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Statistics of Antarctic surface meteorology based on hourly data in 1957−2007 at Syowa Station

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Abstract

Statistical characteristics of the surface meteorology are examined at Syowa Station (69°00′S, 39°35′E), which is located on an island near the coastal region of the Antarctic continent, based on operational observations made over the 50-year period from February 1957 through January 2007, which includes missing periods equivalent to 5 years. Statistics are obtained for the surface temperature, sea level pressure (SLP), and horizontal winds in terms of frequency distribution, frequency power spectra, seasonal variation, diurnal variation, inter-annual variation, and trends, using hourly observation data, and several interesting characteristics are elucidated. The mean temperature, SLP, and wind speed over the 50-year period are −10.5 °C, 986 hPa, and 6.6 m s^{-1}, respectively. The frequency distribution of temperature is far from the normal one, because less variation exists in summer at higher temperatures. The predominant wind direction is northeasterly (southwestward), and a weak secondary peak is observed in the southerly (northward) direction in the frequency distribution. The directional constancy of winds is 0.78. The frequency spectra over a wide range of 2 h to 20 years exhibit clearly isolated peaks corresponding to annual and diurnal frequencies and their higher harmonics. An important finding is that the spectral shape is proportional to a power of the frequency with a transition frequency for all physical parameters. The transition frequencies correspond to about 5 days for temperature and winds and 3 days for SLP, most likely due to cyclonic activity. A peak in the 11-year solar cycle is not identified in any spectrum. Another interesting feature is the dominance of semi-annual and semi-diurnal variations in SLP, while annual and diurnal variations are dominant for temperature and winds. Statistically significant trends are not detected for annual mean surface temperature and SLP over the 50-year period, while a positive trend is significant for wind speed. These trends are also examined as a function of the months. The inter-annual variation of SLP is well correlated with that of the Antarctic Oscillation index, indicating that Syowa Station can be regarded as a typical Antarctic station. Furthermore, statistical analysis was conducted for blizzards (severe snow storms), in terms of duration, and seasonal and inter-annual variation in frequency of occurrence. It is shown that the blizzards are dominant in the period from late March to late October. No systematic variation in blizzard frequency was observed during the 50-year period. Instead, the frequency depends largely on the year with a minimum of nine in 1988 and a maximum of 42 in 1982. As a typical example, a synoptic chart is used to show the cause of a strong snow storm on 27 May 1996, when the absolute maximum gust was observed.

Keywords: Antarctic meteorology; Frequency spectra; Diurnal variation; Seasonal variation; Inter-annual variation; Trend; Climate; Blizzard

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1. Introduction

It has been 50 years since the Japanese Antarctic Research Expedition established Syowa Station (69°00′S, 39°35′E) in 1957 on an island in the coastal region of the Antarctic continent. The length of operational observation data is now sufficient to analyze fluctuations in meteorological parameters over a wide range of time scales. Jacka and Budd (1998) and Turner et al. (2005) examined climate change, such as trends in surface meteorology of the Antarctic, using data from many stations over tens of years. Streten (1990) also used long-term observation data to examine climate at various time scales at Mawson (67°36′S, 62°52′E). Diurnal cycle of temperature and wind was analyzed in terms of the katabatic wind system (e.g., Kodama et al., 1989; Parish et al., 1993; Gallée and Pettré, 1998) and several studies on intraseasonal variability (Yasunari and Kodama, 1993) and seasonal variation (Parish and Bromwich, 1997) have been conducted. Inter-annual variability was recently discussed in terms of the Antarctic Oscillation (AAO), which is a dominant pattern of tropospheric circulation observed in the region to the south of 20°S (Thompson and Wallace, 2000). It is characterized by pressure anomalies of one sign centered in the Antarctic and anomalies of the opposite sign centered at approximately 40°–50°S. The AAO is also referred to as the Southern Annular Mode (SAM). Another phenomenon for examining year-to-year variability is the Antarctic circumpolar wave (ACW), which was first documented by White and Peterson (1996). The ACW is an eastward propagating phenomenon with a wavenumber 2, which is observed in sea ice, pressure, wind, and temperature fields around the Antarctic, and a wave period is about 4 years.

In this paper, we provide statistics for the meteorology at Syowa Station using hourly operational observation data of surface meteorology and blizzard records for the entire 50-year time period from February 1957 through January 2007, including missing periods of 5 years. Although several characteristics documented in this paper have already been reported by previous studies, we describe them in conjunction with new findings in order to establish a systematic understanding of trends and variations over a wide range of time periods, from 2 h to 20 years. The data description is given in Section 2. Statistical results of frequency distribution, spectral characteristics, seasonal, diurnal, inter-annual variations and trends are shown in Section 3. Statistics of severe snow storms (blizzards) are shown in Section 4. The results are discussed in Section 5, and the summary and concluding remarks are given in Section 6.

2. Data description

The surface meteorological observation data at Syowa Station, obtained by the 1st to 47th Japanese Antarctic Research Expeditions (JARE1–JARE47), were analyzed for the 50 years from February 1957 to January 2007, except for the two time periods of March to December of 1958 and of March 1962 to January 1966, which are missing because Syowa Station was closed. Analyzed meteorological parameters included the sea level pressure (SLP) p (instantaneous value), temperature T (instantaneous value), speed and direction of horizontal winds (10 min average). The time intervals are 1 h for the winds over the whole period, and depend on the time period for p and T, namely, 6 h in the period from February 1957 through February 1958 (JARE1), 3 h from January 1959 through January 1982 (JARE2–JARE22), and 1 h from February 1982 up to the present. As a wintering party takes the place of the previous party on the first of February every year, data characteristics such as sampling intervals are constant in a year beginning in February. Thus, we hereafter refer to a particular year as the time period from February of the year to January of the next year.

Current criteria for blizzards at Syowa Station were determined in 1975 (Table 1). We used the data for blizzards redefined using current criteria back to 1957 (JMA, 1989). For the years after 1978, we used the blizzard records in the Japanese Antarctic Research Expedition report published each year.

3. Statistics of surface meteorology

3.1. Frequency distribution

Fig. 1 shows frequency distribution of the temperature, wind speed and wind direction at Syowa Station. All data in the years from 1957 through 2006 were used. The average temperature was −10.5 °C and that of wind speed was 6.6 m s^{-1}. The absolute minimum temperature of −45.3 °C was recorded on 4 September 1982 and the absolute maximum of 10.0 °C on 21 January 1977. The absolute maximum wind speed was 47.2 m s^{-1} on 26 May 1975. The absolute maximum

Table 1
Criteria of blizzards at Syowa Station

Class	Visibility	Wind speed (m s^{-1})	Duration (h)
A	<100 m	≥25	≥6
B	<1 km	≥15	≥12
C	<1 km	≥10	≥6

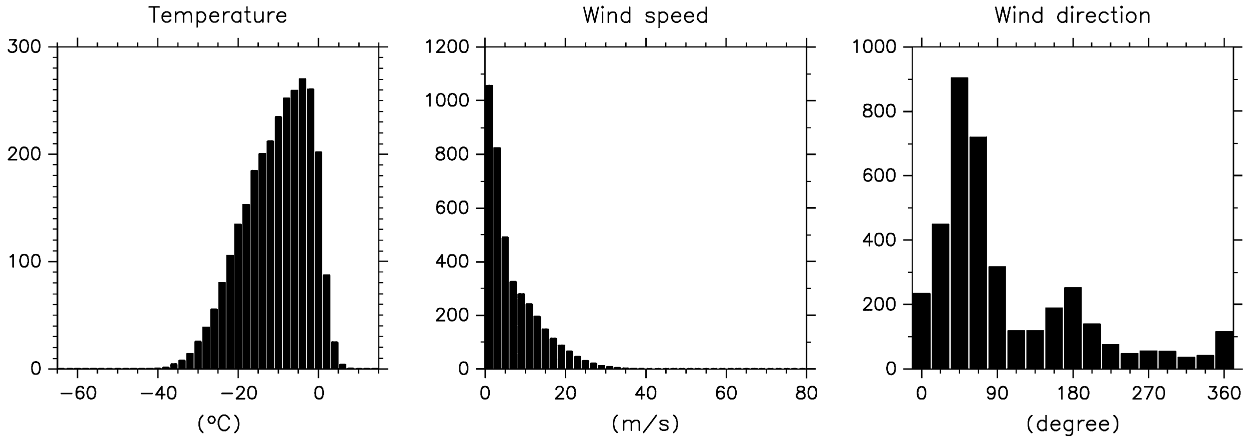

Fig. 1. Frequency distribution of the surface temperature, wind speed, and wind direction at Syowa Station based on hourly operational data for 1957–2006.

gust was 61.2 m s^{-1} on 27 May 1996. The temperature distribution differed markedly from the normal distribution, because temperature fluctuations were weak in summer as shown later. The frequency distribution of wind direction shows the dominance of northeasterly (southwestward) winds. A weak secondary peak was observed for the southerly (northward) wind direction. The frequencies of north-northeasterly, northeasterly, and east-northeasterly wind directions cover 56.8% of the total. The directional constancy that is defined as the absolute value of the vector average divided by the scalar average for winds was 0.78 at Syowa Station. Such high directional constancy is commonly seen at other stations in the continental interior and coast in the Antarctic and is attributed to the dominance of katabatic winds from the Antarctic continent (King and Turner, 1997). A similar double peak structure in the wind direction distribution was also reported for Neumayer (70°39′S, 8°15′W) and Halley (75°35′S, 26°19′W) but not for Dumont D'Urville (66°40′S, 140°1′E) (Konig-Langlo et al., 1998). Konig-Langlo et al. attributed the primary peak observed around the easterly wind direction at Neumayer and Halley to the dominance of synoptically forced easterlies along the Antarctic coast, and the secondary peak to katabatic winds. In fact, only one peak was observed at Mizuho Station (70°42′S, 44°20′E) on the slope of the continent (Ohata et al., 1985). Ohata et al. also conducted an analysis for Syowa Station and inferred that the primary peak around the northeasterly wind direction was due to the circumpolar easterly winds. However, in the case of Syowa Station, the primary peak can also be attributed to katabatic winds because the Antarctic continent is situated about 4 km to the east of Syowa Station. Thus, katabatic winds observed at Syowa Station tend to be easterly and slightly northerly due to the Coriolis effect. Wind speeds of the secondary peak are weak compared to those of the primary peak (Ohata et al., 1985), possibly indicating that the secondary peak corresponds to a far-downstream part of the katabatic flow blowing on the ridge, about 100 km south of Syowa Station.

3.2. Spectral characteristics

Frequency spectra were obtained using the maximum entropy method (MEM). Since the time interval was not constant through the 45 years, as described in Section 2, we used two time series to cover a wide frequency range from (20 years)$^{-1}$ to (2 h)$^{-1}$. One is 3-hourly data for the time period 1966–2006 to estimate spectra in a low frequency range, and the other is hourly data for the time period 1982–2006 in a high frequency range. Missing data were interpolated linearly for both time series. The numbers of data points in the 3 hourly time series and in the hourly time series were 119,800 and 227,904, respectively. Estimated frequency spectra for surface temperature, pressure, zonal (u) and meridional (v) wind fluctuations are shown in Fig. 2. The frequency range of (50 day)$^{-1}$ to (2 day)$^{-1}$ is superimposed for the two spectra. Vertical dotted lines show the periods of 11 year (solar cycle), 1 year, 1/2 year, 1/3 year, 1 day, 1/2 day, 1/3 day and 1/4 day from the left. It is worth noting that there are few reports in which the frequency spectra are examined for such a wide frequency range, even for the middle and lower latitude regions.

Spectral peaks around the frequencies of (1 year)$^{-1}$, (1 day)$^{-1}$, and their higher harmonics are clearly observed in any parameter spectrum. There is no spectral peak corresponding to the solar cycle. A one-year peak

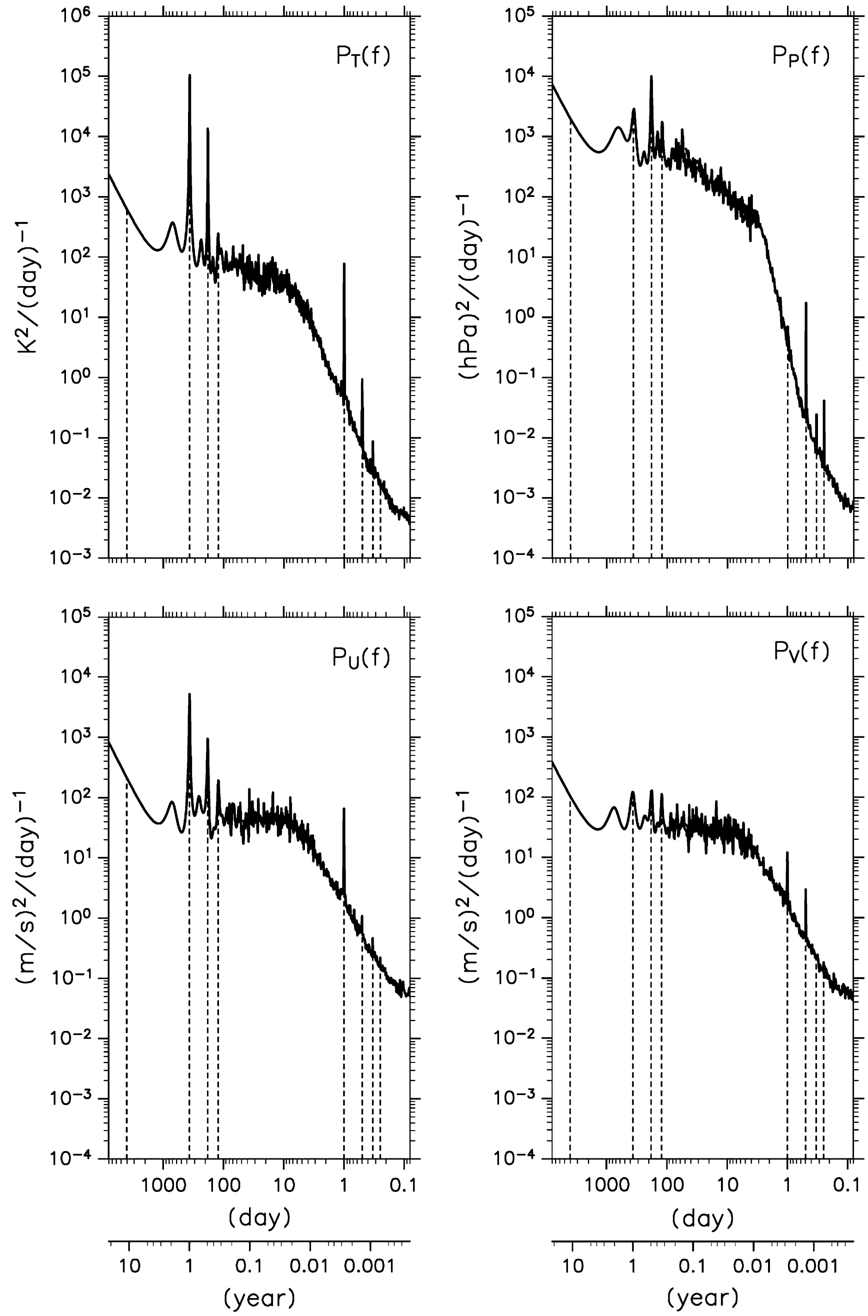

Fig. 2. Frequency spectra of the meteorological parameters at Syowa Station based on the data for 1966–2007, estimated using the maximum entropy method. The top left panel shows the spectrum for temperature fluctuations, the top right for the sea level pressure, the bottom left for the zonal wind, and the bottom right for the meridional wind. The left end of the horizontal axis shows 20 years and the right end 2 h. Dashed vertical lines indicate the period of 11 years (solar cycle), 1 year, 1/2 year, 1/3 year, 1 day, 1/2 day, 1/3 day, 1/4 days from the left.

is dominant in the T and u spectra, while a half-year peak dominates 1 year peak for the p spectrum. A one-day peak is dominant in T, u and v spectra, while a half day peak is dominant for the p spectrum. The confidence intervals are examined for the frequency spectra estimated by the Blackman–Tukey method, since accurate estimates of the confidence intervals are not available for the MEM spectra. Thick and thin curves in Fig. 3 show the frequency spectrum for the SLP with a confidence interval of 90% at each frequency, respectively. It is apparent from Fig. 3 that semi-annual and semi-diurnal variations are dominant for p spectra.

Similarly, statistical significance for the peaks of the other parameters was confirmed (not shown).

An interesting feature is that the spectra have a shape which is proportional to a power of frequency (*f*) with a transition period of several days. For *T*, *u* and *v* spectra, the transition is observed around the period of 5 days, while the transition period of the *p* spectrum is around 3 days. The spectra at lower and higher frequencies than this transition period are proportional to $f^{-0.375}$ ($\sim f^{-1/3}$) and $f^{-2.45}$ ($\sim f^{-7/3}$) for the *T* spectrum, $f^{-0.88}$ ($\sim f^{-7/8}$) and $f^{-4.34}$ ($\sim f^{-13/3}$) for the *p* spectrum, f^{0} and $f^{-1.72}$ ($\sim f^{-5/3}$) for the *u* and *v* spectra, respectively. It is inferred that these transition periods correspond to cyclone activity with time scales of days.

3.3. Seasonal variation

Fig. 4 shows seasonal variation of *T*, *p*, wind speed, wind direction and directional constancy obtained for each 10-day time period, based on all data for 45 years. Standard deviations are calculated using daily mean data and original hourly data, whose ranges are shown by shading and thin curves, respectively. To more clearly observe seasonal variation, a running mean of a month was applied to each curve.

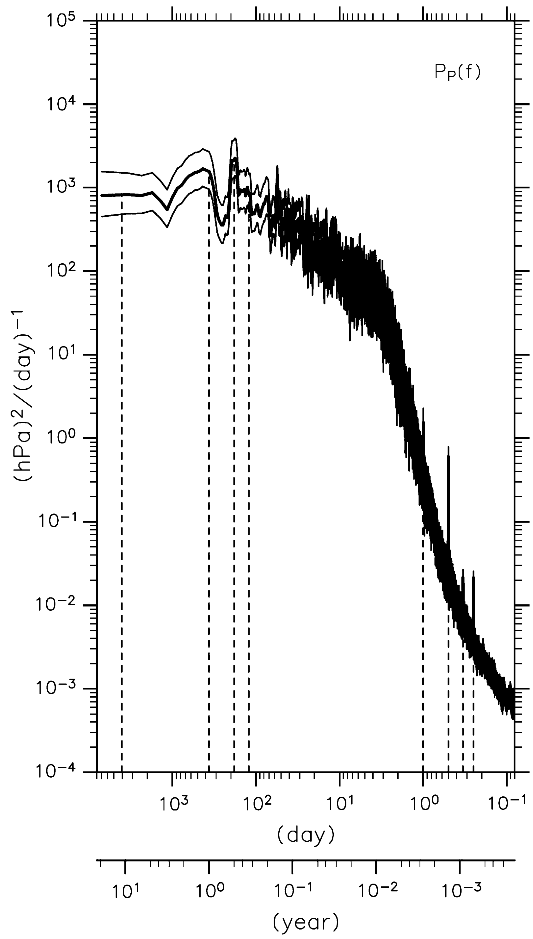

Fig. 3. The same as Fig. 2 but only for the sea level pressure based on the data for 1957–2007 using the Blackman and Tukey method. Confidence intervals of 90% are shown by the thin curves.

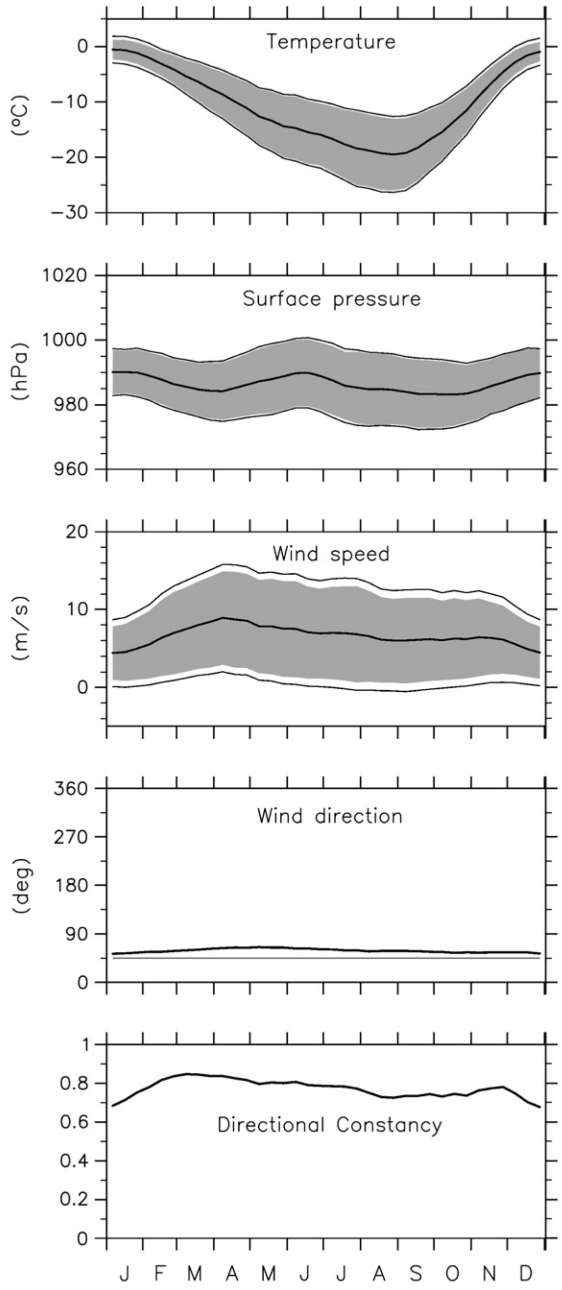

Fig. 4. Seasonal variation of the temperature, sea level pressure, wind speed, wind direction and directional constancy obtained for each 10-day period. The ranges shown by shading and thin curves indicate the standard deviations for each 10-day period using daily mean and original hourly data, respectively.

The monthly mean temperature profile shows clear annual variation with a summer maximum of about −1 °C in late December to early January, and a winter minimum of about −20 °C in August. Both standard deviations, including and not including daily variation, are minimized in summer. This fact indicates that short-period variation (less than 10 days) is dominant in winter, even if larger diurnal variation in summer than in winter is considered as will be shown in Section 3.4.

The SLP is generally low with an average of only about 986 hPa. In addition, extremely low pressure near 950 hPa is not rare. It is likely that such low pressure corresponds to the circumpolar trough, commonly observed in the coastal region of the Antarctic continent in all seasons. The circumpolar trough is unique to the Antarctic and not observed in the Arctic. A number of synoptic and mesoscale lows are embedded in the circumpolar trough. The SLP at Syowa Station exhibits clear semi-annual variation with two maxima in summer and winter, in harmony with the dominant peak of the half-year period observed in the frequency spectra. Similar semi-annual variation in pressure was also reported for the other Antarctic locations (e.g., van den Broeke, 1998a) and related to the circumpolar trough, which is weaker at the solstice and located in lower latitudes (van Loon, 1972). van den Broeke (1998a) reported that the wavenumber 3 structure of the circumpolar circulation is amplified in equinoxes and causes semi-annual variation of the surface temperature at many stations in the coastal region by temperature advection. The seasonal variation in temperature at Syowa Station does not show significant semi-annual variation because the location is less-affected by the wavenumber 3 structure whose phases are almost stationary.

The wind speed is weaker in summer than in winter, although the seasonal variation is not very strong. Short-period variation in wind speed is rather dominant as shown by the range in standard deviation in Fig. 4. The wind direction is almost constant (northeasterly winds) in any season, although the directional constancy decreased slightly in summer.

3.4. *Diurnal variation*

Fig. 5 shows diurnal variations of p, T, wind speed and wind direction as a function of month. The SLP profiles were obtained using time series to which a highpass filter with a cutoff length of 2 days was applied, since the trend over 24 h for the SLP is not negligible. As seen in the frequency spectra, semi-diurnal variation is clearly observed in the p profile. Such dominance of semi-diurnal variation has not been reported so far. The two minima are observed around 0700–0800LT and 1900–2000LT. The minimum around 1900–2000LT is dominant in the summer period from October to February, and is not clear in the winter period from April to August. The minimum around 0700–0800LT is observed in any month, while it is particularly clear in the winter season.

On the other hand, for T and wind speed, diurnal variation is dominant in the summer period from September to March. The diurnal variation in the wind direction is also clear in the summer period from October to February, i.e., the winds are more northerly around noon. In the winter period from May to July, including polar nights over 45 days, no meaningful diurnal variation is seen in T and winds, in harmony with little solar radiation all day long. The dominance of diurnal variation in winds and temperature in summer was also shown by Streten (1990) at Mawson.

3.5. *Trends and inter-annual variation*

Next, annual mean values for T, wind speed and p are examined as a function of year in Fig. 6. Note that the year on the horizontal axis does not indicate a year starting in February as before but a "real year". Horizontal solid lines indicate the average for the whole period. Dashed lines show the linear trend. For any physical parameter, inter-annual variation is large and the trend is small except for wind speed. The linear trend for wind speed is about 0.21 m s^{-1} per decade, whose significance is confirmed by the t-test at the level of 90%. Similarly, increases in temperature and SLP are estimated at about 0.08 K and −0.25 hPa per decade, respectively, although these are not statistically significant. These trends only change by a few percent when we use the data degraded to 3 or 6 hourly.

The inter-annual variation was examined as a function of month. A significant positive trend in wind speed is observed in February (0.59 m s^{-1} per decade), April (0.37 m s^{-1} per decade) and May (0.36 m s^{-1} per decade), which may be related to a significant negative trend of the SLP observed in the same months (i.e., −0.62, −0.86, and −1.34 hPa per decade in February, April and May, respectively). A significant temperature trend is not observed in any month as also shown later.

According to the IPCC report (IPCC, 2001), the temperature trend range is between 0.10 (sea-surface temperature) and 0.13 (land-surface air temperature) K per decade in the Southern Hemisphere for the years of 1976–2000. These values appear similar to the trend of 0.08 K per decade at Syowa Station. However, if we use the data of 1976–2000 which is the same as the

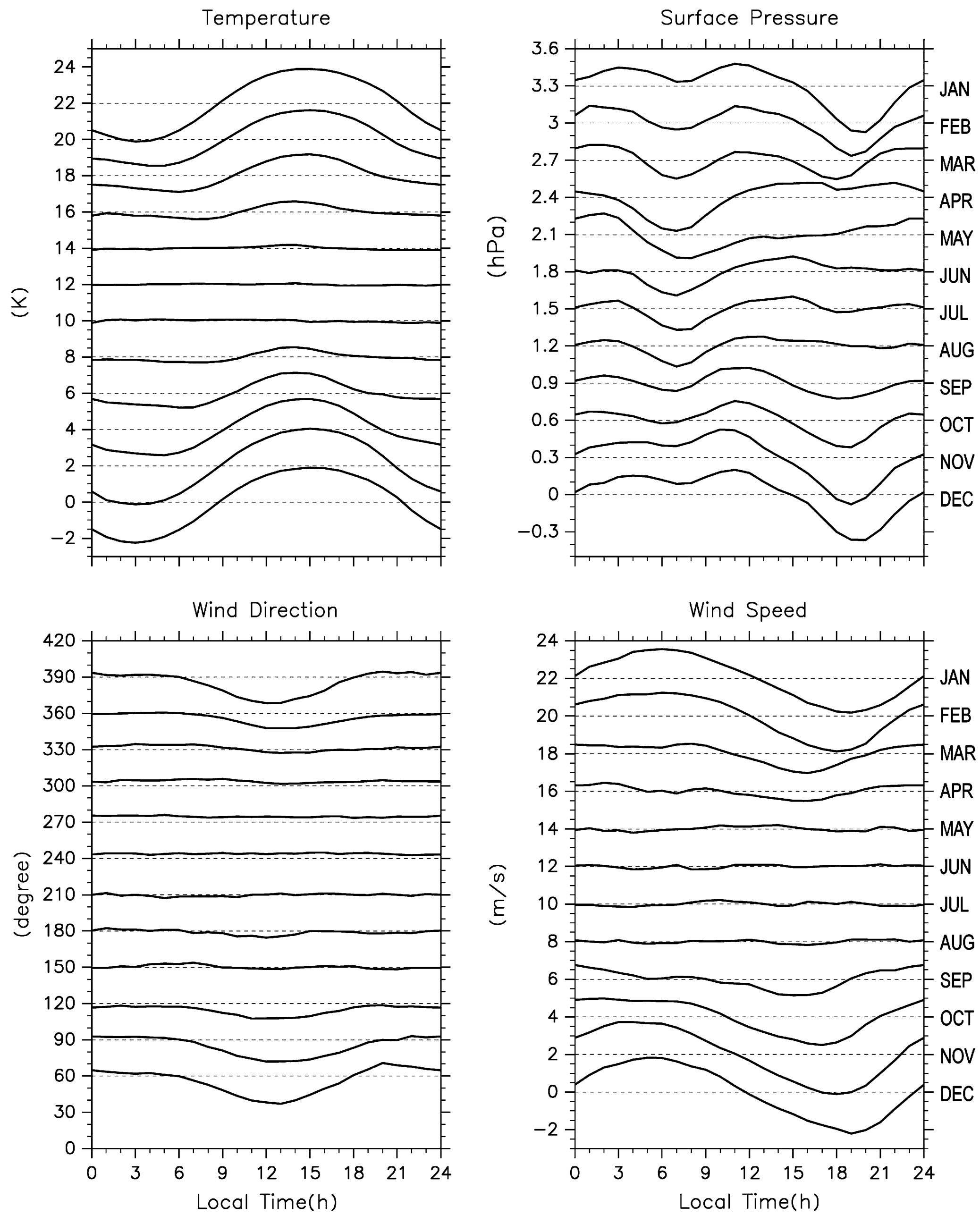

Fig. 5. Diurnal variation of the sea level pressure, temperature, wind speed and wind direction as a function of month. The profiles for respective months are shifted by a length between adjacent dashed lines. The labels on the left are for the profiles of December.

period in the IPCC report, the trend is estimated at −0.017 K per decade at Syowa Station. This is much smaller than the trend reported by IPCC as an average for the Southern Hemisphere. Jones (1995) reported an increase in mean temperature of 0.57 K over 1957–1994 (about 0.15 K per decade) based on the data from 20 stations in the Antarctic. He also noted that the warming occurred before early 1970s and there had been no change since then. Our result is consistent with Jones'. It may be also worth noting that Turner et al. (2005) and Jacka and Budd (1998) reported the temperature trend at Syowa Station as 0.01 K per decade for 1960–2000, and 0.12 K per decade for 1959–1996, respectively. Such a large variation in trends depending on the time period means that the year-to-year variation in temperature is large.

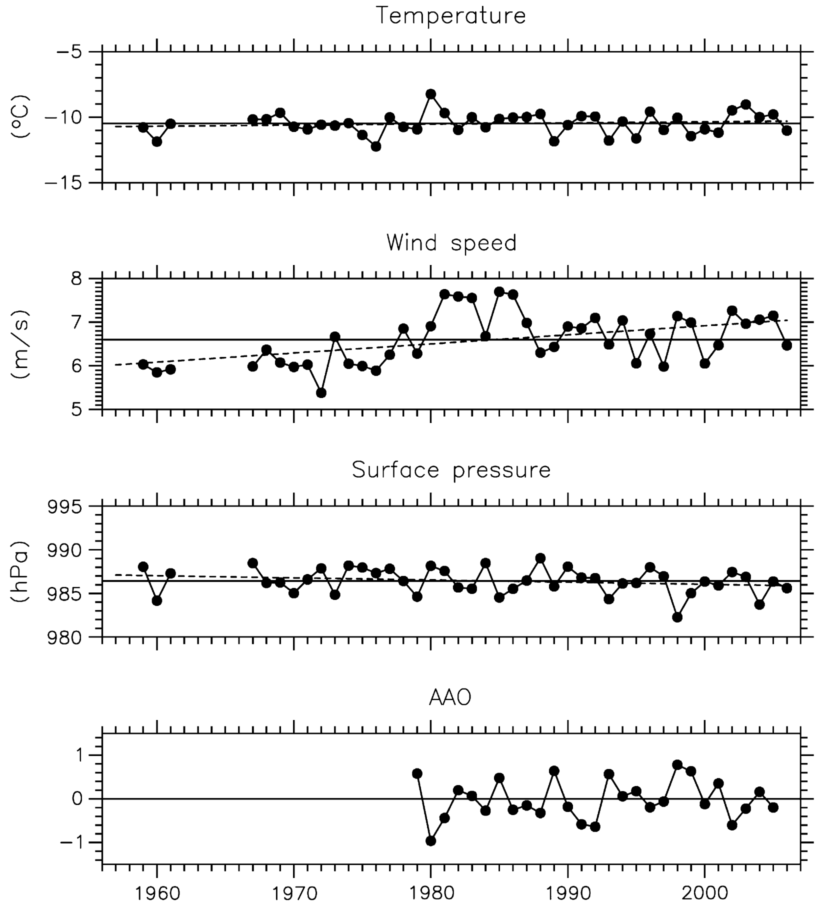

Fig. 6. Annual mean values for wind speed, temperature, and sea level pressure at Syowa Station (from the top) as a function of year. The time series of the annual mean of the Antarctic Oscillation (AAO) index is also shown (bottom). It is clear that the sea level pressure at Syowa Station has a high negative correlation with the AAO index.

The time series shown at the bottom of Fig. 6 is the Antarctic Oscillation (AAO) index beginning in the year of 1979 when operational satellite observations started. The Antarctic Oscillation is a counterpart of the Arctic Oscillation (AO), which has been recognized over the past decade as an important topic in climate research. The oscillation is originally defined as a seesaw of SLP between the middle latitudes and the polar region. From the horizontal pattern of the oscillation, the AO and AAO are also called annular modes. The evidence of the oscillation is observed at least up to the stratosphere. Positive values of the AAO index indicate a phase of low pressure over the Antarctic and high pressure in the middle latitude region. An interesting feature observed in Fig. 6 is that the SLP at Syowa Station has a high negative correlation with the AAO index. The correlation coefficient is −0.82. This means that Syowa Station is a typical Antarctic station.

Thompson and Solomon (2002) indicated by using the data collected until 2000 that the AAO is strongly related to the recent trends of the Southern Hemisphere tropospheric circulation and surface temperatures at the high latitudes during the summer–fall season. A negative temperature trend was also shown for Syowa Station. In order to examine recent variation of the AAO index and its effects on temperature trends, we compared the characteristics of two time periods: 1979–2000 and 1979–2006. Fig. 7 shows the temperature trends and the correlation between the temperature and AAO index as a function of month. For both time periods, meaningful negative high correlations are observed in the summer–fall season. Negative meaningful temperature trends are observed in January, March and April for the period of 1979–2000. These facts are consistent with the findings of Thompson and Solomon. An interesting feature is that the negative trends are smaller and their significance is lowered for the period of

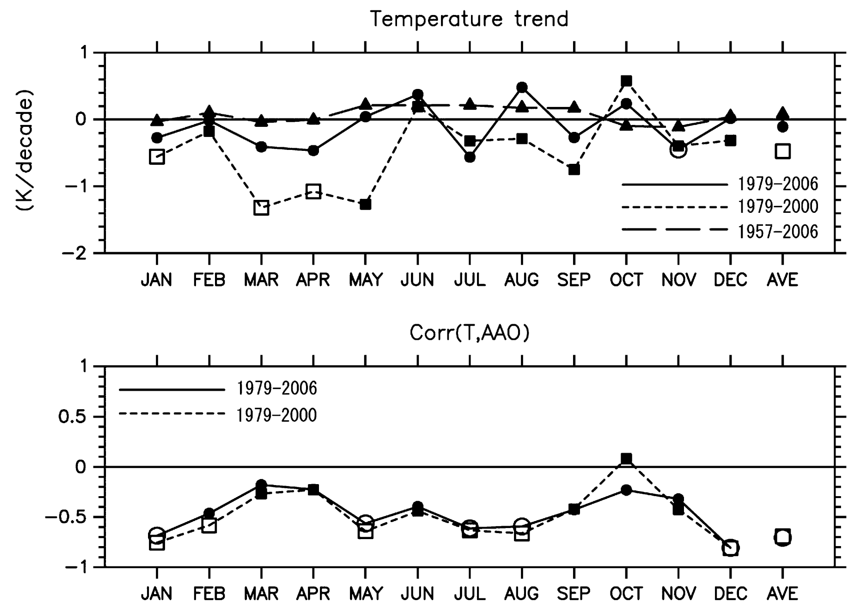

Fig. 7. (Top): temperature trends as a function of month for three time periods: 1979–2006 (circles), 1979–2000 (rectangles), and 1957–2006 (triangles). (Bottom): correlation of the time series of temperature and AAO index as a function of month, for the time periods of 1979–2006 (circles) and 1979–2000 (rectangles). Open circles, triangles, rectangles indicate statistically meaningful values.

1979–2006. Temperature trends are also shown for the whole analyzed period of 1957–2006 in Fig. 7, which have very small values for all months. Fig. 8 shows the time series of the temperature and AAO index in January. It is clear that the trend in the AAO index is largely positive for 1979–2000, but that it gets smaller for 1979–2006 because the recent AAO index oscillates largely between positive and negative values. Accordingly, the negative trend in temperature is smaller for the period of 1979–2006 compared with that of 1979–2000.

4. Statistics of blizzards

First, in this section, the frequency distribution of blizzards is analyzed based on 708 records observed between 1978 and 2006. Fig. 9 shows the frequency of blizzards as a function of month. The outer vertical axis shows the number of blizzard occurrence per year and the inner vertical axis shows the number of blizzards for the entire period. It is clear that the blizzards frequently occur in the time period of late March through late October. An interesting feature is that the

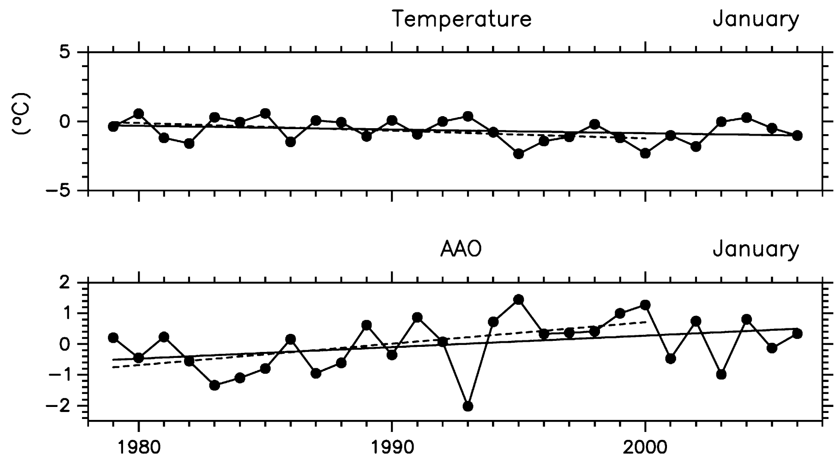

Fig. 8. Time series of temperature at Syowa Station and AAO index in January. Solid and dotted lines indicate trends in the time periods for 1979–2006 and 1979–2000, respectively.

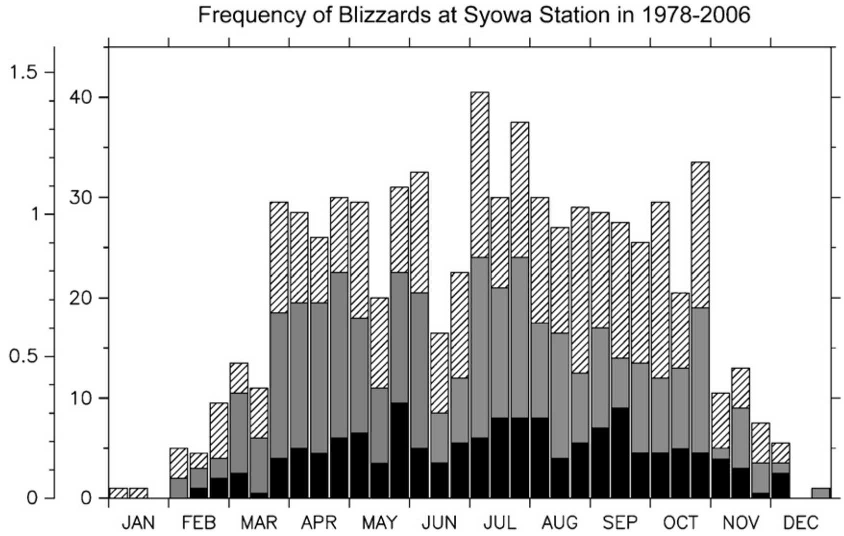

Fig. 9. Seasonal variation in the number of blizzards at Syowa Station based on 708 records in 1978−2006. The outer vertical axis shows the number per year and the inner vertical axis shows the total number in the 29 years for each 10 calendar days. Black, cross shaded and hatched bars show the number of class-A, class-B and class-C blizzards, respectively.

blizzards seem less frequent in midwinter (i.e., middle and late June).

Fig. 10 shows the frequency distribution of blizzard duration. Note that the intervals of duration shown on the horizontal axis are not constant. It is seen that stronger blizzards continue longer. The mean duration is 24.1 h for all blizzards, 31.5 h for blizzards stronger than class-B, and 38.1 h for class-A blizzards. The longest record is 135 h (5 days + 15 h) for a class-B blizzard that occurred in August of 1992, the second is 116 h (4 days + 20 h) for a class-A blizzard in May of 1992, and the third is 110 h (4 days + 14 h) for a class-B blizzard in October of 1978.

The blizzard duration is likely to be dependent upon the scale and shape of cyclones. For example, the longest blizzard in 2003, when one of the authors (K.S.) was at the base, started on 31 July and continued for 55 h was caused by two cyclones approaching Syowa Station without interruption.

A year-to-year variation for the number of blizzards is shown in Fig. 11, based on all records in the years of 1957−2006. Note that the year on the horizontal axis does not indicate a year starting in February as before but ‘‘a real year’’. Bottom labels on the horizontal axis show the order of JARE. The number of blizzards depends largely on the year. The minimum number of blizzards is nine in 1988 (JARE29) and the maximum is 42 in 1982 (JARE23). Generally, although there is no clear trend; it is worth noting that the blizzard is less frequent in the nine years from 1980 through 1988 except for 1982. The average numbers for class-A, class-B, class-C and total blizzards in a year are 5.4, 10.4, 9.2, and 25.1, respectively.

5. Discussion

In this section, possible physical mechanisms are discussed to explain several interesting statistical characteristics in the surface meteorology and blizzards

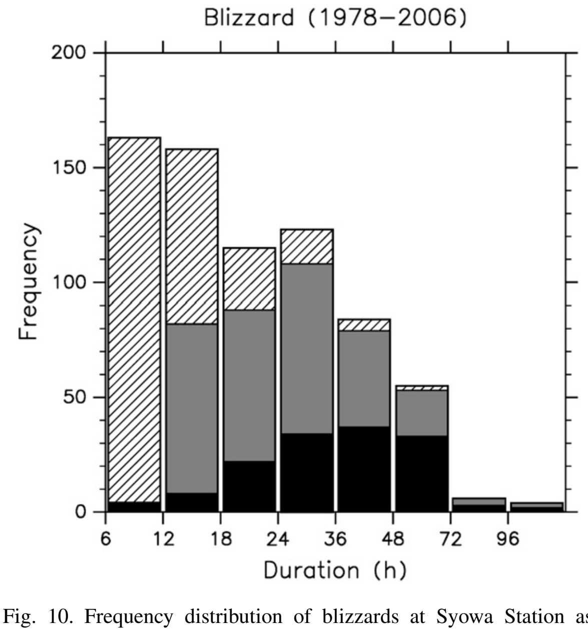

Fig. 10. Frequency distribution of blizzards at Syowa Station as a function of duration, based on the records for 1978−2006. Black, cross shaded, and hatched bars indicate the frequency of class-A, class-B, and class-C blizzards, respectively.

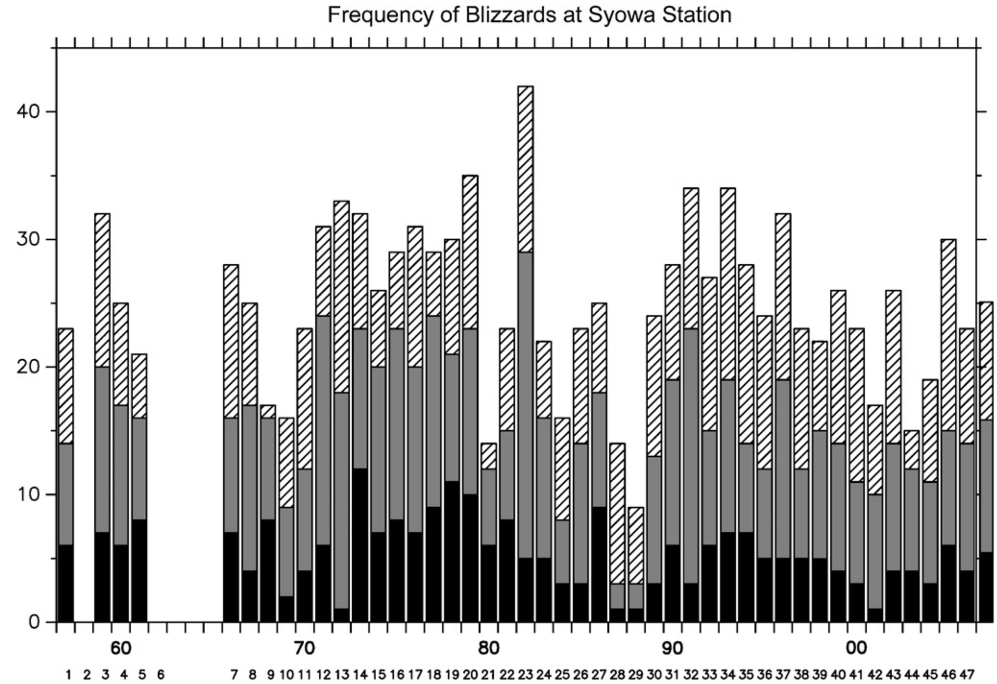

Fig. 11. The number of blizzards in each year at Syowa Station. Black, cross shaded, and hatched bars indicate class-A, class-B, and class-C blizzards, respectively. Upper and lower numerals on the horizontal axis indicate the year and the order of Japanese Antarctic Research Expedition, respectively. The bar on the right end shows the average for the years of 1957 through 2006.

shown in Sections 3 and 4. While some of these are based on speculation, we describe them because they may be of value to future research.

5.1. Possible mechanisms for seasonal variation in the sea level pressure

The low temperatures and marked annual variation in temperature are consistent with that observed for solar radiation. The stronger winds in winter can be explained by the strong radiative cooling on the surface in this season which is favorable for the development of katabatic winds. On the other hand, there are several explanations for the low mean value and dominance of semi-annual variation in the SLP. The low SLP values observed along the coast of the Antarctic are quite apparent. The difference in zonal mean SLP between the Antarctic and Arctic is approximately 20 hPa at the high latitudes of 60°−70° (e.g., Boer, 1992).

A possible mechanism to explain the low SLP is that cyclones propagating from the middle latitude region cannot enter the interior of the Antarctic continent because the continent has a high elevation and hence the cyclones must stop there (e.g., King and Turner, 1997). It may be more accurate to say that when the cyclones land on the continent, they become weakened because the depth of vortex tube decreases. It is important to note that the pressure itself is not a conserved quantity like potential vorticity. Thus, the advection of cyclones to the higher latitudes is not a strict explanation for the low pressure.

Another explanation is due to the katabatic wind effect. Katabatic winds blow on a continental scale in the Antarctic. In winter, the air just above the Antarctic continent is significantly cooled by outgoing radiation and it gets heavier. Since the Antarctic continent is dome-shaped, the downward flow (katabatic winds) blows outward from the interior of the continent. Thus, a significant amount of mass over the continent decreases due to this divergent wind, resulting in low pressure. This mechanism may explain why mean SLP is low only in the Antarctic and not in the Arctic.

The semi-annual variation observed in the SLP was examined comprehensively by a series of studies by van den Broeke (1998a,b, 2000). The latitudinal movement of the circumpolar trough causes semi-annual variation and the amplification of the wavenumber 3 structure in equinoctial seasons causes the dependence of the amplitude of semi-annual variation on location. Such latitudinal movement of the circumpolar trough may be related to the fact that latitudinal gradient of mean solar radiation is maximized during the equinoxes (e.g., Schwerdtfeger, 1984). The amplification of the wavenumber 3 may be due to the interaction of the circumpolar easterlies and topography because the phases are almost fixed.

Another challenging but attractive explanation is a tug of war between the divergent effect of katabatic winds, and the convergent effect due to the radiative cooling over the Antarctic continent (Parish and Bromwich, 1997). The air column that is radiatively cooled on the continent shrinks so as to keep the hydrostatic balance, causing the air in the surrounding region to move into the interior to maintain the geostrophic balance. These physical processes may not occur sequentially but proceed gradually and simultaneously, adjusting toward both of the hydrostatic and geostrophic balances. As a result, a high pressure region like Siberian high is formed in the lower atmosphere over the Antarctic continent. This effect, hereafter referred to as the hydrostatic effect, is considered to be dominant, particularly in the midwinter with no solar radiation. On the other hand, because of the dome shape of the Antarctic continent, the cold air moves downward, i.e., outward as katabatic winds. This process acts to form a low pressure region in the Antarctic as discussed above. The katabatic winds are strong in all seasons except summer (Fig. 4) in the Antarctic. Considering these two effects, the following scenario can be used to illustrate the semi-annual variation of the SLP. In winter, the SLP is high because the hydrostatic effect is stronger than the effect of katabatic winds. In summer, the hydrostatic effect is weak, but the SLP is high because the katabatic wind effect is much weaker. In spring and autumn, the SLP is low because the katabatic wind effect dominates the hydrostatic effect. However, quantitative examinations need to be made to determine how important katabatic wind effects are for the mass budget in the Antarctic.

Seasonal variations in baroclinic wave activity may also contribute to the dominance of semi-annual variation of the SLP. The observed baroclinic wave activity is strong in spring and autumn in the middle latitudes in the Southern Hemisphere (e.g., Trenberth, 1991; Sato et al., 2000), which may be related to a weak minimum of the blizzard frequency observed in midwinter in June (Fig. 9). Thus, the Brewer-Dobson circulation driven by the baroclinic wave disturbances may be strong in spring and autumn. The air mass transported by the Brewer-Dobson circulation in the stratosphere would accumulate in summer and winter in the Antarctic. Therefore, the seasonal variation in the baroclinic wave activity is in harmony with the observed seasonal variation of the SLP. However, Parish and Bromwich (1997) reported that this baroclinic wave effect is not sufficient to explain the observed seasonal variation in the SLP. It is also worth noting that the mechanism of the seasonal variation of baroclinic wave activity in the Southern Hemisphere is not yet completely understood.

5.2. Possible mechanisms for diurnal variation in summer

The wind speed shows a clear diurnal cycle with the maximum around 0600LT and the minimum around 1800LT in summer (Fig. 5). Such diurnal variation may be attributed to katabatic winds whose phases are fixed with the variation of solar radiation (Schwerdtfeger, 1984). The wind speed would be maximized a few hours after the temperature minimum (around 0300LT) because of the accumulation of the cold downward (katabatic) flow on the slope of the continent. The cold air from a more distant region would reach at a later time and then affected by the Coriolis force more significantly. This inference is consistent with the fact that the winds observed at a later time (around noon) have more northerly velocity components (Fig. 5).

The SLP is minimized around 1900–2000LT in summer. This minimum may be partly due to high temperatures in the afternoon and partly due to the divergence effect of katabatic winds which cease around 1800–1900LT. This scenario seems consistent with the observations that the diurnal variation of winds and temperature is not observed in winter and that the minimum SLP around 1900–2000LT is not clear in winter. Pettré et al. (1993) reported that solar heating in summer can produce a pressure gradient force comparable to the katabatic force with an opposite sign and shelter the coastal region from the katabatic winds. The thermal contrast between the ocean and continent depends on ice and snow cover conditions, though. A careful examination on this view point using numerical models is needed. In the diurnal variation of the SLP, there is another minimum around 0700–0800LT. This minimum is observed in any season and may be related to the atmospheric tides.

5.3. Meteorological conditions for blizzards

It seems that the year-to-year variation in the number of blizzards shown in Section 4 is not strongly related to that of meteorological parameters shown in Section 3.5. This is probably because the number of severe blizzards is not controlled by ''in situ'' annual mean meteorological conditions, but by the number of strong cyclones having time scales of several days coming from the lower latitude region. We analyzed synoptic-scale meteorological conditions using ECMWF operational data for 27 May 1996, when a class-A blizzard is observed with a record high gust wind of 61.2 m s^{-1} at Syowa Station. Fig. 12 shows a map of the geopotential height (in km) at the 925 hPa pressure level on the day. A strong cyclone is situated around 65°S to the northwest of Syowa Station, and it is clear that humid air is advected to Syowa Station by the northerly flow to the east of the cyclone. Such a synoptic situation, including a cyclone to the northwest, is likely to be commonly observed for the other severe blizzards.

On the other hand, a combination of two moderately strong cyclones is also important in the formation of severe blizzards. There were several cases in which a cyclone is situated to the northwest of Syowa Station and another one to the east at the same time. In such a situation, strong convection can develop in the convergent zone between a humid northerly flow associated with the former cyclone and a cold easterly flow with the latter one. The latter cyclone to the east is sometimes not resolved by operational analysis, but is clearly recognized in IR satellite pictures as in Fig. 13.

6. Summary and concluding remarks

We analyzed statistical characteristics of surface meteorology at Syowa Station (69°00′S, 39°35′E) based on hourly data of surface temperature, pressure and winds obtained by operational observations and blizzard

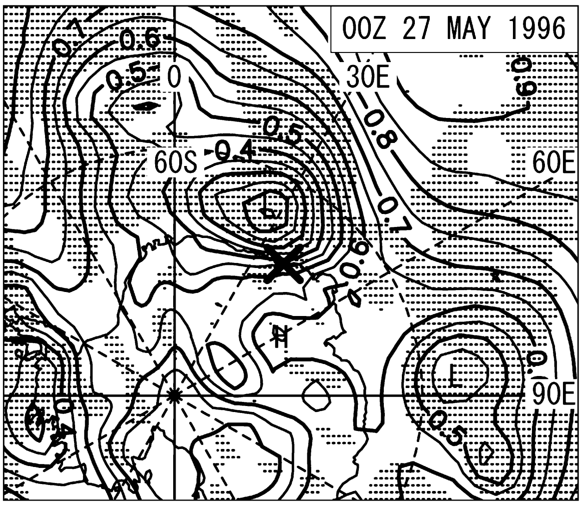

Fig. 12. A contour map of the geopotential height (in km) at 925 hPa when a class-A blizzard with a record high gust wind of 61.2 m s^{-1} occurred at Syowa Station (X) on 27 May 1996. A strong cyclone is situated around 65°S to the northwest of Syowa Station. Shaded are the regions with relative humidity greater than 80%.

records for 50 years from February 1957 through January 2007, except for 1958 and 1962–1965 for which data are missing. Although several characteristics documented in this paper have already been reported in previous studies, we described them in conjunction with new findings in order to establish a systematic understanding of trends and variations for time periods ranging from 2 h to 20 years. The results can be summarized as follows.

- The frequency distribution of temperature is far from the normal distribution, because the short-period variation is weak in summer. The mean values for temperature and wind speed for the entire time period of 45 years are −10.5 °C and 6.6 m s^{-1}, respectively. The surface wind is mostly northeasterly with high directional constancy of 0.78.
- The frequency spectra estimated for the a wide range of 2 h to 20 years have a characteristic shape which is proportional to a power of frequency with a transition period of several days for any parameter. Dominant peaks at the annual and diurnal frequencies and their higher harmonics are also clearly seen. A signal of solar cycle of 11 years was not detected.
- Semi-diurnal and semi-annual variations are markedly apparent for the SLP, while diurnal and annual variations are clear for temperature and winds. All meteorological parameters show characteristic diurnal variations in summer, although they do not vary largely in winter except for the SLP.
- Although positive and negative trends are observed for surface temperatures and pressures, respectively, they are not statistically significant because of large year-to-year variation. A statistically significant positive trend is observed for the wind speed, which is 0.23 m s^{-1} per decade. The interannual variation of the SLP is highly correlated with the AAO index.
- The number of blizzards is large in the time period from late March to late October. A weak minimum is observed in June.
- The duration is longer for more severe blizzards. The mean blizzard duration is 24.1 h for all blizzards, 31.5 h for class-A and class-B blizzards, and 38.1 h for class-A blizzards.
- The number of blizzards is largely dependent on the year. The mean numbers for class-A, class-B, class-C and total number of blizzards in a year are 5.4, 10.4, 9.2, and 25.1, respectively.

Among the statistical characteristics that were analyzed in a systematic manner in the present study, we

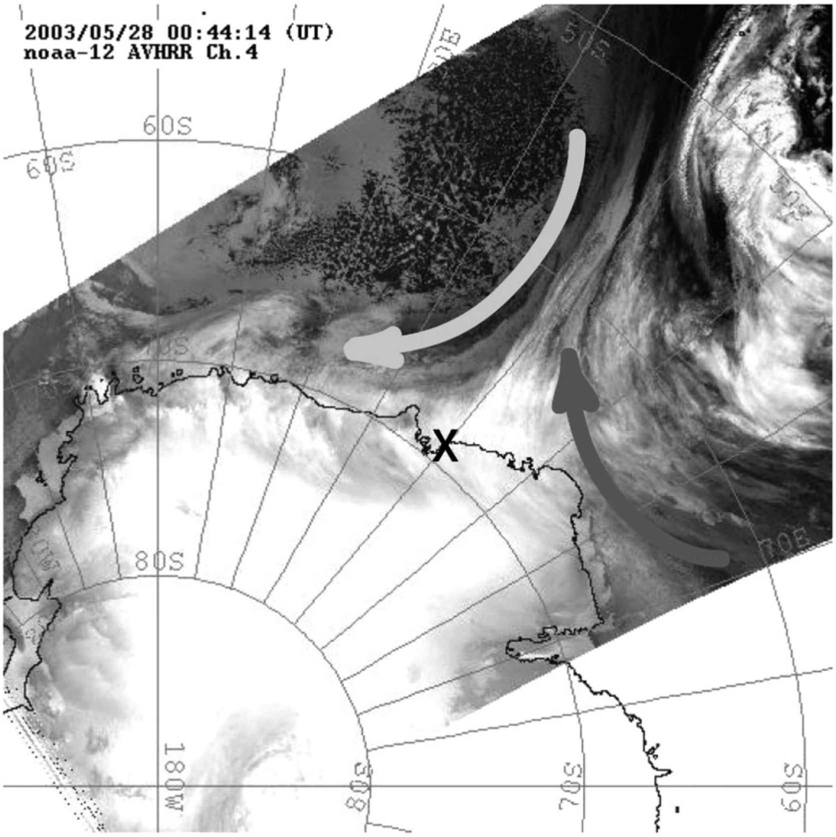

Fig. 13. An infrared satellite picture (NOAA-12) taken on 28 May 2003 when a class-A blizzard was observed at Syowa Station (X). The cyclone to the west of Syowa Station, whose flow is shown schematically by a light gray arrow, is analyzed by operational global data, but the cyclone to the east whose flow is shown by a dark gray arrow is not.

obtained several new and important findings. One is the spectral characteristic in a wide range of frequency covering 2 h and 20 years. There are few studies that have reported the spectra for meteorological parameters over such a wide frequency range, even for low and middle latitude regions where the meteorological records are much longer. It would be quite interesting to examine the difference in the spectral shape among various regions.

Another new finding is a characteristic diurnal variation in the SLP. The variation has weak amplitudes but could be detected with the aid of the very long time series used in the present study. The diurnal variation of the SLP as well as those of temperature and winds was discussed in terms of katabatic winds. It was also suggested that the katabatic wind effect as well as hydrostatic effect may partly explain the seasonal variation in SLP. It is necessary to confirm these scenarios using numerical models.

The high correlation of the SLP at Syowa Station with the AAO index indicates that Syowa Station can be regarded as a typical Antarctic station. It was shown that the positive trend of temperature is not statistically significant and that this is due to its large inter-annual variation. Thus, it is important to continue the operational observations of the surface meteorology at Syowa Station, so as to obtain longer time series as this will allow us to detect climate change. It is also interesting to examine the cause of the statistically significant positive trend detected in the wind speed. The positive trend may be related to a negative trend of the SLP, because both trends are statistically significant in the months of February, April and May.

The detailed mechanisms underlying the formation of severe blizzards are not yet well understood and form one of the interesting topics for future polar research. According to our analysis, the relationship between blizzard occurrence and the surface meteorology was not clear at inter-annual and seasonal time scales. This is partly because the criteria of blizzards are based on information that is closely related to human life, such as visibility. Visibility depends on snow blowing up into the atmosphere from the ground as well as falling snow (i.e., precipitation). Thus, this parameter may not be an appropriate index for examining the snow storm "physics", and it is important to use more appropriate parameters for the purpose of atmospheric research.

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References

Boer, G.J., 1992. Some results from and an intercomparison of the climates simulated by 14 atmospheric general circulation models. J. Geophys. Res. 97, 12771−12786.

van den Broeke, 1998a. The semiannual oscillation and Antarctic climate. Part 1: influence on near-surface temperatures (1957−79). Antarct. Sci. 10, 175−183.

van den Broeke, 1998b. The semiannual oscillation and Antarctic climate. Part 2: recent changes. Antarct. Sci. 10, 184−191.

van den Broeke, 2000. The semiannual oscillation and Antarctic climate. Part 5: impact on the annual temperature cycle as derived from NCEP/NCAR re-analysis. Clim. Dyn. 16, 369−377.

Gallée, H., Pettré, P., 1998. Dynamical constraints on katabatic wind cessation in Adélie Land, Antarctica. J. Atmos. Sci. 55, 1755−1770.

IPCC, 2001. Climate change 2001: the scientific basis. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, p. 881.

Jacka, T.H., Budd, W.F., 1998. Detection of temperatures and sea-ice-extent changes in the Antarctic and Southern Ocean, 1949−96. Ann. Glaciol. 27, 553−559.

Japan Meteorological Agency, 1989. Thirty Year History of Antarctic Meteorological Observation, 384 pp (in Japanese).

Jones, P.D., 1995. Recent variations in mean temperature and the diurnal temperature range in the Antarctic. Geophys. Res. Lett. 22, 1345−1348.

Japanese Antarctic Research Expedition. Report of the 1st (to 18th) Japanese Antarctic Research Expedition (1957−1978). National Institute of Polar Research (in Japanese).

King, J.C., Turner, J., 1997. Antarctic Meteorology and Climatology. Cambridge Univ. Press, 409 pp.

Kodama, Y., Wendler, G., Ishikawa, N., 1989. The diurnal variation of the boundary layer in summer in Adelie Land, Eastern Antarctica. J. Appl. Meteorol. 28, 16−24.

Konig-Langlo, G., King, J.C., Pettre, P., 1998. Climatology of the three coastal Antarctic stations Dumont d'Urville, Neumayer, and Halley. J. Geophys. Res. 103, 10935−10946.

van Loon, H., 1972. Temperature, pressure, and wind in the Southern Hemisphere. In: Newton, C.W. (Ed.), Meteorology of the Southern Hemisphere. Meteorological Monographs, vol. 18. American Meteorol. Soc., Boston, 35, pp. 25−100.

Ohata, T., Kobayashi, S., Ishikawa, N., Kawaguchi, S., 1985. Structure of the katabatic winds at Mizuho Station, East Antarctica. J. Geophys. Res. 90, 10651−10658.

Parish, T.R., Bromwich, D.H., 1997. On the forcing of seasonal changes in surface pressure over Antarctica. J. Geophys. Res. 102, 13785−13792.

Parish, T.R., Pettré, P., Wendler, G., 1993. A numerical study of the diurnal variation of the Adelie Land katabatic wind regime. J. Geophys. Res. 98, 12933−12948.

Pettré, P., Payan, C., Parish, T.R., 1993. Interaction of katabatic flow with local thermal effects in a coastal region of Adelie Land, East Antarctica. J. Geophys. Res. 98, 10429−10440.

Sato, K., Yamada, K., Hirota, I., 2000. Global characteristics of medium-scale tropopausal waves observed in ECMWF operational data. Mon. Weather Rev. 128, 3808−3823.

Schwerdtfeger, W., 1984. Weather and Climate of the Antarctic. Elsevier, New York, 261 pp.

Streten, N.A., 1990. A review of the climate of Mawson − a representative strong wind site in East Antarctica. Antarct. Sci. 2, 79−89.

Thompson, D.W.J., Solomon, S., 2002. Interpretation of recent Southern Hemisphere climate change. Science 296, 895−899.

Thompson, D.W.J., Wallace, J.M., 2000. Annular modes in the extratropical circulation. Part I: month-to-month variability. J. Clim. 13, 1000−1016.

Trenberth, K.E., 1991. Storm tracks in the Southern Hemisphere. J. Atmos. Sci. 48, 2159−2178.

Turner, J., Colwell, S.R., Marshall, G.J., Lachlan-Cope, T.A., Carleton, A.M., Jones, P.D., Lagun, V., Reid, P.A., Iagovkina, S., 2005. Antarctic climate change during the last 50 years. Int. J. Climatol. 25, 279−294.

White, W.B., Peterson, R., 1996. An Antarctic circumpolar wave in surface pressure, wind, temperature, and sea ice extent. Nature 380, 699−702.

Yasunari, T., Kodama, S., 1993. Intraseasonal variability of katabatic wind over East Antarctica and planetary flow regime in the Southern Hemisphere. J. Geophys. Res. 98, 13063−13070.