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A 43-year record of Antarctic sea-ice variability and trends

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Abstract

Using a 43-year long record of satellite passive-microwave measurements during 1979-2021, sea ice extent analyses on monthly, seasonal, inter-annual and decadal timescales are carried out for the Southern Hemisphere (SH). We present monthly averaged sea ice extents, monthly deviations, yearly and seasonal averages, and their trends for the SH. It exhibits largest positive trend in autumn (9.6 ±7.5 10^3 km^2 yr^{-1}) and negative trend in spring (-1.7±7.3 10^3 km^2 yr^{-1}). Temperatures (sea surface and air) anomaly data suggest that the Antarctica region has experienced cooling trends in the last four decades, but drastic change occurred post-2016 resulting in melting of sea ice in few regions of Antarctica. The sea ice increase in the last decade (pre-2015) may be linked to the cooling processes supplemented by the cumulative effect of ocean currents, winds and other ocean-atmospheric parameters. On other hand decrease in sea ice post-2015 has been observed in some regional sectors of Antarctic.

Keywords: Sea ice extent, linear trends and correlations, climatological parameters, southern hemisphere

Introduction

Polar sea ice is an essential part of the Earth's climate system, as it modifies the heat, momentum, and moisture exchanges within the ocean-ice-atmosphere system. Furthermore, it provides early signals of climate change-related to variations in solar energy absorption (Comiso and Nishio, 2008; Convey *et al*., 2014) [6, 7] and affects regional and global climate variability via the ice-albedo feedback (Bintanja *et al*., 2013; Parkinson, 2004; Walsh, 1983) [1, 19, 34]. It's still unclear why Antarctic Sea ice is growing in a warming planet. According to some data and model findings, the Antarctic sea ice cover will shrink under a warmer climate, however more slowly than the Arctic sea ice is expected to (Bromwich *et al*., 2013; Gordon and O'Farrell, 1997; Siegert *et al*., 2019) [2, 10, 30]. However, a study using a coupled ice-ocean-atmosphere model shows that sea ice cover will grow with global warming (Bintanja *et al*., 2013; Zhang, 2007) [1] due to more precipitation in the form of snow on sea ice that will further reduce the salinity of the near-surface ocean layers, resulting in a more stable mixed layer and less heat flux to the surface, leading to increased sea ice. Several studies have used satellite remote sensing to examine interannual variations in the Antarctic sea ice cover and their climate implication (Cavalieri *et al*., 1997; Cavalieri and Parkinson, 2008; Parkinson, 2019, 2002; Parkinson and Cavalieri, 2012; Parkinson and DiGirolamo, 2021; Zwally, 2002) [3, 4, 17, 20, 23, 21, 24, 38].

Due to the continent's remoteness and adverse climate conditions obtaining reliable science-quality data was difficult resulting in incomplete sea ice record. Post 1970's the passive and active microwave observations from space have shown to be incredibly useful for measuring the distribution and Antarctic sea ice extent and its variations (S. E. Stammerjohn & Smith, 1997; Zwally, 2002; Zwally *et al*., 1983) [31, 38, 39]. Previous research concluded that the positive seasonal trend in Antarctic sea ice cover is driven by summer and autumn, with little change in the winter. On decadal and regional time scales, the annual growth and decline of Antarctic Sea ice is governed by very complex physical processes involving the ocean-atmosphere system (Zwally, 2002) [38].

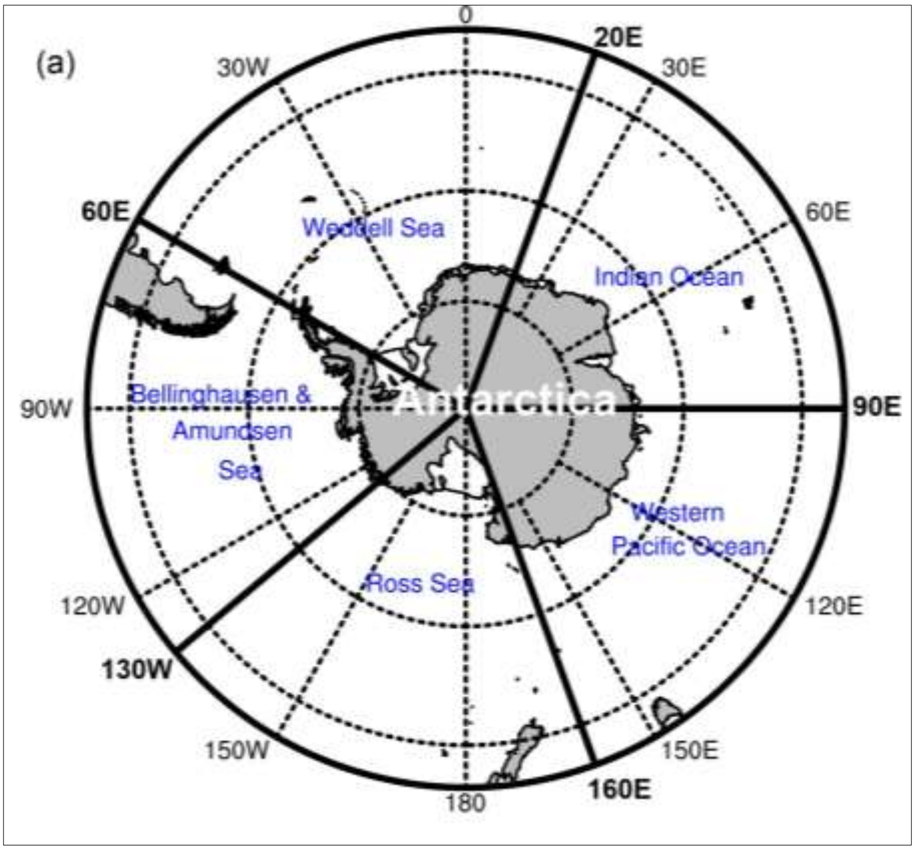


Fig 1: Five regional sectors of Southern Hemisphere

Recently, the sea ice extent has taken a dramatic turn from relatively gradual increases to rapid decreases (Parkinson, 2019) [17]. The peak sea ice extent since 1978, measured on an annual average, occurred in 2014. Since then, there have been such significant drops that the yearly averages for 2017 and 2018 are the lowest in the entire 1979–2018 record, thus cancelling out the 35 years of overall ice extent gains in just a few short years. This abrupt turnabout in the Antarctic sea ice's changes will offer important new data for testing past hypotheses about the long-term increases in Antarctic sea ice. We currently have a 43-year multichannel passive-microwave satellite record of the sea ice cover in Antarctica, which is entirely located in the Southern Ocean. The goal of the present study is to investigate sea ice variability of Southern Hemisphere (SH) as a whole and for the five longitudinal sectors identified in Figure 1.

Data and Methods

Sea ice Extent Analysis

The satellite passive-microwave measurements derived from the Scanning Multichannel Microwave Radiometer (SMMR) on board NASA's Nimbus 7, the Special Sensor Microwave Imager (SSM/I) and Special Sensor Microwave Imager/Sounder (SSMIS) aboard US Defense Meteorological Satellites Program (DMSP) satellites: F8, F11, F13, F17 and F18 for a 43-year record (1979–2021) has been used. The daily measurements of sea ice concentration (SIC) from SMMR (sensor frequencies: 6, 10, 18, 21, 37 GHz) spans October 1978 to August 1987, SSMI (sensor frequencies: 19, 22, 37, 85 GHz) spans September 1987 to December 2008, and SSMIS (sensor frequencies: 19, 22, 37, 91 GHz) spans January 2000 to December 2021. SICs derived from the NASA Team (Gloersen and Campbell, 1987; Parkinson and Cavalieri, 2002) are available from the National Snow and Ice Data Center (NSIDC), which provides daily data from 1979 to 2021. The area covered by ice represents the amount of ice present; it is calculated by multiplying the entire surface area of a pixel by the ice concentration in that pixel. Ice persistence is the percentage of months during which ice was present at a place during the data collection period. The ice extent determines whether or not ice is present in a pixel; in this case, ice is deemed to exist in a pixel if the sea ice concentration in that pixel is more than 15%. The ice extent is derived by summing areas of all grid cells (25×25 km grids with polar stereographic projection, NSIDC, 1992) in the region of interest having at least 15% sea ice concentration (Parkinson and Cavalieri, 2008; Zwally, 2002) [4, 38]. The monthly sea ice extent data for the Southern Ocean, available from the NSIDC at Boulder, Colorado, were used for sea ice trend analyses.

The 43 years long term linear trends were computed using the lines of least-squares fit to monthly, interannual and seasonal mean data, in accordance with the literature (Cavalieri *et al.*, 2003; Parkinson, 2014; Parkinson and Cavalieri, 2012) [5, 18, 21]. The seasonal cycle was eliminated, and the anomaly was calculated by subtracting the 30 years mean (1981-2010) from each individual monthly mean (Figures 2b). Over the 43 years, trends for monthly, seasonal and yearly averages were also computed (Figure 2c, 2d and Table 1). The seasonal cycle was removed in the yearly averages of the monthly mean, and seasonal values are calculated as average for four seasons, i.e., austral summer: January-March (JFM); austral autumn: April-June (AMJ); austral winter: July–September (JAS); and austral spring: October–December (OND) (Zwally, 2002) [38] The standard deviations/errors of the trend were calculated as described in Taylor (1997). The trends were tested for statistical significance using the Student's *t*-test with the null hypothesis of a zero trend and 41 degrees of freedom (43 minus 2 years). We establish a statistical metric. R denotes the relationship between the trend and its standard deviation (Santer *et al*., 2000) [27]. Trends are considered significant at the 95% and 99% confidence levels if R exceeds 2.02 and 2.70, respectively deviation (Santer *et al*., 2000) [27]. According to Parkinson and Cavalieri, 2008 [4], this statistical significance test is criticised for its use of the null hypothesis and the arbitrary levels of significance and issues related to the autocorrelation of the data deviation (Santer *et al*., 2000) [27]. These arbitrary levels of statistical significance were utilised in this study to provide only a relative measure of the robustness of the trend to those trends with lower values of R.

Analysis of Physical Parameters during spring and summer

To understand the sea ice dynamics in the Southern Ocean, we analysed the relation between sea ice and ocean-atmospheric temperatures (SST and T2m) from ERA-5 monthly means provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) (http://data-portal.ecmwf.int/data/d/interim_mnth/). ERA5 model reanalysis data on a single level with a spatial resolution of 0.25°×0.25°. The ERA5 is the fifth generation ECMWF reanalysis (https://cds.climate.copernicus.eu/cdsapp#!/home) for the global climate and weather for the past 4 to 7 decades. SST and T2m data were analysed in this study over the poleward domain of 55°S to 85°S latitude (with the land areas masked).

Results and Discussion

Spatiotemporal changes in sea ice variabilities and trend

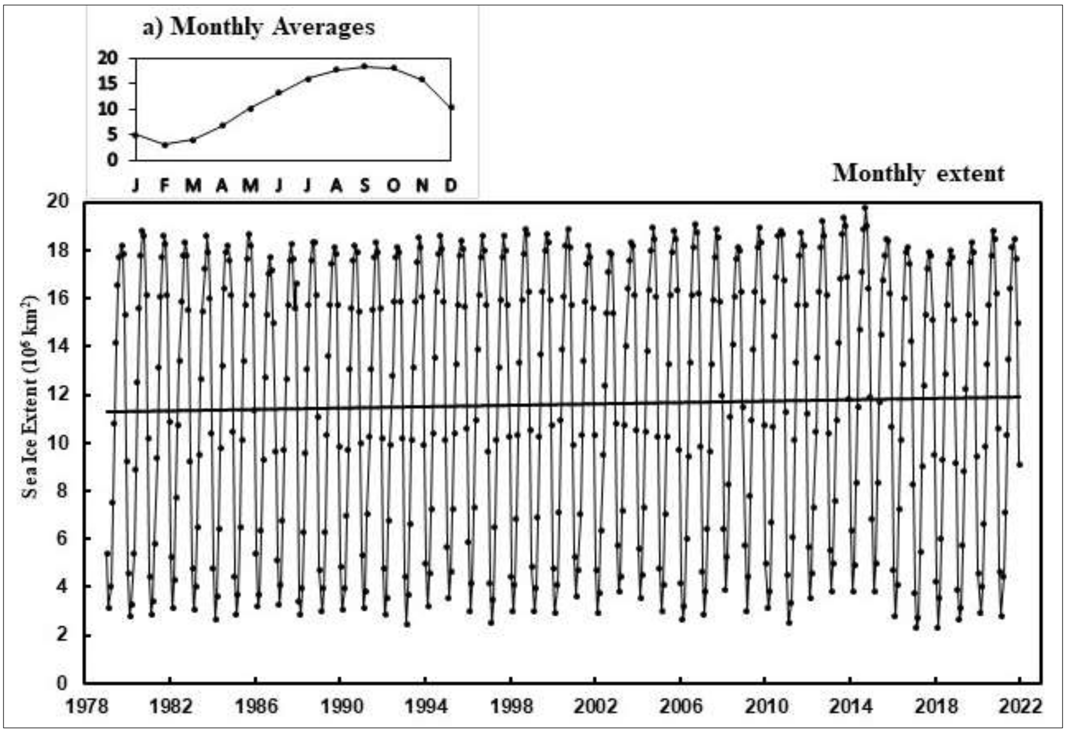
On average, over a 43-year record, maximum sea ice extent occurs in September and minimum in February. The Southern Hemisphere (Antarctic) SIE anomaly and trend vary substantially during monthly, yearly and seasonal scales from January 1979 to December 2021 (Figure 2). Over the 43years, minimum and maximum ice extent occurred in February (3.1×10^6 km^2) and September (18.5×10^6 km^2), respectively (outset in Figure 2a).

Table 1: For the Southern Ocean, yearly and seasonal SIE trends and standard deviations were computed from 1979 to 2021

Year/Season	Slope, 10^3 km^2 yr^{-1}	Slope % decade^{-1}	*R*
Yearly (1979-2021)	4.9±5.1	0.4±0.4	0.9
Summer (JFM)	4.7±6.5	1.2±1.6	0.7
Autumn (AMJ)	9.6±7.5	1.0±0.7	1.2
Winter (JAS)	9.0±4.4	0.5±0.3	**2.0**
Spring (OND)	-1.7±7.3	-0.1±0.5	-0.2

Table 1 For the Southern Ocean, yearly and seasonal SIE trends and standard deviations were computed from 1979 to 2021. R denotes the ratio of the trend's magnitude to its standard deviation. For example, assuming a null hypothesis of zero trend and degrees of freedom is 41, R values in bold are significant at 95% and higher, while those in bold and italics are significant at 99% and above

The SIE in February ranges from a minimum of 2.2×10^6 km^2 in 2017 to a maximum of 4×10^6 km^2 in 2008, whereas in September ice extent varies from a minimum of 18×10^6 km^2 in 1986 to a maximum of 20×10^6 km^2 in 2014 (Figure 2a). The Antarctic SIE trends vary substantially over the seasonal and interannual cycles. The lines of least-square fit exhibit positive trends in the yearly and seasonal ice extent (Figure 2c, Table 1). The yearly SIE trend is almost similar to the monthly deviations.



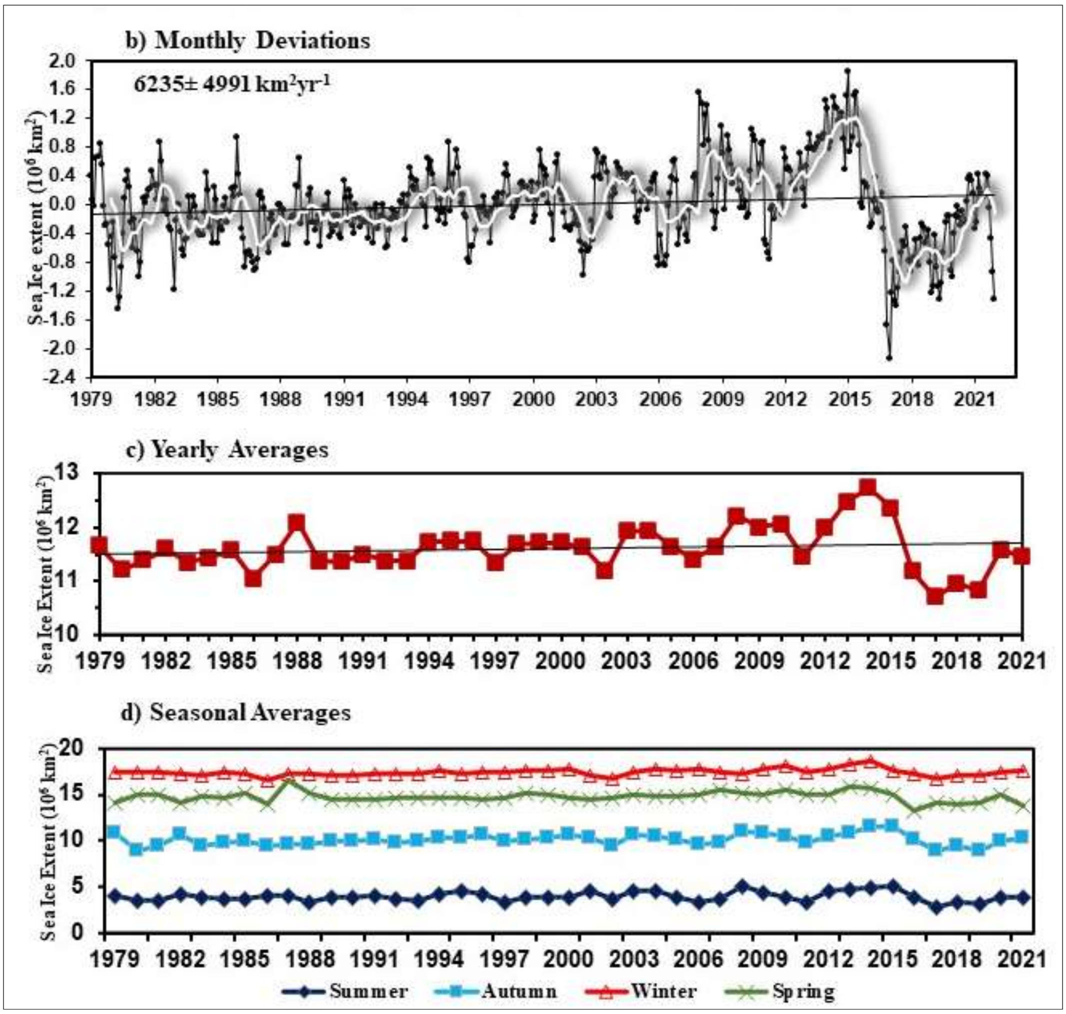


Fig 2: Time series of (a) monthly averages of sea ice extent for the Southern Hemisphere from January 1979-December 2021. The outset shows the annual cycle computed from the 43 years of data, (b) monthly deviations of sea ice extent fitted with a linear least squares best fit trend line, (c) yearly and (d) seasonal averages of sea ice extents with linear least squares best fit trend line. Summer averages (January – March), autumn averages (April-June), winter averages (July – September), and spring averages (October-December).

Seasonal trend analysis shows positive trends for all the seasons (Figure 2c). The Antarctic SIE trends are positive for each season except spring and on a yearly average basis, with autumn having the highest magnitude seasonal trend at 9.6 ± 7.5 10^3 km^2 yr^{-1} (Table 1). However, the seasonal trend for spring ice extent (-1.7 ± 7.3 10^3 km^2 yr^{-1}) shows the lowest magnitude than that of summer ice extent (4.7 ± 6.5 10^3 km^2 yr^{-1}) (Table 1). The variability in sea ice extent is considered to be influenced by large-scale atmospheric forcing in the Southern Ocean (Cavalieri & Parkinson, 2008; Kusahara *et al*., 2017; Schroeter *et al*., 2017; Scott *et al*., 2019; Stuecker *et al*., 2017; Wille *et al*., 2019) [4, 15, 28, 29, 32, 36], which results in a weakening of both the positive (Weddell Sea (WS), western Pacific Ocean (WPO), and Ross Sea (RS) sectors) and negative (Amundsen-Bellingshausen Sea (ABS) sector) trends, as well as a trend reversal in the Indian Ocean (IO) sector. There are numerous atmospheric forcing mechanisms that make a significant contribution to the trends.

In present study, we investigated the role of ocean-atmospheric temperatures on sea ice variability. The long-term annual anomaly has been computed with respect to 30 years climatology (1981-2010) to understand the anomalous changes occurred in sea ice variations as well as in temperature (Figures 3-7).

Role of ocean-atmospheric forcing on Antarctic Sea ice changes: pre-2015 & post-2015

The annual SIC anomaly reveals an overall positive trend over the last four decades. The SST/T2m trend in the region is slightly negative. After 2015, the largest deviation was observed when there was a continual decline in the SIC anomaly. The AT anomaly shows overall cooling in the Southern Ocean, whereas an increase in AT has been observed in the Indian Ocean and Ross Sea sectors. Several studies have been conducted to investigate the relationship between Antarctic Sea ice variability and seasonal air temperatures (Jacobs and Comiso, 1993; Zwally, 2002) [14, 38] and found that the sea ice deviations are negatively correlated with air and sea surface temperature, and their associations are stronger on a regional and seasonal scales than over the whole Antarctica. The highest sea ice deduction is caused by an increased surface heat exchange between the atmosphere and the ocean.

3.2.2 During spring

The spatial trend of the SIC anomaly indicated an overall positive trend (Figure 3b) pre-2015 but changed to negative trend post-2015 (Figure 3c) which show melting of sea ice post-2015. Spatial distribution of SIC anomaly varies drastically post-2015, showing higher SIC values in coastal regions of WS, western IO, WPO continental coasts, western continental regions of RS and the region lying between ABS and RS (120°W- 140°W). In contrast, negative SIC predominates in major part of Antarctic such as eastern WS, IO, RS and western RS sea areas**.** The SST anomaly indicates warming in East Antarctica (Figure 3). The T2m anomaly shows overall cooling in the West Antarctica and warming in East Antarctica. Warming gets predominant in East Antarctica post-2015.

In spring, the spatial computed SIC anomaly exhibits an overall positive trend especially along the Antarctic coastlines (Figure 3a) but negative anomaly in some areas indicating the onset of melt season or spring retreat. The SST anomaly shows a dipole in the Southern Ocean, with a positive anomaly in the east and a negative anomaly in the west (Figure 3d). However, the AT anomaly is mostly positive except in a few regions such as the Bellingshausen Sea, the Western Weddell Sea, and the Western Pacific Ocean sectors (Figure 3g). Sea ice changes in spring have been shown to be substantially associated with zonal wind trends (Holland, 2014) [12]. Further, earlier studies reveal that the SAM is strongest in spring along with winter, which has resulted in significant sea ice retreat in various sectors (Fogt *et al*., 2012; Raphael and Hobbs, 2014) [8, 25].

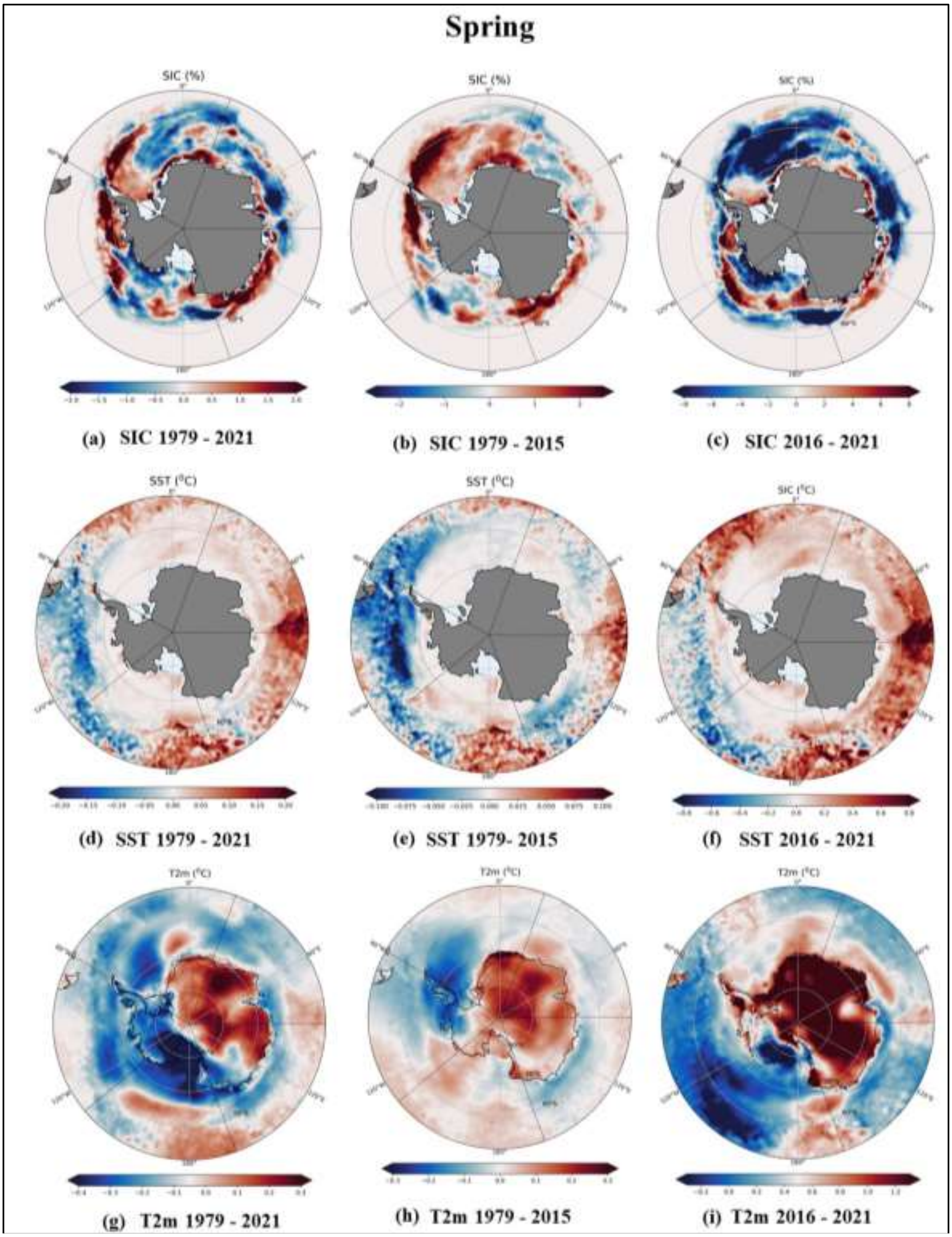
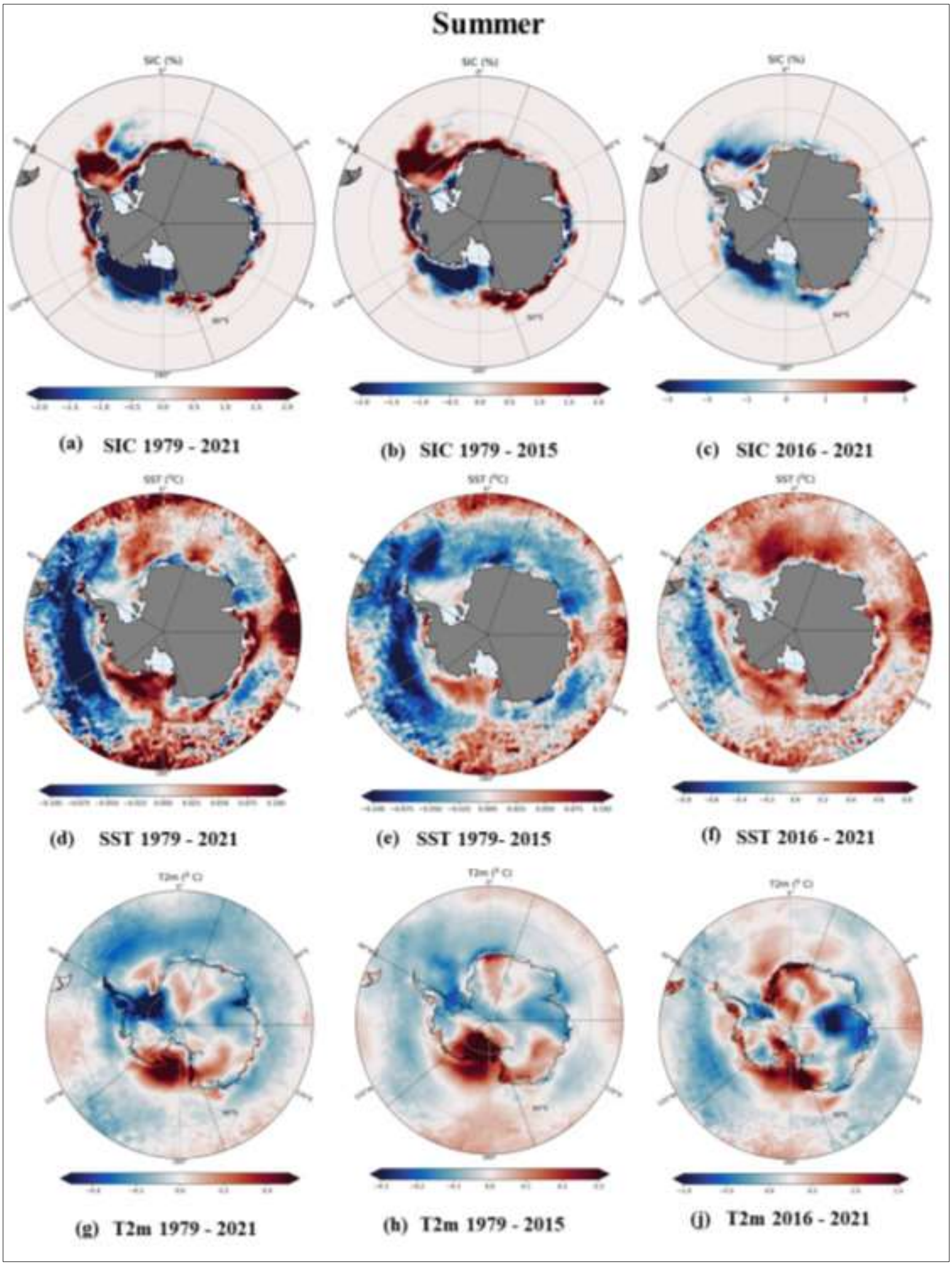


Fig 3: Spring

Additionally, several studies indicate that sea ice can advance under warm atmospheric conditions (Bintanja *et al*., 2013; Zhang, 2007) [1, 37]. They argued that when AT increases, downward long-wave radiation increases, causes the sea surface and resulting in an increase in sea ice melting. This results in reduced brine rejection leading to a decrease in ocean salinity and density. This results in ocean stratification, which restricts upward heat transport in the water, leading in sea ice melting. (Hobbs *et al*., 2016) [11].

3.2.3 During summer

The spatial trend of the SIC anomaly indicated an overall positive trend (Figure 4b) pre-2015 in WS and RS but changed to negative trend post-2015 (Figure 4c). Post-2015, a significant reduction in SIC has been attributed to multiple interconnected ocean-atmosphere interactions. The SST anomaly post-2015 shows positive anomaly in almost all sectors except negative (cooling) in ABS (Figure 4f). In contrast to spring, T2m is found to be negative in IO continent. Considerable negative SIC anomalies are located in the Amundsen Sea, closer to the coast, while high positive SIC anomalies are observed in the Weddell Sea sector (Figure 4a).



(a) SIC 1979 - 2021 (b) SIC 1979 - 2015 (c) SIC 2016 - 2021

(d) SST 1979 - 2021 (e) SST 1979- 2015 (f) SST 2016 - 2021

(g) T2m 1979 - 2021 (h) T2m 1979 - 2015 (j) T2m 2016 - 2021

Fig 4: Summer

Summer SIC anomalies in the Weddell sector have been found to be positively linked with spring intensification (decreased sea ice loss), which persists till autumn (Holland, 2014) [12]. The enhanced wind patterns result in intensification of the Weddell Gyre, which results in the westward advection of sea ice. On the contrary, the Amundsen Sea has been observed previously to undergo large spring sea ice loss, which results in a negative summer sea ice concentration. SST anomaly in comparison to 30 years climatology is increasing, with a concentration along the coast (Figure 4d). The warming in this region has been attributed to the advection of warm air from the tropics to the pole, which warms the atmosphere over the Antarctica landmass (Holland and Kwok, 2012) [12], and can be also be observed in (Figure 4g).

Conclusion

The intricate interconnections between ice, ocean, and atmosphere, Antarctica has a unique set of circumstances that have resulted in the formation of sea ice. This study has addressed some of the key factors that have an important role in influencing the sea ice variability of the SH on a monthly, interannual and seasonal scale from 1979 to 2021. After the unprecedented decline in 2016, the SH can be assumed to be in a "restoration mode" showing a trend of 0.56% per decade. Even though the SH has had a positive trend over the last 43 years, the trend value has been observed to vary for different periods. A strong sea ice decline observed post-2015 has been attributed to several interconnected ocean-atmospheric processes. Strong northerly warm airflow into the higher latitudes, the negative phase of SAM and El Nino conditions that persisted during the summer of 2016, the presence of a zonal wave 3 around Antarctica etc have been some of the pointed reasons for the mentioned anomalous sea ice retreat (Meehl *et al*., 2019; M. N. Raphael *et al*., 2016; Stuecker *et al*., 2017; Turner *et al*., 2017; Wang *et al*., 2019) [26].

The sea ice exhibits a prominent seasonal cycle obtaining a summer minimum extent in February and a winter maximum extent in usually September. We have addressed the seasonal (mainly spring and summer) nature of sea ice in the SH and have concluded that it has a significant negative relationship with ocean-atmosphere temperature. These seasonal characteristics of sea ice and their connection with air and sea surface temperature are more accurate and understandable sector-wise than the entire Southern Ocean, as each sector are showing distinct spatial patterns. It has been observed that the melt season of Southern Ocean Sea ice starts with the onset of spring (OND) known as spring retreat, reaches a seasonal minimum in summer (JFM) and begins advancement in Autumn (AMJ) eventually reaching a maximum in winter (JAS). With the ongoing models and analysis techniques, we may be able to accurately monitor the ocean-atmosphere-anthropogenic drivers and their correlation with Antarctic climate, thus providing a useful oversight and prediction method for future sea ice variations. Post-2015, the Antarctic dataset significantly alters the results, in stark contrast to the situation for the Arctic, as the Antarctic record no longer exhibits a convincing trend toward increasing ice extents, instead dipping to unusually low values in 2016-2019 and then slightly rebounding in 2020 (Parkinson and DiGirolamo, 2021) [24].

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