FOUNDATIONS FOR ECOLOGICAL RESEARCH WEST OF THE ANTARCTIC PENINSULA
ANTARCTIC RESEARCH SERIES, VOLUME 70, PAGES 105-121

SURFACE AIR TEMPERATURE VARIATIONS IN THE WESTERN ANTARCTIC PENINSULA REGION

Raymond C. Smith and Sharon E. Stammerjohn

Institute for Computational Earth System Science (ICESS), Geography Department, University of California, Santa Barbara

Karen S. Baker

Marine Research Division, Scripps Institution of Oceanography University of California, San Diego, La Jolla

Surface air temperature records from several Western Antarctic Peninsula (WAP) stations are examined. The annual progression of surface air temperatures show an along-peninsula gradient indicative of contrasting influences of maritime versus continental climate regimes. WAP temperature records also show a significant warming trend in mid-winter temperatures, with an increase of 4-5°C over the past half-century (1944-1991). Increased temperature variability in fall and winter is linked to the high interannual variability of sea ice coverage. Linear regression analysis shows a significant (99.9%) anticorrelation between air temperature and sea ice extent, even after accounting for serial correlation in the two time series. There are distinct seasonal lead/lag relationships between temperature and sea ice in this region, which underscore the complexity of polar feedback mechanisms. The more than 45 year Faraday air temperature record shows significant (95% confidence level) low frequency coherence with the Southern Oscillation Index (SOI). In addition, high frequency coherences between WAP air temperatures, WAP sea ice extent and SOI support the hypothesis that not only do extreme SOI events affect WAP climate, but monthly SOI fluctuations may be affecting monthly fluctuations in WAP air temperatures and sea ice extent as well. Because sea ice-temperature-SOI relationships appear to be strongly linked in this region, the WAP is an ideal area to study ecological responses to climate variability.

1. INTRODUCTION

Climate variability is of central importance in long term ecological research. The average state of the atmosphere-ocean-cryosphere-lithosphere system establishes the setting in which ecosystems evolve. The Antarctic ecosystem, the assemblage of plants, animals, ocean, sea ice and island components south of the Antarctic Convergence, is among the largest readily defined ecosystems on Earth (36 x 10^6 km^2) [*Petit et al.*, 1991]. The Antarctic marine ecosystem has a climate system that displays extreme seasonal and interannual variability. The focus of the Palmer Long-Term Ecological Research (Palmer LTER) program is the ecology of this region, from phytoplankton to top predators, in the context of how physical forcing influences the abundance and distribution of key species. A fundamental question is the sensitivity of this system to change.

In the context of global climate variation, the polar regions play an essential role. In assessing the possible impact of increased CO_2, many climate models predict enhanced warming at higher latitudes as a result of hypothesized positive feedback mechanisms associated with the variable sea ice cover [*Hansen et al.*, 1988; *Manabe and Stouffer,* 1980; *IPCC,* 1990]. In contrast, time-dependent, general circulation models imply that the thermal capacity of the oceans will delay and effectively reduce enhanced warming, especially at high southern latitudes [*Schlesinger and Mitchell,* 1985; *Stouffer et al.*, 1989; *Lemke et al.*, 1990; *Gates et al.*, 1992]. Other models, linking air-ice-sea interactions, suggest complex feedback mechanisms associated with predicted temperature variability, water column stability, ice cover changes and deep water formation/ventilation [*Gordon and Huber,* 1990; *Martinson,* 1990]. Although the performance of these climate models are problematic when applied to polar regions, evidence nevertheless indicates the importance of the Southern Ocean in an assessment of global climate change.

Antarctic climate trends and sea ice extent changes have been studied by a number of authors [*Budd,* 1975; *Budd,* 1980; *Budd,* 1982; *Damon and Kunen,* 1976; *van Loon and Williams,* 1977; *Ackley,* 1981; *Carleton,* 1981; *Zwally et al.*, 1983; *Jacka,* 1983; *Jacka et al.*, 1984; *Raper et al.*, 1984; *Jones et al.*, 1986; *Jones and Wigley,* 1988; *Jones,* 1990; *Jacka and Budd,* 1991; *Weatherly et al.*, 1991]. These studies reveal considerable interannual variability in both sea ice extent and atmospheric parameters, especially at regional scales, and strong suggestions of ice/atmospheric interactions. Most workers find positive (warming) temperature trends over the period of instrumental meteorological records but, in spite of considerable effort, establishing the statistical significance of these trends has been problematic. Here we address this problem and investigate surface air temperature variability in the WAP region, with particular emphasis on the Palmer LTER study area (Figure 1).

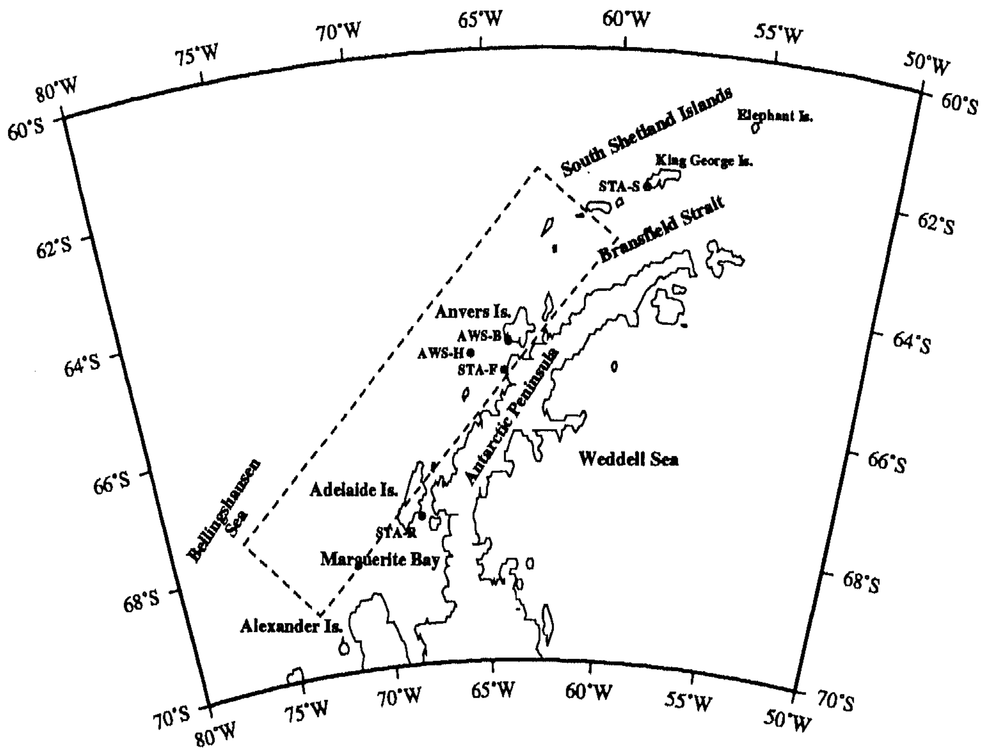

Fig. 1. Universal transverse mercator projection of the Antarctic Peninsula showing locations of meteorological stations mentioned in the text. The AWS sites are located on Hugo archipelago (AWS-H, 64°57.0′S 65°41.5′W) and on Bonaparte Point (AWS-B, 64°46.7′S 64°04.0′W). Palmer Station (not labeled) is located 750 m ENE of Bonaparte Point on Anvers Island. BAS air temperature data are from research stations (1) Rothera (STA-R, 67°34′S 68°08′W) located on Adelaide Island, (2) Faraday (STA-F, 65°15′S 64°15′W) located within the Argentine Islands (not labeled), and (3) Bellingshausen (STA-S, 62°12′S 58°56′W) located on King George Island within the South Shetland Islands (referred to as SSI in the text). The dotted rectangle outlines the Palmer LTER grid.

1.1. Antarctic Surface Air Temperatures

Jones et al. [1986], as well as *Hansen and Lebedeff* [1987], made comprehensive studies of southern hemisphere land-based surface air temperature variations over the past century. The analyses of these two groups are, overall, in good agreement and show a long term warming trend of about 0.5°C (1881 to 1984) and 0.6°C (1880-1985), respectively. In addition, these data are strongly correlated with the southern hemisphere marine series of *Folland et al.* [1984]. *Jones et al.* [1986] also show that the area-average temperatures for the Antarctic region (65°-90°S) have no correlation with temperatures from the rest of the southern hemisphere and use this evidence to imply that the Antarctic is largely decoupled from the rest of the hemisphere. They suggest that the decoupling is due to strong circumpolar circulation that minimizes north-south energy exchanges and/or that the short data records preclude detection of possible longer-term linkages. It should be noted that quality meteorological data records for the Antarctic are relatively short, most dating from the International Geophysical Year (IGY) of 1957-1958, so that prior to the 1950's few data were collected south of 45°S. In addition, there are large data gaps between 45°S and 65°S which may have biased the *Jones et al.* [1986] study. As will be discussed in Section 1.3, recent studies show responses in both Antarctic sea ice extent and various atmospheric variables to variations in the Southern Oscillation Index (SOI), which imply that there are important linkages between Antarctica and the rest of the southern hemisphere, as well as perhaps global teleconnections.

Other studies detecting trends in Antarctic surface air temperatures include an early analysis by *van Loon and Williams* [1977] who show warming trends on the Pacific side and cooling trends on the eastern side of Antarctica using winter surface air temperatures from 1956 to 1973. *Budd* [1980] reported a linear warming trend (significant at the 1% level) from 1954-78 for an average of a number of Antarctic stations. *Raper et al.* [1984] presented an objective analysis of surface air temperature for 16 stations in the Antarctic from 1957-82 and found a positive (warming) trend for both the annual mean and summer areal averages. They also found, for the short 10-year record, that linear trends in hemispheric sea ice extent and mean (areally averaged) temperatures were unrelated. *Sansom* [1989], in a thorough statistical analysis, using data from *Jones and Limbert* [1987] from some 29 stations located around Antarctica, examined air temperatures as possible indicators of global change. In spite of the large interannual variability of monthly mean temperatures, Sansom found that temperature variability was remarkably coherent between all stations. He fitted linear trends over a 30-year data period (1957-87) and concluded that these were *not* statistically significant warming trends. Sansom points out that *Raper et al.* [1984], and many other studies mentioned above, made no allowance for serial correlation which, when accounted for, reduces the trend to non-significance.

More recently, *Jones* [1990], combining climatological station data [*Jones and Limbert,* 1987] and air temperature records for 26 overwinter expeditions in Antarctica, created a time series of mean annual air temperatures from 1898 to 1987. Jones estimated annual air temperature values based upon a modern reference period (1957-75) for each expedition site so that all data could be expressed as anomalies from this reference period. Four out of five of the regions studied showed linear trends which indicated a warming of at least 2°C since the start of this century. He concluded that Antarctica is now at least 1°C warmer than earlier in this century.

1.2. Air Temperature and Sea Ice Extent Relationships

Jacka [1990] compiled Antarctic surface air temperature and sea ice data collected from several publications from a number of countries, including the *Jones and Limbert* [1987] data, and carried out statistical calculations to test for trends. Both *Jacka* [1990] and *Jacka and Budd* [1991] report small trends in temperature (increase) and sea ice extent (decrease), but they provide no quantitative estimate of the statistical significance of these trends.

Using monthly Antarctic station temperatures compiled by *Jones and Limbert* [1987] and sea ice data from two different (but not independent) sources, *Weatherly et al.* [1991] determined regional and seasonal cross-correlations between temperature and sea ice and included a systematic evaluation of lead/lag relationships for the purpose of investigating possible evidence for ice-temperature feedbacks. Analyzing the temperature data by season, they found that all stations show a predominance of positive trends in all seasons for the 30-year period and that those stations near the Antarctic Peninsula show the greatest coherence and have the most significant warming trends in most seasons. Like others, they found that the trend in mean annual temperatures over all of Antarctica is positive but not statistically different from zero at the 95% significance level, and that the 15 year sea ice record shows a slightly negative but not statistically significant trend which is consistent with the findings of *Gloersen and Campbell* [1991] and *Zwally et al.* [1991].

In testing the lead/lag temperature-ice relationships, *Weatherly et al.* [1991] showed quantitative indications of feedbacks that may be more complex than originally supposed in equilibrium general circulation models. They found that "lag correlations between seasonal anomalies are generally stronger with ice lagging the summer temperatures and with ice leading the winter temperatures". They also found that these relationships are strongly dependent upon the region chosen for the analysis so that, for example, the cross correlations between sea ice and temperature anomalies are strongest for areas surrounding the Antarctic Peninsula in autumn and winter seasons. They suggest that the relatively close coupling between sea ice and station air temperatures for the WAP, where positive trends in air temperature and negative trends in sea ice extent are larger and statistically significant, may enhance the associations they found in their Antarctic-wide analysis.

1.3. Southern Oscillation Versus Air Temperature and Ice Extent Relationships

Several authors have investigated possible linkages between low frequency El Niño/Southern Oscillation (ENSO) events and air temperature and sea ice in Antarctica. *Savage et al.* [1988] show a correlation between negative phases of the SOI (occurring between 1955 to 1986) and minimum extremes in South Pole surface air temperature a year later. They also show a spatially coherent pattern in monthly temperature anomalies following the 1982-83 ENSO event and speculate that "anomalously low temperatures in the interior may have been maintained as the result of a large-scale circulation anomaly dynamically linked (teleconnected) to the ENSO phenomenon". *Carleton* [1989] examined relationships between sea ice and southern hemisphere atmospheric circulation indices using correlation analysis. He points out that much of the apparent link between ice and SOI in earlier studies is reduced when effects of autocorrelation in the series are removed. However, by analyzing only the months in which significant correlations occur, Carleton agrees that there are "tentative" regional ice extent-SOI teleconnections, where sea ice extent changes in the Ross and Weddell Seas lag SOI by several months. In order to statistically confirm these "tentative" teleconnections, Carleton maintains that the sea ice extent time series needs to be at least 10 years longer. In a more recent and important study, *Smith and Stearns* [1993] found significant relationships between pressure and temperature anomalies from 24 Antarctic weather stations and the negative phases of the SOI and show that these relationships display strong regional differences. They hypothesize a model providing a mechanistic link between ENSO and Antarctica and present an analysis to support their conclusion that Antarctic climate affects ENSO. *Xie et al.* [1994a, 1994b] find significant correlations between Arctic and Antarctic sea ice and between Antarctic and ENSO events which imply complex atmospheric-oceanic interaction processes, whereby sea ice both influences and is influenced by ENSO events.

Most recently, *Gloersen* [1995], using a multiple-window harmonic analysis technique, has shown that time series of both Arctic and Antarctic sea ice cover contain statistically significant periodicities (both quasi-biennial and quasi-quadrennial) which are associated with ENSO, and that the effect of an ENSO/sea ice linkage on ice cover varies greatly for different regions. *Simmonds and Jacka* [1995] carried out an "exploratory" analysis to investigate the relationships between the interannual variability of Antarctic sea ice and the SOI. Their results show a complicated association between sea ice and the SOI which, in agreement with several authors, is a strong function of both season and region. Finally, there is evidence of ENSO signals in sea surface temperature, meridional surface winds and sea ice extent anomalies, which, when viewed as a function of both space and time, propagate eastward by the Antarctic Circumpolar Current, taking 8-10 years to circle the Antarctic continent (W.B. White and R.G. Peterson, personal communication, 1995). All of these works point to significant teleconnections between ENSO phenomena and Antarctic temperature and sea ice.

1.4. Western Antarctic Peninsula

The analysis of temperatures from 10 m glacier bore holes, which are considered to agree roughly within 1°C with the mean annual air temperature at the surface [*Loewe,* 1956; *Loewe,* 1970], have been used to determine the spatial variation of mean annual surface temperatures over the Antarctic Peninsula [*Martin and Peel,* 1978; *Reynolds,* 1981]. These studies clearly delineate a maritime climate regime on the west coast and a continental climate regime on the east coast of the Antarctic Peninsula, which is related to the topography of the peninsula and to the distinct ocean-ice circulation patterns on each side of the peninsula. Temperatures on the east coast are approximately 7°C lower than those on the west coast at sites of comparable altitude and latitude. Consistent with these ice-core studies are current meteorological observations which indicate two different climate regimes to either side of the Antarctic Peninsula (discussed below). Thus, our current view of east/west differences in Antarctic Peninsula climate appears to be representative of Antarctic Peninsula climate during the past millennium.

Schwerdtfeger [1975, 1979, and 1984] has described, with both observational data and theoretical considerations, the sharp contrast between wind, temperature and ice conditions on the two sides of the Antarctic Peninsula. Average monthly air temperatures on the west side are roughly 2°C (January) to 10°C (July) warmer than at comparable latitudes on the east side [*Schwerdtfeger,* 1984, Figure 1.13]. Schwerdtfeger presents theoretical considerations for the presence of cold, low-level "barrier winds" along the east side of the peninsula that develop "when stable air masses move westward over the ice-covered [Weddell] sea and find their way blocked by the mountainous Antarctic Peninsula" [*Schwerdtfeger,* 1975]. Driven by these barrier winds, which advect colder air from higher latitudes, the western Weddell Sea is a "source region" of ice and cold water flowing toward lower latitudes and into the Antarctic Circumpolar Current in the polar South Atlantic. Thus, the peninsula is an effective physical barrier to tropospheric circulation [*Schwerdtfeger,* 1970; *Schwerdtfeger and Amaturo,* 1979]. The observed difference in east/west Antarctic Peninsula sea ice coverage [*Stammerjohn and Smith,* this volume] is also consistent with this distinct east/west dichotomy.

Recently *King* [1994], making use of the synoptic meteorological observations carried out by the British Antarctic Survey (BAS), has investigated climate variability in the vicinity of the Antarctic Peninsula. King, updating the *Jones and Limbert* [1987] data to 1990 and using air temperature records from stations on the west coast of the Antarctic Peninsula, shows that these stations have a high degree of interannual variability and statistically significant warming trends. In searching for mechanisms driving temperature variations, King found a highly significant correlation between air temperature at Faraday and ice extent during winter and spring just west of the peninsula. He also found in the 1973 to 1990 sea ice extent data a trend of 0.13° latitude poleward retreat per year (significant at the 90% but not 95% level), but he concludes that the shortness of this record precludes conclusive evidence for a decline in sea ice extent in the WAP region. King also found a strong correlation (99% level) between monthly mean temperatures and monthly mean total cloud cover at both Marguerite Bay and Faraday during winter and spring months, indicating that warm winters are associated with increased cloudiness. In addition, King shows a strong correlation between surface air temperature and a meridional sea-level pressure index calculated for the peninsula area which is consistent with *Schwerdtfeger* [1976]. These results show that increased boundary-layer winds, flowing from the northwest sector toward the west coast of the peninsula, are associated with warm air advection and are correlated with above mean temperatures on the WAP. King concludes that the WAP region is climatically sensitive and that the large regional temperature trends observed there may reflect local amplifications of smaller trends observed elsewhere.

Sansom [1989], in a study of Antarctic surface air temperatures, used Faraday station air temperature data to represent the WAP area based upon location and completeness of record. He reported that the air temperatures in the WAP region are distinguished by a distinctive v-shaped annual cycle, strong seasonal temperature variability, and significant seasonal trends. *Stark* [1994], also using Faraday station air temperature data, computed seasonal trends and analyzed the data record for periodicity. Without making statistical allowance for serial correlation, he cites a trend of +0.0606°C/year, which indicates a warming of 2.7°C over the 1947 to 1990 period. In an analysis by season, the warming gradients are greatest for winter (+0.093 °C/year) and autumn (+0.105 °C/year) as compared with summer (+0.037 °C/year) and spring (+0.028 °C/year). Stark also found, using Fourier analysis of the detrended time series, a periodicity in these data at intervals of 5 and 9 years, but statistical significance of these periodicities was not given. Both *Sansom* [1989] and *Stark* [1994] observe that Faraday has a climate affected by both maritime and continental influences. The consequence of these contrasting influences is a typical sea ice free summer and autumn where temperatures are moderated by the ocean and hence show relatively little interannual variability, contrasted to a winter and spring where temperatures are highly variable depending on the extent of sea ice which is associated with continental influences. Therefore, the suggested climatic sensitivity of the WAP region may hinge on shifts in these contrasting maritime and continental influences.

Other evidence of warming trends in the WAP region is the rapid disintegration of the Wordie Ice Shelf, adjacent to Marguerite Bay [*Doake and Vaughan,* 1991], as well as changes in glacial features on the WAP [*Splettstoesser,* 1992]. These authors suggest that ice shelves exist up to a climatic limit and are thus sensitive to atmospheric or oceanic warming, thereby reflecting trends over the past several decades. Recognizing the limitations imposed by the lack of long term station data, *Nicholls and Paren* [1993] attempted to extend the relatively short meteorological record by using ice-sheet temperature profiles. For a temperature reconstruction, this method requires reliable dating of the annual snowfall layers and accurate determination of the isotopic temperature relationship. They used a simple time-dependent heat diffusion-advection model to infer surface temperature variations. Results suggest that there has been an overall *cooling* (1.6± 0.1° C) of the Antarctic Peninsula from 1900 to the start of the Faraday air temperature record in 1944. While these results are in contrast to those obtained from the historical meteorological records [*Jones,* 1990], Nicholls and Paren maintain that the Faraday record began during a colder period and that temperatures a few hundred years ago were probably very similar to those today.

A characteristic of atmospheric variability at high latitudes in the southern hemisphere, which may affect atmospheric-ice interactions in the WAP region in particular, is the half-year cycle displayed in temperature, pressure, wind and precipitation time-series [*van Loon,* 1967; *Schwerdtfeger,* 1984]. As demonstrated by *van Loon* [1967], there is a semiannual variation in the north-south temperature gradient, driven by differences in the seasonal heating and cooling trends in middle (50°S) and high (65°S) latitudes, which becomes largest in spring and autumn. This mid-to-high latitude temperature gradient is linked to both increased cyclonic activity and to a southward shift between 60°S to 70°S in the mean position of the circumpolar low-pressure trough during these equinoctial months. *Enomoto and Ohmura* [1990] referred to this low-pressure belt as the atmospheric convergence line (ACL) and showed that the ACL and the latitude of northernmost limit of sea ice cross twice per year. As noted early by *van Loon* [1967], the sea ice edge is near its extreme poleward (fall) or equatorward (spring) positions when the mean position of the circumpolar trough is nearest the continent, and conversely, the ACL is on average furthest equatorward when the sea ice edge is at an intermediate position. The relative positions of these two lines influence the semiannual cycle of wind and sea ice distribution. Recently, *Harangozo* [1994] showed that varying north-south atmospheric circulation patterns exist in the WAP region and that shifts in these patterns induce contrasting sea ice extent regimes. Harangozo noted a linkage between winter ice extent changes and the north-south component of geostrophic flow but cautioned that the persistence as well as the magnitude of this flow must be considered in assessing seasonal and interannual anomalies. However, these investigations suggest strong linkages between atmospheric forcing, cyclonic activity and sea ice extent, particularly in the WAP region, but these linkages remain to be elucidated.

1.5. Palmer Long Term Ecological Research

The Palmer LTER area encompasses the shelf/slope region west of the Antarctic Peninsula (Figure 1). Within this region, the Palmer LTER has a fixed sampling grid which provides consistent reference locations for seasonal and interannual sampling and a framework for long term measurement comparisons [*Waters and Smith,* 1992]. This grid extends 900 km along the WAP (from King George Island south to Alexander island) and 200 km on/offshore. Also shown in Figure 1 are meteorological station locations along the WAP that are discussed in the text. Historic hydrographic data permit a general description of water mass distributions and circulation patterns for this area [*Hofmann et al.,* this volume]. A central hypothesis of the Palmer LTER is that physical factors force the biology of this system. In particular, we hypothesize that the annual and interannual variability of sea ice is a major physical determinant of spatial and temporal changes in the structure and function of the Antarctic marine ecosystem [*Quetin and Ross,* 1992; *Smith et al.,* 1995].

From the perspective of the Palmer LTER, it is of interest to (1) compare air temperatures from Faraday with the shorter record from Palmer Station, (2) test if these data records can be closely linked so as to provide a longer term temperature record for the Palmer LTER, (3) contrast these data sets with those elsewhere along the WAP, and (4) explore possible mechanisms driving variability in WAP surface air temperatures. To assess surface air temperature variations in the Palmer LTER region, we build upon the excellent BAS weather data, in particular the Faraday station record. In Section 2 we discuss sources of temperature, sea ice and SOI data. In Section 3 we present results and discussion of temperature records from South Shetland Islands, Palmer, Faraday, and Rothera, as well as from recent Palmer LTER automatic weather station (AWS) sites. We compare air temperature and sea ice extent data and present lead/lag correlation analyses to investigate air temperature-sea ice relationships. Also in Section 3 we present evidence of relationships between the SOI and both temperature and sea ice extent in the WAP region. A summary is presented in Section 4.

2. DATA

2.1. Temperature Data

The British Antarctic Survey (BAS) has a long and distinguished history of scientific research, including meteorological observations, in the Antarctic. Monthly average temperature records are available from the mid 1940's until 1986 for a number of peninsula stations [*Jones and Limbert,* 1987] including: Rothera, Faraday, and Bellingshausen on King George Island within the South Shetland Islands (Figure 1). Following the lead of *King* [1994], the Bellingshausen station data will be referred to as South Shetland Islands (SSI) in our discussion so as to emphasize their specific location and to avoid confusion with the Bellingshausen Sea. Monthly temperature BAS data after 1986 were made available from J. Shanklin (personal communication, 1991), and daily Faraday BAS data were made available from C. Stearns (personal communication, 1994). The BAS data are extremely useful because of their length, consistency, and quality control. These data provide not only a relatively long time series (for the Antarctic) but also document the spatial temperature gradient along the WAP.

Weather observations at Palmer station are made four times a day at 0000, 0600, 1200 and 1800 UTC (Coordinated Universal Time). These observations, broadcast into the Global Transmission System data stream for archival, are also available from 1989 as daily summaries. The measurements include daily maximum, minimum and average air temperatures. Daily average air temperature is determined by taking the mean of the daily maximum and minimum air temperatures. Monthly temperature data summaries from 1974 to the present are available from the Antarctic Journal of the U.S. The Palmer air temperature observations show close agreement with contemporaneous AWS data [*Baker and Stammerjohn*, 1995].

A system of AWS units has been developed in Antarctica [*Savage et al.*, 1988; *Bromwich and Stearns*, 1993] with data summarized in yearly data reports [*Keller et al.*, 1995]. AWS data include 1-second temperature measurements, recorded every ten minutes. These readings are broadcast to a NOAA satellite, when satellite receiver and AWS transmitter are in view of each other, and the data are then processed and disseminated through the Argos system. The uploaded data typically provide a 63-83% daily sampling coverage for the mid-peninsula area. Two AWS sites near sea level were designated at the request of the Palmer LTER program. AWS Bonaparte was installed in January 1992 on a rocky point at the entrance to Arthur Harbor about 750 m WSW of Palmer Station. AWS Hugo was installed in December 1994 on an island in the Victor Hugo archipelago, a small group of low lying islands and rocks, approximately 90 km northwest of the peninsula and roughly this same distance WSW of Palmer Station. Since the original AWS was designed for a cold and dry continental atmosphere, success with AWS data collection in the salty marine environment has been intermittent, and platform redesign is underway.

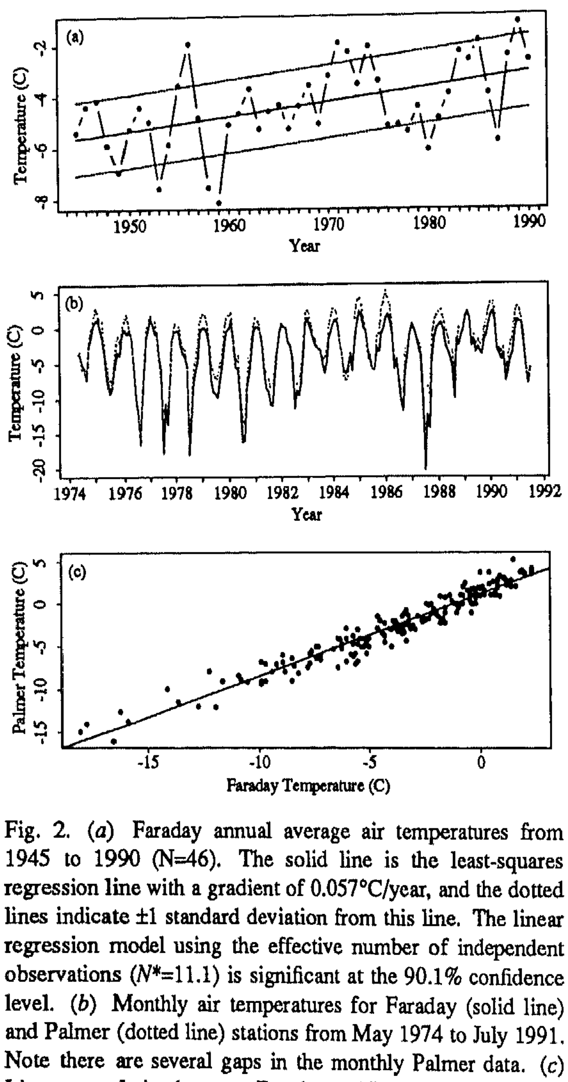

Fig. 2. (*a*) Faraday annual average air temperatures from 1945 to 1990 (N=46). The solid line is the least-squares regression line with a gradient of 0.057°C/year, and the dotted lines indicate ±1 standard deviation from this line. The linear regression model using the effective number of independent observations (N^*=11.1) is significant at the 90.1% confidence level. (*b*) Monthly air temperatures for Faraday (solid line) and Palmer (dotted line) stations from May 1974 to July 1991. Note there are several gaps in the monthly Palmer data. (*c*) Linear correlation between Faraday and Palmer monthly mean air temperatures for period of coincident monthly data from May 1974 to July 1991 (N=188). The linear regression model is: Palmer = 1.15 + 0.96(Faraday), R^2=0.94, and student t-test and F-test are significant at the 99.99% confidence level using N^*=20.1

2.2. Sea Ice and SOI Data

Sea ice extent data for the LTER region from October 1978 to August 1994 is from *Stammerjohn and Smith* [this volume], who show that monthly anomalous ice coverage in the LTER region is coherent with monthly anomalous ice coverage in the greater Bellingshausen region (delimited longitudinally from 60°-90°W). Therefore, ice coverage in the LTER region is representative of ice coverage in the entire WAP region. Ice extent is defined as the total area enclosed by the 10% ice concentration contour.

The Southern Oscillation, named by Sir Gilbert Walker [*Walker*, 1923; *Walker and Bliss*, 1932], refers to the 'seesaw' in sea level pressures between the tropical Pacific and Indian Oceans. A measure of the state of the Southern Oscillation is the Southern Oscillation Index (SOI), which is determined by the standardized sea-level pressure difference between Tahiti and Darwin, Australia. These two stations are located in the core regions of the Southern Oscillation and have long continuous data records. SOI data were obtained digitally from the Climate Diagnostic Data Base (ftp nic.fb4.noaa.gov) which is maintained by the Climate Analysis Center (Department of Commerce, NOAA). The SOI data, used here in comparisons with air temperature and sea ice extent data, are standardized monthly anomalies from January 1951 to March 1995.

3. RESULTS AND DISCUSSION

3.1. Long Term Air Temperature Regime

Annual average Faraday air temperatures from 1945 to 1990 are presented in Figure 2*a*. This figure is very similar to Figure 2 found in *Stark* [1994], with the exception of the additional 1945-46 data. The solid line is the least-squares regression line, which as reported by *Stark* [1994] and *King* [1994], shows a warming trend in the Faraday air temperatures over

TABLE 1: Monthly, seasonal and annual trends in air temperatures from Faraday Station.

Years	Months	Gradient (°C/year)	Standard Error (°C/year)	F-test (%)	D-test (at 99%)
45-91	Jan	0.0225	0.0083	99.0	no
45-91	Feb	0.0372	0.0107	99.9	no
44-91	Mar	0.0347	0.0120	99.4	no
44-91	Apr	0.0558	0.0266	95.8	no
44-91	May	0.0858	0.0273	85.1[a]	inc
44-91	Jun	0.1136	0.0310	99.0	no
44-91	Jul	0.0845	0.0483	91.3	no
44-90	Aug	0.0886	0.0382	97.5	no
44-90	Sep	0.0689	0.0331	95.7	no
44-90	Oct	0.0298	0.0201	85.6	no
44-90	Nov	0.0294	0.0141	95.7	no
44-90	Dec	0.0095	0.0060	87.8	no
45-91	Summer[b]	0.0328	0.0090	99.9	no
44-91	Fall	0.0851	0.0238	99.9	no
44-90	Winter	0.0834	0.0385	72.3[a]	yes
44-90	Spring	0.0344	0.0126	79.5[a]	inc
45-90	Annual	0.0566	0.0158	90.1[a]	yes

[a] Calculated using N^* of 11.2, 12.4, 11.0 and 11.1 respectively
[b] Summer (Jan-Mar), Fall (Apr-Jun), Winter (Jul-Aug), Spring (Sep-Dec)

the last 46 years. However, as pointed out by both *King* [1994] and *Sansom* [1989], the linear regression is *not* significant, if the serial correlation present in the Faraday time series is considered in the regression analysis. When regressing time series data, the regressor and response variables have an inherent sequential order over time, which in most cases leads to correlated error terms, which in turn are a violation of one of the fundamental assumptions in linear regression analysis. There are several statistical methods one could use to account for serial correlation in regression analysis, and there does not seem to be a consensus in the statistical literature as to which is the best or most appropriate method. However, a conservative approach is to penalize the number of degrees of freedom in the calculation of significance testing, or in other words, determine what the *effective* number of *independent* observations is for the time series being regressed [*Bartlett*, 1946; *Davis*, 1976; *Chelton*, 1983; *Trenberth*, 1984]. For example, when regressing two random variables this can be achieved by using Equation 1 from *Chelton* [1983]:

$$N^* = \frac{N}{\sum_{\tau=-\infty}^{\infty} [\rho_{qq}(\tau)\rho_{rr}(\tau) + \rho_{qr}(\tau)\rho_{rq}(\tau)]} \quad (1)$$

where, for example, $\rho_{qr}(\tau)$ is the sample estimate of the true cross correlation between $q(t)$ and $r(t)$ at lag τ. If there is no serial correlation present in the two random variables for $\tau \neq 0$, then the sum of the autocorrelations and cross-correlations, or the spacing between effectively independent observations, would be 1 (ie., at $\tau = 0$), and $N^* = N$. If there is serial correlation, then the spacing between effectively independent observations would be greater than 1 and $N^* < N$.

However, in determining the warming trend in the Faraday annual temperatures, the predictor variable, time, is not a random variable. Therefore, the above equation is modified to account for the autocorrelation in the error terms of the linear regression (J. Michaelsen, personal communication, 1995):

$$N^* = \frac{N-2}{(1 + 2\sum_{\tau=1}^{\infty}[\rho_{ee}(\tau)^2])} \quad (2)$$

where $\rho_{ee}(\tau)$ is the autocorrelation of the residuals at lag τ. The $N-2$ in the numerator is the degrees of freedom for the regression residuals. In the denominator, the sum of the autocorrelation function is actually from $-\infty$ to ∞, so that the '1+' accounts for zero lag, and the sum multiplied by 2 accounts for the negative and positive lags (since the autocorrelation is symmetric about zero). Once again, if there is no serial correlation in the error terms for $\tau \neq 0$, then $N^* = (N-2)$, and if there is serial correlation, then the spacing between effectively independent observations would be greater than 1 and $N^* < (N-2)$.

Thus, the total number N of annual values used in the Faraday linear regression was 46, but the effective number of independent observations, N^*, after considering the serial correlation using Equation 2, becomes 11.1. Using N^* to calculate the degrees of freedom for the F-test, the significance of the Faraday regression model is reduced from 99.9% to 90.1% (Table 1). It should be emphasized that the designations of regression significance using N^* (determined by either Equation 1 or 2 where appropriate) are relatively strict assessments.

Therefore, to better estimate the significance of a warming trend in Faraday air temperatures using linear regression analysis, each month's time series was analyzed separately. Decomposing the seasonal time series in this way helps to eliminate not only serial correlation but also non-constant variance in the error terms, another property which violates a fundamental assumption in linear regression analysis. Table 1 shows the trend detected in each month's time series (as well as in the seasonal and annual time series for comparison), the standard error and the significance of the linear regression analysis as estimated by the F-test. The F-test shows that 8 of the 12 monthly regressions are significant at confidence levels greater than 95%. Also shown are results from the Durbin-Watson D-test [*Durbin and Watson*, 1950; *Durbin and Watson*, 1951; *Durbin and Watson*, 1971] used to detect the presence of autocorrelation in the error terms. The D-test statistic is computed as follows:

$$d = \frac{\sum_{t=2}^{n}(e_t - e_{t-1})^2}{\sum_{t=1}^{n} e_t^2} \qquad (3)$$

where e_t is the linear regression residual at time (t). The D-test assumes that the errors or residuals are generated by a first-order autoregressive process. *Durbin and Watson* [1951] show that d lies between two bounds, a lower bound (d_L) and an upper bound (d_U), such that (1) if d is less than d_L, then autocorrelation is present, (2) if d is greater than d_U, then there is no autocorrelation, and (3) if d is within d_L and d_U, then the test is inconclusive. Since the May, winter, spring and annual regressions had either inconclusive or positive D-tests results, the degrees of freedom were penalized using Equation 2. When the F-tests are recalculated using N^*, the regressions are no longer significant at confidence levels above 95%. Since there was no evidence of autocorrelation in the other months, those F-tests are considered reliable indicators of monthly trend significance. The warming trend in Faraday air temperatures is strongest in mid-winter months and peaks in June at 0.114°C/year, representing a 5.5°C increase in June temperatures over the 48 year record.

The detection of long term trends in other WAP station records is difficult, since no other station along the peninsula has as long a temperature record as Faraday. Yet strong correlations of a given temperature record with Faraday's would indicate similar warming trends throughout the western Antarctic Peninsula region. Figure 2*b* shows monthly air temperatures observed at Faraday and Palmer for the period of overlapping data from 1974 through 1991. Although the Palmer record is not continuous during this time period, it follows a similar seasonal pattern as observed at Faraday and is on average 1 to 3°C higher, as might be expected given its slightly lower latitude location. Figure 2*c* shows the regression of Faraday versus Palmer monthly air temperatures. Serial correlation is present in the regression error terms, so that the 185 monthly values used in the regression is reduced to about 20 independent observations using Equation 1. However, the regression between Faraday and Palmer is so strong that the F-test is still significant at 99.9%, even with an approximate 90% reduction in the number of observations. Thus, the long term Faraday temperature record can be used in the linear regression model given in Figure 2*c* to extend the Palmer record back in time or fill missing data within the currently available record.

Figure 3 shows the annual mean air temperatures from SSI, Palmer, Faraday and Rothera, station records which represent the temperature gradient along the WAP. Visual inspection suggests a strong temporal coherence among stations. Regression of monthly average temperatures between Palmer, Faraday and Rothera have R^2's greater than 0.90 which test significant at the 99.9% confidence level. Regressions between SSI and the other stations have R^2's less than 0.85, intimating that the regional climate affecting SSI temperatures may be different from the regional climate affecting Palmer, Faraday and Rothera, an observation also made by *King* [1994].

3.2. *Maritime Versus Continental Regimes*

The annual progression of temperatures and the amount of variability associated with those temperatures can be used to

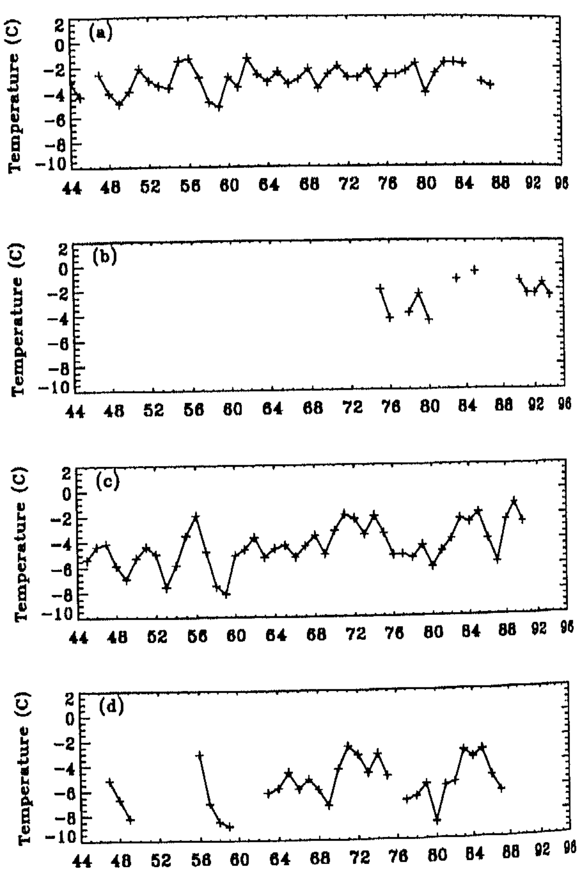

Fig. 3. Mean annual surface air temperatures for (*a*) SSI (1944-1988), (*b*) Palmer (1974-1994), (*c*) Faraday (1944-1991), and (*d*) Rothera (1946-1988). Missing years in the time series are due to one or more months of missing data for that year.

elucidate climate regimes. The mean annual temperature curves for the four representative stations along the WAP are shown in Figure 4*a*. These curves are based on the data record available from each station. Annual curves were computed also for overlapping years from 1974 to 1988, but since the curves were similar to those depicted in Figure 4*a*, it is assumed that there is little bias due to the different record lengths used to generate Figure 4*a*. The average yearly station temperatures computed from these curves are: SSI (-3.0°C), Palmer (-2.3°C), Faraday (-4.4°C) and Rothera (-5.4°C). Rothera has the lowest overall temperatures, as would be expected since it is the most southerly station, although there is some overlap with Faraday for the months of December and January. The SSI annual curve does not conform with the association of higher temperatures at lower latitudes, for SSI has lower mean temperatures from November to July, overlaps with Palmer in August, and then has higher mean temperatures from September to October. The behavior of the SSI annual cycle helps explain the low R^2's observed in the annual mean air temperatures between SSI and the other stations.

One explanation for a different air temperature regime at SSI is given by *Schwerdtfeger* [1975, 1984]. He notes that the WAP has the mildest and wettest climate of the Antarctic with relatively warm winds from the northwest quadrant, while the eastern Antarctic Peninsula is subjected to relatively persistent cold winds from the south and southwest, which results in significantly lower temperatures (about 10°C in winter) on the east side of the peninsula (as mentioned in Section 1.4). *Schwerdtfeger* [1984] presents evidence to show that a branch of these cold eastern barrier winds, which flow toward lower latitudes and into the Antarctic Circumpolar Current in the polar South Atlantic, often curl westward, through the Antarctic Sound near the northeast tip of the Antarctic Peninsula and into the Bransfield Strait. This cold stream of air frequently sweeps the SSI, accounting for the colder air temperatures observed there from November to July (Figure 4*a*).

Another indicator of different climatic influences is the amount of variability in the monthly temperatures. Figure 4*b* shows the standard deviation curves for the above computed mean annual curves. The two distinguishing features about this figure are: (1) the significantly higher variability from May through September at all stations, and (2) the overall higher variability observed for the more southerly stations. Since all of these stations are coastal, the climate in summer, when ice-free conditions typically exist, is mostly maritime, which accounts for the low variability in air temperatures during this time of year. There is evidence to suggest that the increased variability during fall and winter is due to the high variability in year-to-year ice coverage and the corresponding increased continental influence when an extensive ice cover exists. As a consequence, there is a north-south gradient in both sea ice and temperature along the peninsula linked to the balance between maritime and continental climatic influences. The climate at the southernmost station, Rothera, is predominantly continental, both throughout the year and from year-to-year, since sea ice coverage is more consistent and extensive, in comparison with more northerly areas along the peninsula. Thus, the high yearly variability in monthly air temperatures at Rothera is associated with the predominantly continental regime. In contrast, winter sea ice coverage in the vicinity of SSI usually does not last for more than a month or two, and the climate at

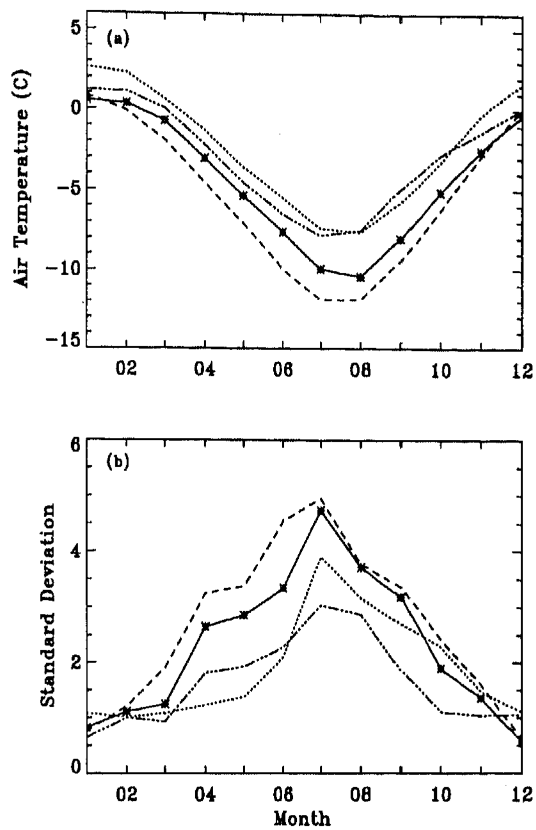

Fig. 4. (*a*) Annual curves of monthly mean surface air temperatures for Rothera (dashed), Faraday (solid), Palmer (dotted) and SSI (dashed-dotted). (*b*) Standard deviations of the monthly mean surface air temperatures shown in (*a*).

SSI is a mix of maritime coupled with the above mentioned influence of barrier winds. Reflecting this maritime influence, the variability in winter air temperatures is lowest at SSI. The mid-peninsula stations, Palmer and Faraday, show seasonal influences from a combination of both maritime and continental regimes. Faraday, more so than Palmer, appears to be more strongly influenced by a wintertime continental regime, accounting for both the lower observed temperatures and the higher interannual variability.

Until 1994 weather data for the WAP region were available only from stations located on the coast or on islands near the coast. Since the installation of the LTER AWS units, a comparison can now be made between weather data from a coastal station (AWS Bonaparte) and from an oceanic station (AWS Hugo) to help characterize the different weather regimes and provide relevant information for the study of marine habitats associated with contrasting weather influences. Daily minimum and maximum temperatures, as well as standard deviations of daily mean temperatures, from AWS Hugo and Bonaparte for the period January through May 1995 are shown in Figure 5. There is little, if any, sea ice in this region for the months shown here, so differences in temperature between the two stations are primarily due to the influence of a maritime coastal environment versus a maritime oceanic environment.

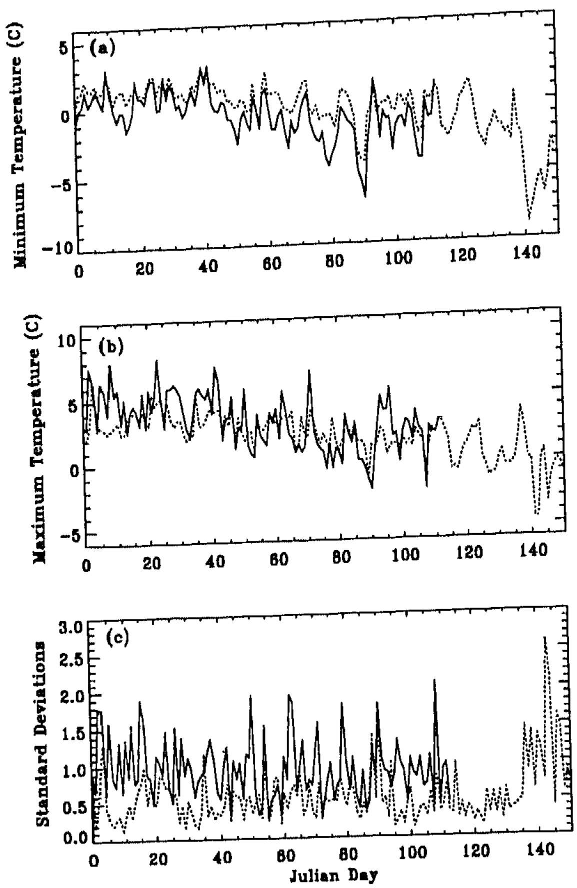

Fig. 5. Air temperatures from AWS Hugo (dotted line) and AWS Bonaparte (solid line) for January through May 1995: (*a*) daily minimum, (*b*) daily maximum, and (*c*) standard deviations of daily means.

For both the minimum and maximum temperature plots in Figures 5*a* and 5*b*, the day-to-day fluctuations between stations are fairly similar in periodicity but not in magnitude. Bonaparte experiences both lower minimum and higher maximum daily temperatures. This appears to indicate that even during ice-free conditions, the air temperatures at this coastal station experience a "continental" influence from the nearby glaciers and high mountains, whereas the air temperatures at Hugo are moderated by the surrounding ocean. This is illustrated more dramatically in Figure 5*c* which shows the standard deviations calculated from the daily mean temperatures. Standard deviations calculated from Bonaparte daily mean temperatures are on average two to three times higher than the standard deviations calculated from Hugo daily mean temperatures. Therefore, in addition to the day-to-day variability, there is also much higher variability *during* any one day in air temperatures at the coastal station, Bonaparte, versus the oceanic station, Hugo. While these AWS records are new and thus too short for long term analysis, they illustrate the distinction between data from coastal stations, which comprise our only historical records, and data from oceanic stations, which are more closely coupled to the marine environment.

Also apparent in the daily analysis of Hugo versus Bonaparte air temperatures is the conspicuous periodicity observed in all three daily variables shown in Figure 5. Since the 1995 AWS Bonaparte and Hugo daily time series are short (about 150 days), spectral analysis was performed on the 1992 AWS Bonaparte daily air temperatures, since data from that year were both complete and continuous, making those data a better candidate for spectral analysis. The 1992 AWS Bonaparte daily time series, shown in Figure 6*a*, shows the conspicuous periodicity, the yearly progression of temperature in the Palmer area, and the increased variability in winter versus summer temperatures. Spectral analysis of these data shows a statistically significant (95%) peak in the autospectrum at an approximate 6-7 day interval (Figure 6*b*). Spectral analysis of 1992 Faraday data gave similar results. Further analysis of Faraday daily data from 1951-1992, which were divided by season, show several periodicities in the 4 to 8 day range which were strongest in summer and fall autospectra and which are most likely associated with quasi-periodic passage of low pressure systems across the WAP region. Spectral analysis performed on 2-day averages of LTER anomalous sea ice coverage from 1978 to 1991, which were aggregated into seasons, also show a significant 5-6 day periodicity, but detectable only in the sum-

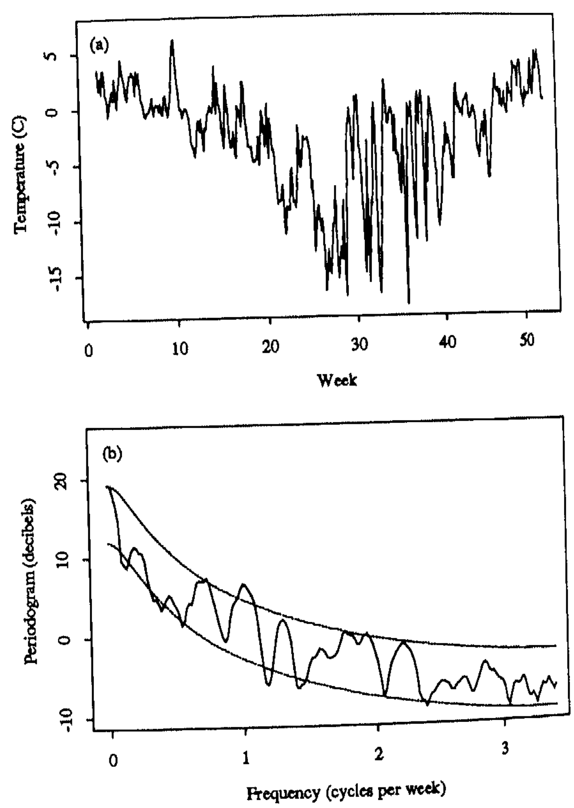

Fig. 6. (*a*) Daily mean air temperature from AWS Bonaparte for 1992. (*b*) Autospectrum of AWS Bonaparte daily mean air temperatures. The dashed lines represent 95% confidence intervals for an autospectrum generated by a first order autoregression model. Peak at 1 cycle/week (i.e., about a 7-day interval) is statistically significant at the 95% confidence level.

mer and fall autospectra [*Stammerjohn and Smith*, this volume]. As will be shown subsequently, there is a significant anticorrelation between anomalous monthly Faraday temperatures and LTER sea ice extent, so that the periodicity detected in both datasets could be the result of the same driving mechanisms.

3.3. *Air Temperature Versus Sea Ice Variations*

Weatherly et al. [1991] and *King* [1994] both observed strong coupling between air temperatures and sea ice extent for the WAP region. In fact, *Weatherly et al.* [1991] show that the relationship between air temperature and sea ice extent is much stronger in the WAP region than elsewhere in the Antarctic. Both studies used air temperatures from the BAS dataset to correlate with sea ice data. *Weatherly et al.* [1991] used two different sources of sea ice data. Both sources were spatially aggregated specifically for the Amundsen/Bellingshausen region and for a 20° longitudinal region encompassing the peninsula and were temporally aggregated into seasons. *King* [1994] used monthly ice ice edge data at 70°W. The study presented here uses monthly ice extent data aggregated for the Palmer LTER study region which encompasses Palmer, Faraday and Rothera stations. Since the Faraday temperature record is continuous during the time of the sea ice record, it is used in the comparisons with the LTER ice extent data.

Monthly standard deviates of Faraday air temperature versus LTER ice extent are shown in Figure 7*a*. Standard deviates are the normalized anomalies which were determined by dividing the anomaly (for the month and year in question) by the standard deviation of the anomaly (for the month in question). Visually there appears to be a strong anticorrelation, as well as long term persistence in both variables. The long term persistence in Faraday air temperatures and LTER ice extent is reflected in significant autocorrelations up to 19 and 17 monthly lags, respectively. This long term persistence in both air temperatures and ice coverage appears to be unique to this region of the Southern Ocean [*Sansom*, 1989; *King*, 1994; *Stammerjohn and Smith*, this volume] and also leads to occurrences of consecutive high then low temperature years concurrent with low then high ice years. For example, from about 1979 to 1982 and from mid 1986 to late 1987, conditions in the WAP region had below mean temperatures and above mean ice extent. From 1983 to early 1986 and from 1988 to late 1991, conditions in the WAP region had above mean temperatures and below mean ice extent. The ice record was too short to show statistically significant periodicity [*Stammerjohn and Smith*, this volume], so spectral analysis was carried out on the 45-year annual averaged Faraday temperature record to determine whether any periodicity could be detected there. Figure 7*b* shows the autospectrum of the Faraday detrended annual mean temperatures (detrending was achieved by subtracting a least squares regression line from the time series). The strongest periodic signal is the broad peak centered at 0.2 cycles per year or 5-year interval (also detected by *Stark* [1994]), but the peak is just below the 95% confidence limit. This suggests either that the record length may be too short to detect this periodicity at a level of confidence or that the frequency of high (or low) ice periods may be aperiodic.

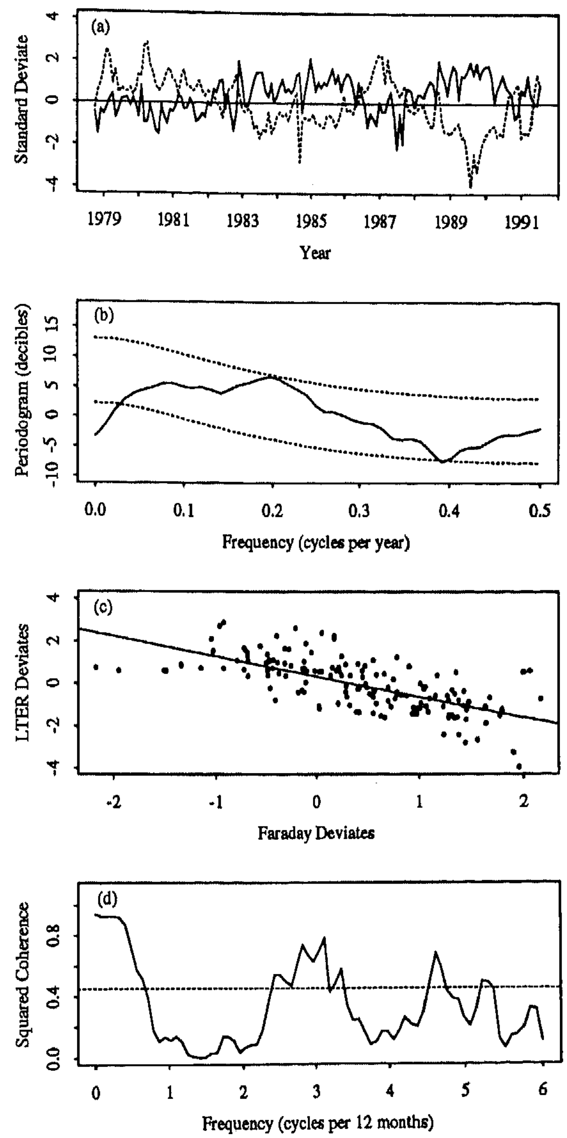

Fig. 7. (*a*) Monthly standard deviates of Faraday air temperatures (solid line) and LTER ice extent (dashed line) from October 1978 to July 1991. (*b*) Autospectrum of Faraday annual air temperatures from 1945-90. The dashed lines represent 95% confidence intervals for an autospectrum generated by a first order autoregression model. (*c*) Linear correlation of monthly standard deviates between LTER sea ice extent and Faraday air temperatures for period of coincident monthly data from October 1978 to July 1991 (N=154). Linear regression model has an R^2 of 0.47, and the F-test is significant at 99.9% using N^*=19.7. (*d*) Squared coherence spectrum of Faraday air temperatures versus LTER ice extent. Values above the dotted line are significantly coherent at the 95% confidence level.

TABLE 2: Correlation coefficients between standard deviates of Faraday monthly temperatures and LTER monthly sea ice extent in preceeding, same and following months.

		Ice in relative month						
Years	Month	-3	-2	-1	0	+1	+2	+3
79-91	Jan	-0.69*	-0.58*	-0.65*	-0.68*	-0.73*	-0.77*	-0.76*
79-91	Feb	-0.89*	-0.84*	-0.66*	-0.69*	-0.50	-0.53	-0.58*
79-91	Mar	-0.63*	-0.74*	-0.73*	-0.80*	-0.85*	-0.58*	-0.45
79-91	Apr	-0.24	-0.25	-0.54	-0.65*	-0.42	-0.41	-0.08
79-91	May	-0.52	-0.54	-0.46	-0.81*	-0.73*	-0.74*	-0.60*
79-91	Jun	-0.66*	-0.78*	-0.90*	-0.91*	-0.74*	-0.51	-0.41
79-91	Jul	-0.86*	-0.74*	-0.68*	-0.68*	-0.54	-0.52	-0.63
79-90	Aug	-0.84*	-0.83*	-0.74*	-0.68*	-0.79*	-0.77*	-0.70*
79-90	Sep	-0.68*	-0.65*	-0.40	-0.57	-0.76*	-0.64*	-0.57
78-90	Oct	-0.36	-0.70*	-0.39	-0.79*	-0.83*	-0.69*	-0.58*
78-90	Nov	-0.50	-0.58	-0.63*	-0.86*	-0.85*	-0.56*	-0.65*
78-90	Dec	-0.51	-0.52	-0.46	-0.62*	-0.55	-0.58*	-0.45

* F-test > 95%

The anticorrelation between Faraday air temperatures and LTER ice extent, apparent in the time series in Figure 7*a*, was tested using both linear regression analysis and cross spectral analysis. Figure 7*c* shows the linear regression of Faraday air temperature versus LTER ice extent for N=154 observations. The linear regression has an R^2 of 0.47 and is significant at 99.9%, even after reducing the effective number of independent observations to N^*=19.7 (using Equation 1). Figure 7*d* shows the squared coherence spectrum. There are significant low frequency coherences at approximately 18-month intervals and greater, which are, as indicated by the phase spectrum (not shown), 180° out-of-phase (ie., anticorrelated). There are also higher frequency coherences at roughly 4-month and 2.6-month intervals, which are not quite out-of-phase, indicating a possible lead/lag relationship.

Lead/lag relationships between Faraday air temperatures and LTER sea ice extent were tested using linear regression on the individual monthly time series of standard deviates. Such lead/lag correlations are considered to be indicative of important potential feedback mechanisms in climate modeling. Table 2 shows the correlation coefficients for ice leading and lagging air temperatures up to three months (to include possible seasonal relationships). In some cases, correlation coefficients were determined for ice leading or lagging air temperatures for intervals greater than 3 months (e.g., for correlations with Faraday air temperatures in January, February, July and August) and, when found to be highly significant, are included in the summarized analysis given below. Since the monthly datasets for determining these correlation coefficients involve only 12-13 points, caution must be used in interpreting any lead/lag relationships. However, there are instances of high correlations which test significant at 95% or higher and which suggest a seasonal pattern of ice extent influencing temperatures and vice-versa.

There are five distinct lead/lag relationships suggested by the groupings of highest correlation coefficients in Table 2: (1) early summer temperatures (January) influence fall ice extent (March-May), (2) late summer temperatures (February) are influenced by previous spring ice extent (October-December), (3) fall temperatures and ice extents are coincident, (4) mid-winter temperatures (July-August) are influenced by previous summer and fall ice extents (January-May), and (5) spring temperatures (September-November) influence the following month's ice extents. The first and fifth relationships indicate that spring and summer temperatures anomalies force ice extent anomalies, but that this forcing is either short term in spring, affecting ice extent most significantly the following month, or long term in summer, where it may influence an above or below mean maximum ice extent for that year. The second and fourth relationships defined above indicate that spring and summer/fall ice anomalies force mid-summer (February) and mid-winter (July and August) temperature anomalies, respectively. *Weatherly et al.* [1991] looked at seasonal lead/lag relationships between sea ice and temperature for various regions in the Southern Ocean and observed the first and fourth relationships above: sea ice extent lags summer air temperatures and sea ice extent leads winter air temperatures. *King* [1994] looked at 1 month lead/lag relationships between Faraday monthly temperatures and ice edge latitude at 70°W and found the short-term forcings described in the third and fifth relationships given above. This lead/lag analysis indicates that linkages between temperature and sea ice involve elements of seasonal timing that are more complex than typically assumed in classical feedback mechanisms.

3.4. SOI Versus Ice and Temperature Variations

Monthly standard deviates of LTER sea ice extent and the SOI are compared in Figure 8. In Figure 8*a* the monthly time series of LTER sea ice extent versus SOI have not been smoothed, while in Figure 8*b* the time series have been smoothed by an equal weight moving average filter. Both the unsmoothed and smoothed time series show an anticorrelation between LTER sea ice extent and SOI. There is longer persistence in the LTER ice extent deviates than in the SOI deviates, where autocorrelations are significant up to 17 and 8 monthly lags, respectively. There is also a high frequency fluctuation

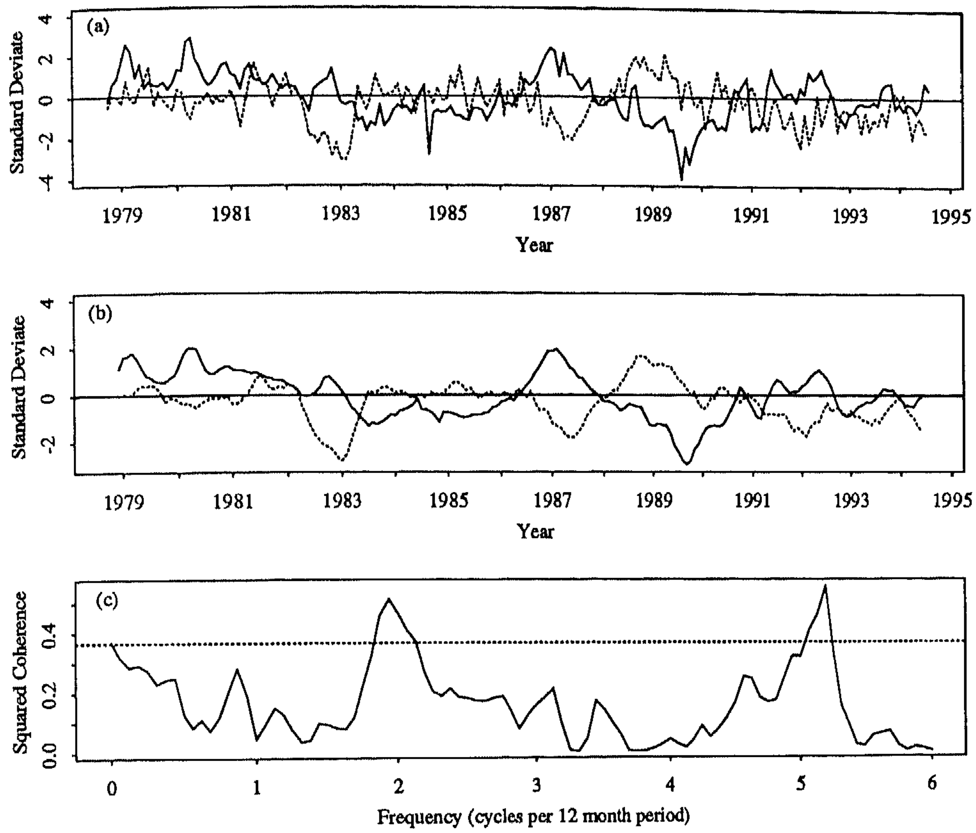

Fig. 8. (*a*) Monthly standard deviates of LTER sea ice extent (solid line) and SOI (dashed line) from October 1978 to July 1991. (*b*) The monthly standard deviates of (*a*), smoothed by an equal weight moving average filter. (*c*) Squared coherence spectrum of LTER ice extent versus SOI. Values above the dotted line are significantly coherent at the 95% confidence level.

superimposed on the long term persistence in both variables as shown in the unsmoothed time series plot in Figure 8*a*. When the higher frequency fluctuation is removed, as in the smoothed time series plot in Figure 8*b*, the long term anticorrelation between the two variables becomes more apparent.

In considering phases of SOI, years identified as El Niño or La Niña are based on the classification methodology described by *Kiladis and Diaz* [1989]. An El Niño year is defined as the year when the SOI changes sign from positive to negative, and when central and eastern equatorial Pacific sea surface temperature anomalies become strongly positive. A La Niña year has the opposite characteristics. Note that a designated El Niño or La Niña year does not reflect the actual timing, magnitude or persistence of the ENSO event. For example, the 1982 El Niño lasted through half of 1983 and the extreme SOI minimum, which was in January of 1983, was the largest SOI negative deviation in the 1951-1994 record. Thus, in referring to an El Niño or La Niña event, the year is meant only as a designation of the entire ENSO event.

With respect to ice-SOI relationships, it appears that in general El Niño events are related to above average ice extents in the WAP region for year 0 of the El Niño event, as was the case in 1982, or for year 0 and +1 of an El Niño event, as was the case in 1986. In addition, for the La Niña event shown in this record period (1988), ice extent in the WAP region is below average for year 0 and +1. Year 1989 was a record low ice year for the WAP region which may be related to the strength and duration of the 1988 La Niña event.

The squared coherencies between the standard deviates of LTER sea ice extent and SOI were computed and are shown in Figure 8*c*. There is significant coherence at approximately 2.4 and 6.1-month intervals which indicate that the high frequency fluctuations seen in Figure 8*a* are significantly correlated. The phase spectrum (not shown) shows that the coherence at the approximate 2.4-month interval is 180° out-of-phase or anticorrelated, whereas the coherence at the 6.1-month interval is approximately 290° out-of-phase, indicating that there is a 3-4 month lag in the anticorrelation between ice extent and SOI at a 6-month interval. However, there is no significant coherence at low frequencies (greater than 1-year intervals) which would have confirmed the long term anticorrelation seen in the smoothed time series. This is most likely due to the short sea ice extent record (just under 16 years) which limits statistical significance of low frequency coherence.

The long, continuous air temperature record from Faraday offers a better comparison for the detection of any low fre-

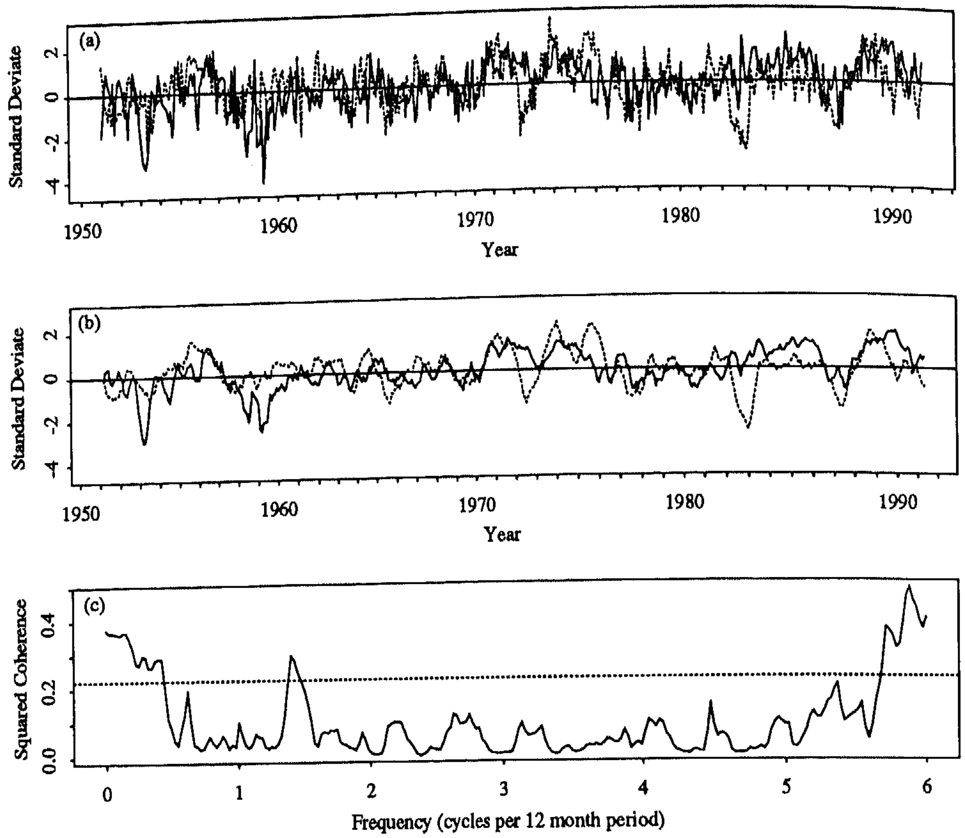

Fig. 9. (*a*) Monthly standard deviates of Faraday air temperatures (solid line) and SOI (dashed line) from January 1951 to July 1991. (*b*) The monthly standard deviates of (*a*), smoothed by an equal weight moving average filter. (*c*) Squared coherence spectrum of Faraday air temperatures versus SOI. Values above the dotted line are significantly coherent at the 95% confidence level.

quency coherence with SOI. Figures 9*a* and 9*b* show the unsmoothed and smooth time series plots of Faraday air temperature versus SOI from January 1951 to July 1991. The unsmoothed data again reveals the high frequency fluctuations superimposed on the long term persistence exhibited by both variables. As with the LTER ice extent versus SOI comparison, the Faraday deviates show longer persistence (autocorrelations significant out to 19 monthly lags) than do the SOI deviates. The smoothed time series show that in general air temperature and SOI follow similar above and below mean long term fluctuations. For example, five out of six La Niña events (1954, 1964, 1970, 1973, and 1988) are associated with above mean Faraday air temperature events, and eight out of ten El Niño events (1953, 1957, 1963, 1965, 1969, 1976, 1982, and 1986) are associated with below mean Faraday temperature events. Although warm and cold air temperature events are associated with La Niña and El Niño events, respectively, the phase and amplitude of this relationship are quite variable. For example, air temperature events may lead or lag SOI events, and for the 1953 and 1957 events there is a much stronger negative temperature deviation than SOI, but for the 1982 event there is a much stronger SOI deviation than temperature. In contrast, there is no association between air temperature events and the 1951 and 1972 El Niño and the 1975 La Niña events.

The significance of the long term correlation between Faraday air temperatures and SOI was tested by the squared coherence spectrum shown in Figure 9*c*. There are significant low frequency coherences at approximately 28-month intervals and greater, which are in phase as indicated by the phase spectrum. There is also coherence at an approximate 8.6 month interval which is 290° out-of-phase and a strong coherence at an approximate 2-month interval which is 180° out-of-phase.

Since it has been established that air temperatures and ice extent in the WAP region are significantly anticorrelated, the low frequency coherence between Faraday air temperatures and SOI supports the existence of a low frequency coherence between LTER ice extent and SOI. In addition, the high frequency coherences shown in both the ice extent and air temperature comparisons with SOI support the hypothesis that not only do the extreme events of ENSO affect WAP climate, but monthly ENSO fluctuations may be affecting monthly fluctuations in WAP air temperature and sea ice extent as well.

4. SUMMARY

By northern hemisphere standards, the climate record of the Antarctic is relatively short and the areal cover limited.

Nonetheless, the records are longest and the coverage most complete for the WAP region, where consistent, quality controlled BAS records date from the mid 1940's and 1950's, with scattered expedition records dating back to the early 1900's. In agreement with previous workers, we find in the Faraday air temperature record an annual warming trend of 2.6°C from 1945 to 1990 (Figure 2*a*). However, in agreement with *Sansom* [1989] and *King* [1994], the annual trend is *not* significantly different from zero at a 95% confidence level or higher after accounting for serial correlation in the time series. On the other hand, 8 of 12 monthly trends, which we show are free of bias from serial correlation, are significant (Table 1) at the 95% confidence level or higher. Monthly trends are strongest in mid-winter and highest in June at 0.114°C/year which represents a 5.5°C increase in June temperatures over the 48 year record (1944-1991). It is important to note that the trend for this region is strongest in mid-winter, which consequently will have important impacts on both maximum ice extent and the marine ecology associated with winter ice extent.

Several station records (Rothera, Faraday, Palmer, SSI) were selected as representative of the temperature gradient along the Antarctic Peninsula. In addition, the short Palmer record was shown to be strongly correlated with the Faraday record in particular. The annual progression of temperatures and the variability associated with these temperatures (Figure 4) show an along-peninsula gradient in the relative influence of maritime versus continental climate regimes. Increased temperature variability in fall and winter is linked to the high variability in year-to-year sea ice coverage and the corresponding increased continental influence when an extensive ice cover exists. Data from AWS Hugo, which is just 90 km seaward of the peninsula, show that standard deviations of daily temperature are significantly lower than those from a coastal station (AWS Bonaparte). Thus, in addition to the along-shore gradient, there is a sharp on/offshore gradient in maritime versus continental regimes. Much of the variability in both air temperature and sea ice in the Palmer LTER region is influenced by these contrasting climate regimes.

The Antarctic Peninsula is a physical barrier to tropospheric circulation which is reflected in the sharp contrasts in temperature and sea ice distributions between the west and east sides of the peninsula. Further, it is the one place on the continent where the axis of the circumpolar low-pressure trough or atmospheric convergence line (ACL) crosses over land. The variability of the mean position of cyclones, as the ACL seasonally and interannually shifts along the Antarctic Peninsula, strongly influences winds, temperature and the distribution of sea ice. Spectral analysis of daily temperature records (Figures 6*b* and 7*c*) are suggestive of quasi-periodic forcing of temperature by the train of low-pressure systems sweeping the peninsula. Linkages between cyclones, temperature and sea ice are complex, varying seasonally and perhaps interannually, and comprise an important topic for future research.

Air temperature-sea ice linkages appear to be very strong in the WAP region. Linear regression analysis shows a significant (99.9%) correlation between temperature and sea ice (Figure 7*b*), even after accounting for serial correlation in the two time series. Also, both air temperature and sea ice extent anomalies show long term persistence which appear to be unique to this region of the Southern Ocean [*Stammerjohn*, 1993; *Stammerjohn and Smith*, this volume]. The ecological consequences of this persistence, which seems to be manifested in the occurrence of consecutive high ice/low temperature years followed by consecutive low ice/high temperature years, appear to have significant impacts on the survival rates, distributions and/or life histories of indicator marine species [*Fraser and Trivelpiece*, this volume; *Trivelpiece and Fraser*, this volume; *Quetin et al.*, this volume]. Linkages between physical forcing and higher trophic level responses remain to be determined. Further, mechanisms that maintain the relatively long persistence of sea ice and temperature anomalies have not yet been identified.

Temperature and sea ice coverage show distinct seasonal lead/lag relationships (Figure 7*d* and Table 2) which underscores the complexity of feedback mechanisms in polar regions [*Kellogg*, 1975]. The albedo-ice-temperature feedback loop, generally considered to be strongly positive, is an important element of equilibrium general circulation models which underscores the high sensitivity of polar regions to climate variability. The temperature-ice correlations suggest that system interactions between the atmosphere-ocean-cryosphere system are more complex and contain linkages beyond those in the classical feedback loop. *King* [1994], seeking mechanisms driving temperature variations in the Faraday data, shows an association between temperature and cloud cover, which suggests the possible importance of the albedo-cloud-temperature feedback loop [*Kellogg*, 1975]. When considering the relative roles of atmospheric and oceanic forcing in the Palmer LTER area, analyses show that the seasonal timing and spatial relationship of indices such as the location of the low-pressure trough, sea ice extent and ocean circulation variability will need to be better understood.

The possible linkages between sea ice, cyclonic activity and global teleconnections have motivated a number of researchers to test Antarctic climate parameters as indices of global change and to seek a connection between the SOI and high southern latitude ice-ocean-atmosphere parameters [*Mo and White*, 1985; *van Loon and Shea*, 1985; *van Loon and Shea*, 1987; *Carleton*, 1988]. The Faraday air temperature record (Figure 9) shows significant (95% confidence level) low and high frequency coherence with the SOI. The sea ice record shows significant high frequency coherence, but may be too short to show significant low frequency coherence with SOI. However, the significant anticorrelation between sea ice and temperature supports the existence of a low frequency coherence between LTER ice extent and SOI as well. Since the El Niño/Southern Oscillation (ENSO) phenomenon is one of the major interannual climate fluctuations affecting the globe [*Philander and Rasmusson*, 1985], and since monthly ENSO fluctuations appear to be linked with monthly fluctuations in WAP air temperatures and sea ice extent, it is of considerable interest for the marine ecology of the WAP to first establish and then understand the linkages associated with this large scale source of climate variability. The WAP area, balanced between contrasting maritime and continental regimes, appears to reflect local amplifications of environmental change and hence may serve as an area for the early detection of trends elsewhere. The marine ecology within this area is strongly coupled to the annual advance and retreat of sea ice, and the relatively large interannual variability in temperature and sea ice provides a study site where "natural" experiments can be conducted to investigate mechanisms linking physical forcing and ecosystem response under vastly different year-to-year climate conditions.

Acknowledgments. This work and the Palmer LTER data archive is supported by NSF, Office of Polar Programs grant OPP90-11927. The early Palmer Station weather record, enhanced and maintained by Al Oxton, continues through the efforts of Antarctic Support Associate's field technicians. Charles Stearns, coordinator of the Antarctic Automatic Weather Station project, and his team have provided data and valuable discussions regarding Antarctic meteorological measurements. Johnathan Shanklin served as an interface to the British Antarctic Survey data. Discussions with Dudley Chelton and Joel Michaelsen regarding time series analysis were most helpful, as well as the critical comments and useful suggestions made by two anonymous reviewers. Charleen Johnson provided important help in the preparation of this document. This is Palmer LTER contribution #84.

REFERENCES

Ackley, S. F., A review of sea ice weather relationships in the Southern Hemisphere, in *Sea Level, Ice and Climatic Change*, edited by Allison, I., pp. 127-159, 1981.

Baker, K. S., and S. Stammerjohn, Palmer LTER: Palmer Station weather records, in press, *Antarct. J. U. S.*, 1995.

Bartlett, M. S., On the theoretical specification and sampling properties of autocorrelated time-series, *Journal of the Royal Statistical Society*, *B8*, 27-41, 1946.

Bromwich, D. H., and C. R. Stearns (Eds.)., *Antarctic Meteorology and Climatology: Studies Based on Automatic Weather Stations*, American Geophysical Union, New York, pp. 207 , 1993.

Budd, W. F., Antarctic sea-ice variations from satellite sensing in relation to climate, *Journal of Glaciology*, *15*(73), 417-427, 1975.

Budd, W. F., The importance of the Antarctic region for studies of the atmospheric carbon dioxide concentration, in *Carbon Dioxoide and Climate: Australian Research*, edited by Pearman, G. I., pp. 115-128, The Australian Academy of Science, Canberrra, 1980.

Budd, W. F., The role of Antarctica in Southern Hemisphere weather and climate, *Australian Meteorological Magazine*, *30*(4), 265-272, 1982.

Carleton, A. M., Ice-ocean-atmosphere interactions at high southern latitudes in winter from satellite observation, *Australian Meteorological Magazine*, *29*, 183-195, 1981.

Carleton, A. M., Sea ice-atmosphere signal of the Southern Oscillation in the Weddell Sea, Antarctica, *Journal of Climate*, *1*, 379-388, 1988.

Carleton, A. M., Antarctic sea-ice relationships with indices of the atmospheric circulation of the Southern Hemisphere, *Climate Dynamics*, *3*, 207-220, 1989.

Chelton, D. B., Effects of sampling errors in statistical estimation, *Deep-Sea Res.*, *30*, 1083-1103, 1983.

Damon, P. E., and S. M. Kunen, Global cooling? No, Southern Hemisphere warming trends may indicate the onset of the CO_2 "greenhouse" effect, *Science*, *193*, 447-453, 1976.

Davis, R. E., Predictability of sea surface temperature and sea level pressure anomalies over the North Pacific Ocean, *J. Phys. Oceanog.*, *6*, 249-266, 1976.

Doake, C. S. M., and D. G. Vaughan, Rapid disintegration of the Wordie ice shelf in response to atmospheric warming, *Nature*, *350*, 328-330, 1991.

Durbin, J., and G. S. Watson, Testing for serial correlation in least squares regression, I, *Biometrika*, *37*, 409-438, 1950.

Durbin, J., and G. S. Watson, Testing for serial correlation in least squares regression, II, *Biometrika*, *38*, 159-178, 1951.

Durbin, J., and G. S. Watson, Testing for serial correlation in least squares regression, III, *Biometrika*, *58*, 1-19, 1971.

Enomoto, H., and A. Ohmura, Influences of atmospheric half-yearly cycle on the sea ice extent in the Antarctic, *J. Geophys. Res.*, *95*(C6), 9497-9511, 1990.

Folland, C. K., D. E. Parker, and F. E. Kates, Worldwide marine temperature fluctuations 1856-1981, *Nature*, *310*, 670-673, 1984.

Fraser, W., and W. Trivelpiece, Factors Controlling the Distribution of Seabirds: Winter-Summer Heterogeneity in the Distribution of Adélie Penguin Populations, this volume.

Gates, W. L., J. Mitchell, G. J. Boer, U. Cubasch, and V. P. Meleshko, Climate modeling, climate prediction and model validation, in *Climate Change 1992 - The Supplementary Report to the IPCC Scientific Assessment*, edited by Houghton, J. T., B. A. Callander, and S. K. Varney, pp. 97-134, Cambridge University Press, New York, 1992.

Gloersen, P., Modulation of hemispheric sea-ice cover by ENSO events, *Nature*, *373*, 503-506, 1995.

Gloersen, P., and W. J. Campbell, Recent variations in Arctic and Antarctic sea-ice covers, *Nature*, *352*, 33-36, 1991 .

Gordon, A. L., and B. A. Huber, Southern Ocean winter mixed layer, *J. Geophys. Res.*, *95*(C7), 11655-11672, 1990.

Hansen, J., and S. Lebedeff, Global trends of measured surface air temperature, *J. Geophys. Res.*, *92*(D11), 13345-13372, 1987.

Hansen, J., T. Fung, A. Lacis, D. Rind, S. Lebedeff, R. Ruedy, and G. Russel, Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model, *J. Geophys. Res.*, *93*, 9341-9364, 1988.

Harangozo, S. A., *Interannual atmospheric circulation-sea ice extent relationships in the Southern Ocean: an analysis for the west Antarctic Peninsula region*, p. 364-367, AMS 6th conference on climate variations, Nashville, Tennessee, 1994.

Hofmann, E. E., J. M. Klinck, C. M. Lascara, and D. Smith, Water Mass Distributions and Circulation West of the Antarctic Peninsula and Including Bransfield Strait, this volume.

IPCC, *Climate Change: the IPCC Scientific Assessment*, edited by Houghton, J. T., G. J. Jenkins, and J. J. Ephraums, Cambridge University Press, New York, pp. 364, 1990.

Jacka, T. H., *A computer data base for Antarctic sea ice extent*, (*ANARE Research Notes*, *13*), 54 pp., Antarctic Division, Dept. of Science and Technology, Kingston, Tasmania, 1983.

Jacka, T. H., Antarctic and Southern Ocean sea-ice and climate trends, *Annals of Glaciology*, *14*, 127-130, 1990.

Jacka, T. H., and W. F. Budd, Detection of temperature and sea ice extent changes in the Antarctic and Southern Ocean, in *International Conference on the Role of the Polar Regions in Global Change: Proceedings of a Conference Held June 11-15, 1990 at the Univesity of Alaska*, edited by Weller, G., C. L. Wilson, and B. Severin, pp. 63-70, Geophysical Institute, and Center for Global Change and Arctic System Research, University of Alaska , Fairbanks, Alaska 99775, 1991.

Jacka, T. H., L. Christou, and B. J. Cook, *A data bank of mean monthly and annual surface temperatures for Antarctica, the Southern Ocean and South Pacific Ocean*, (*ANARE Research Notes*, 22), 98 pp., Antarctic Division, Dept. of Science and Technology, Kingston, Tasmania, 1984.

Jones, P. D., Antarctic temperatures over the present century - a study of the early expedition record, *Journal of Climate*, *3*, 1193-1203, 1990.

Jones, P. D., and D. W. S. Limbert, *A Data Bank of Antarctic Surface Temperature and Pressure Data*, Office of Energy Research, Office of Basic Energy Sciences, Carbon Dioxide Research Division, Washington, D.C., 1987.

Jones, P. D., and T. M. L. Wigley, Antarctic gridded sea level pressure data: an analysis and reconstruction back to 1957, *Journal of Climate*, *1*, 1199-1220, 1988.

Jones, P. D., S. C. B. Raper, and T. M. L. Wigley, Southern Hemisphere surface air temperature variations: 1851-1984, *Journal of Climate and Applied Meteorology*, *25*, 1213-1230, 1986.

Keller, L. M., G. A. Weidner, C. R. Stearns, and M. T. Whittaker, *Antarctic Automatic Weather Station Data for the calendar year 1993*, 473 pp., Department of Meteorology, University of Wisconsin, Madison,Wisconsin, 1995.

Kellogg, W. W., Climatic feedback mechanisms involving the polar regions, in *Climate of the Arctic: Twenty-Fourth Alaska Science Conference, August 15-17, 1973*, edited by Weller, G., and S. A. Bowling, pp. 111-116, Geophysical Institute, University of Alaska, Fairbanks, Alaska, 1975.

Kiladis, N. G., and H. F. Diaz, Global climatic anomalies associated with extremes of the Southern Oscillation, *Journal of Climate*, *2*, 1069-1090, 1989.

King, J. C., Recent climate variability in the vicinity of the Antarctic Peninsula, *International Journal of Climatology, 14*, 357-369, 1994.

Lemke, P., W. B. Owens, and W. D. Hibler, A coupled sea ice-mixed layer pycnocline model for the Weddell Sea, *J. Geophys. Res., 95*, 9513-9525, 1990.

Loewe, F., Contributions to the glaciology of the Antarctic, *Journal of Glaciology, 2*, 657-665, 1956.

Loewe, F., Screen temperatures and 10 m temperatures, *Journal of Glaciology, 9*, 263-268, 1970.

Manabe, S., and R. J. Stouffer, Sensitivity of a global climate model to an increase of CO_2 concentration in the atmosphere, *J. Geophys. Res., 85*(C10), 5529-5554, 1980.

Martin, P. J., and D. A. Peel, The spatial distribution of 10 m temperatures in the Antarctic Peninsula, *Journal of Glaciology, 20*(83), 311-317, 1978.

Martinson, D. G., Evolution of the Southern Ocean winter mixed layer and sea ice: open ocean deepwater formation and ventilation, *J. Geophys. Res., 95*(C7), 11641-11654, 1990.

Mo, K. C., and G. H. White, Teleconnections in the Southern Hemisphere, *Monthly Weather Review, 113*, 22-37, 1985.

Nicholls, K. W., and J. G. Paren, Extending the Antarctic meteorological record using ice-sheet temperature profiles, *Journal of Climate, 6*, 141-150, 1993.

Petit, J. R., J. W. C. White, N. W. Young, J. Jouzel, and Y. S. Korotkevich, Deuterium excess in recent Antarctic snow, *J. Geophys. Res., 96*(D3), 5113-5122, 1991.

Philander, S. G., and E. M. Rasmusson, The Southern Oscillation and El Niño, *Advances in Geophysics, 28A*, 197-215, 1985.

Quetin, L. B., and R. M. Ross, A long-term ecological research strategy for polar environmental research, *Marine Pollution Bulletin, 25*, 233-238, 1992.

Quetin, L. B., R. M. Ross, T. K. Frazer, and K. L. Haberman, Factors Affecting Distribution and Abundance in Macrozooplankton, Including Antarctic Krill, *Euphausia superba*, this volume.

Raper, S. C. B., T. M. L. Wigley, P. R. Mayes, P. D. Jones, and M. J. Salinger, Variations in surface air temperatures. Part 3: the Antarctic, 1957-82, *Monthly Weather Review, 112*, 1341-1353, 1984.

Reynolds, J. M., The distribution of mean annual temperatures in the Antarctic Peninsula, *Br. Antarct. Surv. Bull., 54*, 123-133, 1981.

Sansom, J., Antarctic surface temperature time series, *Journal of Climate, 2*, 1164-1172, 1989.

Savage, M. L., C. R. Stearns, and G. A. Weidner, *The Southern Oscillation signal in Antarctica*, Second Conference on Polar Meteorology and Oceanography: March 29-31, 1988, Madison, Wisc., American Meteorological Society, Boston, Mass., 1988.

Schlesinger, M., and J. Mitchell, *Model projections of the equilibrium climatic response to increased carbon dioxide, the potential climatic effects of increasing carbon dioxide*, Report Number DOE/ER-0237, U.S. Department of Energy, Washington, D.C., 1985.

Schwerdtfeger, W., Chapter 4: The climate of the Antarctic, in *Climates of the Polar Regions*, edited by Orvig, S., (*World Survey of Climatology, Volume 14*), pp. 253-355, Elsevier Publishing Company, New York, 1970.

Schwerdtfeger, W., The effect of the Antarctic Peninsula on the temperature regime of the Weddell Sea, *Monthly Weather Review, 103*(1), 45-51, 1975.

Schwerdtfeger, W., Changes of temperature field and ice conditions in the area of the Antarctic Peninsula, *Monthly Weather Review, 104*, 1441-1443, 1976.

Schwerdtfeger, W., Meteorological aspects of the drift of ice from the Weddell Sea toward the mid-latitude westerlies, *J. Geophys. Res., 84*(C10), 6321-6328, 1979.

Schwerdtfeger, W., *Weather and Climate of the Antarctic*, (*Developments in Atmospheric Science, 15*), Elsevier Science Pub. Co., New York, pp. 261, 1984.

Schwerdtfeger, W., and L. R. Amaturo, *Wind and weather around the Antarctic Peninsula*, 51 pp., University of Wisconsin, Department of Meteorology, Madison, Wisconsin, 1979.

Simmonds, I., and T. H. Jacka, Relationships between the interannual variability of Antarctic sea ice and the Southern Oscillation, *Journal of Climate, 8*(3), 637-647, 1995.

Smith, S. R., and C. R. Stearns, Antarctic pressure and temperature anomalies surrounding the minimum in the Southern Oscillaton Index, *J. Geophys. Res., 98*(D7), 13071-13083, 1993.

Smith, R. C., et al., The Palmer LTER: A Long-Term Ecological Research program at Palmer Station, Antarctica, in press, *Oceanography*, 1995.

Splettstoesser, J., Antarctic global warming, *Nature, 355*, 503-503, 1992.

Stammerjohn, S. E., *Spatial and temporal variability in Southern Ocean sea ice coverage*, 111 pp., M.S., University of California, Santa Barbara, CA 93106, 1993.

Stammerjohn, S., and R. C. Smith, Spatial and Temporal Variability of Western Antarctic Peninsula Sea Ice Coverage, this volume.

Stark, P., Climatic warming in the central Antarctic Peninsula area, *Weather, 49*(6), 215-220, 1994.

Stouffer, R. J., S. Manabe, and K. Bryan, Interhemispheric asymmetry in climate response to a gradual increase of atmospheric CO_2, *Nature, 342* (6250), 660-662, 1989.

Trenberth, K. E., Signal versus noise in the Southern Oscillation, *Monthly Weather Review, 112*, 326-332, 1984.

Trivelpiece, W., and W. Fraser, The Breeding Biology and Distribution of Adélie Penguins in the Western Antarctic Peninsula Region: Adaptations to Environmental Variability, this volume.

van Loon, H., The half-yearly oscillations in middle and high southern latitudes and the coreless winter, *Journal of The Atmospheric Sciences, 24*, 472-483, 1967.

van Loon, H., and D. J. Shea, The Southern Oscillation. Part IV: the precursors south of 15°S to the extremes of the oscillation, *Monthly Weather Review, 113*, 2063-2074, 1985.

van Loon, H., and D. J. Shea, The Southern Oscillation. Part VI: anomalies of sea level pressure on the Southern Hemisphere and of Pacific sea surface temperature during the development of a warm event, *Monthly Weather Review, 115*, 370-379, 1987.

van Loon, H., and J. Williams, The connection between trends of mean temperature and circulation at the surface: Part IV. Comparison of the surface changes in the northern hemisphere with the upper air and with the Antarctic in winter, *Mon. Wea. Rev., 105*, 636-647, 1977.

Walker, G. T., Correlation in seasonal variations of weather. VIII. A preliminary study of world weather, *Mem. Indian Meteorol. Dep., 24*, 75-131, 1923.

Walker, G. T., and E. W. Bliss, World weather. V. *Mem. R. Meteorol. Soc., 4*, 53-84, 1932.

Waters, K. J., and R. C. Smith, Palmer LTER: A sampling grid for the Palmer LTER program, *Antarct. J. U. S., 27*(5), 236-239, 1992.

Weatherly, J. W., J. E. Walsh, and H. J. Zwally, Antarctic sea ice variations and seasonal air temperature relationships, *J. Geophys. Res., 96*(C8), 15119-15130, 1991.

Xie, S., C. Bao, and C. Hao, Study on the oscillation relationship between sea ice of the Arctic and Antarctic, *Proc. NIPR Symp. Polar Meteorol. Glaciol., 8*, 111-128, 1994*a*.

Xie, S., C. Bao, Z. Xue, L. Zhang, and C. Hao, Interaction between Antarctic sea ice and ENSO events, *Proc. NIPR Symp. Polar Meteorol. Glaciol., 8*, 95-110, 1994*b*.

Zwally, H. J., and J. C. Comiso, Variability of Antarctic sea ice, in *International Conference on the Role of the Polar Regions in Global Change: Proceedings of a Conference Held June 11-15, 1990 at the Univesity of Alaska*, edited by Weller, G., C. L. Wilson, and B. Severin, pp. 22, Geophysical Institute, and Center for Global Change and Arctic System Research, University of Alaska , Fairbanks, Alaska 99775, 1991.

Zwally, H. J., C. L. Parkinson, and J. C. Comiso, Variability of Antarctic sea ice and changes in carbon dioxide, *Science, 220*(4601), 1005-1012, 1983.

Raymond C. Smith and Sharon E. Stammerjohn, Institute for Computational Earth System Science (ICESS), Geography Department, University of California, Santa Barbara, 6812 Ellison Hall, Santa Barbara, CA 93106.

Karen S. Baker, Marine Research Division, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093-0218.

(Received July 19, 1995;