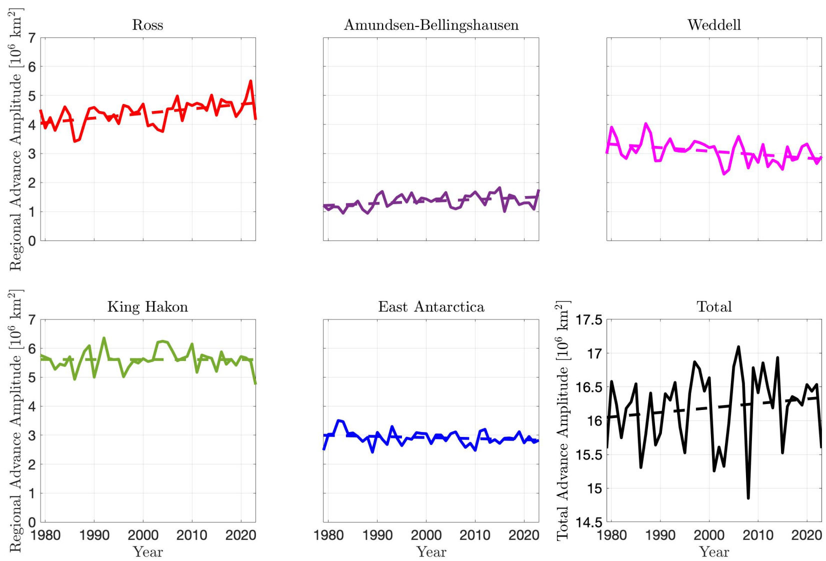

Fig. 12. Advance amplitude of Antarctic sea ice extent for **[a]** the Ross Sea, **[b]** the Amundsen-Bellingshausen Seas, **[c]** the Weddell Sea, **[d]** the King Hakon Sea, **[e]** East Antarctica, and **[f]** the total continent from 1979-2023. Dashed lines show linear regressions.

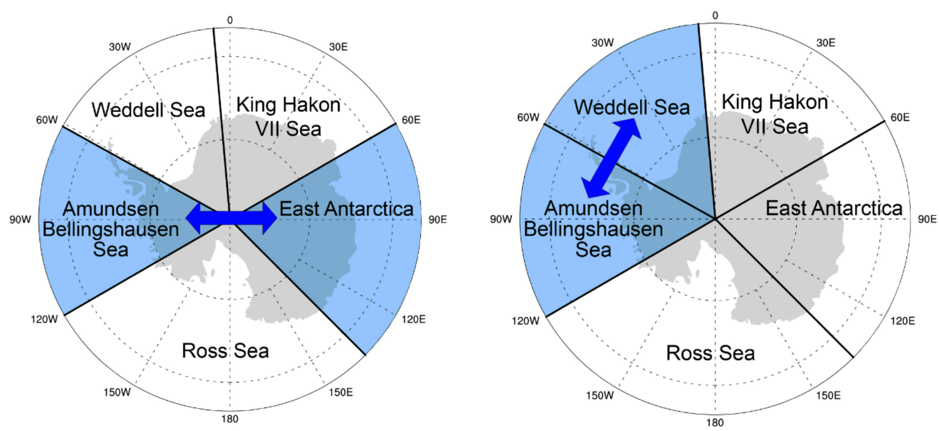

Fig. 13. The five Antarctic sectors, with red representing a positive correlation and blue representing a negative correlation in advance amplitude of sea ice extent between sectors. There is **[a]** a significant negative correlation in advance amplitude between the Amundsen-Bellingshausen Seas and East Antarctica sectors (r = −0.3295, p = 0.0271) and **[b]** a significant negative correlation in advance amplitude between the Amundsen-Bellingshausen Seas and Weddell Sea sectors (r = −0.4879, p = 0.0007).

Data Availability: The data that support the findings of this study are available on Github.

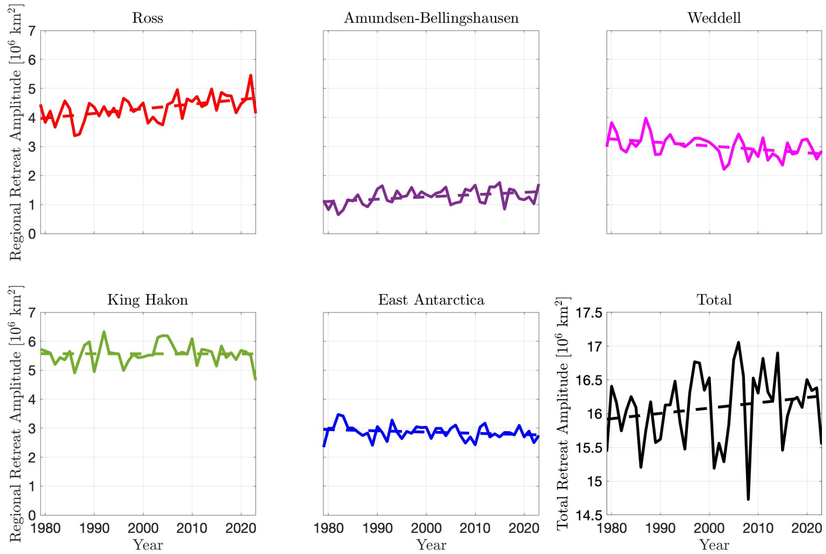

Fig. 14. Retreat amplitude of Antarctic sea ice extent for **[a]** the Ross Sea, **[b]** the Amundsen-Bellingshausen Seas, **[c]** the Weddell Sea, **[d]** the King Hakon Sea, **[e]** East Antarctica, and **[f]** the total continent from 1979-2023. Dashed lines show linear regressions.

$0.01190(\pm 0.0082) \times 10^6$ km^2/year. Considering how this negative correlation occurs between sectors that are geographically adjacent, we can infer that a local-scale mechanism is driving the significant trends and correlations in advance amplitude.

Although advance amplitude in the Amundsen-Bellingshausen Seas and East Antarctica sectors is negatively correlated, advance amplitude in the East Antarctica sector does not have a significant linear trend like in the Amundsen-Bellingshausen Seas sector. Considering how this negative correlation occurs between sectors that are not geographically adjacent, we can conclude that some large-scale atmospheric and/or effect is driving this correlation. We can also expect there to be asymmetry concerning how this atmospheric and/or oceanic mechanism affects the Amundsen-Bellingshausen Seas and East Antarctica sectors, since only the Amundsen-Bellingshausen Seas sector is showcasing increasing intra-annual variability.

3.6. Retreat Amplitude

Retreat amplitude of sea ice extent shows significant trends in three Antarctic sectors: the Ross Sea, the Amundsen-Bellingshausen Seas, and the Weddell Sea sectors (Figure 14; Table 6). Retreat amplitude shows a positive linear trend in the Ross Sea and Amundsen-Bellingshausen Seas sectors, meaning that the difference between annual maximum of sea ice extent of one specified year (e.g. 2023) and annual minimum of sea ice extent of the proceeding year (e.g. 2024) is growing larger in these two sectors. Retreat amplitude shows a negative trend in the Weddell Sea sector, meaning that the difference between annual maximum of sea ice extent of one specified year (e.g. 2023) and annual minimum of sea ice extent of the proceeding year (e.g. 2024) is growing smaller within this sector. While advance amplitude is a measure of intra-annual variability, retreat amplitude is a measure on inter-annual variability. Thus, inter-annual variability is increasing in the Ross Sea and Amundsen-Bellingshausen Seas sectors, while inter-annual variability is decreasing in the Weddell Sea sector.

Data Availability: The data that support the findings of this study are available on Github.

Sector	p-value	R^2	**m** [10^6 km^2/year]
Ross	3.8192e-04	0.2568	0.0160 (±0.0084)
Amundsen-Bellingshausen	0.0100	0.1446	0.0078 (±0.0059)
Weddell	0.0034	0.1833	−0.0119 (±0.0077)
King Hakon	0.9663	4.1933e-05	-1.6946e-04 (±0.0080)
East Antarctica	0.1331	0.0517	−0.0043 (±0.0056)
Total	0.1890	0.0398	0.0078 (±0.0118)

Table 6. P-values (**p**), R-squared values (**R^2**), and slopes (**m**) of linear regressions for retreat amplitude of sea ice extent. Values in parentheses indicate uncertainty of the slope based on 95% confidence intervals.

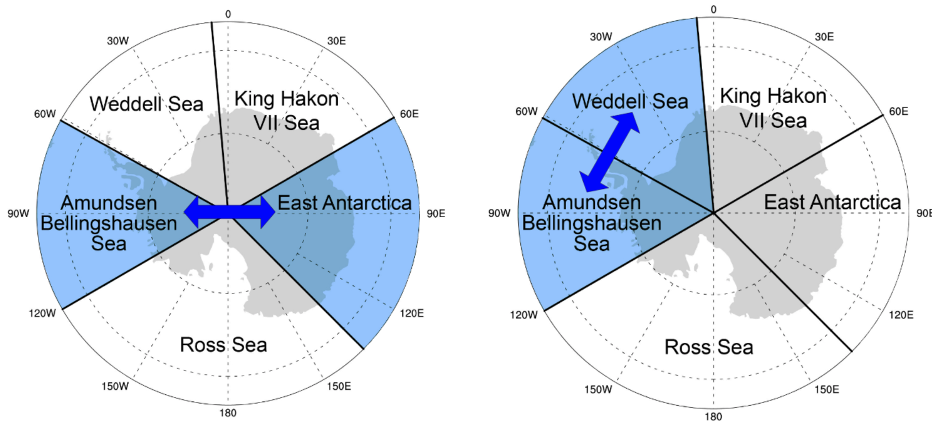

Fig. 15. The five Antarctic sectors, with red representing a positive correlation and blue representing a negative correlation in retreat amplitude of sea ice extent between sectors. There is **[a]** a significant negative correlation in retreat amplitude between the Amundsen-Bellingshausen Seas and East Antarctica sectors ($r = -0.4003$, $p = 0.0064$) and **[b]** a significant retreat correlation in advance amplitude between the Amundsen-Bellingshausen Seas and Weddell Sea sectors ($r = -0.4640$, $p = 0.0013$).

The Amundsen-Bellingshausen Seas sector is involved in all significant correlations that occur in retreat amplitude of sea ice extent between sectors. There are two negative correlations in retreat amplitude of sea ice extent: between [1] the Amundsen-Bellingshausen Seas and East Antarctica sectors and [2] the Amundsen-Bellinshausen Seas and Weddell Sea sectors. As the retreat amplitude grows larger (smaller) in the Amundsen-Bellingshausen Seas sector, the retreat amplitude grows smaller (larger) in the East Antarctica sector and Weddell Sea sector.

The inverse relationship in retreat amplitude between the Amundsen-Bellingshausen Seas and Weddell Sea sectors is reflected in the slopes of the linear trends (Table 6). The retreat amplitude of the Amundsen-Bellingshausen Seas sector is predicted to grow $0.0078(\pm0.0059) \times 10^6$ km^2/year, while the retreat amplitude of the Weddell Sea sector is predicted to decrease $0.01190(\pm0.0077) \times 10^6$ km^2/year. Considering how this negative correlation occurs between sectors that are geographically adjacent, we can infer that a local-scale atmospheric and/or oceanic mechanism is driving the significant trends and correlations in retreat amplitude.

Although retreat amplitude in the Amundsen-Bellingshausen Seas and East Antarctica sectors

Data Availability: The data that support the findings of this study are available on Github.

is negatively correlated, retreat amplitude in the East Antarctica sector does not have a significant linear trend like in the Amundsen-Bellingshausen Seas sector. Considering how this negative correlation occurs between sectors that are not geographically adjacent, we can conclude that some large-scale atmospheric and/or oceanic effect is driving this correlation. We can also expect there to be asymmetry concerning how this atmospheric and/or oceanic mechanism affects the Amundsen-Bellingshausen Seas and East Antarctica sectors, since only the Amundsen-Bellingshausen Seas sector is showcasing increasing inter-annual variability.

4. Discussion

4.1. *Explaining the behavior of annual minimum sea ice extent*

Sea ice extent can reach a record minimum in multiple ways: [1] time of advance occurs later in the year, so sea ice extent is retreating over more days while maintaining a daily rate of change within average range, [2] time of retreat occurs earlier in the year, so sea ice extent is retreating over more days while maintaining a daily rate of change within average range, [3] time of advance and retreat remain relatively constant throughout the years, but sea ice extent has an increasingly negative daily rate of change, or [4] time of advance occurs later in the year and/or time of retreat occurs earlier in the year AND sea ice extent has an increasingly negative daily rate of change. In the first part of this section, annual minimum, time of advance, and time of retreat of sea ice extent are analyzed together to explain the behavior of annual minimum sea ice extent across Antarctic sectors.

4.1.1. Ross Sea and Amundsen-Bellingshausen Seas Sectors

Annual minimum sea ice extent in the Ross Sea and Amundsen-Bellingshausen Seas sectors have a negative trend (Figure 2; Table 1), yet no significant linear trend in time of advance or time of retreat (Figure 6; Table 3; Figure 7; Table 4). Annual minimum sea ice extent is growing lower in the Ross Sea and Amundsen-Bellingshausen Seas sectors, but the Julian day of the year at which the sea ice extent reaches this minimum is relatively not changing. Therefore, we should expect to find that daily rate of change of sea ice extent should be increasingly negative during the retreat period of sea ice extent in these two sectors.

4.1.2. Weddell Sea Sector

Annual minimum sea ice extent in the Weddell Sea sector has a positive trend, while time of advance of sea ice extent in the Weddell Sea sector has a negative trend (Figure 2; Table 1; Figure 6; Table 3). This suggests that the higher annual minimums of sea ice extent we see in the Weddell Sea sector are due to sea ice extent beginning to advance earlier in the year. In other words, sea ice extent is reaching a higher annual minimum because it is retreating over fewer days. Despite sea ice extent in the Weddell Sea sector advancing earlier in the year, annual maximum and time of retreat remain relatively constant.

4.2. *Explaining the behavior of advance amplitude*

Advance amplitude measures intra-annual variability in the magnitude of sea ice extent.

4.2.1. Ross and Amundsen-Bellingshausen Seas Sectors

An increasing trend in advance amplitude over a designated time frame suggests that the annual minimum and maximum of sea ice extent are behaving in one of the following ways; [1] Annual maximum is staying relatively constant, while annual minimum is decreasing over the years. [2] Annual minimum is staying relatively constant, while annual maximum is increasing over the years. [3] Annual maximum is increasing, and annual minimum is decreasing over the years.

Data Availability: The data that support the findings of this study are available on Github.

Recall that the Ross Sea sector and Amundsen-Bellingshausen Seas sectors show significant negative trends in annual minimum sea ice extent, but no significant linear trends in annual maximum sea ice extent (Figure 2; Table 1; Figure 4; Table 2). Thus, the significant positive trends in advance amplitude that we see in these two sectors, signifying increasing intra-annual variability in the magnitude of sea ice extent, can be accredited to the decrease of the annual minimum of sea ice extent over the years (Figure 12; Table 5).

4.2.2. Weddell Sea Sector

A decreasing trend in advance amplitude over a designated time frame suggests that the annual minimum and maximum of sea ice extent are behaving in one of the following ways: [1] Annual maximum is staying relatively constant, while annual minimum is increasing over the years. [2] Annual minimum is staying relatively constant, while annual maximum is decreasing over the years. [3] Annual maximum is decreasing, and annual minimum is increasing over the years.

The Weddell Sea sector shows significant positive trend in annual minimum sea ice extent, but no significant linear trends in maximum sea ice extent (Figure 2; Table 1; Figure 4; Table 2). Thus, the significant negative trend in advance amplitude that we see in the Weddell Sea sector, signifying decreasing intra-annual variability in the magnitude of sea ice extent, can be accredited to the increasing of the annual minimum of sea ice extent over the years (Figure 12; Table 5).

4.3. Explaining the behavior of retreat amplitudes

Retreat amplitude measures inter-annual variability in the magnitude of sea ice extent.

4.3.1. Ross and Amundsen-Bellingshausen Seas Sectors

An increasing trend in retreat amplitude over a designated time frame suggests that the annual minimum and maximum of sea ice extent are behaving in one of the following ways: [1] Annual maximum is staying relatively constant, while annual minimum of the proceeding year is decreasing. [2] Annual maximum is increasing over the years, while annual minimum of the proceeding year is staying relatively constant. [3] Annual maximum is increasing, and annual minimum of the proceeding year is decreasing.

Recall that the Ross Sea sector and Amundsen-Bellingshausen Seas sectors show significant negative trends in annual minimum sea ice extent, but no significant linear trends in annual maximum sea ice extent (Figure 2; Table 1; Figure 4; Table 2). Thus, the significant positive trends in retreat amplitude that we see in these two sectors, signifying increasing inter-annual variability in the magnitude of sea ice extent, can be accredited to the decrease of the annual minimum of sea ice extent over the years (Figure 14; Table 6).

4.3.2. Weddell Sea Sector

A decreasing trend in retreat amplitude over a designated time frame suggests that the annual minimum and maximum of sea ice extent are behaving in one of the following ways: [1] Annual maximum is staying relatively constant, while annual minimum of the proceeding year is increasing. [2] Annual maximum is decreasing over the years, while annual minimum of the proceeding year is staying relatively constant. [3] Annual maximum is decreasing, and annual minimum of the proceeding year is increasing.

The Weddell Sea sector shows significant positive trend in annual minimum sea ice extent, but not significant linear trends in maximum sea ice extent (Figure 2; Table 1; Figure 4; Table 2). Thus, the significant negative trend in advance amplitude that we see in these Weddell Sea sector, signifying decreasing inter-annual variability in the magnitude of sea ice extent, can be accredited to the increasing of the annual minimum of sea ice extent over the years (Figure 14; Table 6). .

Data Availability: The data that support the findings of this study are available on Github.

4.4. Honing in on atmospheric drivers

The intra- and inter-annual variability we see in sea ice extent in the Ross Sea, Amundsen-Bellingshausen Seas, and Weddell Sea sectors is dominated by change in minimum. Thus, in order to hone in on major driver(s) of both intra- and inter-annual sea ice extent variability, we focus on atmospheric mechanisms that occur during Austral spring/summer, since sea ice extent reaches its annual minimum around February/March.

4.4.1. Why does the Weddell Sea sector display opposite trends in annual minimum, advance amplitude, and retreat amplitude of sea ice extent to the Ross Sea and Amundsen-Bellingshausen Seas sectors, despite geographic proximity?

The Amundsen Sea Low (ASL) is a climatological low pressure center located between the Antarctic peninsula and the Ross Sea (Bertler et al. 2004). Most studies on the impact of the ASL on sea ice variability focus on the annual and/or monthly mean magnitude of sea ice extent. Wang et al. (2023) find that correlations between September-October-November (SON) ASL and regional sea ice extent are largest in February and only statistically significant in February and March, which is when sea ice extent reaches its annual minimum and when sea ice variability in the Ross-Amundsen-Weddell Seas dominate the overall Antarctic sea ice extent change. Wang et al. (2023) find that increased depth of the ASL is correlated with decrease in February sea ice extent in the northern Weddell and eastern Ross Seas and increase in February sea ice extent in the interior of the Bellingshausen and Weddell Seas.

It is key to note that a decreasing trend in annual minimum sea ice extent in the Ross Sea and Amundsen-Bellingshausen Seas sectors does not necessarily guarantee that mean annual sea ice extent and mean monthly sea ice extent in February/March are also decreasing in these sectors. In the same manner, an increasing trend in annual minimum sea ice extent in the Weddell Sea sector does not necessarily guarantee that mean annual sea ice extent and mean monthly sea ice extent in February/March is also increasing in this sector. Thus, we should not expect identical correlatations between ASL strength and annual minimum sea ice extent that the Wang et al. (2023) study found between ASL strength and mean monthly Antarctic sea ice extent values. Wang et al. (2023) also divided Antarctic sectors up on smaller scales (e.g. northern Weddell, eastern Ross, etc.), so direct comparison is not possible.

However, correlating Actual Central Pressure (ACP) of the ASL in September-October-November (SON) and annual minimum sea ice extent across the Antarctic sectors is a necessary future step of this study in order to determine if the ASL is influencing the negative correlation in annual minimum we see between the Amundsen-Bellingshausen Seas and Weddell Sea sectors. Multiple studies find that the depth of the ASL during the advance period of sea ice is significantly correlated with meridional and zonal winds during the retreat period of sea ice extent. There is an increase in southerly winds over the Ross Sea during a strong (deep) ASL, which is associated with increased meridional transport of sea ice, increased absorption of solar radiation by exposed waters, and increased sea ice melting. Meanwhile, ice-ocean albedo feedback in the Weddell Sea is driven by northerly winds and is associated with sea ice decrease at the edge during spring and summer and a slight increase in the interior Weddell during December-January-February (Raphael et al. 2018; Wang et al. 2023). Perhaps the ice-ocean albedo feedback resulting from the ASL leads to an increasingly negative daily rate of change of sea ice extent during retreat period in the Ross Sea and Amundsen-Bellingshausen Seas sectors, causing the decreasing trend in annual minimum. It is also possible that the slight increase in the interior Weddell during December-January-February is why we see time of advance occurring earlier and annual minimum sea ice extent increasing in the Weddell Sea sector.

Data Availability: The data that support the findings of this study are available on Github.

4.4.2. Other atmospheric mechanisms influencing annual minimum sea ice extent?

Various atmospheric and oceanic drivers can simultaneously influence sea ice advance and retreat, not just the ASL. If two sectors behave in similar (or opposing) ways, this can indicate a local-scale or large-scale mechanism is driving this behavior. Annual minimum of sea ice extent is positively correlated between the Weddell Sea and King Hakon Sea sectors, and the Weddell Sea and East Antarctica sectors. The positive correlation between the Weddell Sea and King Hakon Sea sectors could be due to Zonal Wave Three, the asymmetric component of atmospheric circulation over the Antarctic continent (Raphael 2007).

5. Conclusion

5.1. Summary

In this study, using data spanning 1978-2023 we decompose the annual cycle of sea ice extent of the five Antarctic sectors (the Ross Sea, Amundsen-Bellingshausen Seas, Weddell Sea, King Hakon Sea, and East Antarctica sectors) and of the total Antarctic continent into six key components: annual minimum, annual maximum, time of advance, time of retreat, advance amplitude, and retreat amplitude. According to a linear regression model, there is about a $0.0107(\pm 0.0060) \times 10^6\,\mathrm{km}^2/\mathrm{year}$ decrease in annual minimum in the Ross Sea sector, $0.0056(\pm 0.0025) \times 10^6\,\mathrm{km}^2/\mathrm{year}$ decrease in annual minimum in the Amundsen-Bellingshausen Seas sector, and a $0.0068(\pm 0.0057) \times 10^6\,\mathrm{km}^2/\mathrm{year}$ increase in annual minimum in the Weddell Sea sector. Time of advance is occurring about $0.2229(\pm 0.1569)$ decimal Julian days earlier each year in the Weddell Sea sector, and $0.0916(\pm 0.0868)$ decimal Julian days earlier each year for the total Antarctic continent. There is about a $0.0158(\pm 0.0084) \times 10^6\,\mathrm{km}^2/\mathrm{year}$ increase in advance amplitude in the Ross Sea sector, $0.0067(\pm 0.0050) \times 10^6\,\mathrm{km}^2/\mathrm{year}$ increase in advance amplitude in the Amundsen-Bellingshausen Seas sector, and a $0.0119(\pm 0.0082) \times 10^6\,\mathrm{km}^2/\mathrm{year}$ decrease in advance amplitude in the Weddell Sea sector. Similarly, there is about a $0.0160(\pm 0.0084) \times 10^6\,\mathrm{km}^2/\mathrm{year}$ increase in retreat amplitude in the Ross Sea sector, $0.0078(\pm 0.0059) \times 10^6\,\mathrm{km}^2/\mathrm{year}$ increase in retreat amplitude in the Amundsen-Bellingshausen Seas sector, and a $0.0119(\pm 0.0077) \times 10^6\,\mathrm{km}^2/\mathrm{year}$ decrease in retreat amplitude in the Weddell Sea sector.

Within individual Antarctic sectors, intra- and inter-annual variability do not substantially vary from one another; the magnitude of variability in sea ice extent we see within one designated year (e.g. 2023), is similar to the magnitude of variability in sea ice extent we see between one designated year and the proceeding year (e.g. 2023 and 2024). However, these significant linear trends in advance and retreat amplitude suggest that intra- and inter-annual variability is increasing in the Ross Sea and Amundsen-Bellingshausen Seas sectors and decreasing in the Weddell Sea sector. Furthermore, we find that intra- and inter-annual variability in sea ice extent are both dominated by change in annual minimum. Since annual minimum is significantly and negatively correlated between the Weddell Sea and the Amundsen-Bellingshausen Seas sectors, we propose that the Amundsen Sea Low (ASL) is a primary atmospheric mechanism driving the increasing intra- and inter-annual variability we see across the Ross Sea and Amundsen-Bellingshausen Sea sectors, and the decreasing intra- and inter-annual variability we see in the Weddell Sea sector.

We cannot draw any conclusions concerning the behavior of annual minimum sea ice extent, advance amplitude, and retreat amplitude in the King Hakon Sea and East Antarctica sectors, along for the total Antarctic continent, considering how there are no significant linear trends for any of these sectors. We cannot draw any conclusions concerning the behavior of time of retreat for the Ross Sea, Amundsen-Bellingshausen Seas, King Hakon Sea, and East Antarctica sectors, along for the total Antarctic continent, considering how there are no significant linear trends for any of these sectors. We cannot draw any conclusions concerning the behavior of annual maximum sea ice extent and time of retreat for any of the Antarctic sectors and for the

Data Availability: The data that support the findings of this study are available on Github.

total Antarctic continent, considering how there are no significant linear trends.

5.2. Future Work

Daily rate of change of sea ice extent needs to be calculated for the five Antarctic sectors and total Antarctic continent, in order to further investigate why we see a negative trend in annual minimum in the Ross Sea and Amundsen-Bellingshausen Seas sectors and a positive trend in the Weddell Sea sector (Refer to section 4.1.1).

It is necessary to perform correlations between ASL Actual Central Pressure (ACP), annual minimum, and time of advance of sea ice extent across the Antarctic sectors in order to determine if the ASL truly is influencing the increasing intra- and inter-annual variability in the Ross Sea and Amundsen-Bellingshausen Seas sectors and the decreasing intra- and inter-annual variability in the Weddell Sea sector (Refer to section 4.4.1).

[1–7]

References

1. N. Bertler, P. Barrett, P. Mayewski, *et al.*, "El nino suppresses antarctic warming," Geophys. Res. Lett. **31** (2004).
2. C. Eayrs, X. Li, M. N. Raphael, and D. M. Holland, "Rapid decline in antarctic sea ice in recent years hints at future change," Nat. Geosci. **14**, 460–464 (2021).
3. P. Gloersen, W. J. Campbell, D. J. Cavalieri, *et al.*, "Arctic and antarctic sea ice, 1978-1987: Satellite passive-microwave observations and analysis," (1992). National Aeronautics and Space Administration, Washington, DC.
4. M. S. Handcock and M. N. Raphael, "Modeling the annual cycle of daily antarctic sea ice extent," The Cryosphere **14**, 2159–2172 (2020).
5. M. N. Raphael, "The influence of atmospheric zonal wave three on antarctic sea ice variability," Clim. Dyn. **112** (2007).
6. M. Raphael, M. M. Holland, L. Landrum, and W. R. Hobbs, "Links between the amundsen sea low and sea ice in the ross sea: seasonal and interannual relationships," Clim. Dyn. **52** (2018).
7. National Snow and Ice Data Center, "SMMR/SSMI," (2024).

Data Availability: The data that support the findings of this study are available on Github.