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Article

Surface Air Temperature Variations around the Antarctic Peninsula: Comparison of the West and East Sides of the Peninsula

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Abstract : This study investigated the spatial characteristics of warming trends and the dipole-like pattern of temperature field in the Antarctic Peninsula using surface air temperature (SAT) of 10 stations in the vicinity of the Antarctic Peninsula. SAT data for the 1962-2001 period at 6 stations (Rothera, Faraday/Vernadsky, Bellingshausen, Orcadas, Esperanza, Halley) revealed in general the larger warming trends in autumn and winter except for Halley. The largest warming was shown for August in the west side of the Peninsula (more than 0.9°C/decade). On the other hand, the recent 14-year SAT data showed the strong warming trends at 9 stations except for Halley in the earlier period (April-June) than August for the 1962-2001 period. The largest warming appeared in May at Esperanza and Butler Island. SAT of the two sides showed significant positive correlations over most of the period except for the mid- and the late 1970s, in which significant negative correlations were found. In the correlation analysis between SAT and sea surface temperature (SST) anomalies in the NINO 3.4 region, strong negative correlation was found in the west side of the Peninsula. Details of the correlation analysis exhibited that the negative correlation was significantly strong from the early 1980s to the mid-1990s. However, it was difficult to find significant correlations of ENSO with SAT in the east side of the Peninsula. So, in this study it failed to find out clearly the out-of-phase relationship of SAT across the Antarctic Peninsula.

Key words : Surface Air temperature, Antarctic Peninsula, El Niño/Southern Oscillation (ENSO).

1. Introduction

In recent years, it is well known that the region of the Antarctic Peninsula has experienced a marked warming and retreat of ice shelves (King 1994; Vaughan and Doake 1996) and also is the center of the Antarctic Dipole reflecting an out-of-phase relationship in surface air temperature and sea ice edge between the Pacific and the Atlantic polar oceans (Yuan and Martinson 2000). In the Antarctic region, surface air temperature data are generally sparse, but are most dense in the Antarctic Peninsula because of the large number of bases operating in this relatively warm and accessible region. Now these data are available through World Wide Web (http://www.nerc-bas.ac.uk/icd/gjma/) which can be accessed in digital format. Even though some of these records are discontinuous and short, these data may be valuable to those who are interested in the spatial distribution of warming trend and the dipole-like pattern of temperature field in the vicinity of the Antarctic Peninsula.

The Antarctic Peninsula is the 1,200-2,000 m high and narrow mountain ridge which projects from a part of west Antarctica and then northeastward up to 63°S (Fig. 1). It extends northward to a much lower latitude than any other Antarctic land mass. By the Peninsula, the west Antarctic Ocean is divided into the Pacific and the Atlantic sectors. Therefore, the Antarctic Peninsula may be the favorable region to compare the climatic variability in both the Pacific and the Atlantic sectors. One of the distinct climatic characteristics of the Peninsula is a sharp contrast

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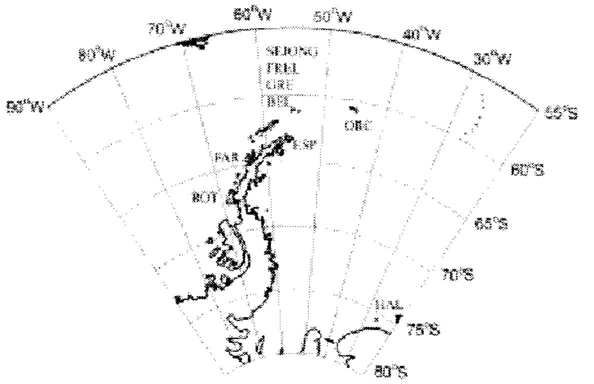

Fig. 1. Location of each station in and around the Antarctic Peninsula.

between wind and temperature field in the two sides of the Peninsula. On its west coast, the westerly surface winds are predominant, but along its east coast, the frequent, strong, southerly and southwesterly surface winds are observed because of the tall mountain barrier, which is called barrier winds with the air moving essentially parallel to a mountain. So its west side displays much milder conditions than the east side at which cold air masses move into from the Antarctic Continent with the barrier wind (Schwerdtfeger 1976, 1979).

In the period from 1945 to 2000, the global data of surface air temperature reveals that a warming is the greatest in the Antarctic Peninsula in addition to the mid- and high latitudinal areas of the Northern Hemisphere continents (IPCC 2001). Three stations (Bellingshausen, Faraday and Orcadas) around the Antarctic Peninsula show a rate of warming of 0.3-0.4°C/decade in the period 1969-1999 (Marshall and Lagun 2002). This warming of the Peninsula is the greatest particularly in austral winter. It is explained that the winter warming is related to a reduction in sea level pressure and the associated increase in northerly wind and resultant decrease of sea ice extent in the Bellingshausen Sea on the west of the Peninsula, which is strongly correlated with the Peninsula temperature (King 1994; Jacobs and Comiso 1993).

Vaughan and Doake (1996) reported that a number of ice shelves (for example, Wordie Ice Shelf, Prince Gustav Channel Ice Shelf, Larsen Inlet, Larsen-A) had retreated dramatically in the past fifty years and these retreat is related to the thermal limit of ice-shelf viability which have been driven southward by the atmospheric warming. They predicted that given continued warming, Larsen-B will probably continue to retreat and eventually Larsen-C may well behave in a similar way. And then, recent satellite imagery taken on March 5 of 2002 reveals that the northern section of the Larsen-B ice shelf, a large floating ice mass on the east side of the Antarctic Peninsula, has shattered and separated from the Continent (http://earthobservatory.nasa.gov/Newsroom/NewImages).

It is also found from NCEP/NCAR reanalysis data that the dominant inter-annual variability structure of surface air temperature in the Antarctic Peninsula and its surrounding oceans is organized as a quasi-stationary wave which is called the "Antarctic Dipole". It is characterized by dipole-like pattern reflecting an out-of-phase relationship between sea ice extent and temperature anomalies in the central/eastern Pacific and Atlantic sectors of the Antarctic. The dipole is clearly associated with the tropical El Niño/Southern Oscillation (ENSO) events (Yuan and Martinson 2001).

From a model-simulation study, Rind *et al.* (2001) showed that ENSO-related anomalies in tropical sea surface temperature are accompanied by a change in latitudinal temperature gradient and result in a further change of subtropical jet stream. During El Niño years, the latitudinal temperature gradient increases in the Pacific and so subtropical jet stream is intensified. In the Southern Hemisphere this leads to a decrease of storm intensity near the Pacific-Antarctic region and less winds to blow sea ice farther out into the ocean, which result in sea ice reduction and temperature increase. At the same time, subsidence over the Tropical Atlantic owing to warming of the Tropical Pacific weakens the subtropical jet stream in the Atlantic Ocean and it results in an increase of storm intensity and sea ice extent, and a decrease of surface air temperature in the Atlantic-Antarctic region. During La Niña years, there is an opposite effect, where sea ice extent (temperature) decreases (increases) on the Atlantic side and increases (decreases) on the Pacific side.

Harangozo (2000) reported that inter-annual variability of winter temperature at Faraday station is indirectly related with ENSO via alterations in the local ice extent that is sensitive to the local meridional circulation variations. And Smith and Stearns (1993) found using lagged correlation analysis that strong negative correlations between temperature and Southern Oscillation Index (SOI) occurred with lead time of 10 months at Signy (60°43'S, 45°36'W) and Orcadas stations, while strong positive correlation occurred at Faraday station at a lag of 5 months. Even within the region of the Antarctic Peninsula, the considerable differences in the relationship between temperature and ENSO are shown.

In order to investigate the spatial characteristics of warming trends and the dipole-like pattern of temperature field in the vicinity of the Antarctic Peninsula, the inter-annual temperature variations are examined across the Antarctic Peninsula in this study. The east and west coasts of the Antarctic Peninsula are respectively connected with two different ocean sectors, the Atlantic Ocean and the Pacific Ocean, and also governed by different atmospheric circulation pattern. Through the comparison of temperature field in the two sides of the Peninsula, we may have some insights in understanding the inter-annual climate variability in the west Antarctic.

Section 2 describes temperature data used in this study and SST anomalies of the Tropical Pacific used for quantifying the ENSO phenomenon. The characteristics of annual temperature variations in the Peninsula are also presented. The spatial distribution of warming trend is shown in section 3. The inter-annual temperature variations are compared across the Peninsula in section 4. Conclusions regarding analyzed results are discussed in section 5.

2. Characteristics and description of data

The data used in this analysis are monthly mean surface air temperature (SAT), much of it obtained from the internet web site (http://www.nerc-bas.ac.uk/icd/gjma/) which it is updated monthly. Only the temperature data at Frei station are provided directly from Direccion Meteorologica de Chile. Most stations used in the analysis are located in the Antarctic Peninsula or in King George Island except for Orcadas and Halley stations. Orcadas station is situated on the island far apart northeastward from the northern tip of the Antarctic Peninsula and Halley station is situated on the Brunt Ice Shelf of the East Antarctica (Fig. 1). Among 8 stations in the Peninsula including King George Island, 6 and 2 stations are located, respectively, in the west and east sides of the Peninsula. Although Halley station is located in the distance from other stations in the Peninsula, it is also included in the east Peninsula side to get the intention of complementing the temperature data. In this study, stations located in King George Island are also considered as sites in the Antarctic Peninsula for convenience's sake.

Of 10 stations, 6 stations including Halley, Rothera, Faraday/Vernadsky, Esperanza, Bellingshausen, Orcadas, have the temperature records more than 40 years. Among them Orcadas station has the longest temperature records from 1903 to 2002. On the other hand, 4 stations including Butler Island AWS, King Sejong, Great Wall and Frei have the records of about 14 years (Table 1). So the periods of the analysis are chosen to be 40 and 14 years, respectively, based on the record length and the amount of missing data.

Fig. 2 shows the annual temperature cycles and the standard deviations of 5 stations (Rothera, Faraday/Vernadsky, Esperanza, Bellingshausen, Orcadas) which have relatively longer temperature records. These are calculated from the monthly data for the period of 40 years (1962-2001). Here, Rothera, Faraday, and Bellingshausen are in the west side of the Peninsula, while Esperanza is in the east side. Rothera is the southernmost of these stations and Orcadas is on Laurie Island situated far apart from the northern tip of the Peninsula. However, Halley station having more than 40 years data is excluded because of its much colder climate to be compared with other stations

Table 1. Location of each station and the period of monthly temperature records used in this study.

Stations	Latitude/Longitude	Years with data	Years with no data
Halley	75°34'S/26°32'W	1957 Jan.-2002 Apr.	
Butler Island AWS	72°13'S/60°10'W	1986 Mar.-2002 Feb.	1987 Jul.-1988 Jul./1989 May-Dec. 1993 Nov.-1994 Apr.
Rothera	67°34'S/68°07'W	1946 Apr.-2002 Apr.	1950 Feb.-1951 Mar./1952 Mar.-1955 Feb. 1960 Jan.-1962 Apr./1976 Jan.-Feb.
Faraday/Vernadsky	65°15'S/64°16'W	1950 Apr.-2002 Apr.	
Esperanza	63°23'S/56°59'W	1945 Mar.-2002 Apr.	1949 Jan.-1952 Mar. 1979 Jan., Mar./Sep.-Dec.
Frei	62°12'S/58°57'W	1970 Jan.-2000 Dec.	
King Sejong	62°13'S/58°47'W	1988 Feb.-2002 Mar.	
Great Wall	62°12'S/58°57'W	1985 Jan.-2001 Nov.	
Bellingshausen	62°11'S/58°57'W	1944 Jan.-2002 Apr.	1946 Jan.-Dec.
Orcadas	60°44'S/44°44'W	1903 Apr.-2002 Apr.	1992 Jan.

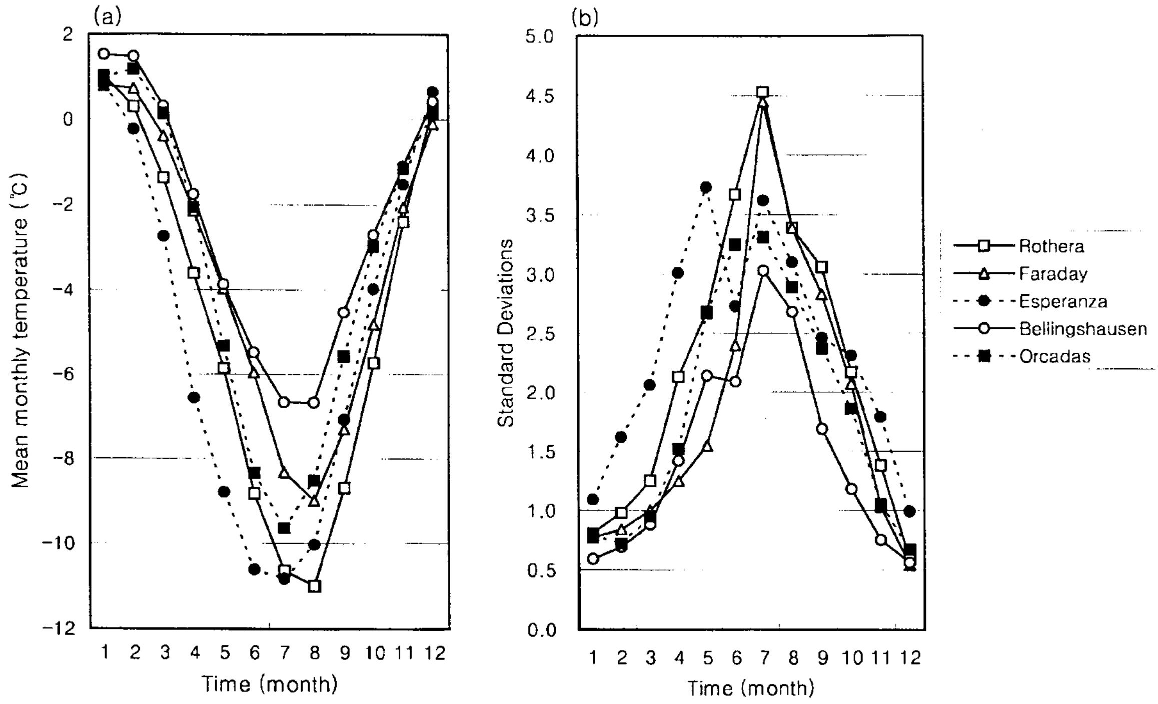

Fig. 2. Annual temperature variations at each station for the period 1962-2001: (a) mean monthly temperature and (b) standard deviations of monthly temperature.

In Fig. 2a, all 5 stations show in general a V-shaped cycle over the year. The detailed comparison, however, shows that minimum peaks are found in August at Rothera, Faraday and Bellingshausen, while they are in July for Esperanza and Orcadas. And even though Esperanza and Orcadas are more than 4 degrees of latitude further north than Rothera and Faraday, the annual temperature distributions are comparable. It is also found that Esperanza and Orcadas are much colder particularly in autumn and winter than Rothera and Faraday. These differences may be interpreted by the amount of continental influence at Esperanza and Orcadas. These results are in a good agreement with the well-known climatic characteristics in the Antarctic Peninsula: milder conditions in the west side of the Peninsula and colder conditions in the east side. And these results are also consistent with the prevailing southerly and southwesterly surface winds in autumn and winter. In this study, therefore, Rothera/Faraday and Esperanza/Orcadas are representing the west and east side of the Peninsula, respectively.

Fig. 2b clearly shows that at all stations much greater temperature variability is shown in winter than any other seasons and least in summer because of swift variability between cold and warm air masses. The standard deviations of the winter (JJA) temperature are 2.1-4.5°C and those of the summer (DJF) are 0.5-1.6°C. Thus, it is noted that caution is required in comparing the data of the different months of the year because of much different temperature variability on the months of the year.

In order to examine the relationship between SAT in the Antarctic Peninsula and ENSO, SST anomalies in the eastern Tropical Pacific are used. In recent years, Trenberth (1997) reported that SST anomalies in the NINO 3.4 region (5°N-5°S, 120°W-170°W) match the ENSO identified historically. So in this study SST anomalies in the NINO 3.4 region is used for quantifying the intensity of ENSO phenomenon.

3. Spatial distribution of warming trends in the Antarctic Peninsula

Linear trends of SAT in the four seasons are calculated for the 1962-2001 period at 6 stations (Rothera, Faraday/Vernadsky, Bellingshausen, Orcadas, Esperanza, Halley). Except for Halley, 5 stations show larger warming trends in autumn/winter and more statistically significant trends in summer/autumn (Table 2). But Halley shows insignificant or rather cooling trends (in autumn) in all four seasons.

Table 2. Trends and variance explained by the trend of seasonal mean temperature for the period 1962-2001 around the Antarctic Peninsula.

Stations	Annual		Summer (DJF)		Autumn (MAM)		Winter (JJA)		Spring (SON)	
	Trend (°C/10 yr)	Explained Variance	Trend (°C/10 yr)	Explained Variance	Trend (°C/10 yr)	Explained Variance	Trend (°C/10 yr)	Explained Variance	Trend (°C/10 yr)	Explained Variance
Rothera	0.42	**0.11***	0.28	**0.22****	0.63	**0.17****	0.60	0.05	0.17	0.01
Faraday/Vernadsky	0.47	**0.18****	0.17	**0.09***	0.41	**0.22****	0.97	**0.15****	0.29	0.05
Bellingshausen	0.26	**0.14****	0.23	**0.27****	0.32	**0.12***	0.53	**0.09***	0	0
Orcadas	0.25	**0.10***	0.42	**0.16****	0.35	**0.09***	0.30	0.02	0.01	0
Esperanza	0.36	**0.15****	0.52	**0.40****	0.65	**0.11***	0.44	0.06	–0.02	0
Halley	–0.16	0.03	0.02	0	–0.76	**0.16****	0.02	0	0.09	0

* and ** of bold character denote significance at the 5% and 1% level, respectively.

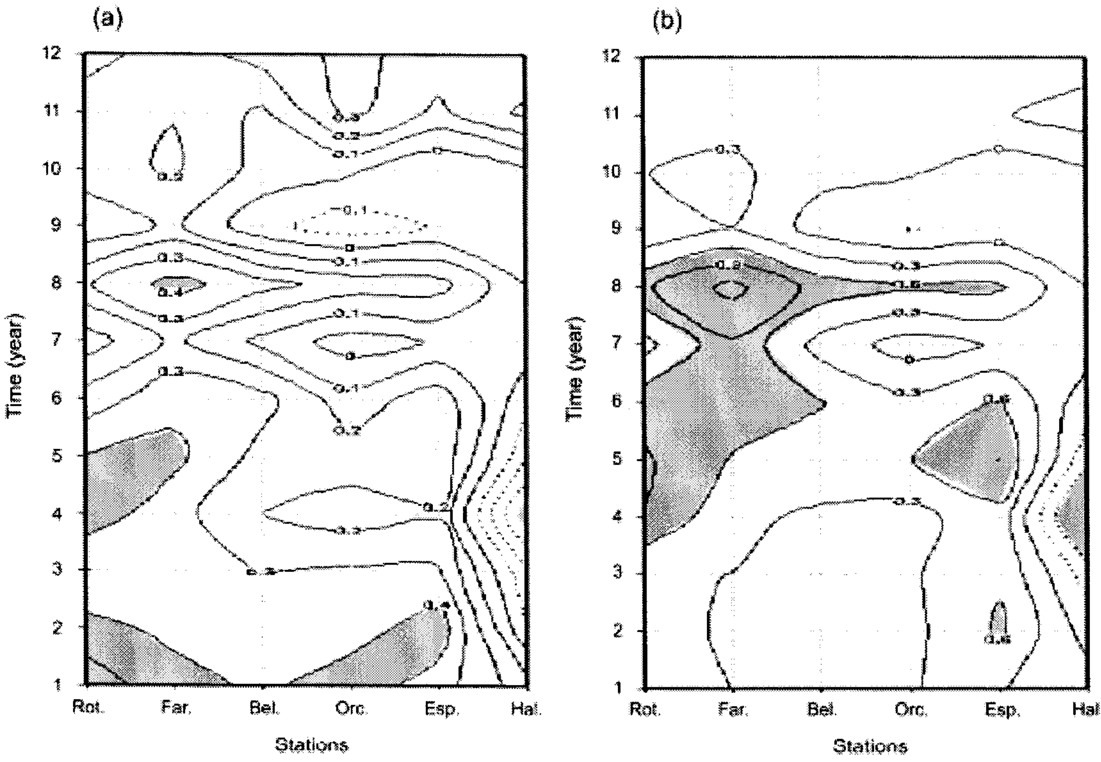

Fig. 3. Temperature variations on the months of the year at each station in and around the Antarctic Peninsula for the period 1962-2001: (a) correlation coefficient and (b) trend (°C/decade). Correlation coefficients greater than 0.4 or less than –0.4 and trends greater than 0.6°C/decade are shaded.

The warming trends in winter of 5 stations is not quite significant in the comparison with autumn/summer owing to the large inter-annual temperature variability. The warming trends in winter are in general larger in the west side of the Peninsula than in the east side. The largest warming trend is found in winter at Faraday.

Details of the linear trends on the months of the year are shown in Fig. 3. The warming trends larger than 0.6°C/decade are found for the period of May-August at Rothera and Faraday and for May/June at Esperanza. The largest warming appears at Faraday in August (amounting to 1.2°C/decade). The more significant trends (5% level) are found for the period of January/February at all 5 stations except for Halley. On the other hand, Halley shows significant cooling trends in April, which is amounting to –0.6°C/decade at the 5% level of significance.

In order to examine the variations in the annual temperature cycle, the harmonic analysis was performed for each year on the monthly data for the period of 1962-2001. The 1st harmonic explains for most time period

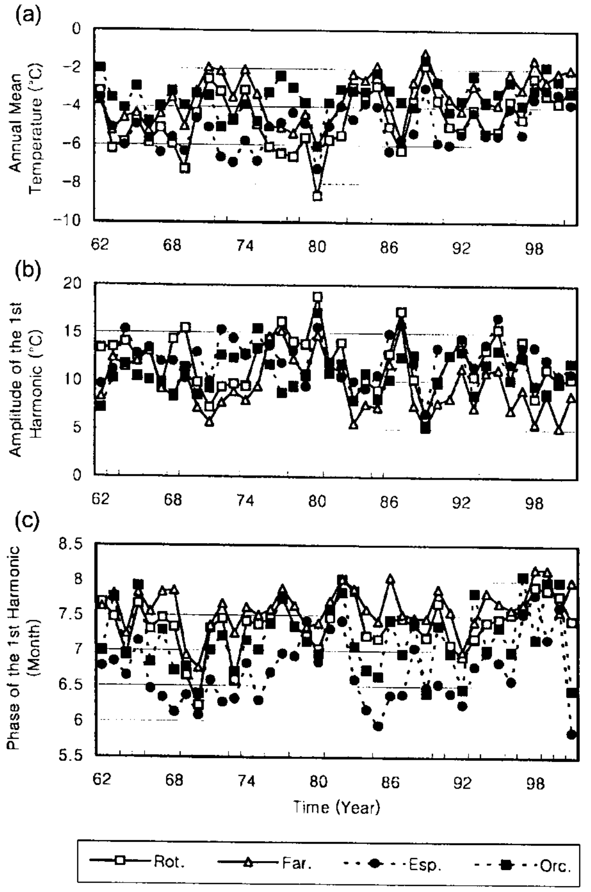

Fig. 4. Inter-annual variability of (a) annual mean temperature, (b) amplitude of the 1st harmonic, and (c) phase of the 1st harmonic at 4 stations for the period 1962-2001.

more than 80% of annual variability at 4 stations (Rothera, Faraday, Orcadas, Esperanza). The time series of the annual parameters (annual mean, and amplitude and phase of the 1st harmonic) calculated from the harmonic analysis are compared each other in Fig. 4. In this comparison, Rothera/Faraday and Esperanza/Orcadas are representing the west and east sides of the Antarctic Peninsula, respectively.

Notable features of the annual mean temperature series in Fig. 4a are the warming trends in all stations and the negative correlations between Rothera/Faraday and Esperanza/Orcadas most evident from about 1974 to 1980. The early 1970s shows relatively warmer temperature at Rothera/Faraday and colder temperature at Esperanza/Orcadas compared with the late 1970s, and vice versa. So in this period SAT data display an out-of-phase relationship across the Antarctic Peninsula. Except for the above period, the annual mean temperature series are closely related to each other between the west and east sides of the Antarctic Peninsula. The annual mean temperature series of Rothera and Faraday are comparable with those of Esperanza and Orcadas, respectively.

In Fig. 4b the amplitude series of the 1st harmonic shows an out-of-phase relationship with the annual mean temperature series. The decreasing trends are also shown in the amplitude series. It can be explained by that the annual mean temperature and the 1st harmonic amplitude (the amplitude of annual cycle) vary in a close relationship with the winter temperature because of its larger inter-annual variability than the other season temperature. That is, if the winter temperature increases, in general the annual mean temperature also increases and the amplitude of the 1st harmonic decreases inversely.

Fig. 4c shows the phase series of the 1st harmonic, which corresponds to the time of minimum of the 1st harmonic function. So the phase series can be interpreted as the occurrence time of minimum temperature in the annual cycle. The time of minimum temperature is found almost between July and August at Rothera and Faraday and is relatively early between mid-June and mid-July at Esperanza and Orcadas. The phase series of Esperanza and Orcadas have larger variability than Rothera and Faraday. It is also found that there is little or no consistency between the phase series of the west and east sides of the Peninsula. In particular, Esperanza phase series shows considerable variability with the possibility of about 20-year variation. Therefore, interpreting the Esperanza inter-annual temperature variability based on month or season, it is needed to take into account the variation of the minimum occurrence time. Though not obvious, the phase series of Esperanza shows an increasing trend from the mid-1980s (the minimum occurrence time is getting late).

In order to investigate the recent trends of SAT around the Antarctic Peninsula, the trend calculation is repeated over the 14 years data for the 1988-2001 period at all 10 stations. Fig. 5 shows details of the linear trends on the months of the year. The warming trends larger than 2°C/decade are found for the period of April-June at all station except for Halley having cooling trend, which are approximately significant in the 10% level. It is also noted that the cooling trends are found in February and September. The largest warming appears in May at Esperanza and Butler Island (amounting to 5°C/decade). Even though it can be overestimated owing to the short data records, the remarkable warming trends of Esperanza

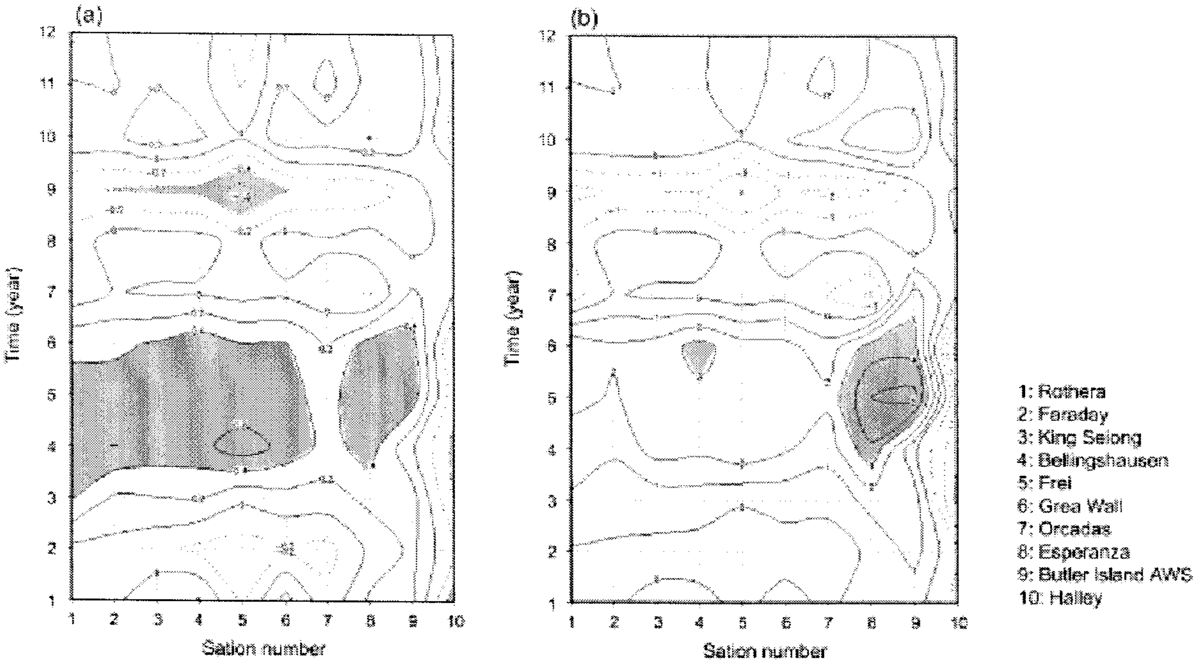

Fig. 5. Temperature variations on the months of the year at each station in and around the Antarctic Peninsula for the period 1988-2001: (a) correlation coefficient and (b) trend (°C/decade). Correlation coefficients greater than 0.4 or less than –0.4 and trends greater than 3°C/decade are shaded.

and Butler Island are consistent with the recent breakup of the Larsen-B ice shelf on the eastern side of the Antarctic Peninsula. It is postulated that the warming of Esperanza and Butler Island can be amplified in part by the phase variation in an annual temperature cycle (the time delay of the minimum occurrence) in Fig. 4c.

4. Comparison of SAT across the Antarctic Peninsula

Inter-annual variations of SAT

NCEP/NCAR reanalysis temperature data show an out-of-phase relationship between temperature anomalies in the central/eastern Pacific and Atlantic sectors of the Antarctic (Yuan and Martinson 2000, 2001). In this study, the observational data of temperature in the vicinity of the Antarctic Peninsula are examined to find out an out-of-phase relationship of SAT across the Antarctic Peninsula. The relationships between SAT at 6 stations are analyzed for the period of 40 years.

Table 3 presents the correlation coefficients between the seasonal temperature data of 4 stations. The western and eastern sides of the Peninsula are represented by Rothera/Faraday and Esperanza/Orcadas, respectively. A temperature relationship between the west side and the east side shows almost positive correlation (0.3-0.6), though it is relatively less significant than the relationship within the two sides of the Peninsula. The temperature correlations between the two sides are similar over the four seasons and the lowest is found in summer (less than 0.4). Within the one side of the Peninsula, Rothera temperature is more closely related to Faraday temperature than Esperanza is related

Table 3. Correlation coefficients of seasonal mean temperature among 4 stations (Rothera, Faraday, Orcadas, Esperanza) for the period 1962-2001.

Seasons	Rot. - Far.	Rot. - Orc.	Rot. - Esp.	Far. - Orc.	Far. - Esp.	Esp. - Orc.
Summer (DJF)	0.83	0.35	0.33	0.36	0.17	0.54
Autumn (MAM)	0.90	0.56	0.43	0.50	0.31	0.71
Winter (JJA)	0.89	0.56	0.63	0.49	0.59	0.73
Spring (SON)	0.91	0.44	0.45	0.38	0.34	0.73

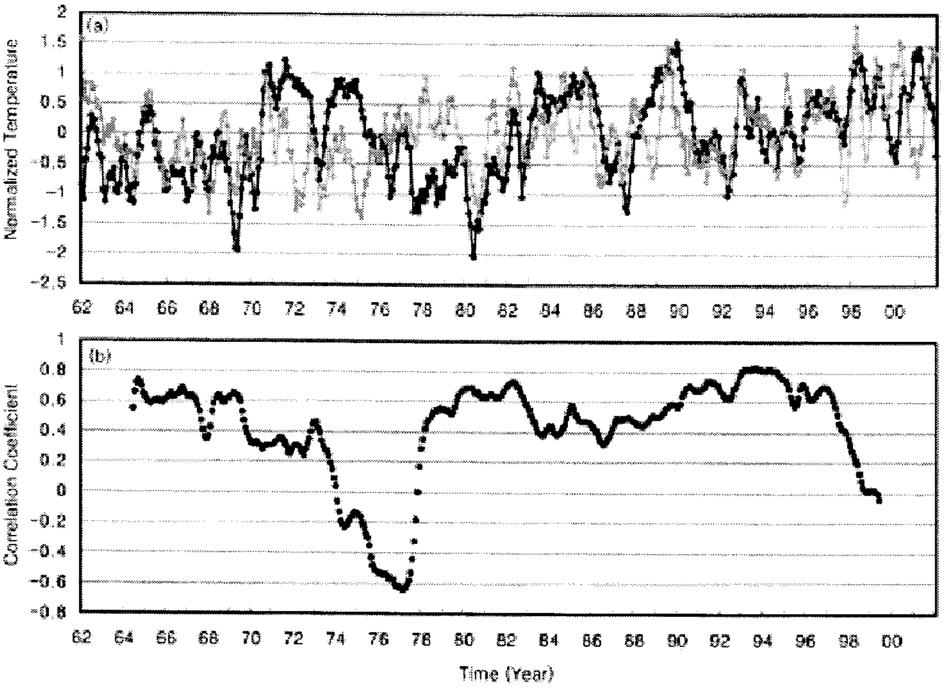

Fig 6. Normalized monthly temperature of Rothera/Faraday (solid line) and Esperanza (gray line): (a) the distribution of 5-month running mean and (b) correlation coefficient between them for 5-year moving period.

to Orcadas.

Therefore, using the mean temperatures of Rothera and Faraday which represent the west side of the Peninsula, the correlation analysis is performed on the monthly temperature at each of 6 stations (Rothera, Faraday, Bellingshausen, Orcadas, Esperanza, and Halley). Fig. 6 shows some results of the correlation analysis on the Esperanza temperature. The used values are the normalized 5-month running mean and correlation coefficients are calculated for 5-year moving period. The time period of 5 years is chosen for eliminating the influence by long-term trend of temperature. Over most of the period, positive correlations are shown which are greater than 0.5, but in the mid- and the late 1970s significant negative correlations (less than −0.5) are found. These negative correlations are consistent with the negative correlation between annual mean temperature in the west and east sides.

Fig. 7 shows the results of correlation analysis for all 6 stations. On the mean temperature of Rothera and Faraday, the correlation coefficients of SAT for 6 stations gradually decrease in the order of Bellingshausen, Orcadas, Esperanza, and Halley. In the mid-1970s and the late 1990s negative correlations are found at Esperanza, Orcadas and Bellingshausen. At the Halley a considerable part of the period shows negative correlations. Therefore,

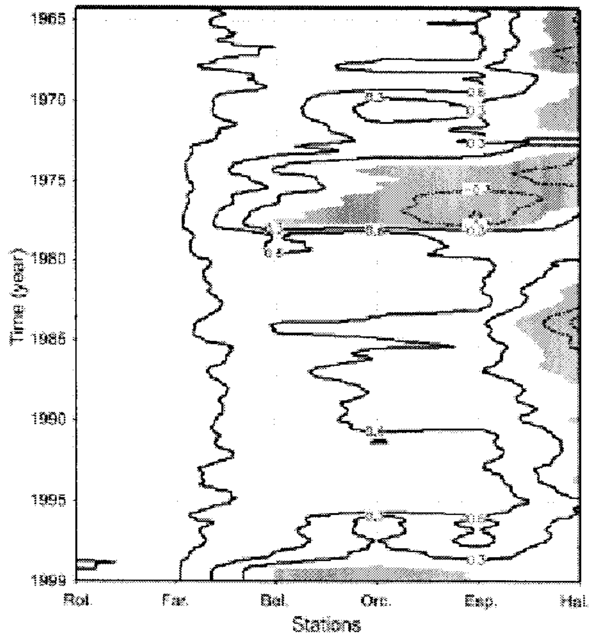

Fig. 7. Correlation coefficient between mean monthly temperature of Rothera and Faraday and monthly temperature at each station. These values are normalized 5 month running mean. Shading denotes negative correlation coefficients.

Table 4. Lagged correlation between SST anomaly in the NINO 3.4 region and monthly temperature of each station around the Antarctic Peninsula.

Stations	Correlation coefficient	Lag, months (Correlation coefficient)
Rothera	−0.33	2 (−0.35)
Faraday	−0.32	2 (−0.34)
Bellingshausen	−0.27	4 (−0.30)
Orcadas	−0.29	3 (−0.34)
Esperanza	−0.14	6 (−0.16)

it can be concluded that it is difficult to find an out-of-phase relationship of SAT across the Antarctic Peninsula except for the 1970s, but there is insignificant negative temperature correlation between the west side of the Peninsula and Halley on the coast of Weddell Sea in the East Antarctica.

Relationship with ENSO

In order to examine the relationship between SAT in the Antarctic Peninsula and ENSO, the lagged correlation coefficients for 6 stations between normalized SAT and SST anomalies in the NINO 3.4 region are calculated for the period of 40 years (Table 4). Lag correlations are created by lagging SAT to SST anomalies from lagging SAT by 12 months to leading SAT by 12 months (a negative lag). Through the 25-month time step, the maximum correlation coefficient from the absolute values is chosen. The correlation coefficients between normalized SAT and SST anomalies are about −0.3 except for Esperanza having the correlation coefficient of −0.14. The lagged correlations also show similar values at a lag of 2-6 months. Without accounting the auto-correlations, the correlation of about −0.3 is significant at the level of 1%.

For further examination, SST anomalies in the NINO 3.4 region are correlated with normalized monthly temperature at 6 stations. Correlation analyses are performed on the 5-month running mean of the two time series over the moving period of 5 years. The short time period such as 5 years is used in order to reduce the effect of long-term variation on the above correlation, instead of removing the trend. The statistical test is conducted for the significance of the correlations by the Monte Carlo technique (Livezey and Chen 1983). First, one of two time series (in this case, normalized SAT) is randomly reordered, based on the yearly data and averaged for a 5-month moving period. And a correlation coefficient is calculated

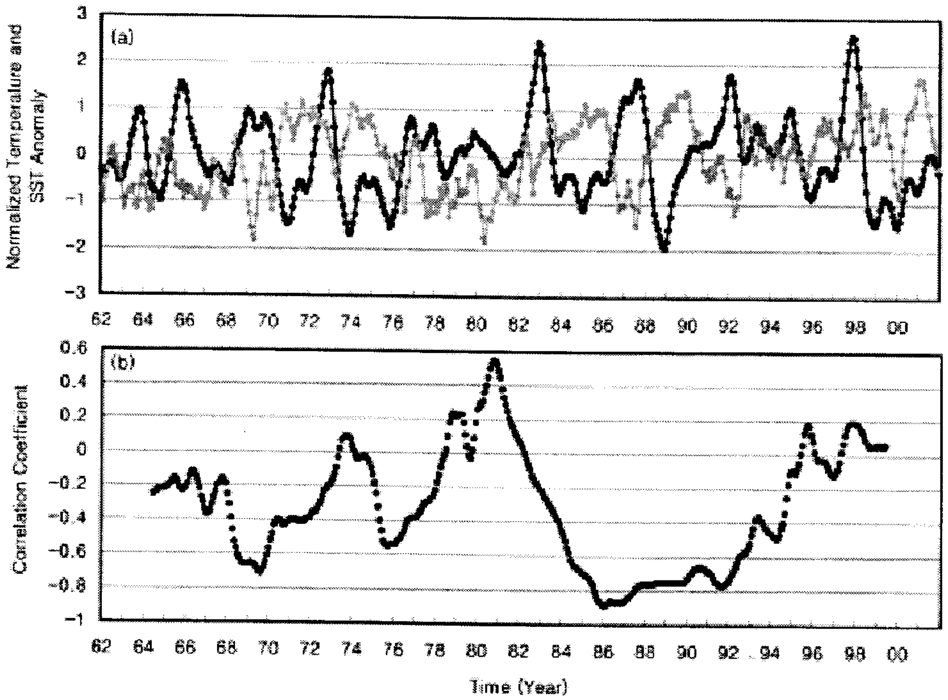

Fig. 8. Relation between SST anomaly in the NINO 3.4 region (solid line) and normalized monthly temperature at Faraday (gray line): (a) the distribution of 5-month running mean and (b) correlation coefficient between them for 5-year moving period.

between normalized SAT and SST anomalies for a given 5-year period. This procedure is repeated sufficiently for Faraday station with each trial having different randomized order. The field significance at the 1% level is determined by the correlation coefficient at 99% cumulative frequency. In this study, the correlation coefficient at the 1% significance level is –0.53 at Faraday for the 5 years of 1986-1990. This value is used for statistical test at all 6 stations and for the entire period.

First, Fig. 8 shows the distribution of SAT of Faraday and SST anomalies and their correlation coefficients. From the early 1980s to the mid-1990s, there are strong negative correlations (less than –0.53) between the Faraday SAT and SST anomalies. Besides, the significant negative correlations are found in the short periods of the late 1960s and the mid-1970s. The significant positive correlations appear only for a short period of the early 1980s. Therefore, there is in general a negative correlation between the Faraday SAT and SST anomalies in the NINO 3.4 regions and this relation is noticeably strong from the early 1980s to the mid-1990s.

In the above results, the negative correlation means that increases in SST anomaly are matched with decreases in the Faraday SAT, and vice versa. That is, in the extreme case the Faraday SAT is colder in the El Niño period, while warmer in the La Niña period. Furthermore, it is noted that the strong negative correlations occur in the 1982-1994 period when the extreme events of the ENSO are frequent.

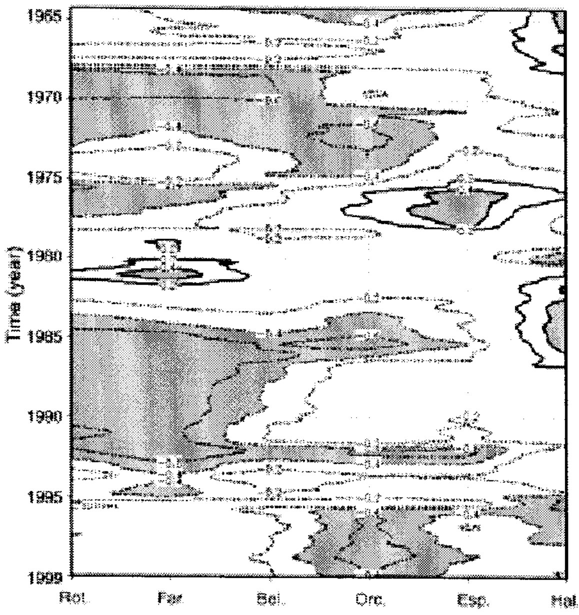

Fig. 9. Correlation coefficient between SST anomaly in the NINO 3.4 region and normalized monthly temperature at each station for 5 year moving period. SST anomalies and normalized temperature are 5 month running mean. Correlation coefficients greater than 0.4 or less than –0.4 are shaded.

Fig. 9 shows the distribution of correlation coefficient between SAT and SST anomalies for 6 stations. In the west side of the Peninsula (Rothera/Faraday), in general the strong negative correlations are found, while the relation at Esperanza and Halley is insignificant. Although the period is not consistent with that of Rothera and Faraday, Bellingshausen and Orcadas show negative correlations as well. And it is noticeable that the strong negative correlation between SAT and SST anomalies is in a good agreement with the ENSO signal (strong negative correlation with the SST anomalies) during 1980s in Frei precipitation (Kwon and Lee 2002) and in the west Antarctic precipitation (Bromwich *et al.* 2000).

5. Summary

This study investigated the spatial characteristics of warming trends and the existence of dipole-like pattern of temperature field in the vicinity of the Antarctic Peninsula. The inter-annual temperature variations were examined across the Antarctic Peninsula. East (west) side of the Antarctic Peninsula is connected with the Atlantic Ocean (the Pacific Ocean), and also governed by different atmospheric circulation pattern. Using SAT data of 10 stations in the vicinity of the Antarctic Peninsula, the inter-annual temperature variations on the two sides of the Peninsula were compared.

SAT data for the 1962-2001 period at 6 stations (Rothera, Faraday/Vernadsky, Bellingshausen, Orcadas, Esperanza, Halley) revealed in general larger warming trends in autumn and winter except for Halley. These warming trends were larger in the west side of the Peninsula than in the east side. The largest warming appeared at Faraday in August (amounting to 1.2°C/decade). On the other hand, the recent SAT data for the 1988-2001 period at 10 stations showed the warming trends larger than 2°C/decade for the period of April-June except for Halley. The largest warming appeared in May at Esperanza and Butler Island (amounting to 5°C/decade). Even though it can be attributed to lack of statistical significance due to the short data records, the remarkable warming trends of Esperanza and Butler

Island are consistent with the recent breakup of the Larsen-B ice shelf on the eastern side of the Antarctic Peninsula. It is postulated that the warming of Esperanza and Butler Island can be related in part to the phase variation in an annual temperature cycle (the time delay of the minimum occurrence).

In this study, in order to examine an out-of-phase relationship of SAT across the Antarctic Peninsula, the correlation analysis was performed on SAT in the two sides of the Peninsula. The western and eastern sides of the Peninsula were represented by Rothera/Faraday and Esperanza/Orcadas, respectively. SAT of the two sides showed significant positive correlations over most of the period, but in the mid- and the late 1970s significant negative correlations were found. SAT of Halley showed negative correlations with SAT in the west side of the Peninsula in a considerable part of the period. Therefore, it can be concluded that it was difficult to find out an out-of-phase relationship of SAT across the Antarctic Peninsula except for the 1970s.

The ENSO related variability of SAT which was examined by the correlation analysis between SAT and SST anomalies in the NINO 3.4 region, showed the strong negative correlation in the west side of the Peninsula. Details of the correlation analysis exhibited that the negative correlation was significantly strong from the early 1980s to the mid-1990s. It is noticeable that the strong negative correlation between SAT and SST anomalies was in a good agreement with the ENSO signal (strong negative correlation with the SST anomalies) during 1980s in Frei precipitation (Kwon and Lee 2002) and in west Antarctic precipitation (Bromwich *et al.* 2000). However, it was difficult to find significant correlations of ENSO with SAT in the east side of the Peninsula.

In recent years, several research works (Yuan and Martinson 2000, 2001; Rind *et al.* 2001, etc.) reported that the distribution of temperature and sea ice in the vicinity of the Antarctic Peninsula is characterized by a dipole-like pattern reflecting an out-of-phase relationship in the central/eastern Pacific and Atlantic sectors of the Antarctic. And they reported that the dipole is clearly associated with the tropical ENSO events. That is, during El Niño years, sea ice (SAT) decreases (increases) on the Pacific side and increases (decreases) on the Atlantic side, and during La Niña years vice versa. Nevertheless, because it failed to find out clearly the out-of-phase relationship of SAT across the Antarctic Peninsula in this study, we will have a task to monitor it continuously.

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