Climate Dynamics (1989) 3:207-220

Climate Dynamics

Antarctic sea-ice relationships with indices of the atmospheric circulation of the Southern Hemisphere*

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Abstract. A link between the Antarctic sea-ice extent and low-frequency atmospheric variations, particularly ENSO, has been suggested by recent modeling and empirical studies. This question is examined here using a high-resolution (by week, by region) data base of Antarctic sea-ice extent for the 1973-1982 period. Although of relatively short duration by Northern Hemisphere standards, such a data base offers an opportunity rare in Southern Hemisphere climate studies. The sea-ice variations are examined in the context of longer-term indices of the large-scale atmospheric circulation. These are a Southern Oscillation Index (SOI) and an index of sea-level pressure (SLP) wavenumber one in the Southern Hemisphere extratropics. The indices are updated through 1982, and their associations with regional-scale pressure indices in the Australia-New Zealand sector are also examined. The 1973-1982 period is anomalous when compared with the period 1951-1972. Correlation analysis of the monthly sea ice and circulation index values reveals that much of the apparent link between the ice and the SOI suggested in previous studies arises from autocorrelations present in both data sets and the strong annual cycle of sea-ice extent. Removing these effects from the data and re-running the correlations reveals that most of the resulting "significant" associations between the ice and one or other of the circulation indices can probably be explained on the basis of chance. In order to reconcile these findings with previous studies that show some strong ice-circulation interactions on regional scales, only those months in which significant correlations occur between both large-scale circulation indices and the sea ice are examined further. These occur preferentially in the Ross and Weddell sectors, which constitute the regions contributing most to the variability of Antarctic sea ice. The analysis suggests that the sea-ice-extent changes lag the SOI by several months but may precede changes in extratropical SLP wavenumber one. Confirmation of these tentative regional ice extent-circulation teleconnections necessarily awaits the forward extension of the high-resolution sea-ice data base beyond the 10 years available here.

1 Introduction

Climate variations over extratropical regions of the Southern Hemisphere show generally close associations with changes in the latitudinal extent of circulation features, especially the subtropical anticyclones (Pittock 1973, 1980; Streten and Pike 1980a) and the middle-latitude westerlies (Trenberth 1976a; Streten 1977; Salinger 1980). Numerous studies in recent years demonstrate that such regional variations in circulation climate often manifest the coupled ocean-atmosphere ensemble of El Nino Southern Oscillation (ENSO) (e.g., Streten 1982; Pittock 1984; Nicholls 1985; Gordon 1986). Teleconnections to the tropical ENSO phenomenon occur in preferred regions of the southern extratropics (Streten 1975; van Loon 1984; van Loon and Shea 1987; Mo and White 1985; Meehl 1988), and persist via sea-air interactions (Trenberth 1975a; Dyer 1979; Streten 1983a; van Loon and Shea 1987). Further, these teleconnections may involve the Antarctic (Zillman and Johnson 1985; Krishnamurti et al. 1986). Thus, Savage et

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* This paper is based on material presented at the Conference on Mechanisms of Interannual and Longer-Term Climatic Variations held at the University of Melbourne, Australia: December 8-12, 1986

al. (1988) identify a lagged signal of the ENSO in Antarctic temperatures and surface winds.

The potential role of the high latitudes in global climate variations is enhanced by the large-scale thermal effects of the sea-ice cover (Fletcher 1969). This is particularly so in the Antarctic where ice anomalies tend to be large and persist over several months (Lemke et al. 1980), especially in the embayments (Streten and Pike 1980b; Jacka 1983, Chiu 1983a). The ice variations are reflected in a number of meteorological elements both within and outside the sea-ice zone (Budd 1982). The large annual variation of the sea ice (see Fig. 1), which is of the order of 17×10^6 km^2 (Zwally et al. 1983), makes it probably the most significant surface climate variable on seasonal time scales for the southern extratropics. Thus, changes in the meridional temperature gradient effected by variations of the sea-ice extent should, by application of the thermal wind rule, be manifest as fluctuations in the westerlies over higher latitudes. While this is generally supported for certain times of the year by empirical studies (Streten and Pike 1980b; Wendler and Nagashima 1987), the higher-latitude responses generated in GCM experiments are not always intercomparable. These appear to be largely model dependent (cf. Mitchell and Hills 1986; Simmonds and Dix 1986). However, these model studies indicate some quite large tropical, as well as extratropical, atmospheric responses when anomalies of the Antarctic sea ice are specified in the models. The former appear to have an ENSO signature [e.g., Fig 7c in Mitchell and Hills (1986); Figs. 5 and 6 in Simmonds and Dix (1986)].

Empirical studies linking ENSO with Antarctic sea-ice variations have been few, owing mainly to the lack of a long-term sea-ice data base. Sea-ice extent in the Ross and Weddel Seas for the "cold" ENSO event winter of 1973 shows substantial departures from the 5-year (1972-1977) means (Streten 1983b). Monthly associations between a Southern Oscillation Index (SOI) and the total area occupied by the Antarctic sea ice were derived for the 1972-1980 period by Chiu (1983b). He shows some strong SOI-ice correlations, including a lead of the winter sea ice with respect to SOI; however, the contribution to this result of the temporal autocorrelations present in both data sets or of the large annual cycle of ice extent were apparently not examined. Carleton (1988) shows the effects on the pack ice of the Weddell Sea of the higher-latitude circulation changes associated with extreme phases of ENSO using historical observations. Some convincing evidence for cross-hemispheric influences of the Antarctic sea-ice extent on the West Pacific subtropical high and the hydroclimatology of China are presented by Peng and Domros (1987). However, the potential physical reasons underlying such associations were not explored.

The present paper examines the question of a link between the Antarctic sea ice and the broad-scale atmospheric circulation of the Southern Hemisphere tropics and extratropics. High-resolution (by week, by region) sea-ice data are available for the 10-year period 1973-1982. While not a long period by Northern Hemisphere standards, these data offer an opportunity rare in Southern Hemisphere surface — climate interaction studies. This study builds on that of Chiu (1983b) by examining the ice-circulation interactions in the context of the autocorrelations present in both variables, and the large annual cycle of the sea ice. The relationships are also examined on a regional scale. It is found that many of the "significant" correlations between the two variables, at least for the period 1973-1982, can be explained as chance occurrences arising from the large size of the correlation matrices. At the same time, some possibly meaningful ice-circulation associations are identified for the Ross and Weddell Sea sectors. These warrant study in the future as the sea-ice record is extended forward in time and our knowledge of the natural variability of Antarctic sea ice and Southern Hemisphere circulation becomes better defined.

2 Circulation indices and their interrelationships, 1951-1982

2.1 Large-scale indices: SOI, TPI

The lack of reliable long-term spatial analyses of the Southern Hemisphere atmospheric circulation necessitates the use of synoptic indices that are based on pressure (or tropospheric height) differences for station pairs across widely separated latitudes or longitudes (e.g., Trenberth 1976a; Streten and Pike 1980a; Streten 1982; Rogers 1983; Kidson 1988). This technique is, accordingly, used in the present analysis. The longer-term nature of the indices offers a necessary context within which to place the ice-circulation results determined for the 1973-1982 period. Variations in the broad-scale circulation of the Southern Hemisphere tropics and extratropics can be determined using, respectively, an SOI and a Trans-Polar Index (TPI) (see Fig. 1). While there exist

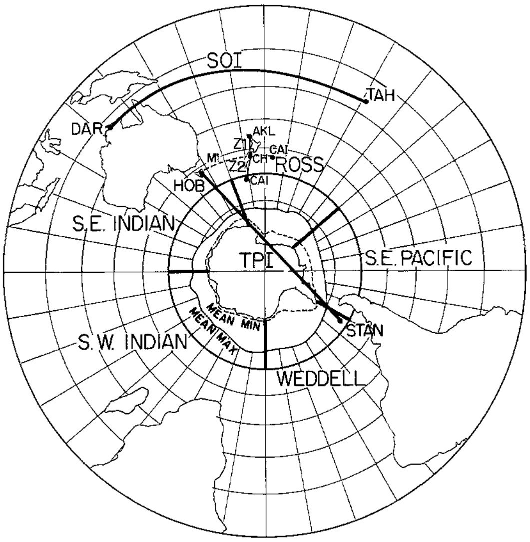

Fig. 1. Map of the Southern Hemisphere showing broad-scale circulation indices (Troup's SOI, Trans-Polar Index), regional zonal and meridional pressure indices (Z1 — Δp Auckland-Christchurch; Z2 — Δp Christchurch-Campbell Island; M1 — Δp Hobart-Chatham Island) and five sectors for the Antarctic sea ice (refer to text). The mean minimum and mean maximum ice limits for 1973-1982 are taken from Jacka (1983)

several measures of the Walker Circulation, the most preferred for diagnostic studies is the SLP index Tahiti minus Darwin (Trenberth 1984). Although Tahiti-Darwin SOI may be determined in slightly different ways (e. g., Parker 1983), that originally developed by Troup (1965) has proven reliable (Ropelewski and Jones 1987). In the Troup SOI, the SLP anomaly difference Tahiti minus Darwin is normalized to the standard deviations of the differences for a given record length. In the present study, this period is 1932-1977. The Troup SOI was provided by A. Barrie Pittock (personal communication 1985) and updated to 1985 by the author. Figure 2 shows the mean annual values of SOI for the 1951-1985 period. The large interannual variations in the index for the period are evident. The major "warm" ENSO event of 1982-1983 contrasts strongly with the "cold" (anti-El Nino) years of 1974 and 1975. Superimposed on Fig. 2 is a regional-scale circulation index for the Tasman Sea (the M1 index) which is discussed in detail below. The antiphase relationship between SOI and M1 is apparent.

The TPI (Pittock 1980, 1984) is a measure of extratropical SLP wavenumber one, which dominates the mean pressure and height fields (Trenberth 1980) and also contributes to the interannual variability of the zonal westerlies (Rogers and van Loon 1982). The TPI is the normalized pressure anomaly difference Hobart minus Stanley (Fig. 1). It is significantly correlated with precipitation over Australia, South Africa and Argentina/Chile (Pittock 1984 — his Fig. 2). In order to evaluate the interrelationships among circulation indices and the Antarctic sea ice, it was first necessary to update the original Pittock (1980) TPI from 1961 through 1982. (A copy of the monthly values is available from the present author.) The annual mean values of the TPI for the 1951-1985 period are plotted in Fig. 3. A lack of SLP data for Stanley in 1961 and again after 1981 did not enable annual values to be calculated for those years. However, for the post-1981 period the SLP data for Ushuaia (55° S, 68° W) were substituted for Stanley (52° S, 58° W). This is permissible given a correlation of the annual values of SLP for Stanley and Ushuaia of 0.814 over the 1951-1980 period. The latter is statistically significant at better than the 95% confidence level. Small differences in monthly normalized TPI values between Pittock's (1980) and the present tabulations occur for the overlapping period 1951-1960 (Fig. 3). They arise due to the use of slightly different long-term means and standard deviations.

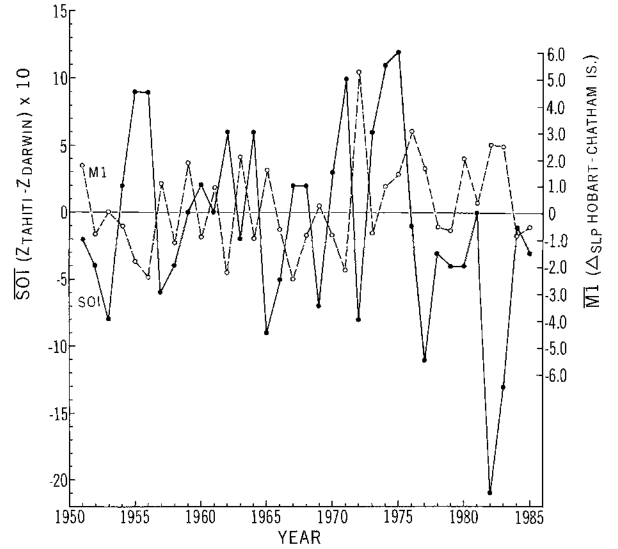

Fig. 2. Annual values of Troup's SOI *(solid line)* and the M1 index *(dashed line)* for the 1951-1985 period (refer to text)

There is no statistically significant trend in the TPI for the full period. However, there is an apparent tendency for the interannual variations of TPI to display less amplitude in the more recent part of the record (Fig. 3). This may relate to the change in the phase and/or amplitude of wavenumber one that occurred in the 1951-1982 period compared with the 1941-1960 period studied by Pittock (1984). This is given by the lack of cor-

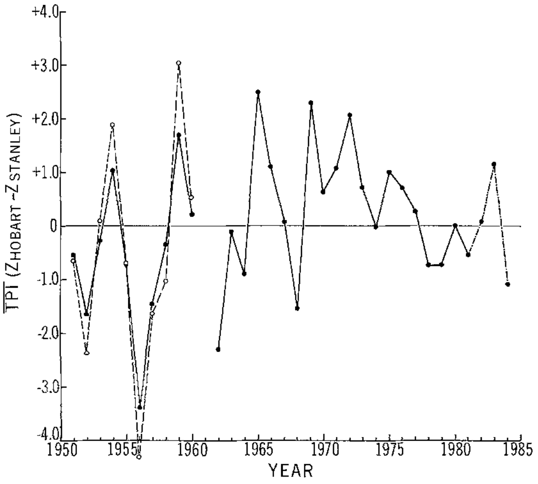

Fig. 3. Annual values of Pittock's Trans-Polar Index (Hobart-Stanley) for the 1951-1984 period. The values in the 1951-1960 period *(dashed line)* are based on standard deviations for an earlier time period (Pittock 1980). Insufficient data are available for 1961. The *chain line* connecting values in the 1981-1984 period indicates a TPI based on the SLP anomaly difference, Hobart minus Ushuaia (refer to text)

relation between the mean annual SLP at Stanley and at Hobart in the 1951-1982 period ($r = -0.115$, cf. $r = -0.68$ for 1941-1960), and is consistent with other studies (e.g., Trenberth 1980; Swanson and Trenberth 1981; Rogers and van Loon 1982; Mo and van Loon 1984, 1985) that show temporal changes in the Southern Hemisphere waves. These observations raise the issue of the "best" stations to use in a Southern Hemisphere Trans-Polar Index and the time periods to which they are applicable. This question is to be addressed fully elsewhere. However, given that the TPI remains a useful indicator of the apparent preference for the southern circumpolar vortex (SCPV) to be displaced towards either the Australian or South American sectors, the index originally proposed by Pittock and applied in other studies of recent circulation climate variations (e.g., Rogers and van Loon 1982) is the one used here.

2.2 Regional-scale indices: Z1, Z2, M1

As useful as large-scale circulation indices are for studies of climate variations, they provide only a gross representation of a picture that may contain many subtleties (Trenberth 1976a). Regional-scale indices that selectively depict the behavior of atmospheric circulation systems in key geographic locations ("centers of action") also need to be examined. These have included the latitude of the subtropical high (Pittock 1973, 1980) and the strength of the extratropical westerlies (Rogers 1983), both of which can be measured along key longitudes. An analysis of the patterns of variability of circulation in the Australia-New Zealand sector by Trenberth (1976a) identified several useful regional SLP indices. Of these, three are selected for analysis and update for the present study. They are the two zonal indices Z1 and Z2 representing, respectively, the pressure difference Auckland-Christchurch and Christchurch-Campbell Island, and the meridional M1 index, or Δp Chatham Island-Hobart (Fig. 1).

On an annual basis, the sea-level pressures at Auckland and Campbell Island are uncorrelated for both the full 1951-1982 period and the 1973-1982 subperiod. As Table 1 shows, the two zonal indices are not correlated in the 1951-1982 period (see also Trenberth 1976a) but are significantly correlated ($r = 0.735$, $p \leq 0.05$) for the 1973-1982 subperiod. The M1 index is a useful indicator of the trough in the Tasman Sea. The wave has a strong half-yearly component related to variations in the position and intensity of the circumpolar trough (van Loon and Rogers 1984). This seasonal variation is negatively related to the Southern Oscillation (van Loon 1984), and is confirmed here by Fig. 2 and Table 1.

Annual mean values of Z1 and Z2 are plotted for the 1951-1985 period in Fig. 4. Large (small) values of Z1 and Z2 indicate strong (weak) zonal flow in the New Zealand sector. The westerlies are stronger and exhibit greater year-to-year variability for the southern (Z2) zonal index (Fig. 4). Further, years that can be considered extreme for one index are not always extreme for the other (e.g., compare 1974 and 1976).

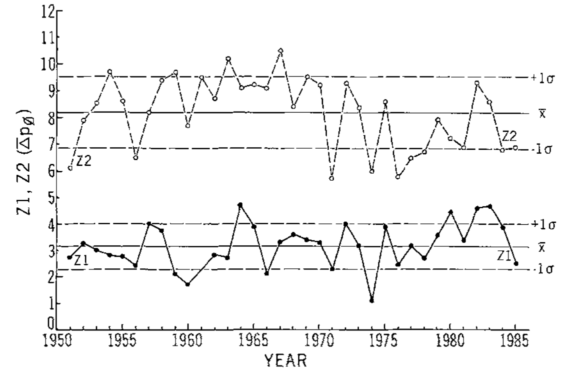

Fig. 4. Annual values of Trenberth's regional Z1 and Z2 zonal pressure indices for New Zealand, 1951-1985. The variability of each is indicated by the one standard deviation limit (assumes zero trend)

Table 1. Correlation matrix of annual circulation, sea-ice indices, (1951-1982) 1973-1982

	SOI	TPI	Z1	Z2	M1	Total ice	Ross Sea ice	S. E. Indian Ocean ice	S. W. Indian Ocean ice	S. E. Pacific Ocean ice	Weddell Sea ice
SOI	1.0										
TPI	0.303 (−0.273)	1.0									
Z1	−0.520 (−0.313)	0.050 (0.010)	1.0								
Z2	−0.231 (−0.170)	0.181 (0.291)	0.735[a] (0.333)	1.0							
M1	−0.322 (−0.466[a])	0.482 (0.514[a])	0.173 (0.183)	−0.120 (0.011)	1.0						
Total ice	0.447	0.425	−0.223	0.404	−0.320	1.0					
Ross ice	0.549	0.581	−0.487	0.068	0.023	0.787[b]	1.0				
S. E. Indian ice	−0.067	0.348	0.110	0.671[a]	−0.038	0.750[a]	0.653[a]	1.0			
S. W. Indian ice	0.067	0.361	0.038	0.271	−0.106	0.692[a]	0.429	0.441	1.0		
S. E. Pacific Ice	0.067	0.130	−0.504	−0.262	−0.255	0.130	0.312	0.155	−0.067	1.0	
Weddell Sea ice	0.275	−0.178	0.201	0.410	−0.499	0.403	−0.131	0.082	0.180	−0.478	1.0

[a] statistically significant at 5% (two-tailed); [b] statistically significant at 1% (two-tailed)

2.3 Annual relationships among circulation indices

The stability through time of relationships exhibited between indices of the atmospheric circulation and climate and, hence, their predictive value is a key focus in climate dynamics (e.g., Ramage 1983; Pittock 1984; Nicholls 1985; Carleton 1987). Pittock (1984) establishes some significant associations between precipitation and temperature variations over the middle-latitude land areas of the Southern Hemisphere and Troup's SOI and the TPI. He finds a significant positive correlation between the two circulation indices when TPI leads by up to 1 year, but cautions against extrapolating beyond the 1931-1960 period for which the climate — circulation relationships were derived. A similar significant lead of the middle-latitude westerlies with respect to phases of ENSO was found by Trenberth (1975a, b).

The correlation matrix of annual values of the circulation indices and the areal extent of the Antarctic sea ice for the sectors depicted in Fig. 1 is given for the 1973-1982 period in Table 1. The presence of only eight significant correlations in a 12 x 11 diagonal matrix is not far above the number expected to occur from chance at the 5% level. The need for caution in assigning physical significance to the ice-circulation results on an annual basis is confirmed by the apparent temporal changes in the associations among circulation indices (see also Trenberth 1976a). For example, the negative association SOI, M1 is not statistically significant in the more recent part of the record (1973-1982), but is significant over the longer term. Similarly, the significant positive association TPI, M1 in the 1951-1982 period is not significant in the 1973-1982 subperiod. Thus, little in the way of convincing evidence for a circulation — ice teleconnection can be found in correlations of the annual values of these variables. However, previous studies (e.g., Chiu 1983b; Wendler and Nagashima 1987) have suggested that such associations are better expressed on monthly time scales, and these are now examined.

2.4 *Monthly relationships between SOI and TPI*

A reliable indication of associations among the broad-scale circulation indices (SOI, TPI) and the sea ice at monthly time scales must consider the presence of serial autocorrelations in the data sets. Once these have been taken into account, estimates of statistical significance that assume independence can be applied to the correlation coefficients. A test conducted on the monthly values of TPI reveals that the autocorrelation is negligible, as in the analysis of the index for the 1931-1960 period (Pittock 1984). While this limits the utility of TPI as a predictive measure of the extratropical circulation, it also removes the need to transform the index prior to undertaking an analysis of its associations with the other indices and with the Antarctic sea ice. This is not the case for SOI, which was determined as having significant autocorrelations of up to about 6 months in the present analysis (see also Troup 1965; Trenberth 1976b, 1984).

One simple but effective way of removing the autocorrelation, while still retaining the maximum number of available data points, is to calculate the change in a variable between consecutive months rather than using the absolute values. This was performed on the monthly SOIs for the 1951-1982 period investigated here. Values of ΔSOI were then combined into a regression analysis with monthly values of TPI, since the latter exhibits negligible autocorrelation, and the residuals were tested for autocorrelation. The resulting plots (not shown) confirm that the residuals are now uncorrelated. Thus, the monthly ΔSOI values are used in the correlation analysis of monthly SOI-TPI and SOI-ice associations. A similar differencing technique was applied to the monthly values of the Antarctic sea ice for each of the five sectors (below).

Table 2 shows correlations of the monthly values of SOI and TPI for the full 1951-1982 period and two subperiods (1951-1972, 1973-1982). The last is particularly pertinent to this study of sea-ice-circulation interactions. Only statistically significant (two-tailed) coefficients are shown. In two out of the three time periods studied (1951-1982, 1973-1982), the number of significant correlations is very close to that expected by chance in a 12 × 12 matrix at the 5% level (i.e., 7). Only in the 1951-1972 period is the number of significant correlations considerably greater (14) than the number expected by chance. These results suggest a lack of temporal stability to the ice-circulation associations for the 1973-1982 period, since that interval is anomalous when compared with the preceding 20-year period (1951-1972).

Tab. 2. Significant correlations of monthly ΔSOI, TPI for three time periods: 1951-1982 *(underlined)*, 1951-1972 *(in parentheses)*, 1973-1982

TPI ΔSOI	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec.
Jan			0.7714^{b}									
Feb		(0.4997^{a})		$\underline{0.3548^{a}}$ (0.4533^{a})					0.7476^{a}			
Mar					-0.8474^{b} (0.4435^{a})			$\underline{0.3655^{a}}$ (0.4515^{a})				
Apr				$-\underline{0.4137}^{a}$								
May												(0.4625^{a})
Jun			-0.7429^{a}	$-\underline{0.3717}^{a}$								(-0.4411^{a})
Jul											0.6596^{a}	
Aug		$\underline{0.3684^{a}}$ (0.4367^{a})								-0.6485^{a}	(0.5168^{a})	
Sep												
Oct				(-0.4366^{a})			0.8353^{b} $\underline{0.3756^{a}}$				-0.7359^{a} $-\underline{0.6323}^{b}$ (-0.5795^{b})	
Nov					$\underline{0.4349^{a}}$ (0.5997^{b})					(0.4667^{a})	(0.5016^{a})	
Dec			(-0.6170^{b})									

[a] statistically significant at 5% (two-tailed); [b] statistically significant at 1% (two-tailed)

3 Antarctic sea-ice-circulation interactions, 1973-1982

3.1 *Antarctic sea-ice variations*

The present study is not the first to make use of the high-resolution data on the Antarctic sea-ice extent compiled for the 1973-1982 period by Naval Oceanography Command Detachment (1985). Analysis of the annual and interannual variations of the sea ice and their regional dependence have been described for much of this period by Jacka (1983), Ropelewski (1983), Sturman and Anderson (1985) and others, and are not repeated here. However, since this study examines sea-ice-circulation interactions, some discussion of the salient features of the sea-ice regime (full Antarctic, by sector) for the 10-year period is warranted. Figure 5 shows the seasonal and interannual variations in areal extent of the sea ice for the entire Southern Ocean and for two sectors that are known to interact strongly at certain times with the synoptic-scale atmospheric circulation: the Ross Sea and the South-East Indian Ocean (e.g., Carleton 1981; Cavalieri and Parkinson 1981; Streten 1983b, c). The curves for the full Antarctic show the simple, but marked, annual cycle of ice extent from minimum (February/March) to maximum (September/October). Interannually, the greatest (least) amount of ice occurred in the early (late) part of the satellite ice record (Fig. 5). The trend for the full Antarctic is not statistically significant in this period (Chiu 1983b; Zwally et al. 1983), although this may have changed in more recent years (Gloersen and Campbell 1988). The seasonal range, timing of maximum and minimum extent, and the interannual variability of the ice vary greatly according to sector (see also Ropelewski 1983). Thus, maximum ice extent occurs slightly earlier in the Ross Sea compared with the South-East Indian Ocean (Fig. 5). There is also evidence of a double maximum in the Indian Ocean in some years that is related to the advection out of, and transport between, adjacent sectors (Ropelewski 1983). This may help explain some of the intercorrelations of ice extent (Table 1). The advection may be both oceanic and wind-induced (Lemke et al. 1980), although the relative importance of each to the ice transport shows some sector dependence. The seasonal range is much greater in the Ross Sea compared with the adjacent sector to the west. It is largest of all in the Weddell Sea-South Atlantic sector (e.g., Ropelewski 1983), where the ocean circulation exerts a major influence on the seasonal patterns of ice advance and decay (Lemke et al. 1980; Hibler and Ackley 1983).

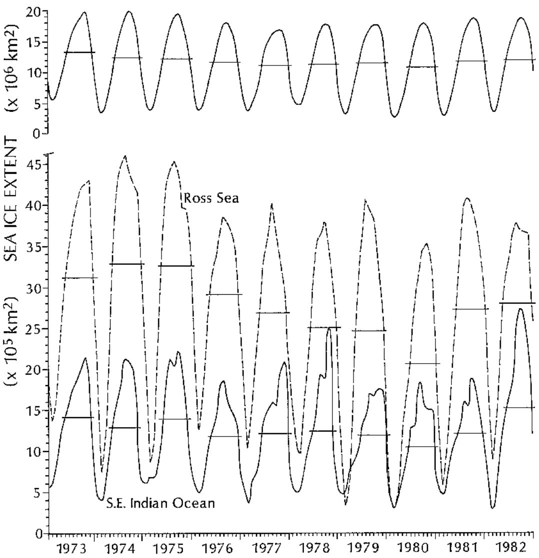

Fig. 5. The annual cycle of sea-ice areal extent for the full Antarctic (*top*, $\times 10^6$ km^2) and for two adjacent sectors (Ross Sea, South-East Indian Ocean; $\times 10^5$ km^2) in the 1973-1982 period. Note the interannual differences in extent and timing between sectors (refer to text). The graph is compiled from data tabulations in Naval Oceanography Command Detachment (1985)

3.2 *Analysis of monthly sea-ice-circulation interactions*

An examination of Antarctic sea-ice-circulation-index associations beyond that attempted by Chiu (1983b) requires that the serial autocorrelations in both the SOIs and the ice be removed, along with the seasonal cycle in the latter dataset. An autocorrelation analysis carried out on the weekly ice area values for each Antarctic sector confirms the results of Chiu (1983b), whereby autocorrelations become small and nonsignificant beyond about week 12 for most sectors. The autocorrelation was removed by expressing the ice area as a difference (Δice) obtained by subtracting the value for week 1 from that for week 4 in a given month. The Δice values were then regressed against associated values of TPI, since this index exhibits negligible autocorrelation. The residuals were then tested for autocorrelation. As in the case of the SOI, the results indicate that the autocorrelation becomes nonsignificant. Thus, based on these results, the monthly Δice values were used in the ice-circulation analyses. This technique differs from that used in the analysis of the SOI by Trenberth

(1984) and as applied in the ice-climate studies of Peng and Domros (1987) and Niebauer (1988). Removal of the annual cycle in the sea-ice data was achieved by normalizing, to the standard deviations for the 10-year period, the Δice values in a given month. While it would be preferable to have a greater number of years over which to normalize the data, this must await the forward extension of the data set. Note that this procedure was not necessary for SOI and TPI since these indices are, by definition, normalized to remove the annual cycle.

3.3 SOI and TPI interactions with regional ice conditions

Table 3 summarizes the significant monthly correlations of SOI and TPI with the regional ice extents for 1973-1982. Positive SOI-ice coefficients imply stronger Walker Circulation and more extensive ice in the sector concerned. Positive TPI-ice values indicate greater ice growth, with the trough displaced towards South America. However, in a similar way to the associations presented in Table 2, the number of significant ice-circulation correlations per sector in Table 3 is generally similar to what would be expected from chance (5% level) in two 12 × 12 matrices (i. e., 14). A possible exception is the Weddell Sea sector (Table 3), where 19 significant correlations occur. Moreover, nine of these are located at or close to the diagonal (i. e., contemporaneous or at small lags), where the expectation due to chance is reduced compared with the matrix as a whole. The Weddell sector is examined in more detail below.

Stratifying the number of "significant" correlations in Table 3 over all sectors by season of occurrence (summer, winter, transition) in a contingency table (not shown) reveals that the observed cell frequencies are not significantly different from the expected. Thus, there is no strong seasonal dependence to the correlations. A consistent Antarctic sea-ice-broadscale-circulation link is, therefore, not apparent for the 1973-1982 period. Since this period may be anomalous with respect to the relationship between SOI and TPI (above), due in part to temporal changes in the Southern Hemisphere long waves, only the forward extension of the sea ice and circulation-index data can clarify the existence of an ice-circulation teleconnection. Thus, much of the temporally coherent structure to the significant correlations between the sea ice and circulation that appear in studies such as those of Chiu (1983b) and Wendler and Nagashima (1987) occurs because of autocorrelations in one or both variables. This effect may be enhanced, particularly in the Antarctic case, by the large annual cycle of sea-ice extent.

3.4 Potentially significant circulation-sea-ice associations

Some close associations have been identified between the synoptic circulation and the regional sea-ice extent in previous work (e.g., Carleton 1981; Cavalieri and Parkinson 1981; Rogers and

Table 3. Significant correlations of broad-scale circulation indices and sea ice by sector, 1973-1982

SOI, *TPI*												
Ice	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Jan	−*0.650*				(0.681)			−*0.636*	−0.768 −*0.635*			*0.736*
Feb	−0.665		−*0.749*			0.671						*0.654*
Mar	(0.641)		*(0.690)* −0.785		−0.680 *0.823*				0.642 *0.731*			
Apr	−0.745							−0.681		*0.665*		
May		*(−0.684)*										
Jun	*0.635*	*0.794*		−*0.741*								
Jul				0.647	(0.637)						*0.808*	0.650
Aug		−*0.825*		−0.643								−0.672
Sep		0.795		(0.647)					−*0.700*			
Oct					(0.638)							−0.638
Nov			(−0.737)		*(0.739)*						*0.686*	
Dec	*0.761* *(0.658)*	−0.657 −*0.715*										

Ross Sea; South-East Indian Ocean *(parentheses);* South-West Indian Ocean *(underlined)*

Table 3 (contd.). Significant correlations of broad-scale circulation indices and sea ice by sector, 1973–1982

	SOI, *TPI*											
Ice	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Jan						*0.680* *0.798*				(0.828)		
Feb	(−0.663)	0.648				(0.770) 0.668					−0.831	
Mar			−0.710		*0.673*							
Apr	−0.675 −0.721											
May		−0.719					*−0.686*		*(0.775)* *0.721*			
Jun	*0.725*			*−0.715*	*0.636*		−0.711	(0.671)		*(−0.678)*		
Jul								0.691				*0.655*
Aug		*−0.677*									−0.676	
Sep	(0.662)	−0.731 −0.795							*−0.955*			
Oct			−0.630		*0.749*		(0.708)				*(0.676)*	
Nov				0.770			0.789				*0.638*	0.634 *0.656*
Dec									(−0.728)		*−0.636* *−0.663*	

Weddell Sea; South-East Pacific Ocean *(parentheses)*; Full Antarctic *(underlined)*

van Loon 1982; Rogers 1983; Streten 1983b, c, 1984). Thus, one should attempt to reconcile those results with the findings presented above, and also with those generated in GCM experiments (e.g., Mitchell and Hills 1986; Simmonds and Dix 1986). While the shortness of the sea-ice record does not permit a full determination of Antarctic sea-ice–circulation teleconnections, the occurrence of "significant" correlations is probably least likely to have occurred by chance when the sea ice correlates highly with both SOI and TPI and in more than one sector (compare Tables 2 and 3). The relative impacts of the three variables (ΔSOI, TPI, Δice) to such an association can be estimated using partial correlation analysis (e.g., Clark and Hosking 1986; Chapt. 10).

Table 4 presents the results of a partial correlation analysis for months and regions having statistically significant coefficients for at least two of the simple correlations among the three variables (from Table 3). The coefficients were calculated using Kendall's rank correlation method (τ), which is a non-parametric statistic. Thus, the coefficients in Table 4 may differ from those given in Table 3. The right-hand side of Table 4 shows the change in the circulation-index–sea-ice correlation that occurs as a result of controlling the bivariate correlation for the influence of the third variable. Only the Weddell and Ross Seas are represented by more than one significant correlation, although the same months are represented in both the South-West Indian Ocean sector and full Antarctic (Table 4). This result may reflect the dominance by the Ross and Weddell sectors in the annual and interannual variations of ice extent (Lemke et al. 1980).

The biggest change in the simple correlations is noted for the significant association between the ice in the Weddell Sea in September and the SOI in February. This coincides with a significant SOI, TPI correlation (refer also to Table 2). The latter correlation drops dramatically from 0.578 to −0.098 when controlling for the influence of the Weddell Sea pack ice in the association (column 4 of Table 4), and represents a change of 46% in the R^2 value. The significant correlation between the SOI and the Weddell Sea ice (−0.667) decreases by a lesser amount when controlling for the influence of TPI (a change of 6% in R^2). Thus, for this case, the Weddell Sea ice around the time of maximum extent has a bigger effect on the association between SOI and TPI than does the influence of TPI on the strong association SOI (February) and the September ice. A similar, although less dramatic, result appears for the association between the Weddell Sea ice in November and the SOI in July, given the association between SOI and TPI in those months (Table 4).

Thus, the influence of the ice on the interaction between the two circulation indices seems larger than the effect of one or other index on the association between the ice and the second circu-

Table 4. Partial correlation analysis for months when significant sea-ice-circulation associations (Table 3) occur concurrently with high correlations of SOI, TPI (Table 2)

Sector, association	*Kendall rank correlation coefficients*			*Partial correlation coefficients*			
	τSOI, TPI (1)	τSOI, Ice (2)	τTPI, Ice (3)	τSOI, TPI:Ice Controlled (4)	Δτ (4-1) ΔR (%)	τSOI (TPI), Ice:TPI (SOI) Controlled (5)	Δτ (2 or 3-5) ΔR (%)
Weddell Sea							
a) Ice Sep, SOI Feb, TPI Sep,	0.578^b	-0.667^b	-0.911^c	−0.098	−0.68 46.2%	−0.415	0.25 6.2%
b) Ice Nov, SOI Jul, TPI Nov	0.378	0.511^a	0.289	0.279	−0.10 1.0%	0.453	−0.06 0.4%
c) Ice Mar, TPI May, SOI Mar	-0.733^c	-0.555^a	0.555^a	−0.614	0.12 1.4%	(0.261)	−0.29 8.4%
Ross Sea							
a) Ice Sep, SOI Feb, TPI Sep,	0.578^b	-0.578^b	-0.467^a	0.430	−0.15 2.2%	−0.427	0.15 2.2%
b) Ice Jul, TPI Nov, SOI Jul	0.378	0.244	0.511^a	0.303	−0.075 0.6%	(0.467)	−0.04 0.2%
S. W. Indian							
Ice Mar, TPI May, SOI Mar	-0.733^c	-0.689^b	0.600^b	−0.552	0.18 3.2%	(0.193)	−0.41 16.8%
S. E. Indian							
Ice Mar, SOI Jan, TPI Mar	0.555^a	0.555^a	0.555^a	0.247	−0.31 9.6%	0.247	−0.31 9.6%
Full Antarctic							
Ice Sep, SOI Feb, TPI Sep	0.578^b	-0.578^b	−0.333	0.502	−0.08 0.6%	−0.502	0.08 0.6%

^{a} = statistically significant at 5% level; ^{b} = statistically significant at 1% level; ^{c} = statistically significant at 0.1% level

lation index. The reverse is the case with respect to the ice in the Weddell Sea and South-West Indian Ocean in March (TPI in May, SOI in March), where the strongest effect is that of SOI on the significant association TPI and ice (Table 4). In certain other situations (South-West Indian Ocean, Ross Sea, full Antarctic) the ice-circulation interactions involving the three variables appear to vary about equally. These exploratory results suggest that the ice, particularly in the Weddell and Ross Seas, may interact with the broad-scale atmospheric circulation in certain months. At the same time, they are difficult to explain physically except, perhaps, where occurring at small lags.

The thermal and dynamical feedbacks between the atmosphere and the sea-ice cover are complicated (1) by the ocean circulation, and (2) by the different time scales (leads, lags) on which the variables operate and interact. Studies for the Arctic (e.g., Walsh and Johnson 1979; Wendler and Nagashima 1987) demonstrate that this two-way interaction may be regionally, as well as seasonally, dependent. These complexities preclude, at this time, a detailed examination of the leads and lags that are involved in the possibly significant circulation (SOI, TPI)-Antarctic sea-ice associations noted above. Such an analysis awaits a longer period of high-resolution data on the Antarctic sea ice and Southern Hemisphere circulation beyond those currently available. However, it is possible here to identify whether the circulation-sea-ice associations noted from Table 4 involve the atmosphere leading the ice or, perhaps more interestingly, the ice leading the atmosphere. This is not readily obtained from an examination of Table 3, for instance. While examples of the atmosphere leading the ice can generally be explained by combinations of wind stress and thermodynamic effects on the pack (e.g., Carleton 1988; Niebauer 1988), cases of the reverse (ice leads, atmosphere lags) are generally the more difficult to explain physically (e.g., Peng and Domros 1987). The mediating effect of the ocean circulation is undoubtedly crucial in these associations (see Chiu and Newell 1983).

Accordingly, the atmospheric circulation index (either SOI or TPI) and sea ice were rank correlated for (1) the circulation leading the sea ice and (2) the circulation lagging the ice, for the months and regions identified in Table 4. The results appear in Table 5. Note that these apply only to the 1972-1983 period, which may have been anomalous. In the case of the westerlies (TPI), the significant correlation seems to come about either synchronously with the ice or when the circulation index lags the ice-extent changes by up to about 4 months. However, with respect to the SOI, the significant associations generally occur when the index leads the ice. This observation is particularly apparent for the Weddell Sea and is in line with the recent analysis of sea-ice conditions in that sector and their response to high-latitude circulation patterns associated with "warm" and "cold" ENSO events (Carleton 1988).

An intriguing exception occurs for the Ross Sea, where it is seen that — at least for the 1973-1982 period — the correlation is considerably improved and explains about 52% of the variance, when the ice of the preceding late winter leads the SOI of the following February. This contrasts with the reverse situation when SOI (February) leads the September ice, and results in about 33% of the variance being explained. The negative association indicates that the Ross Sea ice around the time of maximum extent increases (decreases) ahead of a weaker (stronger) Walker Circulation. Since the association of the Ross Sea ice with TPI is also significant in September (refer to Table 4), it seems possible that the ice-SOI teleconnection — if verified subsequently from analysis of longer-term data — involves interactions of both variables with wavenumber one and the westerlies over middle latitudes. That relationship for the Ross Sea in September is negative, and implies increasing (decreasing) ice when the trough is displaced towards the Australasian: negative TPI (South American: positive TPI) sector. The relationships of strong middle-latitude westerlies with more extensive sea ice is consistent with observations by Streten and Pike (1980b) and with the GCM study of Mitchell and Hills (1986). Thus, stronger westerlies would be expected over longitudes of New Zealand, ahead of weaker trade winds over the tropical Pacific, and these would be maximized at negative extremes of the ENSO [i.e., an El Niño event: see also Trenberth and Shea (1987)]. This possibility can be examined if one determines composite values of the M1 regional index according to their occurrence in positive or negative extremes of TPI for the 1951-1982 period. August, rather than September, is selected for characterizing extreme TPI in order to obtain more closely similar numbers of years for each composite; TPI (September) is dominantly strongly negative in the 1951-1982 period, in association with the semi-annual oscillation. The results (Table 6) show statistically significant differences in the phase and amplitude of the trough in the Tasman Sea between extremes of TPI. Positive (negative) TPI is associated with amplification (weakening) of the trough between August and September, in association with increasing (decreasing) sea ice in the Ross Sea and South-East Indian Ocean sectors (Table 1).

Table 5. Preliminary lead/lag associations between significant circulation indices and sea-ice conditions shown in Table 4

Sector	*Kendall rank coefficient*	
	Circulation index leads ice	Circulation index lags ice
Weddell Sea		
a) SOI Feb, Ice Sep	-0.667^{b}	-0.067
b) SOI Jul, Ice Nov	0.511^{a}	-0.200
c) TPI May, Ice Mar	-0.200	0.555^{a}
Ross Sea		
a) SOI Feb, Ice Sep	-0.578^{b}	-0.722^{b}
b) TPI Nov, Ice Jul	-0.111	0.511^{a}
S. W. Indian		
TPI May, Ice Mar	0.244	0.600^{b}
S. E. Indian		
SOI Jan, Ice Mar	0.555^{a}	-0.267
Full Antarctic		
SOI Feb, Ice Sep	-0.578^{b}	-0.200

[a] = statistically significant at 5% level; [b] = statistically significant at 1% level; [c] = statistically significant at 0.1% level

Table 6. Composite variations in index M1 (mbar) for extreme phases of TPI (August) in the 1951-1982 period

Index	TPI positive (≥2.0) $n=11$	TPI negative (≤−2.0) $n=10$
$\overline{\text{M1}}$ (August)	0.01	−2.86
$\overline{\text{M1}}$ (September)	−3.92	−0.73
$\Delta\overline{\text{M1}}$ (Sep-Aug)	−3.93	+2.13

The possible interactions between the sea ice and atmospheric circulation of the south-west Pacific (Tables 4-6) are shown schematically in Fig. 6. The figure is highly generalized and applies only to the 1973-1982 period. While the relationships between the seasonal variations of the Tasman Sea trough and the ENSO have been shown before (van Loon 1984), these results suggest that the teleconnection may involve the sea ice in the south-west Pacific.

4 Summary and concluding remarks

An analysis of the interactions between the Antarctic sea-ice extent and broad-scale indices of the atmospheric circulation of the Southern Hemisphere (SOI, TPI) finds little evidence of strong and coherent interactions on annual and monthly time scales for the 1973-1982 period. Many of the apparently significant index-index or ice-index correlations could occur by chance once the autocorrelations in the data and the annual cycle of the ice extent are removed from the series. Further, the associations between SOI and TPI show little stability over time. This seems to originate primarily from changes in the extratropics. There is evidence that the 1973-1982 period was anomalous in comparison with the previous two decades 1951-1972.

An effort is made to reconcile these largely inconclusive results with previous studies that show some strong regional-scale ice-atmosphere interactions in the Antarctic. Examination of cases when both SOI and TPI correlate highly with the regional sea-ice extent is made using partial correlation analysis. These cases occur mainly for the Ross and Weddell sectors. For the most part, the regional ice-extent changes tend to lag the SOI but lead the TPI in key months. The ice may enhance the association between the two broad-scale circulation indices at those times. In the 1973-1982 period, changes in the late winter sea ice of the Ross Sea sector apparently preceded the SOI of the following late summer. The reality of these teleconnections can, of course only be confirmed with an eventual forward extension of the sea-ice and circulation data.

Acknowledgements. I am grateful to the following: N. Shiwdhan (Indiana University) for assistance in collecting station pressure data and for updating the TPI, the National Snow and Ice Data Center (CIRES, University of Colorado, Boulder) for access to the Sea Ice Climatic Atlas, A. Barrie Pittock (CSIRO Division of Atmospheric Research, Aspendale, Australia) for the Troup SOI, and J. Michael Hollingsworth (Indiana University) for drafting the figures. I also appreciate the useful discussions on statistical aspects of this research with my colleagues, Drs. John Odland and Dan Knudsen. The helpful comments of two anonymous reviewers on an initial draft of this paper are acknowledged.

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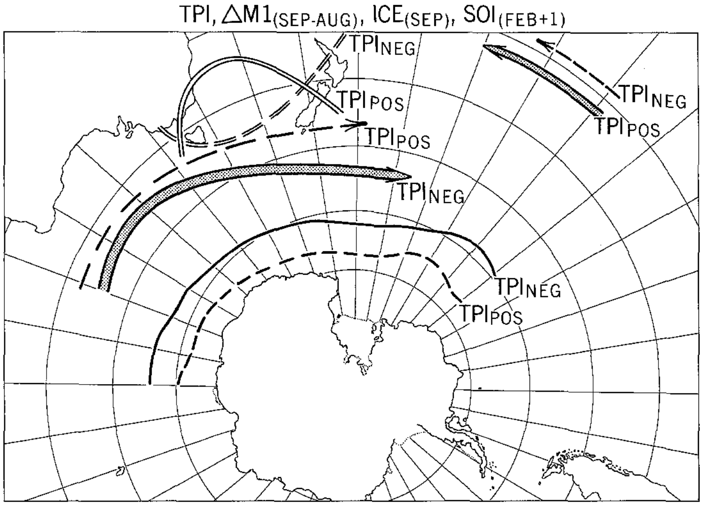

Fig. 6. Schematic diagram showing the possible interrelationships between the sea-ice extent and atmospheric circulation in the south-west Pacific for the 1973-1982 period, as inferred from Tables 4-6. Increasing (decreasing) ice occurred in late winter when TPI was negative: waves displaced towards Australia (positive: displaced towards South America) and the Tasman Sea trough amplified (weakened) between August and September. These apparently preceded, by about 5 months, changes in the Walker Circulation (refer to text). Extreme September ice limits for the period are from Jacka (1983)

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Received June 22, 1988/Accepted November 8, 1988