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SHORT COMMUNICATION

THE SEMI-ANNUAL OSCILLATION AND ANTARCTIC CLIMATE. PART 4: A NOTE ON SEA ICE COVER IN THE AMUNDSEN AND BELLINGSHAUSEN SEAS

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ABSTRACT

The climate of Faraday, situated at the west coast of the Antarctic Peninsula (AP), is strongly influenced by the extent of sea ice cover in the Amundsen and Bellingshausen Seas (ABS). ABS sea ice cover is negatively correlated with Faraday annual mean temperature, wind speed and cloudiness, while a positive correlation was found with precipitation frequency. The amplitude of the semi-annual oscillation (SAO) and wintertime ABS sea ice extent are coupled as follows: in years with a poorly-developed SAO, the northwestward migration of the circumpolar pressure trough from April to July is suppressed, causing negative sea ice anomalies in the ABS that persist throughout the winter. The weakening of the SAO since the late 1970s has led to: an increase of annual mean wind speed and cloudiness in the region, one of the possible causes for the onset of the long-term ABS sea ice cover decrease; and changes in the annual cycles of wind speed and cloudiness such that sea ice growth in the period April–July has decreased, causing negative winter sea ice anomalies in the ABS and enhanced regional warming. Copyright © 2000 Royal Meteorological Society.

KEY WORDS: Antarctic climate; semi-annual oscillation; sea ice cover; Amundsen and Bellinghausen Seas

1. INTRODUCTION

The semi-annual oscillation (SAO) in the Southern Hemisphere consists of the twice-yearly contraction and expansion of the circumpolar pressure trough (CPT). This happens in response to the differences in energy uptake between Antarctica and its oceanic surroundings, resulting in a half-yearly wave in baroclinicity and depression activity (Van Loon, 1967; Meehl, 1991; Walland and Simmonds, in press). Figure 1 schematically illustrates the movement of the CPT in the Pacific Ocean sector of Antarctica. At the time of maximum contraction of the CPT (March and September) low pressure areas migrate southeastwards over the Amundsen Sea to end up close to the coastline of West Antarctica (bold southernmost **L** in Figure 1). In the expansion phases (April–July and October–January), this area migrates to the north and west, resulting in a pronounced semi-annual cycle in surface pressure, wind speed and cloudiness.

The amplitude of the SAO shows considerable decadal oscillations (Van Loon *et al*., 1993; Hurrell and Van Loon, 1994). This variability influences temperature (trends) in Antarctica in a longitudinally dependent manner (Van den Broeke, 1998a,b), either directly through changes in warm air advection, or indirectly through changes in local wind speed and cloudiness (Van den Broeke, 2000).

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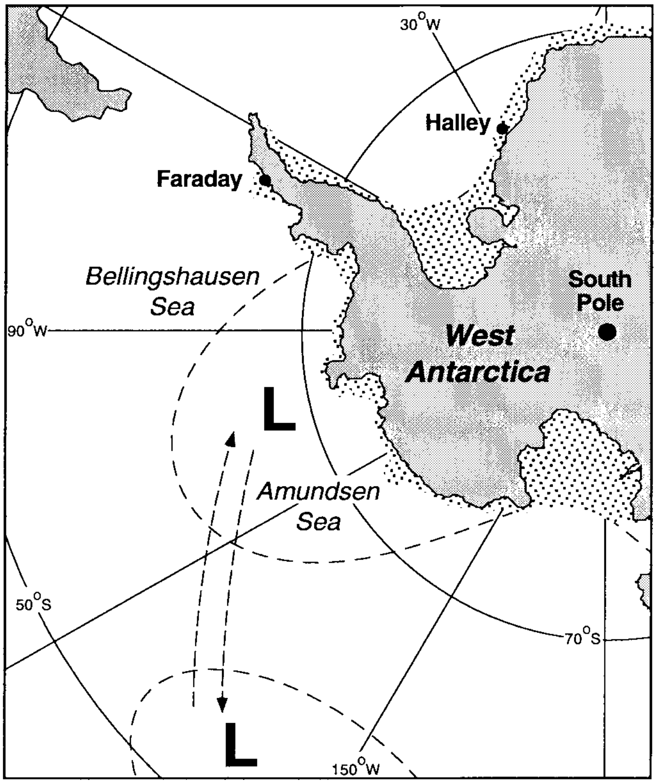

Figure 1. Schematic outline of pressure and circulation changes in the South Pacific during the SAO contraction/expansion phases. Dashed arrows connect locations of largest pressure changes

A region with exceptional climate variability and sensitivity is the west coast of the Antarctic Penninsula (AP), bordering the Bellingshausen Sea. It is believed that the strong feedback of local temperature with Amundsen and Bellingshausen Seas (ABS) sea ice cover is, at least partly, responsible for the anomalous warming of this region in the last 50 years, as well as secular changes in circulation (King, 1994; King and Harangozo, 1998). Enomoto and Ohmura (1990) found that latitudinal sea ice extent in the ABS fluctuates synchronously with the movement of the CPT, probably a result of the south–north directed orientation of the AP. Watkins and Simmonds (in press) further explore the interaction between the location of the CPT and the sea ice edge. Harangozo (1997) studied interactions of Ross Sea and ABS sea ice extent with atmospheric circulation during two years with maximum (1986) and minimum (1983) northward winter sea ice extent. He concluded that in years with a large amplitude of the half-yearly wave in meridional circulation (i.e. a well-developed SAO), maximum northward winter sea ice extent in the ABS was above-average.

In this note 22 years of sea ice and meteorological data is used to further explore the link between the SAO and regional climate (trends) in the region of the AP. In line with the previous parts of this paper, the impact of changes in the strength of the SAO is studied by considering the mean annual cycle of two periods, namely before and after 1979 (well developed SAO and poorly developed SAO, respectively).

2. DATA

Satellite-derived monthly mean sea ice cover values (January 1973–November 1994) in the ABS were used, between 60°W and 130°W, as presented by Jacobs and Comiso (1997). Sea ice is defined present when ice concentration exceeds 15% for passive microwave data or 10% when NOCDA data were used

(41% of the months prior to 1978). Faraday (65.3°S, 64.3°W, 9 m a.s.l.) monthly mean surface pressure (P, in hPa), 2-m temperature (T, °C), 10-m wind speed (V, m s^{-1}) and observed total cloudiness (N, in octas) in the period 1973–1994 were obtained from the British Antarctic Survey, as were time series of monthly totals of continuous plus intermittent precipitation reports (Prec), as reported in Turner *et al.* (1997).

3. ABS SEA ICE AND FARADAY CLIMATE

The mean annual cycle of ABS sea ice cover for the period 1973–1979 can be well described by its first two harmonics (Figure 2). In spite of its small amplitude, the half-yearly wave H_2(SeaIce) has a stable phase (5.13 ± 0.09 months). Its timing is such that it opposes sea ice growth in the contraction phases of the SAO, when depression activity is greatest over the ABS and wind speed and cloudiness peak (February/March and August/September). Neither of the amplitudes correlate in a significant way with annual mean sea ice extent. However, the amplitudes of both harmonics are positively correlated with each other ($R = 0.78$, confidence $> 99.9\%$), which indicates that the amplitudes of both harmonics vary synchronously from year to year.

Several interesting correlations are found of ABS sea ice cover with climate parameters at Faraday (Table I). Unexpected is the *positive* correlation between precipitation frequency and ABS sea ice cover, while the latter and cloudiness are *negatively* correlated; no explanation was found for this. ABS sea ice cover is positively correlated with the amplitudes of the yearly and half-yearly temperature wave at Faraday, $H_1(T)$ and $H_2(T)$ (Table I, Figure 3). Note that the inverse of $H_1(T)$ can be used as a measure

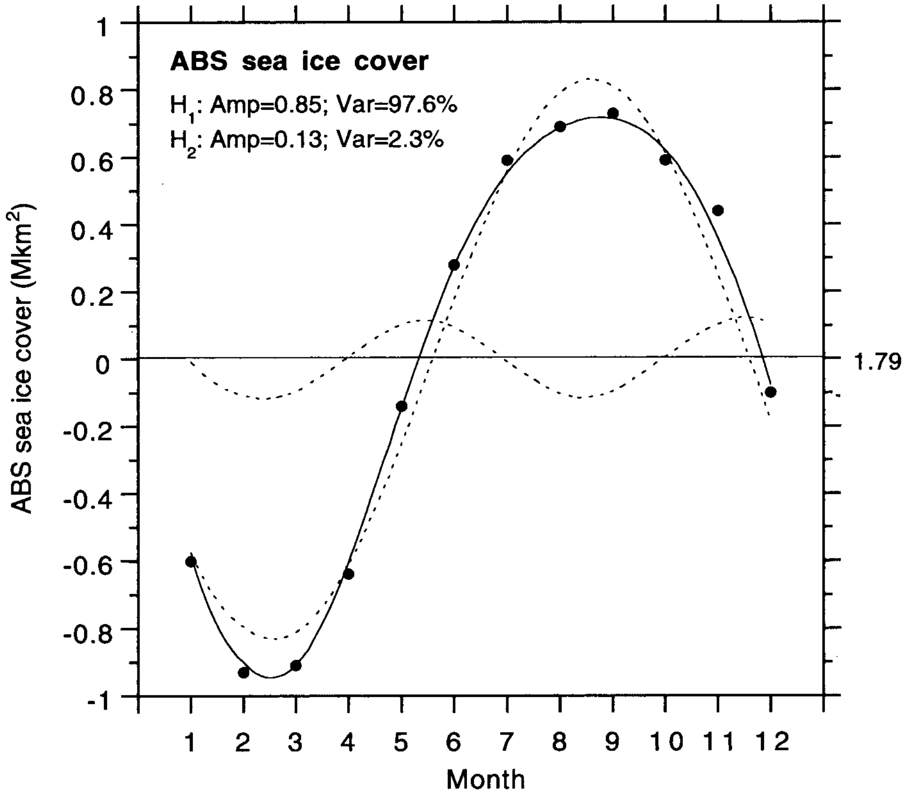

Figure 2. Observations (black dots), first harmonic H_1 and second harmonic H_2 (dashed lines) and $H_1 + H_2$ (solid line) of 1973–1979 mean annual cycle of ABS sea ice cover

Table I. Matrix of linear correlation coefficients of sea ice cover in the ABS and amplitude of first two harmonics H_1(SeaIce) and H_2(SeaIce) with Faraday climate variables and amplitudes of their first two harmonics

ABS sea ice cover	Annual mean	Amplitude H_1(SeaIce)	Amplitude H_2(SeaIce)
Faraday			
Pressure (P)	0.39	−0.44*	−0.07
Amp. $H_1(P)$	−0.73***	−0.39	−0.52*
Amp. $H_2(P)$	0.42*	0.63**	0.62**
Temperature (T)	−0.84***	0.18	−0.21
Amp. $H_1(T)$	0.92***	−0.08	0.17
Amp. $H_2(T)$	0.91***	0.11	0.29
Wind speed (V)	−0.68***	0.61**	0.31
Amp. $H_1(V)$	−0.15	0.18	−0.18
Amp. $H_2(V)$	0.71***	0.51*	0.48*
Cloudiness (N)	−0.92***	−0.05	−0.05
Amp. $H_1(N)$	−0.28	−0.12	0.20
Amp. $H_2(N)$	0.66**	0.32	0.11
Precipitation frequency (Prec)	0.84***	−0.26	0.11
Amp. H_1(Prec)	0.29	0.13	−0.32
Amp. H_2(Prec)	0.70***	0.32	0.18

Harmonics performed on and annual means based on 5-year running means (1973–1994, $n = 18$). Confidence levels (one-sided test): * 95–99%; ** 99–99.9%; *** better than 99.9%.
For further explanation see text.

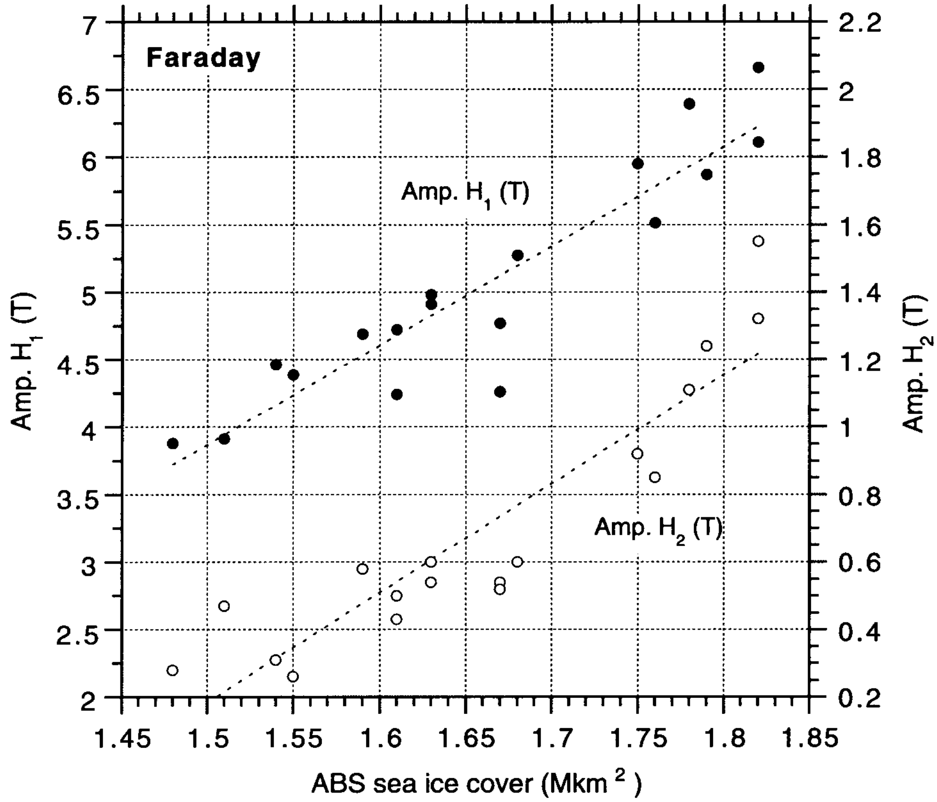

Figure 3. First $H_1(T)$ and second harmonic $H_2(T)$ of annual temperature cycle at Faraday as a function of annual mean ABS sea ice cover (1973–1994, based on 5-year running means)

of annual mean temperature, because almost all of the interannual temperature variability stems from the winter months (King, 1994). The positive correlation with the amplitude of $H_2(T)$ implies that in years with above average ABS sea ice extent, the annual temperature curve at Faraday resembles that of a continental or ice shelf station with a strong surface inversion and a 'coreless winter' (Phillpot, 1997). In years with low ABS sea ice cover, the amplitude of $H_2(T)$ drops to near-zero values, indicating a weak or absent coreless winter in the annual temperature march.

Annual mean sea ice cover in the ABS is positively correlated with the amplitude of the second harmonic of all available variables at Faraday: $H_2(P)$, $H_2(T)$, $H_2(V)$, $H_2(N)$ and H_2(Prec). Moreover, the amplitudes of both harmonics are positively correlated with $H_2(P)$. It may therefore be concluded that in years with a well developed SAO, sea ice cover in the ABS has above-average mean extent as well as a larger amplitude of the yearly and half-yearly wave. The implications of this are discussed in the next section.

4. RECENT CHANGES

The amplitude of $H_2(P)$ has decreased significantly from the late 1970s well into the 1990s. Especially in the South Pacific, changes have been quite dramatic: when the mean annual pressure cycle of two periods (1957–1979 and 1980–1995) are compared, the amplitude of $H_2(P)$ at Faraday has fallen from 2.9 to 1.1 hPa, and the variance explained by it from 77 to 10%, respectively. Note that a small part of this difference can be explained by the differences in the averaging period, as outlined by Simmonds and Jones (1998). At the same time, strong climate signals have been observed in the area of the AP. Figure 4 shows time series of Faraday temperature and ABS sea ice cover. In spite of the large interannual variations, significant trends are detectable: 2-m temperature has increased with 0.61°C per decade (confidence level

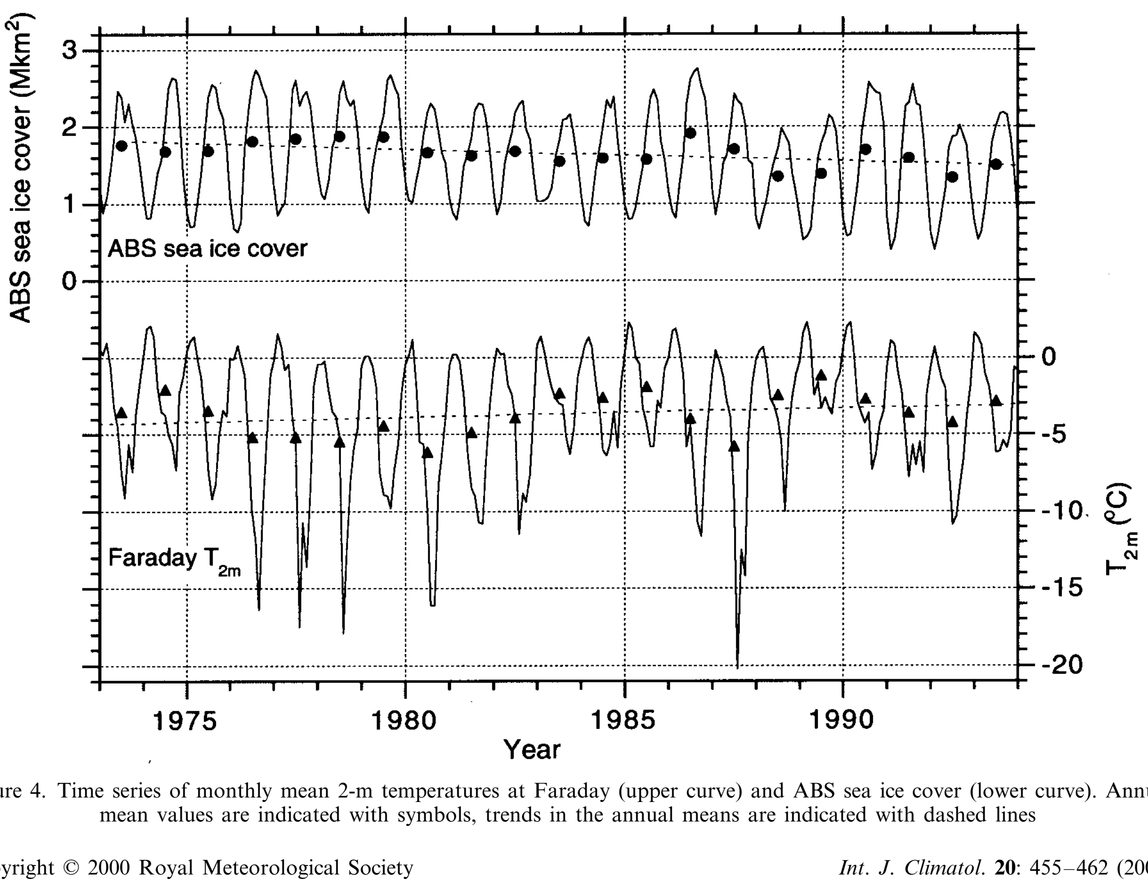

Figure 4. Time series of monthly mean 2-m temperatures at Faraday (upper curve) and ABS sea ice cover (lower curve). Annual mean values are indicated with symbols, trends in the annual means are indicated with dashed lines

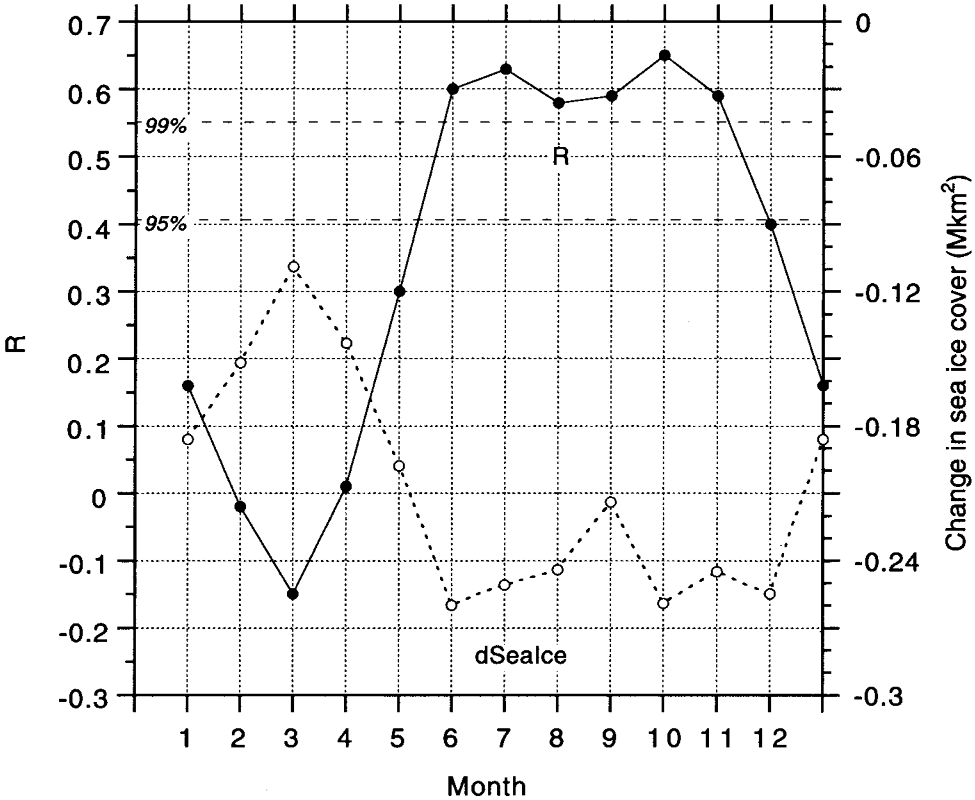

Figure 5. Solid line: linear correlation R of monthly mean ABS sea ice cover with $H_2(P)$ at Faraday, 1973–1994 (based on 5-year running means). Dashed line: changes in monthly mean (1980–1995 and 1973–1979) ABS sea ice cover (dSeaIce). Both curves are smoothed with 3-monthly running means

95%), while sea ice cover (black dots) decreased at a rate of approximately 160 000 km^2 per decade (confidence level 99%). The warming has led to extensive surface melting, resulting in the disintegration of some of the northerly ice shelves (Vaughan and Doake, 1996).

Not only temperature, but also wind speed and cloudiness have increased at Faraday with 0.24 m s^{-1} and 0.11 octas per decade, respectively (confidence levels better than 99.9%). In the third part of this paper it is shown that changes in these variables can be ascribed with confidence to the recent weakening of the SAO (Van den Broeke, 2000). Enhanced northerly winds and suppressed cooling of ice-free waters through increased cloudiness could well have initiated the general decrease of sea ice cover in the ABS.

Figure 5 shows the annual cycle of the correlation R between the monthly mean ABS sea ice cover and $H_2(P)$ at Faraday (solid line). The pronounced annual march of the correlation explains why *annual mean* sea ice cover is only modestly correlated with $H_2(P)$ in Table I: years with above-average ice cover in winter have weakly below-average ice cover in March, i.e. a bigger amplitude of the annual cycle. The critical months for positive winter sea ice anomalies to develop are April to July, just after the minimum in ABS sea ice cover. In years with a weakly developed SAO, i.e. a stationary CPT that does not migrate northwestwards, conditions during these months are unfavourable for fast ice growth (above normal depression activity with high wind speed and cloudiness). The limited impact of the second contraction phase on the correlation on sea ice cover (July–September, Figure 5) could result from the non-linearity of sea ice growth, a result of its positive feedback with local temperatures: once positive anomalies exist, they tend to persist throughout the winter.

The differences in the mean annual cycles of ABS sea ice cover of two periods were compared, one with strong (1973–1979) and one with weak SAO (1980–1996) (Figure 5, dashed line). Superimposed on the sea ice loss of approximately 200 000 km^2, a pronounced annual cycle that mirrors the correlation curve (correlation −0.94) is found. This implies that the winter months, that are most sensitive to the strength of the SAO as indicated by the dashed curve, have lost most sea ice cover. This is in agreement with the recent weakening of the SAO. Given the high correlation between Faraday winter temperatures and ABS sea ice cover, this chain of events (weaker SAO > stronger winds, more clouds > less sea ice > higher temperatures > less sea ice, etc.) is a strong candidate to explain the anomalous strong increase of winter temperatures at the west coast of the AP.

5. SUMMARY AND CONCLUSIONS

Significant interactions were found between the extent of sea ice cover in the ABS and the annual mean and annual cycle of temperature, wind speed, cloudiness and precipitation frequency at Faraday. In years with above-normal sea ice extent, the annual temperature curve at Faraday resembles that of a continental or ice shelf station, with below-normal winter temperatures and a coreless winter. Annual mean wind speed and cloudiness at Faraday are negatively correlated with ABS sea ice cover, while an unexpected and unexplained positive correlation was found of ABS sea ice cover with precipitation frequency at Faraday.

A positive coupling exists between the amplitude of the SAO and wintertime ABS sea ice extent. In years with a weakly-developed SAO, the failure of the circumpolar pressure trough to move northwestward from April to July suppresses sea ice growth; these anomalies subsequently persist throughout the winter. Combining this with earlier results, it can be concluded that the recent weakening of the SAO has: increased annual mean wind speed and cloudiness at Faraday, possibly initiating the long-term decrease of ABS sea ice cover; and modified the annual cycle of wind speed and cloudiness, in such a way that sea ice growth is suppressed during the first expansion phase (April–July).

These results are in agreement with the findings of Harangozo (1997). Marshall and King (1998) showed that warm/cold winters (JJA) at Faraday in the period 1973–1992 have below/above average 500 hPa heights in the Amundsen Sea area and higher/lower depression activity, with opposite anomalies in the Pacific Ocean at lower latitudes. This anomaly distribution is remarkably consistent with a poorly developed expansion phase of the SAO during the winter months.

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