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SEA ICE EXTENTION AROUND ANTARCTICA: ASSOCIATION WITH AUSTRALIAN RAINFALL VIA CHANGES IN SOUTHERN HEMISPHERE CYCLONE AND ANTICYCLONE BEHAVIOR

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1. INTRODUCTION

Interactions occurring over the Southern Ocean between the Antarctic sea ice, the atmosphere and the ocean form a vastly complex system. The sparcity of data available over this region has traditionally greatly inhibited the study of this system, a situation that has been significantly improved in recent times by the advent of a range of satellite products. Understanding of Antarctic sea ice and its interactions with the Southern Ocean circulation is of interest in Australia due to its potential influences on Australian climate.

The aim of this study is to explore the relationship and possible connection between Antarctic sea ice extent and rainfall in southern Australia. As part of this exploration, an examination of regional circulation changes associated with the sea ice extent is performed. Although the relationship between sea ice extent and southern ocean circulation has been the subject of a number of studies (*Simmonds and Budd*, 1991; *Carleton*, 1992; *Simmonds and Wu*, 1993; *Godfred-Spenning and Simmonds*, 1996, amongst others) this is the first detailed analysis performed focusing on the Australian region.

The study is performed for the period for which reliable remotely sensed sea ice data is available, namely 1979-2003.

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2. DATA AND METHODOLOGY

This study consists of two main elements. An initial statistics component examines correlations between sea ice extent and rainfall in southern Australia by means of station data for Melbourne (latitude 37°S, longitude 145°W, elevation 35m) and Perth (latitude 31°S, longitude 116°E, elevation 66m), these two cities being chosen as representative of typical mid-latitude conditions in the eastern and western parts of Australia respectively. Correlations are performed based on the extent of the entire pack, as well as each of five longitudinal sectors, for both yearly and seasonally averaged data. This work allows for a broad assessment of the relationship between sea ice extent and southern Australian rainfall, guiding the second section of the work.

The second section examines circulation changes in the Australian region associated with different states of the ice given by the cyclone and anticyclone track distributions. This analysis is carried out with the Melbourne University Tracking Scheme, an automatic computer cyclone tracking program.

Several different sources are utilised to assemble the required data, with all sources covering. Sea ice extent data was obtained from NASA's National Snow and Ice Data Center (NSIDC) and was originally produced by the Goddard Space Flight Centre (GSFC). This data is derived from remotely sensed Nimbus-7 Scanning Multi-channel Microwave Radiometer (SMMR) and Defence Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSM/I) passive microwave data, processed with NASA's team algorithm.

For the statistics component of the study, daily minimum and maximum temperature and daily rainfall for both Perth and Melbourne was obtained from the Australian Bureau of Meteorology.

For the circulation analysis, MSLP data from the NCEP/DOE Reanalysis-2 (NCEP2) is used. This updated version of the NCEP/NCAR data set contains several relevant 'fixes', fully detailed in (*Kistler et al.*, 2001) and (*Kanamitsu et al.*, 2002). Although the NCEP2 data set covers a significantly shorter period than the this original product, as it covers the same period for which sea ice data is available, these improvements make it the logical choice here.

The Tracking Scheme was applied to this MSLP data to assemble the required track statistics. Developed by *Murray and Simmonds* (1991a, b) and undergoing a minor revision in 1999 (*Simmonds and Murray*, 1999a; *Simmonds et al.*, 1999), the Melbourne University Tracking Scheme has been used in many studies and has proven to be very robust and reliable. It has been applied to observational analysis (eg *Jones and Simmonds*, 1993, 1994; *Godfred-Spenning and Simmonds*, 1996), as well as to the output from model climate and sensitivity experiments (eg *Simmonds and Wu*, 1993; *Murray and Simmonds*, 1995; *Simmonds and Jacka*, 1995) and has been used to reveal many aspects of synoptic behaviour in long data sets.

Cyclone and anticyclone system density and system depth (a measure of system strength) are analysed for periods of anomalously high and anomalously low sea ice extent, with the aim of identifying any corresponding anomalies in the circulation associated with these states of the ice. This analysis explores the role of circulation changes in any possible relationship apparent from the correlations.

3. RESULTS AND DISCUSSION

Initial statistical investigations suggested that, due to opposing sea ice extent anomalies in different sectors of the ice, anomalies in the pack as a whole are unlikely to yield any significant relationship. This lead to the exploration of connections, via the calculation of correlations between Perth and Melbourne rainfall and each of five sectors of the ice shown in figure 1 (where the Bellinghausen and Amundsen sectors are combined).

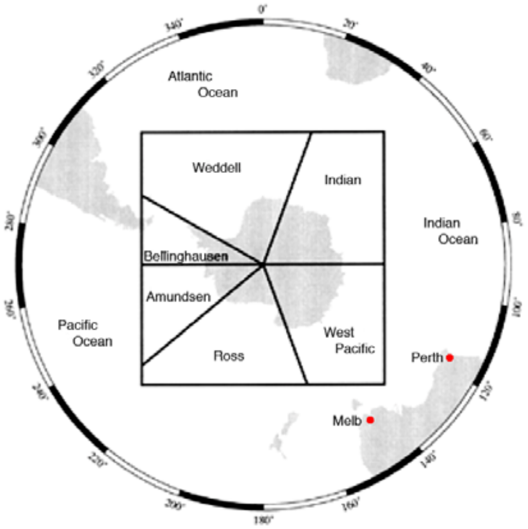


Figure 1: Southern Ocean map in polar stereographic projection. The pie sections delineate the six main regions highlighted in this study (from *Stammerjohn and Smith*, 1997). Locations of Perth and Melbourne are shown.

Results from this analysis suggest that local and slightly 'upstream' sectors show highest statistical associations, with rainfall in Perth most strongly associated with sea ice extent in the Indian Ocean sector, and that of Melbourne showing strongest associations with the state of the West Pacific sector. This is consistent with interaction occurring between sea ice and local cyclone and anticylone tracks in the Australian region.

Yearly averaged data yielded low correlations, while seasonally averaged data revealed associations to be most significant in winter. This seems reasonable, given that this is the time when the ice is physically closest to the Australian continent. It is also a time when the passage of cyclones and associated frontal systems dominates the weather experienced in the region, increasing the direct effect of changes to the passage of these systems.

The winter correlations between Perth and the Indian Ocean sector, and Melbourne and the West Pacific sector are negative, with low sea ice extent in these sectors associated with high rainfall in the corresponding region and visa versa.

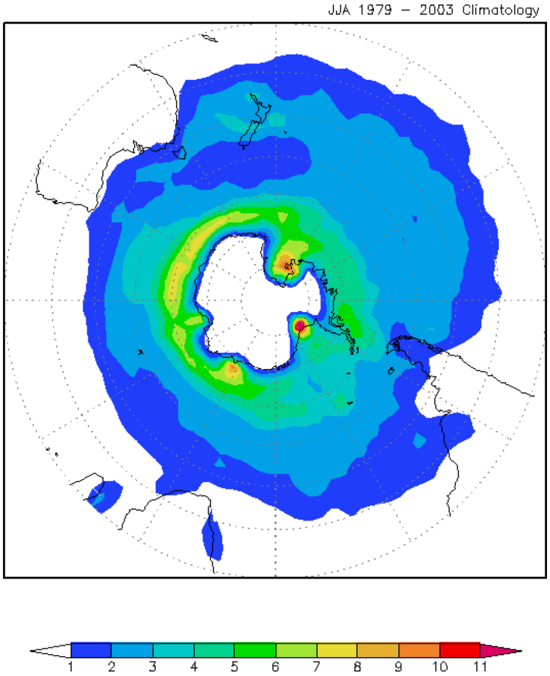
Table 1, shows correlations between Perth precipitation and sea ice extent for each longitudinal sector, for each season. The winter correlation of 0.49 with the Indian Ocean sector clearly stands out, a result that varies significantly from zero at a 99% confidence level (given be a two tailed student t-test).

Table 1: Perth rainfall data correlations with individual sea ice sectors for individual seasons, 1979-2003 (bold font represents correlations significant above the 99% level)

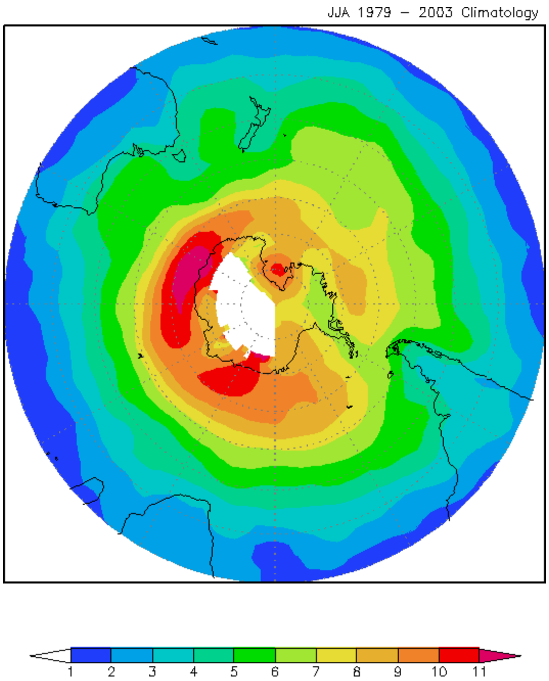
	Weddell	Indian	W.Pac	Ross	Belling
DJF	0.10	0.36	-0.32	0.04	-0.12
MAM	-0.27	-0.14	-0.37	-0.13	-0.05
JJA	0.21	**-0.49**	0.10	-0.17	0.01
SON	0.03	-0.02	-0.32	0.29	-0.21

We next explore the mechanisms responsible for these associations, and specifically target the role of the Southern Ocean synoptics in this. Based on the statistics findings, this analysis with the tracking scheme focused on the Indian and West Pacific sectors of the ice, looking only at winter. Specifically, separate composites of track statistics are constructed for years when the winter average sea ice extent in each of these influential sectors was anomalously high and anomalously low.

Figure 2 shows climatologies of (a) cyclone system density and (b) average cyclone depth for winter for the period studied. System density refers to the average number of systems within a given grid box per analysis, giving information about the relative time for which a region is under the influence of cyclonic (or anticyclonic) systems. Average system depth refers to the average depth of all the systems that pass over a given grid point for the specified period. The depth itself can be thought of as the difference between the pressure at the 'edge' of the system, and that at the centre, and is widely regarded as the best available measure of system strength (*Simmonds et al.*, 1999).



(a) Cyclone System Density



(b) Cyclone Mean System Depth

Figure 2: Climatologies for JJA, 1979-2003 south of 20°S in South Polar stereographic projection for (a) Cyclone system density ($10^{-3} cyclones/(^{\circ} lat.)^2$) and (b) Cyclone mean system depth (*hPa*)

Any changes in synoptic conditions can be directly related to rainfall. In general, low pressure is associated with ascending air, leading to cloud formation and precipitation, while the subsidence within a high produces generally clear conditions. This produces a strong relationship between MSLP and rainfall on a synoptic time-scale. Following a drop in rainfall in SWWA in the mid 1970's, several studies have investigated the relationship between MSLP and rainfall on climatological time scales in this region. *Allan and Haylock* (1993), for example, show that over the period 1886-1989, a strong inverse relationship existed between Perth rainfall and MSLP, with approximately 60% of the total variance in winter rainfall explained by fluctuations in MSLP, irrespective of the time scale considered. Similarly, *Smith et al.* (2000) calculate the correlation between JJA rainfall and MSLP in Perth for the period 1907-1994 at -0.83.

As system density provides information about the dominant synoptic patterns over a given region, from the above discussion, it becomes apparent that this parameter has a large impact on rainfall. This relationship has been investigated in several studies. *Smith et al.* (2000), looked at the impact of system density, in relation to rainfall in south west Western Australia. They separately analysed two decades, 1959-1968 and 1969-1978, representing the years immediately prior to and following the commencement of rainfall decreases in the region. Comparing the two, they observed a marked decrease in cyclone system density over the SWWA region and surrounding oceans, coinciding with the decrease in rainfall.

Likewise, the average strength of systems passing over a given region will impact on rainfall. This was investigated in the Australian region by *Simmonds et al.* (2001). They found not only significant associations between total rainfall and system depth over much of southern Australia, but also that to the south of the continent. This is consistent with the fact that stronger cyclonic systems tend to have stronger associated frontal systems. Hence an increase in depth to the south of Australia could result in more intense frontal systems hitting southern Australia, in turn, impacting on rainfall.

The analysis performed here, appears to show some consistency with the statistical findings. Winter cyclone and anticyclone behaviour, given by these two track statistics, show clear anomalous patterns associated with different states of Antarctic sea ice. Generally, low sea ice is associated with increased cyclone system density over regions of southern Australia and vice versa. Figure 3 shows cyclone system density anomalies for (a) the five highest and (b) five lowest years of sea ice extent in the West Pacific sector. Large areas of negative anomalies are observed over the south east of Australia in the case of high sea ice extent, with positive anomalies occurring over the region when the ice is low. These results are consistent with the observed negative correlations between ice and rainfall in Melbourne and Perth, given that regions of increased cyclone system density are likely to receive more rainfall.

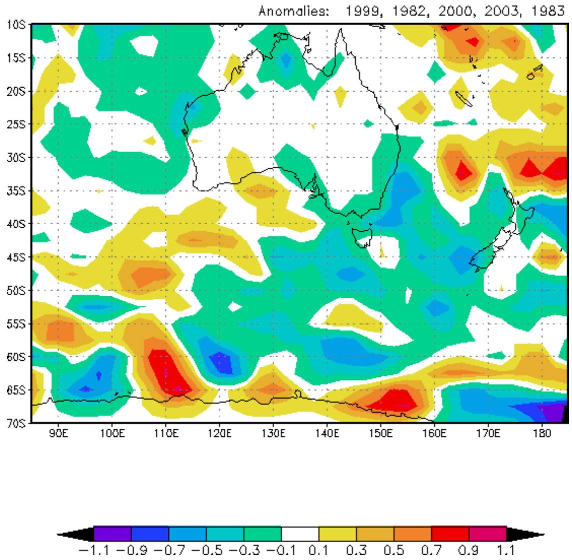
Furthermore, results are consistent with correlations regarding regional influences of each sector, suggesting the strongest association exists between the Indian Ocean sector and the Perth region, while the Melbourne region is most strongly associated with the state of the West Pacific sector. Looking again at figure 3, a large area of negative anomalies is observed over the Melbourne region in the case of high sea ice extent in the West Pacific sector, while low sea ice extent is associated with an area of positive anomalies over this region. In contrast, very little signal is seen over the Perth region, suggesting that the West Pacific sector has weaker links to this region.

Similarly, figure 4 shows anticyclone system density for the same (a) five highest and (b) five lowest winters of sea ice extent in the West Pacific sector. These results appear to complement those for the cyclone analysis, with a similar, but opposing pattern observed, giving positive anomalies over the Melbourne region in the case of high sea ice extent and negative anomalies over this region during years of low sea ice extent. A consistent regional influence is also observed, with the signal over the Melbourne region dominating that over Perth.

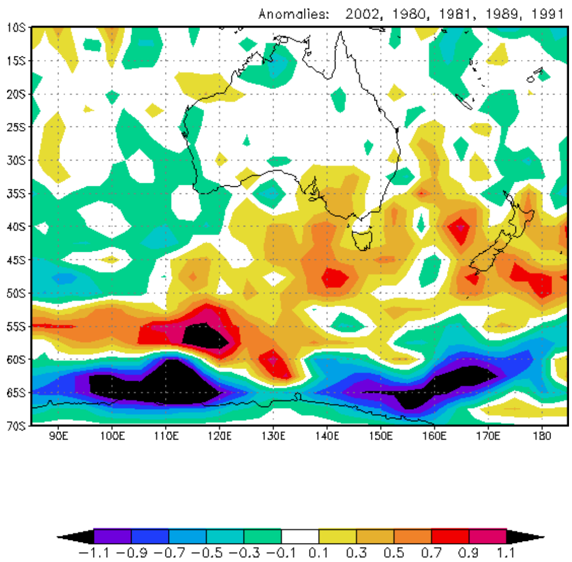
While not discussed in detail here, cyclone and anticyclone depth also show changes associated with these sea ice extend anomalies that appear consistent with correlation results. In agreement with the previously mentioned work of *Simmonds et al.* (2001), areas to the south of the continent appear important with respect to this parameter.

4. CONCLUSIONS

This work suggests that there is a connection between Antarctic sea ice extent, and rainfall in southern Australia. It appears that local and 'upstream' sectors of the ice show the strongest associations, and that these connections are most prominent in winter. Our analysis of cyclone and anticyclone behaviour appears to demonstrate a physical mechanism for this connection, creating a coherent argument for the existence of this link. It remains uncertain from this work if the ice is driving these circulation anomalies, or if it is being driven by them, a relevant topic for future research.

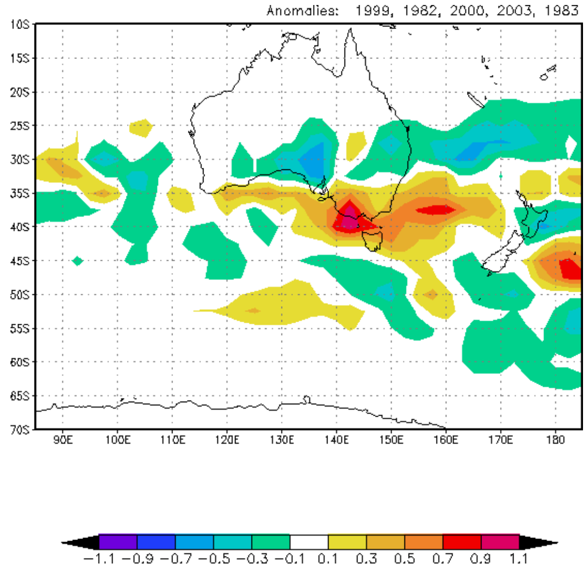


a) High - Anomaly

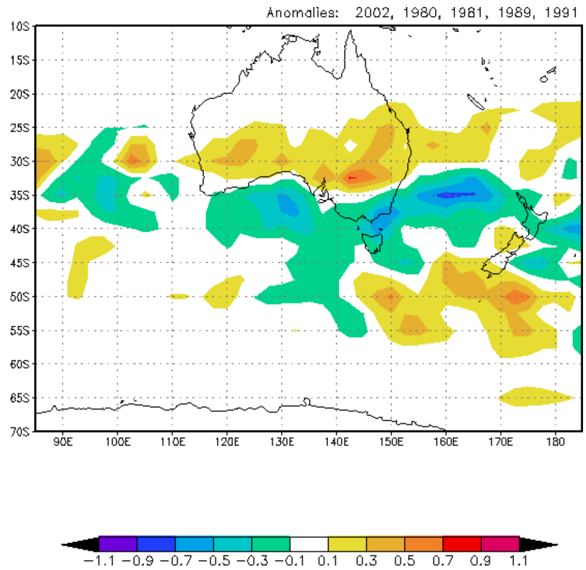


(b) Low - Anomaly

Figure 3: Cyclone system density composites for the (a) five highest and (b) five lowest winters of sea ice extent in the West Pacific sector, 1979-2003 ($10^{-3} cyclones/(^{\circ} lat.)^2$)



a) High - Anomaly



(b) Low - Anomaly

Figure 4: Anticyclone system density composites for the (a) five highest and (b) five lowest winters of sea ice extent in the West Pacific sector, 1979-2003 ($10^{-3} cyclones/(^{\circ} lat.)^2$)

A limited investigation was performed into the possible role of the El Niño/Southern Oscillation (ENSO) and the Southern Annular Mode (SAM) in this relationship. Though a major influence on Melbourne rainfall, it was found that ENSO is unlikely to play much of a part. It seems that SAM, on the other hand, is likely to be of more importance in this context, with results indicating that the prominent influence of SAM on Southern

Ocean circulation is likely to be intimately involved in this relationship.

Further aspects of these mechanisms are currently being investigated.

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