# Antarctic Sea Ice Trends and its Response to the Southern Annular Mode

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**Abstract**

Sea ice covers vast regions of the Southern Ocean and impacts on the climate as well as the plant and animal life of the region. The variability of sea ice in the Southern Ocean affects the entire food web of the region, from phytoplankton to Antarctic krill through to the apex predators such as seals and penguins. Sea ice variability is determined by shifts in the atmospheric temperature distribution and shifts in the atmospheric circulation. The Southern Annular Mode (SAM) is the primary mode of variability in the atmospheric circulation of the Southern Hemisphere. Despite the overall warming of Antarctica, sea ice extent and sea ice area show a positive trend in the Southern Ocean and all its sectors except in the Bellingshausen/Amundsen Seas sector which displays a negative trend for the period 1979-2007. The SAM index also shows a positive trend during this period indicating a shift towards the more positive phase. The monthly and seasonal correlations between the SAM index and sea ice concentrations display a dipole, with more ice occurring in the Ross Sea during the positive phase of SAM and less ice occurring in the Weddell Sea.

**Key words:** Southern Ocean, Southern Annular Mode, Sea ice area, sea ice extent, sea ice concentration.

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## 1. Introduction

The structure and functioning of ecological systems are determined by various biological and physical factors. One of the major physical factors that impact on ecosystems is climate processes (McGowan et al. 1998, Stenseth et al. 2002). The impact of climate- related physical fluctuations in the marine environment can occur through remote changes in oceanic or sea ice processes that show marked coherent spatial and temporal variability as well as through local atmospheric effects (Stenseth et al. 2003, Pershing et al. 2004).

It is now well established that the Antarctic Peninsula (AP) region as well as the adjacent southern Bellingshausen and the northwestern Weddell Seas are experiencing significant climatic changes (Domack et al. 2003). The annual mean surface air temperature of the Antarctic Peninsula has increased by 2°C since 1950 thus making this region one of the most rapidly warming regions on Earth (Meredith and King 2005). Vaughan et al. (2003) found a mean warming of 0.8 ± 1.6°C per century for Antarctica over a 33 year period.

The dominant mode of variability in the atmospheric circulation of the extratropical Southern Hemisphere is the Southern Annular Mode (SAM) also known as the Antarctic Oscillation (Sen Gupta and England 2007a, Marshall 2003). The SAM is characterized by zonally symmetric atmospheric pressure anomalies of opposite signs in the midlatitudes and high latitudes (Figure 1) (Marshall 2003). It is also responsible for climate variability over the entire Southern Hemisphere on timescales from intraseasonal to interannual (Thompson and Wallace 2000). For example Reason and Rouault (2005) found that a relationship exists between the winter rainfall over western South Africa and the Southern Annular Mode. It has also been found that warm dry conditions over the South Island of New Zealand and southern South America are associated with the positive phase of the SAM (Gillett et al. 2006). The

negative phase of the SAM is associated with an increase in precipitation over southern Australia and Tasmania (Meneghini et al. 2007).

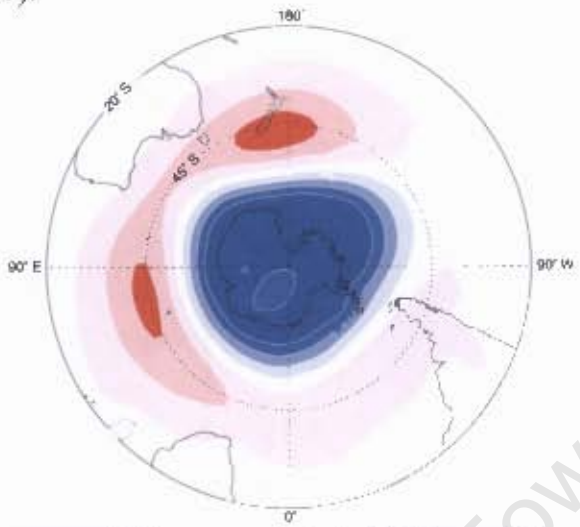


Figure 1: Pattern of the pressure variations associated with the positive phase of the SAM. Blue shading indicates negative atmospheric pressure anomalies and red shading indicates positive atmospheric pressure anomalies, after Gong and Wang (1999)

The SAM represents a large-scale exchange of atmospheric mass between the mid- and high-latitudes (Hartmann and Lo 1998) and a zonally symmetric shift in the position and strength of the subtropical jet. A negative SAM phase corresponds to a weaker lower-latitude jet and the positive phase corresponds to a stronger more pole-ward contracted jet (Lovenduski and Gruber 2005, Sen Gupta and England 2007b, Stammerjohn et al. 2008b, Yuan and Li 2008). These westerly winds are the driving force behind the circulation of the Southern Ocean, and using general circulation models it has been shown that SAM associated wind shifts, alter the circulation patterns of the Southern Ocean substantially (Hall and Visbeck 2002).

A number of studies (Hall and Visbeck 2002, Lefebvre et al. 2004, Lovenduski and Gruber 2005) found that during a positive SAM, westerly winds at 55°S are intensified by the anomalously strong pressure gradient while the westerly winds (easterly anomaly) at 35°S are weakened (Figure 2). These studies

showed that the surface easterly anomalies associated with a positive SAM generate southward Ekman drift from 30° to 45°S, while the surface westerly anomalies stimulate northward Ekman drift from about 45° to 65°S (Figure 2). The result of this is increased divergence and thus increased upwelling of cold iron-enriched water around the Antarctic coast and increased convergence of water in the Subantarctic Zone (SAZ), the region between the Subantarctic Front (SAF) and Subtropical Front (STF), causing downwelling of water from the surface to depth.

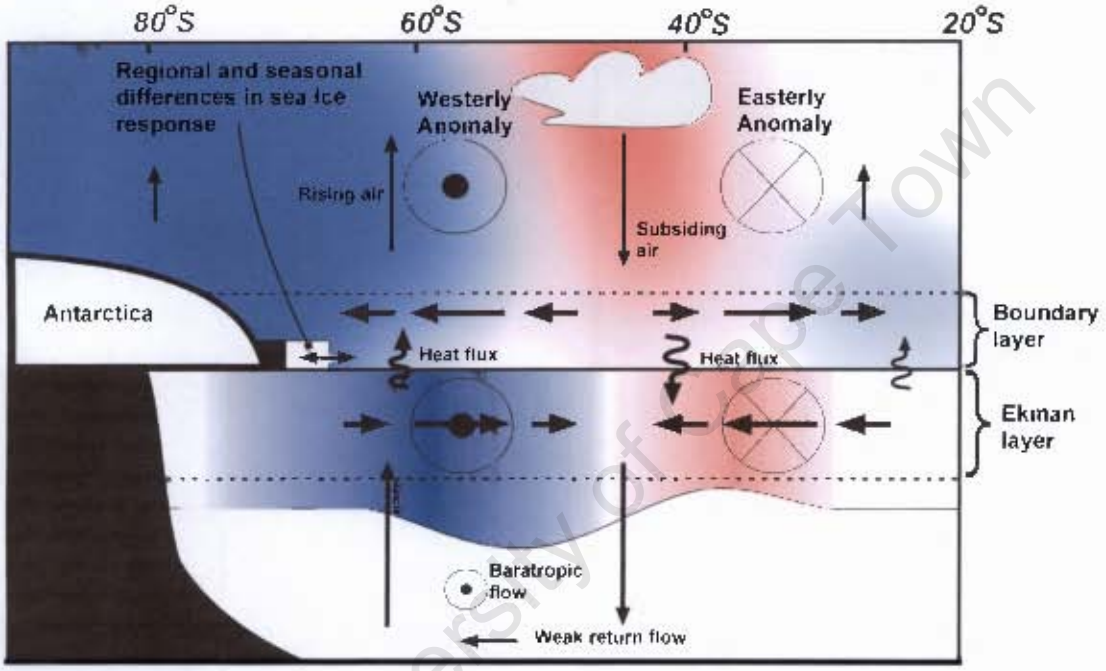


Figure 2: Schematic representation of the climate system response to a positive phase of the SAM. High-latitude atmospheric/oceanic cooling is denoted by blue shading and red shading represents warming in the lower latitudes. Arrow heads/tails denotes flow out of / into the page respectively. The negative phase of the SAM exhibit the same pattern as displayed here, only with reversed directions of circulation and the opposite sign for anomalies and fluxes, after Sen Gupta and England (2007).

Stronger, more poleward westerly winds are expected during positive SAM conditions. This would cause stronger Ekman sea ice drift to the north and promote early sea ice advance everywhere except in

the region where more northeasterly winds occur and thus inhibit sea ice advance. Weaker westerly winds are expected to occur under negative SAM conditions. These weaker westerlies in turn would result in weaker Ekman sea ice drift to the north and inhibit sea ice advance. However in the region that experience more southwesterly winds, the Ekman sea ice drift to the northeast will promote early sea ice advance (Figure 2) (Stammerjohn et al. 2008b). Leferbvre and Goose (2005) found that under positive SAM conditions the lower air temperature resulted in an increase in sea ice concentration across most of the Southern Ocean except in the Weddell Sea and around the Antarctic Peninsula where there is a decrease in ice concentration because of the warmer air temperature. Thus both the mechanical (wind stress) and the thermal (air temperature) components of the SAM have an impact on the sea ice.

The advance and retreat of sea ice as well as the seasonal coverage west of the Antarctic Peninsula appear to be changing in response to the pronounced climate changes in this region (Stammerjohn and Smith 1996, Stammerjohn et al. 2003). In the western Ross Sea there has been a significant increase in sea ice, while the western Antarctic Peninsula and the Bellingshausen Sea are experiencing a remarkable decline in sea ice. These opposite trends average out the total sea ice extent (Yuan and Li 2008). It would thus seem that Antarctic sea ice is not affected by long-term atmospheric climatic change. However, this is not the case and Stammerjohn et al. (2008b) showed that the early retreat and late advance of sea ice in the western Antarctic Peninsula region is caused by the increasing positive SAM in phase with the impact of La Nina events.

It has been shown that in the western Antarctic Peninsula region maximum sea ice extent is not decreasing but yearly sea ice duration and monthly sea ice concentration are decreasing (Stammerjohn and Smith 1997, Smith and Stammerjohn 2001). Instead sea ice is, on average, reaching its most northward position but the duration thereof is not as long. Recent studies confirm that strong trends in

the timing of sea ice advance and retreat is responsible for the observed decrease in the duration of winter sea ice extent in that the advance is occurring later while the retreat is occurring earlier (Stammerjohn et al. 2008a, Stammerjohn et al. 2008b).

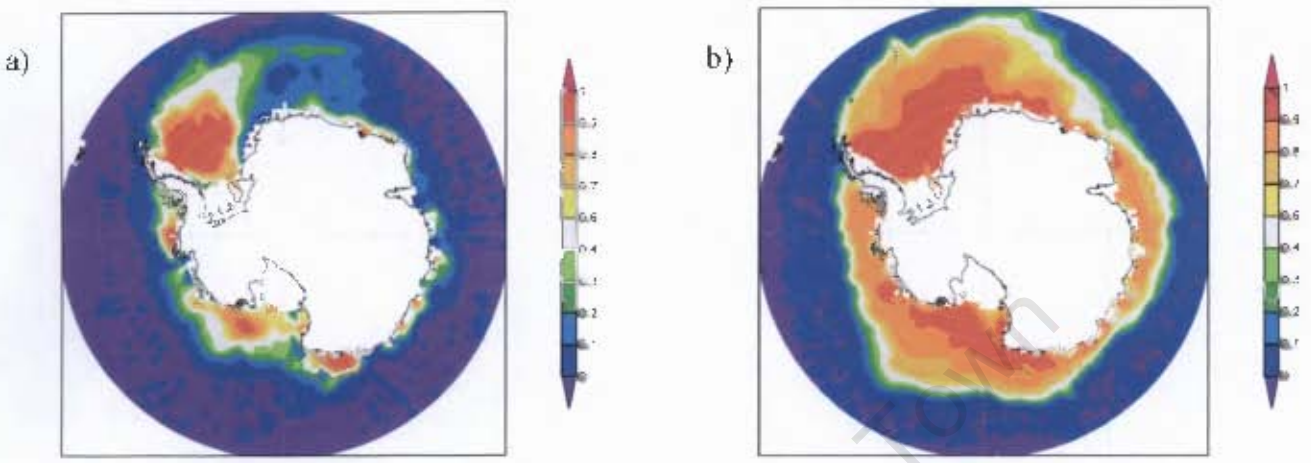


Figure 3: Sea ice concentration in a) summer (December-January-February) and b) winter (June-July-August) for the year 2003.

The Antarctic continent is surrounded by sea ice that varies in extent from 4 million $km^2$ in summer (Figure 3a) to 20 million $km^2$ in winter (Figure 3b) (Zwally et al. 1983, Garrison and Siniff 1986). During maximum extent, the extent varies around the continent; sea ice can extend to 55-60°S in the Weddell Sea and Indian Ocean sectors, whereas in the Ross and Bellingshausen/Amundsen Seas sectors sea ice maximum often occurs south of 65°S. During minimum extent large ice-covered regions remain off east Antarctica in the western Weddell Sea, the Bellingshausen/Amundsen Sea and the eastern Ross Sea, but the Antarctic coast is surrounded by small sea ice patches (Zwally et al. 1983, Parkinson 1998). The sea ice season decreases in length with distance from the continent and can vary from a few days to year-round (Parkinson 1998).

The sea ice habitat of the Southern Ocean represents one of the largest and most dynamic ecosystems on Earth (Arrigo et al. 1997) as it provides habitat for a variety of animals from bacteria and metazoans to

marine mammals and birds (Garrison 1991). Spatial, seasonal and interannual variation exists in the extent, concentration, timing and type of sea ice that surrounds Antarctica (Lizotte 2001). Therefore, many levels of the Antarctic marine ecosystem, from the magnitude and timing of primary production to the survival and breeding success of apex predators, are affected by the variability of sea ice (Ross et al. 1996, Ducklow et al. 2007).

The objective of this study is to determine the current trends in sea ice area and extent as well as disentangle the response of sea ice to the Southern Annular Mode. It is important to understand the variability associated with sea ice in the Southern Ocean as well as the mechanisms that influence sea ice because changes in the sea ice will impact on the Antarctic marine ecosystem from the smallest microbe to the biggest apex predator.



**2. Data and Methods**

The sea ice concentration data used in this study were derived from NASA's Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) and the Defense Meteorological Satellite Program's (DMSP) Special Sensor Microwave/Imager (SSM/I). The SMMR provide data every other day and was in operation from 26 October 1978 to 20 August 1987, while the DMSP series of F8, F11 and F13 SSM/I operated from 9 July 1987 to 31 December 2007 and beyond providing data on a daily basis. The F8 SSM/I operated from 9 July 1987 to 18 December 1991, while the F11 SSM/I operated from 3 December 1991 to 30 December 1995 and the F13 SMM/I operated from 3 May 1995 through 31 December 2007 and beyond (Cavalieri and Parkinson 2008). Thus the time period for which satellite data is available extends from November 1978 to December 2007. The data are provided as daily and monthly sea-ice concentrations that are mapped to 25 km x 25 km grids on a polar stereographic projection (Yuan and Martinson 2000, Stammerjohn et al. 2008a).

This study uses the monthly averaged data as provided by the EOS Distribution Active Archive Center (DAAC) at the National Snow and Ice Data Center (http://nsidc.org).The sea ice concentration data were used to calculate total-ice covered area, and ice extent. The sea ice area is defined as the cumulative area of the ocean that is actually covered by sea ice and is calculated as the sum of the products of pixel area and ice concentration for ice concentration greater than 15%. The sea ice extent was calculated by summing the number of pixels that had an ice concentration of at least 15% multiplied by the area of each pixel (Cavelieri and Parkinson 2008). The sea ice area and extent were calculated for the entire Southern Ocean as well as for each of the five regions: the Weddell Sea (60°W-20°E), Indian Ocean (20°E-90°E), western Pacific Ocean (90°E-160°E), the Ross Sea (160°W-140°W), and the Bellingshausen/Amundsen Seas (140°W-60°W) (Figure 4).

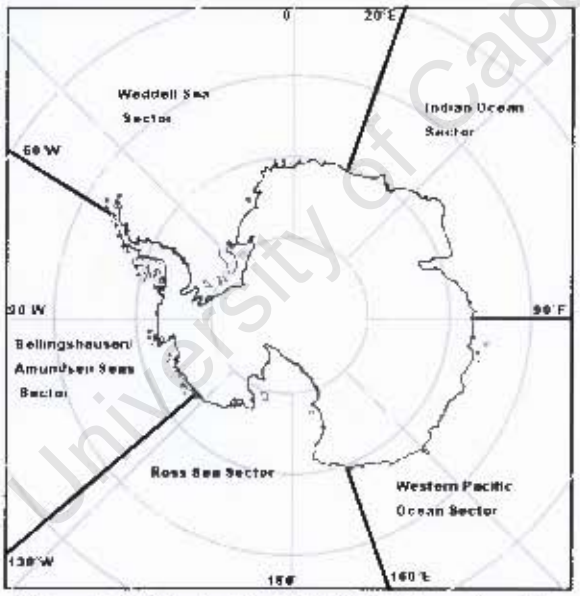

Figure 4: Southern Hemisphere sector map.

Even though the data period used for analysis in this study is referred to as 29 years, the actual period is the 29 years of 1979-2007 as well as the two preceding months (November and December 1978). However, only the full years 1979-2007 were used for the analysis of the yearly and seasonal averages. Seasonal averages for the entire time series were calculated by taking the average sea ice area and extent

of the three months that fall into the respective seasons. In this study December to January was taken to be summer months, March to May were taken as autumn months, winter months were taken to be June to August and spring months were taken to be September to November. The trends for monthly area anomalies, annual averaged sea ice area, and seasonal averaged sea ice area were all determined through fitting a linear least squares best fit trend line to the data. The same was done to determine the trends for monthly extent anomalies, annual averaged sea ice extent and seasonal averaged sea ice extent.

Annual, seasonal and monthly Southern Annular Mode (SAM) index data (Marshall 2003) were obtained from http://www.antarctica.ac.uk/met/gjma/sam.html. This index is updated monthly and data from 1957-2007 is available. However, only data from November 1978 to December 2007 were used for the correlation between sea ice concentration and the SAM index because the satellite measurements for sea ice concentration are only available from November 1978. The SAM index used in this study is calculated as the monthly mean difference between the mean sea level pressures (SLP) anomaly at 12 stations, six of which is situated close to 65°S and the other six is situated close to 40°S (Gong and Wang 1999). Correlations were performed between the monthly and seasonal SAM and sea ice concentrations for each of the five Southern Ocean regions as well as for the Southern Ocean as a whole.



## 3. Results

### *3.1 Sea Ice Areas*

#### 3.1.1 *Southern Ocean*

Generally, sea ice area in the Southern Ocean reaches its minimum during February, in late summer, and its maximum during September, in early spring (Figure 5). This same trend is evident for each of the five individual sectors (not shown) indicating that sea ice area growth and decay follow the same annual pattern in all regions of the Southern Ocean. Figure 5 indicates that sea ice growth is particularly strong

from March to July and ice decay is particularly strong from November through December to January. It is also evident that sea ice decay is faster than sea ice growth. The sea ice growth in the Southern Ocean occurs during approximately seven months of the year whereas sea ice decay only occurs during approximately five months of the year.

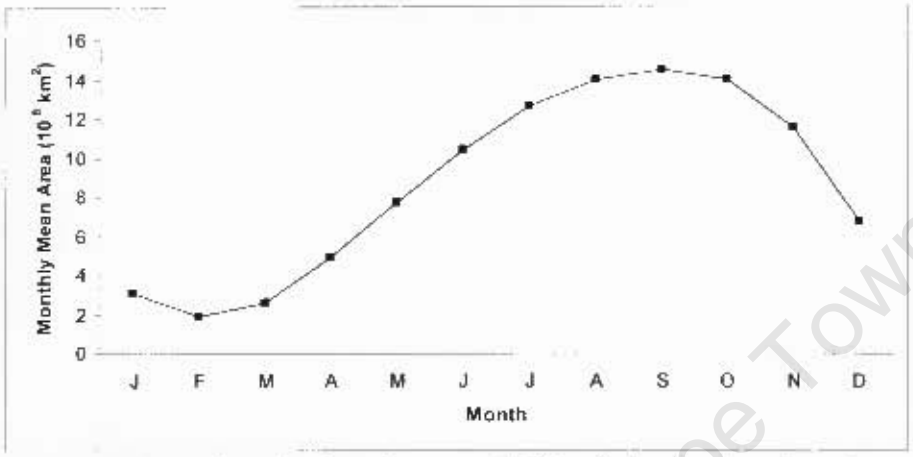


Figure 5: Annual cycle of sea ice area ($10^6$ km$^2$) for the Southern Ocean, for the period 1979 - 2007.

The sea ice area for the Southern Ocean as a whole shows inter-annual variability (Figure 6a), this is more clearly shown in the sea ice area anomalies (Figure 6b). The smallest inter-annual fluctuations occurred from 1989 to 1993. There is a significant positive trend of 11 184 ± 2 384 km$^2$y$^{-1}$ in the monthly anomalies of sea ice area ($R^2 = 0.0596$, $p < 0.0000$). During the time period from 1979 to 1993 the Southern Ocean experienced more negative sea ice area anomalies than positive anomalies. However from 1993 there were more positive anomalies than negative anomalies. This indicates that there has been a shift in sea ice area in that the sea ice coverage exceeds the average coverage more often in the last 14 years of the time series than in the first 14 years.

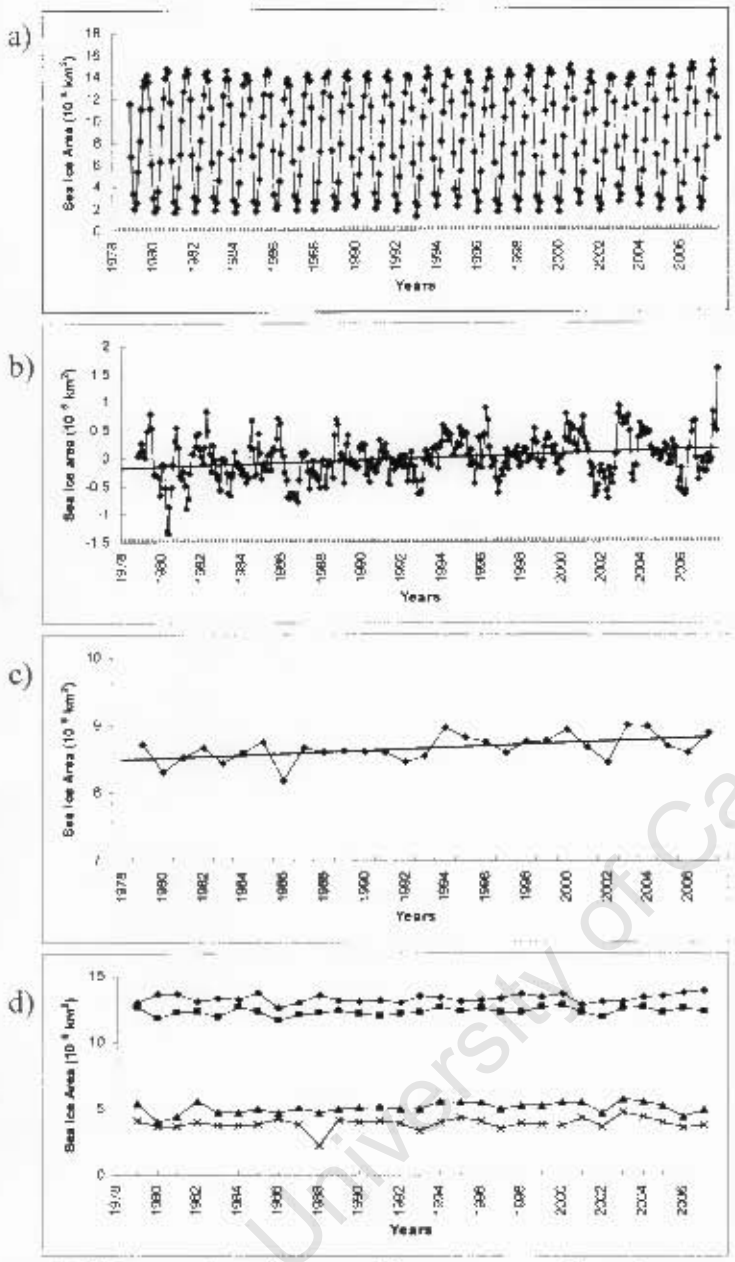


Figure 6: Time series of a) monthly averages of sea ice area for the Southern Ocean from November 1978 to December 2007 b) monthly anomalies of sea ice area c) annual averages of sea ice area d) seasonal averages of sea ice area from December 1978 to November 2007. Summer averages (crosses) are for December-February, autumn averages (triangles) are for March-May, winter averages (squares) are for June-August and spring averages (diamonds) are for September-November.

The annual averaged sea ice area of the Southern Ocean as a whole also shows a significant positive trend ($R^2 = 0.2355$, $p < 0.01$) and on average the sea ice area is increasing by 11 000 ± 3 800 $km^2y^{-1}$ (Figure 6c). Seasonally averaged sea ice areas show a positive trend for all seasons, however not all of the seasonal trends are significant (Figure 6d and Table 1). The trend for sea ice area during autumn shows the greatest increase, 16 700 ± 8 900 $km^2y^{-1}$, while the trend for spring, 8 200 ± 6 900 $km^2y^{-1}$, is the smallest. Figure 6d also indicates that the sea ice area in spring is greater than the sea ice area in winter. Thus the sea ice of the different regions of the Southern Ocean needs to be analysed separately as the different areas may respond differently to mechanical and thermal forcing.

*3.1.2 Weddell Sea*

Sea ice area in the Weddell Sea sector shows considerable inter-annual variability (Figure 7a), with deviations from the trend line of up to nearly $1x10^6$ $km^2$ occurring at times (Figure 7b). The over all trend for sea ice area anomalies of this sector is positive with an increase of 3 680 ± 1 972 $km^2y^{-1}$ and this trend is significant at the 90% level ($R^2 = 0.0099$, $p < 0.1$). The annual sea ice area shows a very slight positive trend of 3 600 ± 4 400 $km^2y^{-1}$ but this trend is not statistically significant ($R^2 = 0.0244$, $p > 0.1$) (Figure 7c). The seasonally averaged sea ice areas for the Weddell Sea sector show positive trends for summer, autumn and winter and a negative trend for spring (Figure 7d), however none of these trends are statistically significant (Table 1). The positive trends for summer and autumn and the negative trend for spring corroborates with the findings of Cavalieri and Parkinson (2008) but the positive trend for winter does not.

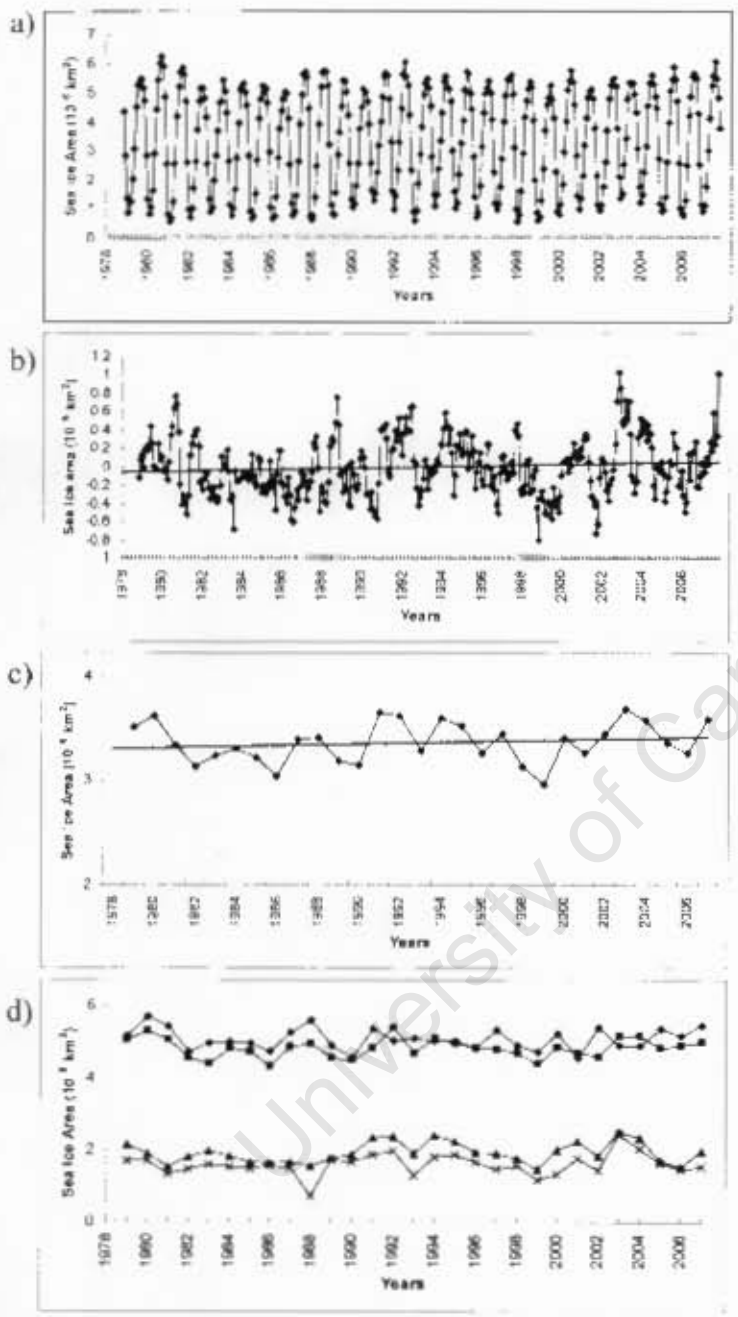


Figure 7: As for Figure 6 but for the Weddell Sea sector.

Table 1: Annual and seasonal sea ice area trends with standard deviations for the period 1979-2007.

| *Region* | *Yearly* | | *Summer* | | *Autumn* | | *Winter* | | *Spring* | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Trend ($10^3km^2y^{-1}$) | P[a] | Trend ($10^3km^2y^{-1}$) | P[a] | Trend ($10^3km^2y^{-1}$) | P[a] | Trend ($10^3km^2y^{-1}$) | P[a] | Trend ($10^3km^2y^{-1}$) | P[a] |
| SO[b] | 11.0±3.8 | ** | 9.5±9.6 | NS | 16.7±8.9 | NS | 10.9±6.3 | NS | 8.2±6.9 | NS |
| Weddell | 3.6±4.4 | NS | 6.7±6.8 | NS | 6.5±6.4 | NS | 2.1±6.1 | NS | -1.4±6.7 | NS |
| Indian | 1.9±2.1 | NS | 1.8±2.1 | NS | 2.4±2.0 | NS | 1.3±3.9 | NS | 3.2±4.1 | NS |
| Pacific | 2.3±1.5 | NS | 1.9±1.8 | NS | 4.1±2.1 | NS | 3.3±2.4 | NS | -2.0±3.0 | NS |
| Ross | 9.8±3.4 | * | 8.5±3.6 | ** | 11.0±5.0 | ** | 6.9± 5.3 | NS | 13.3±4.9 | ** |
| Bell/Am[b] | -6.6±2.2 | ** | -9.4± 2.6 | *** | -7.3±2.8 | ** | -2.6±3.6 | NS | -6.9±4.2 | NS |

[a] Level of significance. NS: not significant, * significant at the 90% level ($p< 0.1$), ** significant at the 95% level ($p<0.05$), *** significant at the 99% level ($p<0.01$).

[b] Southern Ocean is abbreviated as SO and Bellingshausen/Amundsen Seas is abbreviated as Bell/Am.



*3.1.3 Indian Ocean*

Although the magnitude of sea ice anomalies in the Indian Ocean sector is less than the sea ice anomalies of the Weddell Sea sector, there is a significant inter-annual variability due to the smaller total sea ice area of the Indian Ocean sector (Figure 8a). In summer there is almost no sea ice in the Indian Ocean sector whereas in the Weddell Sea summer sea ice area never drops below 0.5 million $km^2$. The monthly sea ice area anomalies show a positive trend (Figure 8b) of 2 116 ± 984 $km^2y^{-1}$ that is statistically significant at the 95% level ($R^2 = 0.0132$, $p < 0.05$).

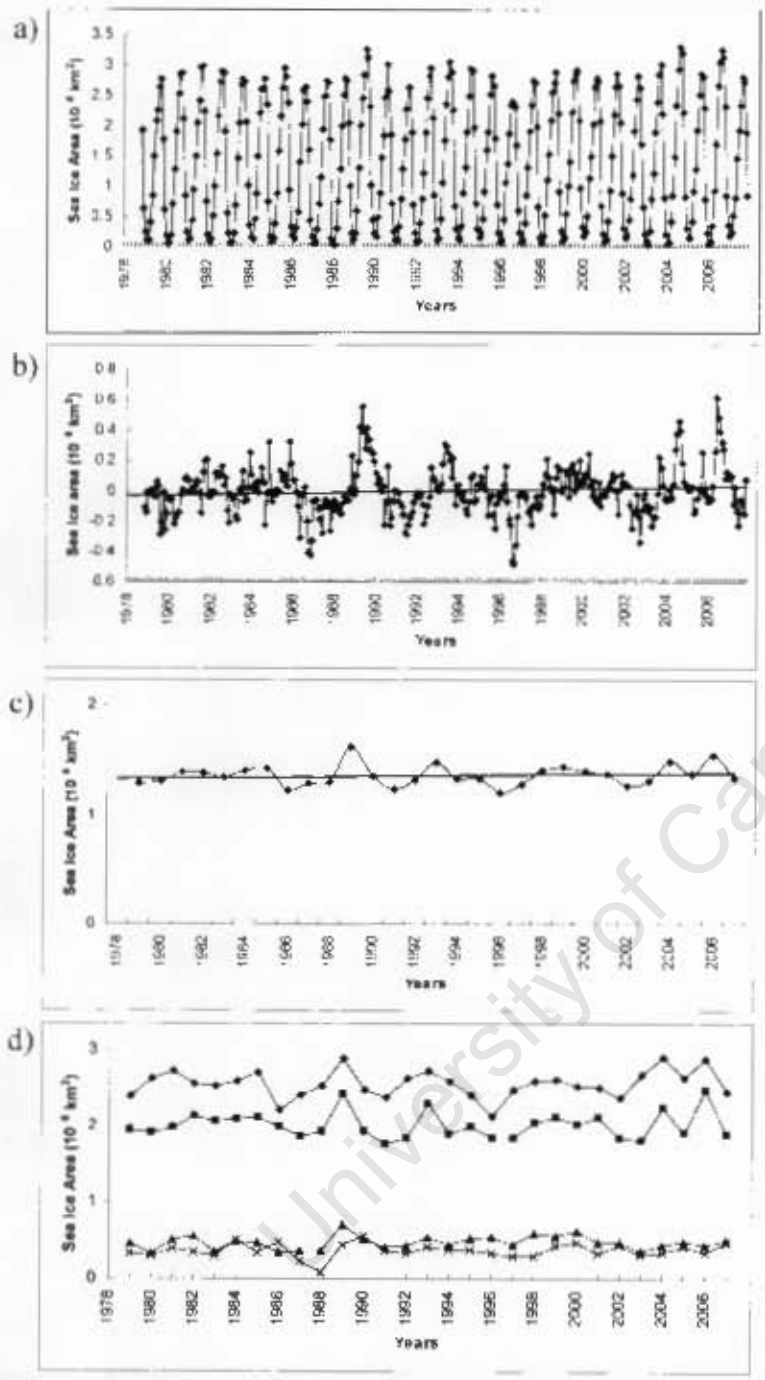


Figure 8: As for Figure 6 but for the Indian Ocean sector.

In the Indian Ocean sector the annual sea ice area shows a positive trend (Figure 8c and Table 1) however this trend is not statistically significant ($R^2 = 0.0281$, $p > 0.1$). On average there is an increase of 1 900 ± 2 100 $km^2y^{-1}$ in sea ice area. The seasonally averaged sea ice areas for all four seasons show positive trends (Figure 8d) however none of these trends are statistically significant (Table 1). The biggest increase in sea ice area in the Indian Ocean occurred during spring, 3 200 ± 4 100 $km^2y^{-1}$, and the smallest increase occurred in winter, 1 300 ± 3 900 $km^2y^{-1}$.

*3.1.4 Western Pacific Ocean*

The western Pacific Ocean sector is the smallest of the five Southern Ocean regions and thus has the smallest ice coverage. The western Pacific Ocean sector shows considerable inter-annual variability in both minima and maxima sea ice area values (Figure 9a). There is a significant positive trend (Figure 9b), 2 243 ± 751 $km^2y^{-1}$, in the monthly sea ice area anomalies of this region ($R^2 = 0.0251$, $p < 0.05$). The yearly sea ice area also shows a positive (Figure 9c), albeit statistically insignificant ($R^2 = 0.0775$, $p > 0.1$), trend of 2 300 ± 1 500 $km^2y^{-1}$ over the 29 years that this study covers.

The seasonally averaged sea ice areas for summer, autumn and winter show positive trends (Figure 9d), however none of these trends are statistically significant (Table 1). Spring shows a negative trend that is not statistically significant (Table 1). This indicates that over the past 29 years there has been an increase in sea ice area during all seasons except in spring where there has been a decrease in sea ice area.

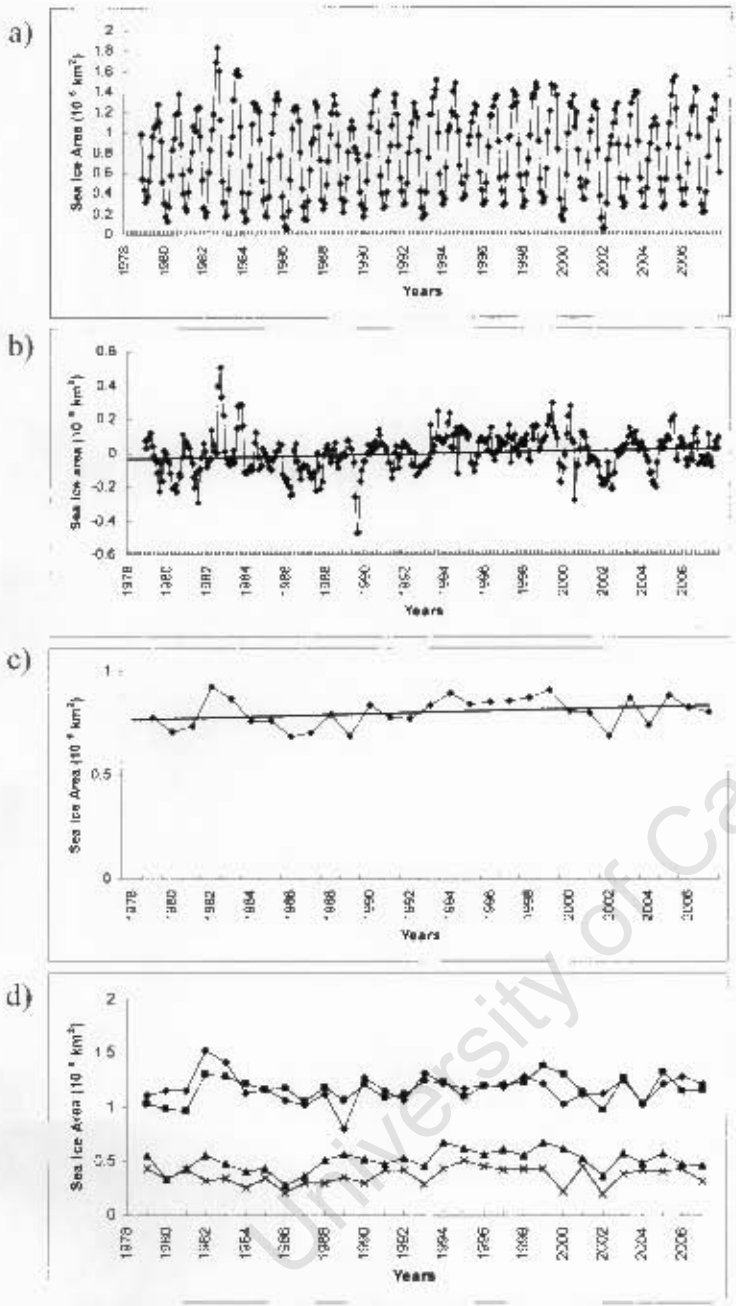


Figure 9: As for Figure 6 but for the western Pacific Ocean sector.

*3.1.5 Ross Sea*

Despite the fact that the overall ice cover of the Ross Sea is smaller than that of the Weddell Sea, the inter-annual variability of sea ice area in the Ross Sea is greater (Figure 10a). The Ross Sea sector shows great inter-annual variability in its monthly sea ice area anomalies. The trend of the area

anomalies is a highly significant ($R^2 = 0.1143$, $p < 0.000$) positive trend (Figure 10b) with an increase in sea ice area anomalies of 10 044 ± 1 501 $km^2y^{-1}$. From 1979 to 1994 this region has experienced more negative area anomalies than positive and thereafter it experienced more positive area anomalies.

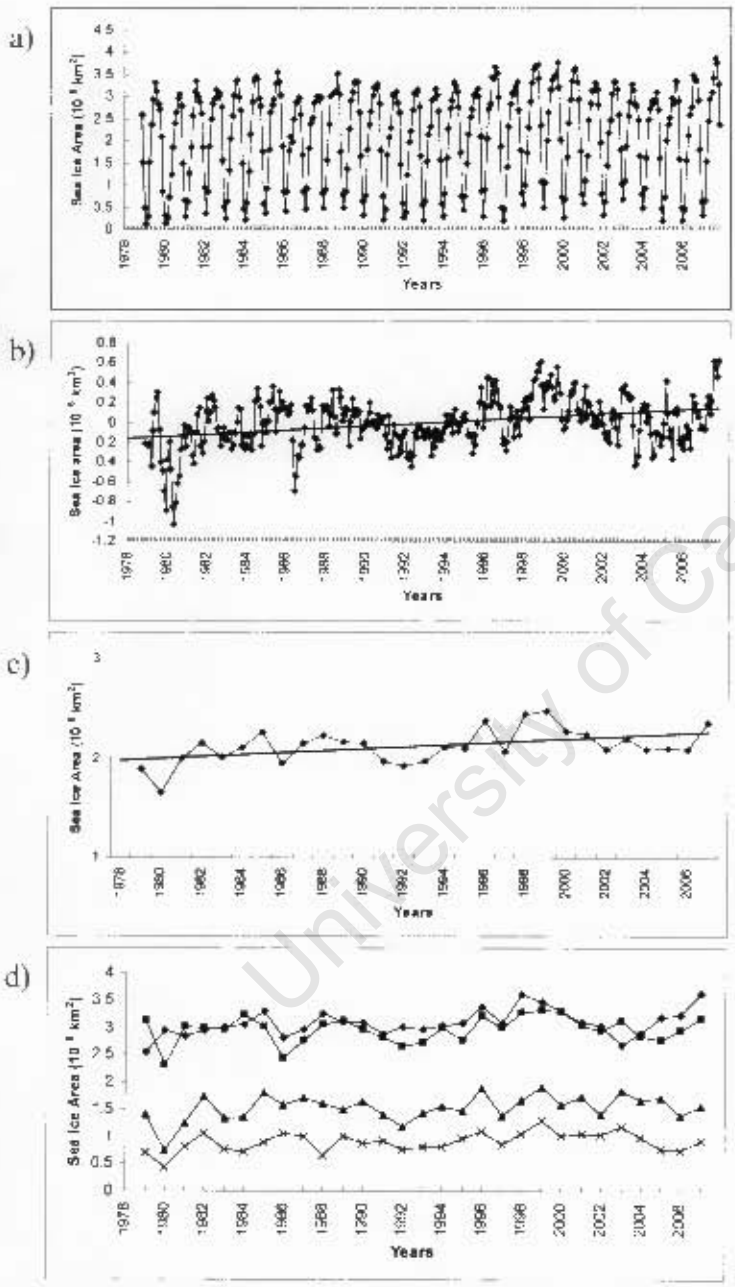


Figure 10: As for Figure 6 but for the Ross Sea sector.

There is also a significant positive trend (Figure 10c) in the annual sea ice area of this sector ($R^2$ = 0.2342, $p < 0.01$). There has been an increase of 9 800 ± 3 400 $km^2y^{-1}$ in sea ice area in this region from 1979 to 2007. The seasonal trends for all seasons are positive (Figure 10d), however, it is only the trends for summer, autumn and spring that are statistically significant (Table 1). In this region spring shows the biggest increase in sea ice area, 13 300 ± 4 900 $km^2y^{-1}$, and winter shows the smallest increase in sea ice area, 6 900 ± 5 300 $km^2y^{-1}$.

*3.1.6 Bellingshausen/Amundsen Seas*

Sea ice area in the Bellingshausen/Amundsen Seas sector shows great inter-annual variability (Figure 11a). It also appears as if there has been a general increase in the amplitude of the seasonal sea ice cover in this sector since 1990 in response to a decrease in summer ice cover. The overall trend of the monthly sea ice area anomalies is a negative trend (Figure 11b), -6 898 ± 1 058 $km^2y^{-1}$, that is statistically significant ($R^2$ = 0.1091, $p < 0.000$). This region has experienced more positive area anomalies from 1979 to 1990 and more negative area anomalies from 1990. The annual sea ice area of this region also shows a negative trend (Figure 11c) of -6 600 ± 2 200 $km^2y^{-1}$, that is significant ($R^2$ = 0.2505, $p < 0.01$). The seasonally averaged sea ice areas show negative trends for all four seasons (Figure 11d) however, it is only the trends for summer and autumn that are statistically significant (Table 1).

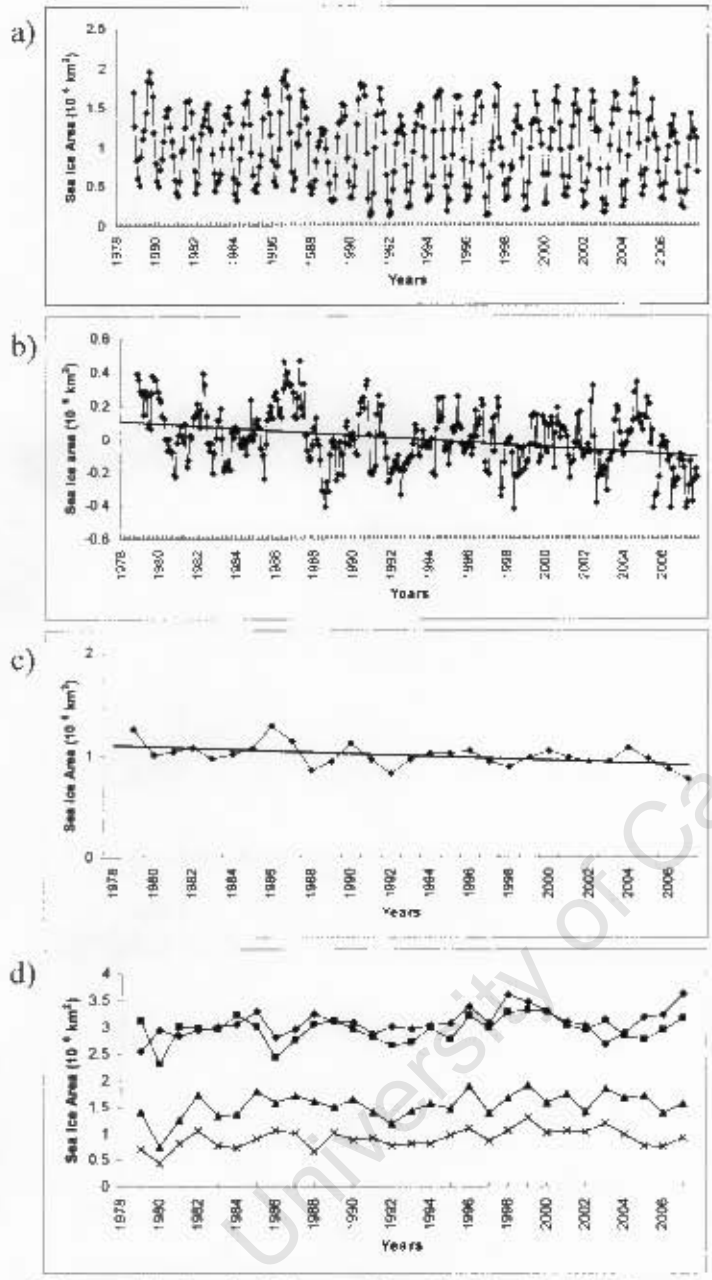


Figure 11: As for Figure 6 but for the Bellingshausen/Amundsen Seas region.



*3.2 Sea Ice Extent*

The same analyses used for sea ice area were performed for sea ice extent. These results indicated that the time series for sea ice extent are generally similar to those of sea ice area except that the magnitudes of ice extent are always larger. As with sea ice area, sea ice extent in the Southern Ocean generally

reaches its minimum during February and its maximum during September (not shown). This same trend exists for each of the five individual sectors except for the Indian Ocean sector which displays a maximum extent in October rather than in September.

The sea ice extent anomalies of the Southern Ocean as a whole has experienced a trend of 11 830 ±2 669 $km^2y^{-1}$, which is statistically significant ($R^2 = 0.0536$, $p < 0.0000$) whereas the trend of 3 724 ± 2 308 $km^2y^{-1}$ for the extent anomalies of the Weddell Sea region is not significant ($R^2 = 0.0072$, $p > 0.1$). The Indian Ocean region has experienced a positive trend of 3 406 ± 1 194 $km^2y^{-1}$ in sea ice extent anomalies and this trend is statistically significant ($R^2 = 0.0229$, $p < 0.00$). The smallest positive trend, 843 ± 1 003 $km^2y^{-1}$, in sea ice extent anomalies occurred in the western Pacific Ocean region however this trend is not significant ($R^2 = 0.0203$, $p > 0.1$). The biggest trend, 13 239 ± 1 796 $km^2y^{-1}$, occurred in the Ross Sea region and this trend is statistically significant ($R^2 = 0.1354$, $p < 0.00000$). The Bellingshausen/Amundsen Seas region is the only region that experienced a negative trend in sea ice extent anomalies, -9 382 ± 1 382 $km^2y^{-1}$, and this trend is statistically significant ($R^2 = 0.1172$, $p < 0.00000$). The annual sea ice extent trends for the Southern Ocean as a whole and four of its regions have the same signs as the annual sea ice area trends but have bigger magnitudes (Table 1 and Table 2). For the western Pacific Ocean region the sea ice extent trend has the same sign as the sea ice area but the sea ice extent magnitude is smaller than that of sea ice area. This confirms the suggestion from other studies that the density of the ice cover of this sector is increasing whereas the density of the ice cover in other sectors with positive trends is decreasing (Cavalieri and Parkinson 2008). Overall for the 29 year time period covered by this study there is an increase in sea ice extent of 12 000 ± 4 400 $km^2y^{-1}$ for the Southern Ocean as a whole. This is in agreement with the findings of Zwally et al. (2002) but contradicts the findings of Cavalieri et al. (2003).

The seasonally averaged sea ice extent trends for the Southern Ocean, the Indian Ocean region, western Pacific Ocean region and the Bellingshausen/Amundsen Seas region all correspond to those of sea ice area. However, the seasonal sea ice extent trend for autumn in the Ross Sea is not significant, whereas the trend for sea ice area in this region is significant (Table 2). It was also found that in the Weddell Sea region the seasonal sea ice area trend for spring was significant over the 29 years but the sea ice extent trend is not significant.

Table 2: Annual and seasonal sea ice extent trends with standard deviations for the period 1979-2007.

| *Region* | *Yearly* | | *Summer* | | *Autumn* | | *Winter* | | *Spring* | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Trend ($10^3km^2y^{-1}$) | p[a] | Trend ($10^3km^2y^{-1}$) | p[a] | Trend ($10^3km^2y^{-1}$) | p[a] | Trend ($10^3km^2y^{-1}$) | p[a] | Trend ($10^3km^2y^{-1}$) | p[a] |
| SO[b] | 12.0±4.4 | ** | 11.0±15.2 | NS | 14.7±10.1 | NS | 10.6±6.1 | NS | 15.0±6.2 | ** |
| Weddell | 3.9±5.5 | NS | 6.5±9.9 | NS | 6.5±7.4 | NS | 2.0±7.5 | NS | 1.0±7.4 | NS |
| Indian | 3.1±2.4 | NS | 4.1±3.7 | NS | 3.3±2.9 | NS | 2.0±4.4 | NS | 5.2±4.3 | NS |
| Pacific | 0.9±2.1 | NS | 0.3±2.0 | NS | 4.1±2.6 | NS | 2.0±3.1 | NS | -2.0±4.5 | NS |
| Ross | 13.1±4.3 | *** | 12.8±5.8 | ** | 12.3±6.1 | NS | 10.0±5.7 | NS | 17.6±5.3 | *** |
| Bell/Am[b] | -9.0±2.8 | *** | -12.7±3.4 | *** | -11.4±3.5 | *** | -5.4±4.9 | NS | -6.7± 5.2 | NS |

[a] Level of significance. NS: not significant, ($p > 0.1$) * significant at the 90% level ($p< 0.1$), ** significant at the 95% level ($p<0.05$), *** significant at the 99% level ($p<0.01$).

[b] Southern Ocean is abbreviated as SO and Bellingshausen/Amundsen Seas is abbreviated as Bell/Am.

*3.3 The Southern Annular Mode*

The relationship between the Southern Annular Mode (SAM) and sea ice was also examined since the SAM is an important component of seasonal and inter-annual variability in the Southern Hemisphere. It also plays an important role in the atmospheric circulation of this region and thus will have an impact on the sea ice.

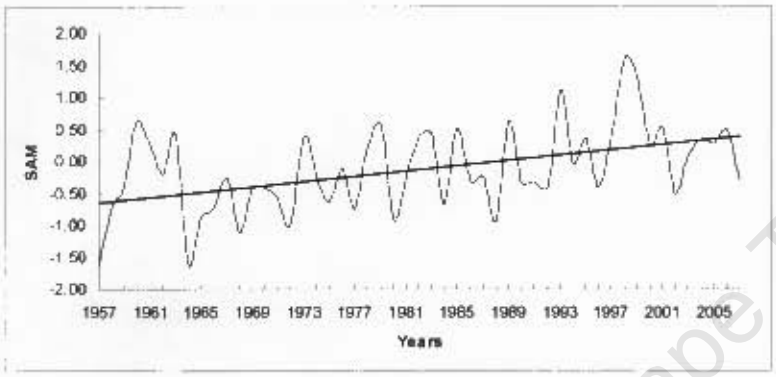


Figure 12: Annual averaged SAM from 1957 to 2007

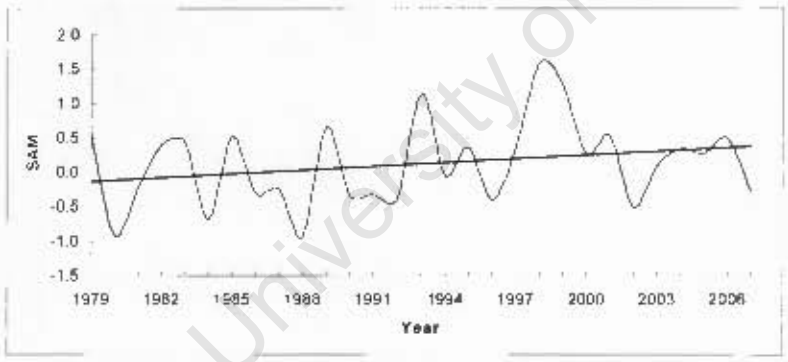


Figure 13: Annual averaged SAM from 1979 to 2007

From 1957 to 2007 there has been a significant positive trend in the SAM index ($R^2 = 0.2107$, $p < 0.001$) (Figure 12). The trend for the SAM index over the 50 year period is an increase in the SAM index of about $0.021 \pm 0.006$ per year. This indicates that there is a trend towards smaller negative and larger positive values. The largest negative SAM values all occurred in the 1950's and the 1960's, whereas the largest positive SAM values all occurred in the 1990's. The 25 year period from 1957 to 1981 was

dominated by negative annual SAM values whereas the 26 year period from 1982 to 2007 was dominated by positive annual SAM values.

There is an increasing trend of about $0.252 \pm 0.144$ per year in the averaged annual SAM from 1979 to 2007 (Figure 13), however this trend is only significant at the 90% significance level ($R^2 = 0.101963$, $p < 0.1$). In the 14 years from 1979 to 1992 there has been nine years in which the averaged annual SAM index had a negative sign. However, in the 15 years from 1993 to 2007 there has only been four years in which the averaged annual SAM index was negative. This suggests that there has been a shift in the SAM index to more positive SAM values in the last 15 years.

During summer there is a strong positive correlation between sea ice concentration and the SAM index in the Ross Sea sector, the Bellingshausen/Amundsen Seas sector as well as in the Indian Ocean. However, west of the Antarctic Peninsula in the Bellingshausen/Amundsen Seas sector there is a strong negative correlation. In the western Weddell Sea sector there is also a negative correlation between sea ice concentration and the SAM index (Figure 14a). In the autumn there is a strong positive correlation between sea ice concentration and the SAM index in the Indian Ocean, western Pacific Ocean, Ross Sea and the Bellingshausen/Amundsen Seas sectors. However, west of the Antarctic Peninsula in the Bellingshausen/Amundsen Seas sector and in western Weddell Sea sector there is a strong negative correlation (Figure 14b).

There is a strong positive correlation between the SAM index and sea ice concentration in the Indian Ocean sector, the Western Pacific Ocean sector, the Ross Sea close to the Ross Ice Shelf, and the Bellingshausen/Amundsen Seas sector during winter. However, there is a strong negative correlation between the sea ice concentration and the SAM index in the eastern part of the Ross Sea sector as well

as in the Weddell Sea (Figure 14c). During spring there is a strong negative correlation between the SAM index and sea ice concentration in the Weddell Sea and in the eastern part of the Ross Sea sector. In the Bellingshausen/Amundsen Seas sector, the Indian Ocean sector as well as in the western Pacific Ocean there is a strong positive correlation (Figure 14d).

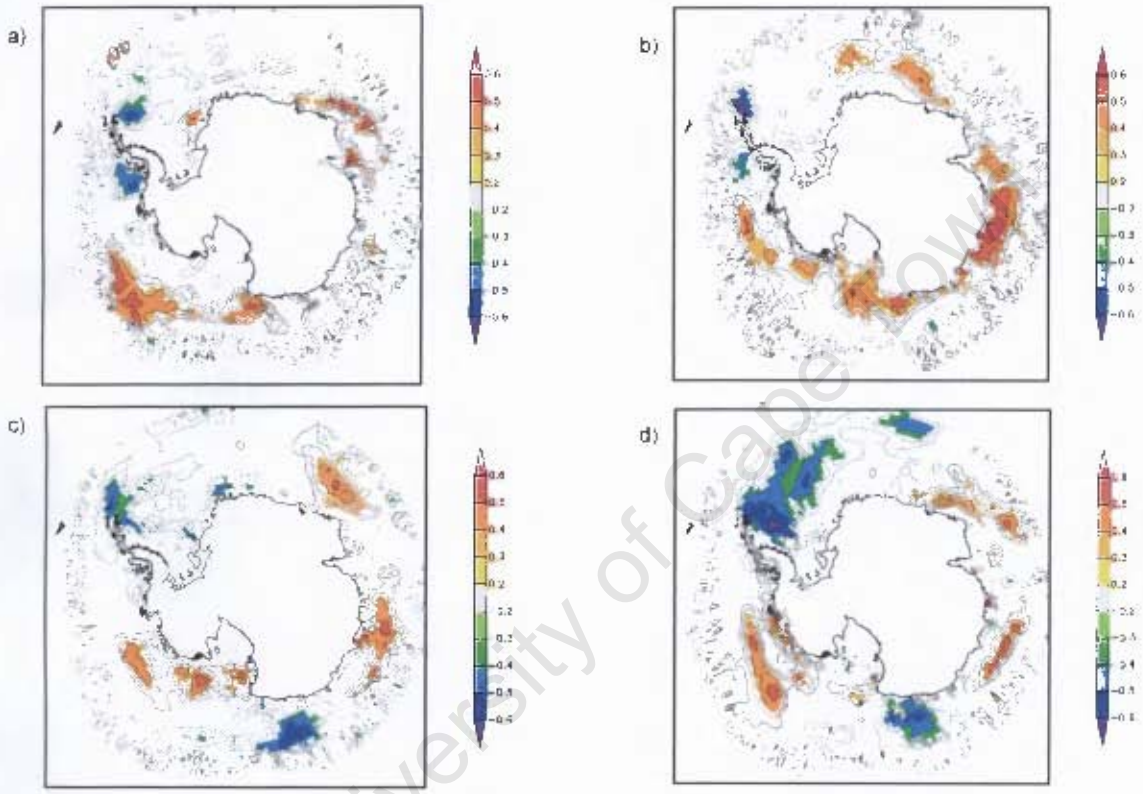


Figure 14: Correlation of seasonally averaged SAM and sea ice concentration for the period 1979 to 2007. A) Summer (December - January - February) b) Autumn (March – April – May), c) Winter (June – July - August), d) Spring (September – October - November).

During January-April, June, and October there are very few regions where there is a strong correlation between sea ice concentration and the SAM index (Figure 15a-d, f and j respectively). There is a strong positive correlation between the SAM index and sea ice concentration during May in the Indian Ocean sector, western Pacific Ocean sector, as well as the Bellingshausen/Amundsen Seas sector (Figure 15e).

However, during this month there is a strong negative correlation at the tip of the Antarctic Peninsula in the Weddell Sea sector. During the month of July there exists a strong negative correlation between sea ice concentration and the SAM index to the north and west of the Antarctic Peninsula in the Weddell Sea sector as well as in the Bellingshausen/Amundsen Seas sectors (Figure 15g). There is a strong positive correlation in the Indian Ocean sector, western Pacific Ocean sector, Ross Sea sector and southern Bellingshausen/Amundsen Seas sector. However there is a small region in the eastern Ross Sea sector where there is a negative correlation between the sea ice concentration and the SAM index.

In the Weddell Sea sector and the Ross Sea sector there exists a strong negative correlation between sea ice concentration and SAM during the month of August, although during this same month there is strong positive correlation in the western Pacific Ocean sector and the Bellingshausen/Amundsen Seas sector (Figure 15h). During September there is a strong negative correlation in the Weddell Sea sector and the Ross Sea sector and a strong positive correlation in the Indian Ocean, western Pacific Ocean, and Bellingshausen/Amundsen Seas sectors (Figure 15i). In the Weddell Sea sector and the eastern Ross Sea sector there exists a strong negative correlation whereas there is a strong positive correlation in the western Ross Sea during November (Figure 15k). During December there is also a strong positive correlation in the Ross Sea between sea ice concentration and the SAM index (Figure 15l).

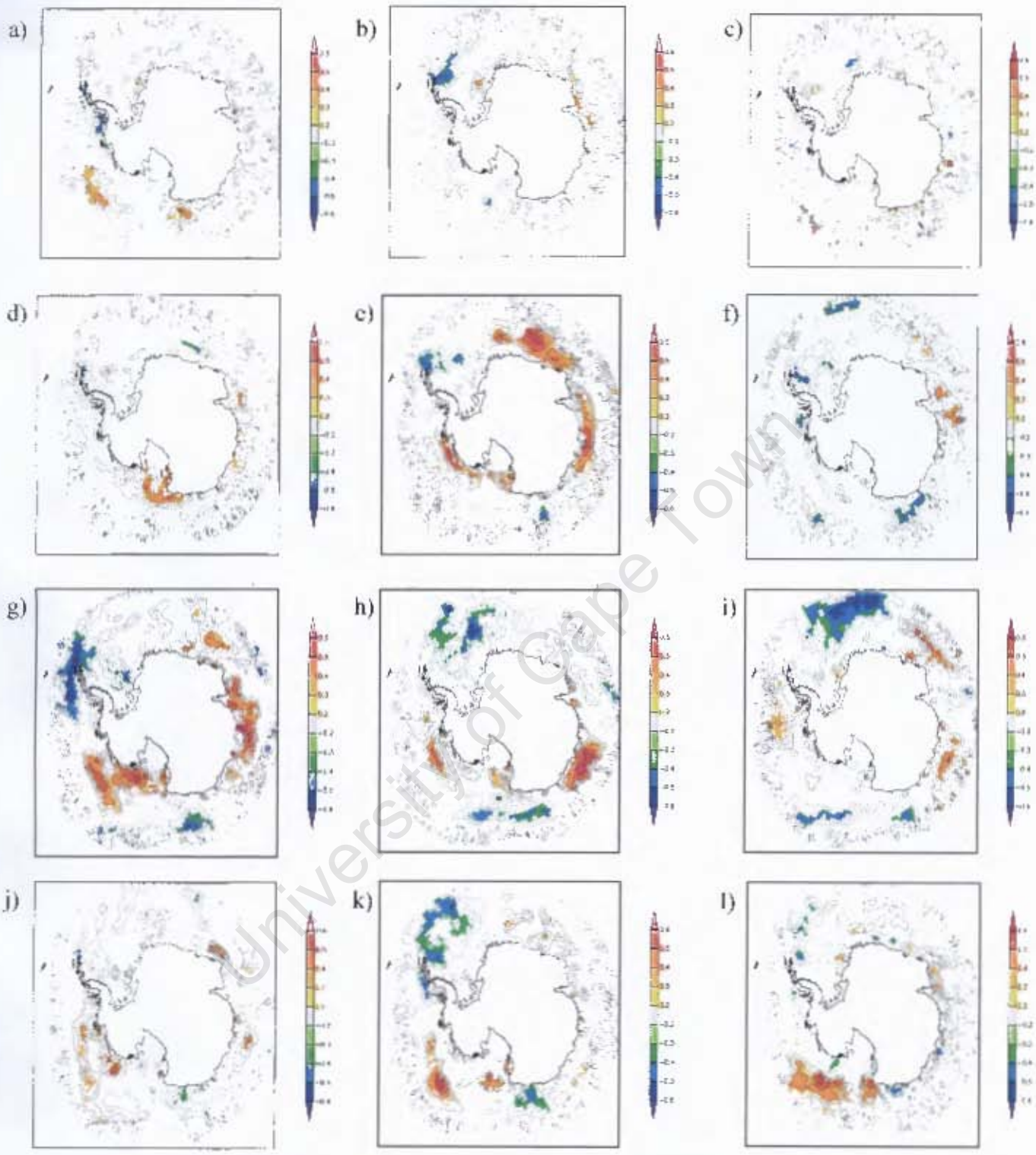


Figure 15: Monthly correlation between sea ice concentration and SAM for the period 1979 to 2007. a) January, b) February, c) March, d) April, e) May, f) June, g) July, h) August, i) September, j) October, k) November, l) December.

## 4. Discussion

The sea ice of the Southern Ocean covers vast areas and thus has numerous impacts on the climate of this region as well as on the fauna and flora residing in its vicinity (Parkinson 2004). One of the most important climate impacts of sea ice is that it reflects most (50-70%) of the incoming solar radiation due to its high albedo. This contributes to keeping the region cool. The sea ice also acts as an insulator thus restricting the exchange of mass, momentum and heat between the atmosphere and ocean. The restriction of momentum reduces wave motion whereas the restriction of heat exchange preserves the ocean heat (Parkinson 2004). The Southern Ocean sea ice is also very important to a wealth of animal and plant life. Despite serving as a platform for animals such as penguins and seals, it also provides a suitable habitat for many microorganisms. The sea ice also provides insulation against the cold polar atmosphere to organisms residing beneath the ice (Parkinson 2004). Consequently, changes in the sea ice of the Southern Ocean will have far reaching consequences. It is thus important to examine and understand the changes in ice cover to fully understand the changes in the environment. Sea ice in the Southern Ocean surrounds the Antarctic continent with no peripheral seas and physical boundaries. Environmental factors such as surface air temperatures, ocean currents, tides, winds, and sea surface temperatures are therefore responsible for the variability of the sea ice cover.



The sea ice area of the Southern Ocean ranges from 1.9 $x10^6$ $km^2$ in summer to 14.5 $x10^6$ $km^2$ in spring. On average, minimum sea ice coverage occurs during February and maximum sea ice coverage occurs in September (Figure 5). This is indicative of the annual cycle of sea ice in that sea ice advance occurs during late summer throughout autumn and into winter whereas sea ice retreat occurs in early spring and summer. It is also evident that the majority of the sea ice advance occurs during autumn. These results are in agreement with the results of Stammerjohn et al. (2008b) who examined annual sea ice retreat and

advance and found that sea ice retreat, on average, began in September and lasted for about 4-5 months. They also found that advance began in February and lasted for about 7-8 months. The annual cycle observed in sea ice is caused by the seasonal cycle of solar isolation and temperature which drives the melting and freezing of ice within each sector (Zwally et al. 2002).

Analysing temperature records for a period of more than 33 years, Vaughan et al. (2003) found a mean warming of 0.8 ± 1.6 °C (century)$^{-1}$ for Antarctica. This and a mean global warming trend of 0.6±0.2°C during the 20$^{th}$ century has led to the popular believe that the polar ice caps are melting. However, warming around the Antarctic continent is not uniform. During the last two decades there has been pronounced warming of the Antarctic Peninsula (Vaughan et al. 2003), while a number of weather stations on the coast and plateau of West and East Antarctica have reported cooling trends (Comiso 2000).

Despite the overall warming of Antarctica the findings of this study indicates that there has been a positive trend in sea ice area and extent (11.0 ± 0.3 x10$^3$ km$^2$yr$^{-1}$ and 12.0 ± 0.4 x10$^3$ km$^2$yr$^{-1}$ respectively) for the Southern Ocean as a whole for the period 1979-2007. A large regional variation is evident in the trend of Antarctic sea ice. Regionally the trends for extent and area are positive for the Weddell Sea sector, the Indian Ocean sector, the western Pacific Ocean sector and the Ross Sea sector (Table 1 and 2). The Bellingshausen/Amundsen Seas sector is the only region that displays a negative trend in sea ice area and extent.

The overall increase observed in the sea ice area and extent for the Southern Ocean supports the findings of Zwally et al. (2002) who found an 11 181± 4190 km$^2$yr$^{-1}$ increase in sea ice extent and 10 860± 3720 km$^2$yr$^{-1}$ increase in sea ice area for the 20 year period 1979-1998. When Cavalieri et al. (2003) examined

sea ice extent trends for the period 1973 to 2002 they found a negative trend of -0.15 ± 0.08x$10^6$ $km^2 decade^{-1}$, which supported the findings of Bjørgo et al. (1997) for the period 1978-1994. The negative trend observed by Cavalieri et al. (2003) can be attributed to the dramatic decrease in sea ice cover that occurred over the period 1973-1977. The decrease in sea ice cover from 1973 to 1976 is part of a sea ice anomaly that started in the late 1960's (Streten 1973). The 1973-1976 decrease was preceded by an increase in sea ice extent from 1968 to 1973. However in 1973 a large positive sea ice anomaly occurred which has been associated with a La Niña event (Streten 1973, Carleton 1989). Zhang (2007) was able to model the increase in Antarctic sea ice with the prevailing warming trends of the atmosphere and the ocean by including coupled ice-ocean-atmosphere interactions in the model. Zhang (2007) found that an increase in the surface air temperature results in an increase in the temperature of the upper-ocean and consequently a decrease in the sea ice growth, leading to a decrease in salt rejection from the new ice. The water density of the upper ocean decreases due to the lower ocean salinity and warmer sea surface temperature (SST). The result of this is a more stable mixed layer which reduces the heat flux available for melting of sea ice. Thus there is an increase in sea ice because ice melting decreases faster than ice growth.

The regional trends in sea ice area and extent indicate that while the Bellingshausen Sea has experienced a significant decrease in sea ice for the period 1979-2007, the Ross Sea has experienced a significant increase in sea ice during the same period. The Weddell Sea, Indian Ocean, and western Pacific Ocean regions also experienced an increase in sea ice during this period but these increases are statistically insignificant. This corresponds to satellite observations of sea ice over the last two decades which indicate that sea ice concentration in the western Ross Sea is increasing and decreasing in the western Antarctic Peninsula/southern Bellingshausen Sea region (Zwally et al. 2002, Parkinson 2004). Historic high surface air temperatures and more southerly surface winds along the Antarctic Peninsula west coast

in 1989 were suggested as the causes of the decrease in sea ice extent in the Bellingshausen Sea from mid-1989 to early 1991 by Jacobs and Comiso (1993). They also reported that a higher than normal ice cover in 1986-87 preceded this retreat (Figure 11).

The sea ice area and extent trends for all the sectors of the Southern Ocean had the same sign. The sea ice extent trends for all the sectors also had bigger magnitudes than the sea ice area trends with the exception of the western Pacific Ocean sector where the sea ice extent magnitude was smaller than that of sea ice area. This implies that the ice cover of the sectors with positive trends are becoming less compact while the sea ice cover of the western Pacific Ocean sector is becoming more compact (Cavalieri and Parkinson 2008). A probable cause for the greater density of the sea ice pack in the western Pacific Ocean could be a reduction in the forcing of the ice divergence by the wind fields (Zwally et al. 2002).

The sea ice area anomalies as well as the extent anomalies for the Southern Ocean show a significant positive trend for the period 1978-2007. The Indian Ocean, Weddell Sea, western Pacific Ocean and the Ross Sea regions all show positive trends in the area and extent anomalies. This means that in these regions and for the Southern Ocean as a whole there is a trend towards smaller negative anomalies and larger positive anomalies as well as a trend towards more positive anomalies. The Bellingshausen/Amundsen Seas region shows a significant negative trend in sea ice area and extent which indicates that in this region there is a trend towards more negative anomalies meaning that sea ice reaches less than average sea ice coverage more often. This negative trend is also indicative of a trend towards smaller positive anomalies and larger negative anomalies.

Temperatures in Antarctica range from a winter average of -60°C to an average of -27.5°C in summer. Thus due to the colder temperatures in winter it is expected that the sea ice coverage would be bigger in winter and the smallest in summer due to the warmer temperatures. Seasonal analysis of sea ice area and extent data demonstrated that in all the regions of the Southern Ocean summer, consistently, had the smallest ice coverage with the exception of the Bellingshausen/Amundsen Seas region where summer and autumn ice coverage had approximately the same magnitude. Contrary to expectation, it was found that, on average, the biggest sea ice coverage occurred during spring and not winter. The sea ice coverage during spring and winter in the western Pacific Ocean, Ross Sea and Bellingshausen/Amundsen Seas regions had approximately the same magnitude. The larger sea ice coverage of spring compared to winter can be explained in light of the annual cycle of sea ice.

Generally, sea ice advance begins in late summer (February) and maximum sea ice coverage is reached at the start of spring (September). Thus it is due to the inclusion of September as a spring month that spring had the biggest sea ice coverage of all the seasons. Even though sea ice retreat starts in spring, it is relatively slow during the first month of spring after which retreat accelerates to reach minimum sea ice coverage in late summer. During winter the Weddell Sea sector has the largest ice extent while the Ross Sea sector has the second largest sea ice extent of the five sectors. This is not surprising since the Ross Sea region is one of the coldest regions and it is also closest to the South Pole. The western Pacific Ocean sector on the other hand is situated furthest from the South Pole and thus has the least ice cover among the five sectors (Zwally et al. 2002).

The seasonal sea ice area and sea ice extent trends for the Southern Ocean are positive during all four seasons. The biggest trend for sea ice area occurs during autumn whereas the biggest trend for sea ice extent occurs during spring. Both the Ross Sea region and the Indian Ocean region show positive trends

during all four seasons for seasonal sea ice area and extent. The seasonal trends for sea ice area and sea ice extent in the Weddell Sea region and the western Pacific region show positive trends during summer, autumn, and winter but show negative trends during spring. Negative trends for seasonal sea ice area and sea ice extent were observed during all four seasons for the Bellingshausen/Amundsen Seas region. Larger sea ice cover in the Indian, Pacific, Ross and Amundsen sectors is caused by the colder air in these regions. During autumn and winter the effect is the strongest because it is during these seasons that the biggest changes in temperature occur. However, the marginal decrease in winter sea ice concentration in the Weddell and Bellingshausen sectors is a result of an increase in air temperature. During autumn, larger temperature differences occur in these regions which induce lower ice extent thus leading to lower autumn ice production (Lefebvre and Goosse 2005). Changes in the annual cycle of sea ice have been observed by Stammerjohn et al. (2008b); however, these changes differ from region to region. These authors determined that the sea ice season in the Antarctic Peninsula and southern Bellingshausen Seas regions are decreasing whereas the sea ice season in the western Ross Sea region is increasing.

All results for sea ice area and sea ice extent of this study support the results of Cavalieri and Parkinson (2008) except the results for seasonally averaged sea ice area and extent. Cavalieri and Parkinson (2008) found that the magnitude of sea ice area and of sea ice extent for winter is always greater than that of spring as one would expect, however this study revealed that the magnitude of spring sea ice area and extent is generally greater than that of winter. This discrepancy can be explained by the fact that Cavalieri and Parkinson (2008) used data from October to December to calculate the spring averages and data from July to September were used to calculate winter averages whereas in this study the spring months were classified to be September to November and winter months were taken to be June to August. The results of Cavalieri and Parkinson (2008) also indicate that the seasonally averaged sea ice

area and extent generally separates out for the different seasons, but in this study the seasons do not separate out as clearly.

Shifts in the atmospheric circulation and associated temperature distributions are important causes of variation in sea ice. Changes in ocean circulation and associated water mass distributions are also related to sea ice variability but these factors were not considered in this thesis. Sea ice growth and decay are influenced by the atmospheric temperature distribution while the north-south position of the ice edge is determined by the atmospheric circulation. In the Southern Hemisphere extratropics and high latitudes, the primary mode of variability in the atmospheric circulation is the SAM (Marshall 2003). During the positive phase of the SAM, a positive geopotential height anomaly occurs over mid-latitudes and a negative geopotential height anomaly occurs over the polar cap. This causes the storm track over the Southern Ocean to strengthen and shift poleward (Thompson and Wallace 2000). Thus, the SAM represents a shift in the strength and the position of the subtropical jet that is zonally symmetrical. As a result of this zonally symmetric shift, a positive SAM phase corresponds to a stronger more poleward jet while a weaker lower-latitude jet is associated with the negative phase of the SAM (Sen Gupta and England 2007b).



The SAM index shows a significant positive trend for the period 1957-2007 (Figure 8). This positive trend observed for the past five decades supports the findings of Yuan and Li (2008) for the period 1950 to 2003, Thompson and Wallace (2000) for the period 1958-1997, and Thompson et al. (2000) for the period 1950-2000. The positive trend in the SAM index indicates that there has been a shift towards the positive phase of the SAM i.e. a shift from mostly negative to mostly positive indices, and this shift mainly occurred during the 1970's. From Figure 12 and 13 it is evident that this trend has been occurring since the mid-1960's through to the present day. However in 1964 there was an abrupt

downward spike in the SAM index and Angell (1998) suggested that a potential cause for this was the volcanic eruption of Mount Agung in 1963. The negative impact on tropospheric temperatures of this eruption was greater in the southern mid-latitudes than in the high latitudes (Angell 1998), which would act to weaken poleward geopotential gradients and thus decrease the strength of the SAM (Marshall 2003). The trend towards the more positive phase of the SAM indicates a strengthening in westerly winds due to an increasingly higher pressure in the midlatitudes and a lower pressure over Antarctica (Yuan and Li 2008). Thompson and Solomon (2002) suggested that ozone loss and global warming is responsible for the increasing trend observed in the SAM index. They also suggested that the rapid surface warming and sea ice retreat in the western Antarctic Peninsula is a result of the increasing trend in the SAM.

The seasonal correlations between the SAM index and sea ice concentration indicate that there is a positive correlation for all seasons in the Indian Ocean sector, the western Pacific Ocean sector and the southern Bellingshausen/Amundsen Seas sector. However, the Weddell sector shows negative correlations between the SAM index and sea ice concentration during all seasons while the western Antarctic Peninsula shows negative correlations only in summer and autumn. This corresponds to the findings of Kwok and Comiso (2002), Liu et al. (2004) and Lefebvre et al. (2004) who showed that the response of sea ice to SAM variability appears to be mainly characterized by an increase in the Ross and Amundsen sectors and a decrease in the Weddell and Bellingshausen sectors.

The seasonal and monthly correlations between sea ice extent and the SAM index displays a dipole, with less ice in the Weddell Sea and more ice in the Ross Sea (Figures 14 and 15). The cause of this non-annular pattern appears to be a negative sea level pressure anomaly in the Bellingshausen/Amundsen Seas when the SAM is high (Lefebvre and Goosse 2005). Lefebvre et al. (2004) suggested that it is this

non-annular spatial component of the SAM variability that is responsible for the regional sea ice response to the SAM. The dipole-like feature of the SAM creates a meridional component to the otherwise zonally symmetric surface wind stress field. The result of this is warm northerly winds in the western Weddell and Antarctic Peninsula region during a positive SAM phase and cold southerly winds in the Amundsen-Ross Seas (Stammerjohn et al. 2008a). The southerly winds in the Amundsen-Ross Seas contribute to positive sea ice anomalies whereas the northerly winds contribute to negative sea ice anomalies in the western Weddell and Antarctic Peninsula region, resulting in the dipole observed (Lefebvre et al. 2004). Thus an increase in SST, due to the warm northerly winds associated with a positive SAM phase in the Weddell and the Antarctic Peninsula regions, causes a decrease in sea ice concentration in these regions. In the southern Bellingshausen/Amundsen Seas and the western Ross regions the cold southerly winds cause a decrease in SST and consequently an increase in sea ice concentration during the positive phase of SAM (Lefebvre et al. 2004). Figure 14 and 15 also display a wave number 3 circulation pattern which is unusual since the Gong and Wang (1999) definition of the SAM was used for this study, however, this was beyond the scope of this study.

During the positive phase of the SAM Ekman pumping is stimulated which results in higher upward oceanic velocities close to the Antarctic continent. The result of this is the melting of the ice due to upwelling of warmer water in the Indian, Pacific, Ross and the Bellingshausen/Amundsen regions. In the Weddell Sea the increased Ekman pumping also causes an increase in surface salinity which destabilizes the water column. The result of this is a decrease in sea ice area due to increased mixing layer depth (Lefebvre and Goosse 2005).

Another explanation for the dipole observed between the sea ice extent in the Weddell Sea and the Ross Sea is the Antarctic Dipole. Yuan and Martinson (2001) used the term "Antarctic Dipole" to describe the

predominant mode of interannual variability in the surface air temperatures and sea ice cover of the Southern Ocean. The Antarctic Dipole is a part of the ENSO global anomaly and represents an out-of-phase relationship between temperature and ice anomalies in the Atlantic and central/eastern Pacific sectors of the Southern Ocean (Yuan and Martinson 2001). This means that the Pacific centre of the dipole experiences warm temperatures and less sea ice during El Niño events, while, simultaneously, the Atlantic centre experiences cold temperatures and more sea ice. The Pacific Ocean experiences less ice during El Niño events due to a weakened polar front jet and an enhanced subtropical jet while more ice occur in the Atlantic Ocean due to the more poleward direction of the subtropical jet. During La Niña events the central/eastern Pacific sectors experience a decrease in temperature which results in an increase in sea ice whereas the Atlantic sectors experience a decrease in sea ice (Rind et al. 2001).

Warm sea surface temperatures in the tropical Pacific enhance the tropical convection and meridional thermal gradient during El Niño events. The result of this is strengthening and an equatorward shift of the subtropical jet in the South Pacific due to the contraction and strengthening of the Hadley Cell. However, in the tropical Atlantic there is an eastward shift in the zonal circulation which expands and relaxes the Hadley Cell resulting in a poleward shift of the subtropical jet (Rind et al. 2001). Concurrently in the Atlantic the Ferrell Cell is weakened in response to El Niño events while it is strengthened in the Pacific. This has a direct influence on the formation of the Antarctic dipole through the decrease in the poleward heat flux that occur in the Atlantic and the increase poleward heat flux that occur in the Pacific (Liu et al. 2004). During El Niño events a high-pressure centre exists in the Bellingshausen Sea. This creates a regional circulation resulting in a northward flow of cold air in the Weddell Sea and a southward flow of warm air in the Pacific Ocean thus contributing directly to the formation of the Antarctic Dipole (Yuan and Martinson 2001).

The survival of many species in the Antarctic ecosystem are closely linked to the sea ice and thus changes in sea ice in response to the SAM will have a direct impact on the Antarctic ecosystem. It is thus important that efforts are made to determine the impact that SAM related changes in sea ice will have on the biological components of the ecosystem.

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