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Fifty-year Amundsen–Scott South Pole station surface climatology

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ABSTRACT

Fifty-four years of Amundsen–Scott South Pole Station meteorological data have been analyzed to develop a comprehensive climatology from the station's meteorological observations. In reaching the goal of a full climatological analysis, a meteorological station history was required and a full quality control review of the data was conducted. Analysis of the general fifty-year climate is presented for temperature, pressure, wind speed and wind direction along with averages (means), extremes and records, daily ranges, trends and discontinuities. Additional investigations include how often the temperature reaches −100 °F and changes in the flying season as seen via acceptable temperatures. The analysis found slight decreases in the temperature and pressure over the 1957–2010 time period that are not statistically significant. The wind speed, however, does show a significant downward trend of 0.28 m s^{-1} decade^{-1} over the same period. The seasonal time series of temperature and pressure illustrate how longer term oscillations are superimposed on shorter-term fluctuations. The seasonal mean wind speed over the 54 year period shows a consistent pattern of decreasing speed for all seasons. In contrast to the mean wind speeds, the maximum wind speeds are increasing for the summer and transition seasons, and the increases are statistically significant. Finally, for the period 1983–2010, the average annual snow accumulation is decreasing at a statistically significant downward rate of −2.9 mm year^{-1}.

Contents

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1. Introduction

The characteristics of the weather and climate of Antarctica continue to elicit a great deal of interest (e.g. Warren, 1996; Warren and Town, 2011). Surface trends of temperature and precipitation are becoming more critical as the fate of the ice shelves in a warmer climate is examined. The paucity of surface based observations led researchers to use a variety of techniques to expand the available information to cover the entire continent. Comiso (2000) studied surface temperatures constructed from satellite thermal infrared observations, and Schneider et al. (2004) examined climate variability by constructing surface temperatures from satellite thermal infrared observations and passive microwave brightness temperatures. Reconstructions of surface temperature from statistical techniques that combine satellite and surface observations (Steig et al., 2009; O'Donnell et al., 2011) have also been performed. Model analyses combined with surface observations such as Monaghan et al. (2008) are another means used to study continent wide variability.

Amundsen–Scott South Pole Station (here after referred to as South Pole or SP), in particular, has been a destination for exploration since the early part of the twentieth century. The 100th anniversary of the Amundsen and Scott expeditions was commemorated in December 2011. Forty-five years after those original visits, a research station was established, and continuous weather observations commenced at the geographic South Pole. The South Pole area is unique in that it does not have a diurnal cycle in the summer, unlike some of the High Polar Plateau automatic weather stations such as Dome C (II), Dome Fuji, and Panda-South. It is also located in an area of extreme surface temperature inversions which can be as large as 20–25 °C in the winter (Connolley, 1996). As the years of record have accumulated, several studies of conditions at the South Pole have been undertaken. Turner et al., 2005 examined the changes in near surface temperature, pressure and wind speed for a 50-year period over Antarctica. While most of the stations they examined were along the coast, South Pole and Vostok were included to represent the interior of the continent. Trenberth and Olson (1989) investigated the annual cycle of temperature and the 30-year trends for South Pole and McMurdo, and trends at South Pole for surface wind speed and temperature were explored by Neff (1999).

This report examines the surface parameters measured at South Pole Station since its inception. The focus is on an updated climatology for the station and an analysis of changes or trends over the period of record. In the study of the climate of a particular station, one of the most important aspects is the timeline of station changes such as different instruments or locations (see Fig. 1) that may impact the information in the observations. A station history of the South Pole, focusing on meteorological instrumentation, follows. Additionally, the types of errors, which can occur in data sets that are not collected as part of a specific climate oriented study, are detailed.

2. Station history

2.1. 1950s

South Pole Station was established by the United States (US) Navy in the austral summer of 1956–1957. The first aircraft landing this season was the famous US Navy R4D aircraft named “Que Sera Sera”. It arrived to a surface temperature of −50 °C/−58 °F. During the construction of the station, Dr. Paul Siple, science leader of the first winter crew, recorded weather observations until the Weather Bureau meteorologists, Edwin Flowers and John Guerrero, set up a U.S. Weather Bureau meteorological station (Siple, 1959). The initial set of instrumentation installed in January of 1957 included Kollsman aneroid barometers, a Bendix–Friez barograph, and an approximate 3-meter (10-foot) aerovane wind system. The wind system was raised to 10 m by March of 1957, and a “thermohm” resistance thermometer was installed. Additional resistance thermometers were installed the following month, at different heights along the 10-meter tower as well as in the surface snow. This productive year for meteorological instrumentation at the Pole also saw the installation of a set of radiometers and two precipitation gauges. Unfortunately, the radiation measurements lasted only a few years. The first research snow stake field to measure net annual snow accumulation was established at South Pole in 1958. The array was a 42-pole pentagon established 3 km upwind of the station. Data were intermittently collected here until 1964. The measurement of precipitation very quickly led to the realization of how significant an impact blowing and drifting had on the observations. In November 1958, standard liquid-in-glass thermometers were installed. These were removed by January of 1960 and replaced with aspirated thermohms.

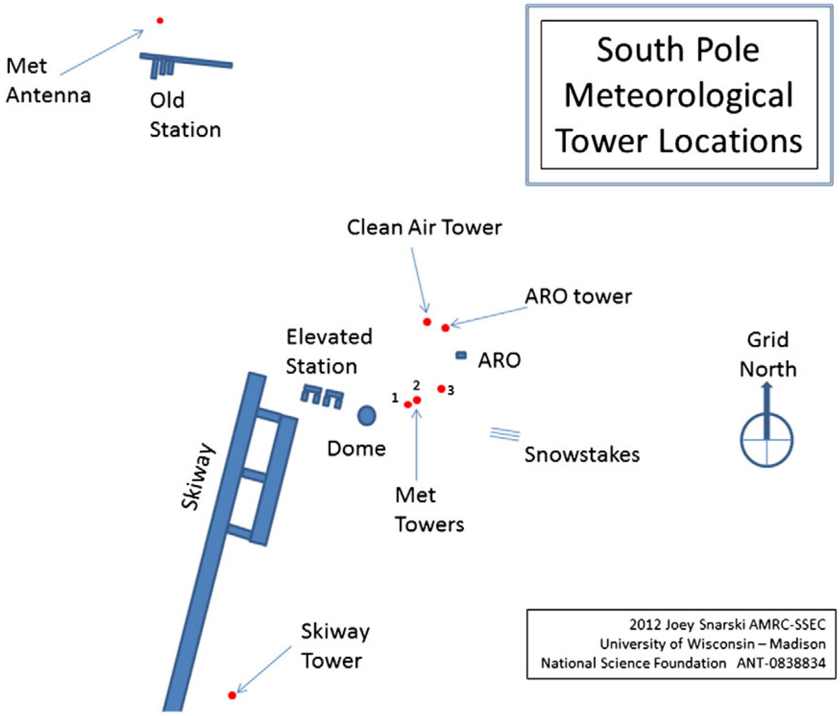

Fig. 1. Locations of the historical and current stations and meteorological towers. The original meteorology tower (Met Antenna) location (1957–1975) is to the grid north of the Old Station. Meteorological (Met) Towers 1, 2, and 3 were used when observations were taken at the Dome (1975–2005). The Clean Air Tower and Skiway Tower are where observations have been recorded from 2005 to the present.

During this same time period, a radiosonde system was installed with the first launch of weather balloons occurring on 27 March 1957, and twice daily launches were made by 15 April 1957. By 22 June 1957, a pilot balloon sounding system was installed, and two piball measurements per day were taken, commencing in October 1957.

2.2. 1960s

In September/October of 1960, 8 new radiometers were installed to replace the two initial systems; however, all but one was removed by December 1962. Another research snow stake network shaped like a cross with arms oriented along grids 30, 120, 210, and 300° was established in 1962. Each arm was 11 km long with 35 poles. This network was only measured once (in 1970) and gave an 8 year accumulation total. By August 1963, the station did have aspirated psychrometers installed, but temperatures were too low to make reliable relative humidity (RH) measurements. This month also saw the removal of precipitation gauges and establishment of an official snow stake field, consisting of 50 stakes, ten feet apart. Visibility markers were installed out to 1.6 km (1 mi). The first installation of a Campbell–Stokes sunshine recorder was accomplished in September of 1964, along with a new radiometer. The late 1960s saw the continued maintenance of the instrumentation at Pole, with the installation of a new aspirated thermohm thermometer mounted 1.2 m (4 ft) above the surface on the same mast as the wind measurements. For upper air measurements, piballs were discontinued during this period, and radiometersondes were launched every third day from March to September 1963.

2.3. 1970s

The early 1970s were focused on building the new Dome facility. The 1970s brought changes in the management of South Pole Meteorology Office. The original South Pole Station was closed in February 1975, as operations were moved to a new station under a geodesic dome. On 1 November 1975, the New Zealand Weather Service took over for the US Weather Bureau. A Honeywell mini-computer was added in 1973, and a Hewlett-Packard mainframe computer was installed in 1976 — the first use of a computer system at the station for meteorological data coding, reduction and transmission of observations as well as record keeping. Changes occurred again in 1978, with the NSF contractor Holmes and Narver with some support from the Navy Weather section at McMurdo Station and Pt. Mugu, California, assuming responsibility for South Pole meteorology operations. This also marks the beginning of the model currently employed at South Pole, where the operational observing program is run by the National Science Foundation (NSF) United States Antarctic Program (USAP) contractor, and all instrumentation is acquired, calibrated, maintained, and installed by the US Navy support or today Space and Naval Warfare Systems Command (SPAWAR). In 1978, Ohio State researchers set up two snow accumulation lines along grid 130 and 178°, which were 5 km long and had 11–12 poles. The line along 178° was buried after 4 years, but the line along 130° was recovered and measured annually or semiannually from 1985 to 1990. In 1979, the Rosemount temperature probe was in use with an Esterline Angus recording chart, along with a Bell and Howell digital barometer. A much-needed new radiosonde system was also installed.

2.4. 1980s

Complete backup equipment was installed at the station in 1982, including a Belfort microbarograph, an additional Rosemount temperature probe, and an aerovane wind system. Wind systems were changed out for new instruments in 1984. This marks the start of known routine calibration and reconditioning efforts with all instrumentation at the station. In 1986, the University of Wisconsin installed an automatic weather station. Also, two Omega temperature probes were installed along with a platinum resistance temperature detector (RTD) probe to run concurrently with the existing Rosemount/Esterline Angus systems. The computer systems were continually updated starting with the installation of a DEC PDP/11 in 1984 and a VAX computer in 1987. The end of the 1980s decade marked the installation of a new upper air system.

2.5. 1990s

The start of the 1990s decade saw the installation of a model 453X Princo mercurial barometer that was used to check the existing barometric measurement system at the station. In the 1991–1992 field season, the temperature probes were raised to two meters and aspirated. Table 1 outlines the instrumentation cataloged in the 1991–1992 season and the changes that were made by 1999. In 1992 the Ohio State researchers installed a six-line snow stake array centered on the station with each arm 20 km long. The entire array contained 235 poles installed in the six grid directions at 45, 110, 170, 230, 290, and 350° (see Mosley-Thompson et al. (1995, 1999) for more details on the snow accumulation networks and research results). By 1991/1992, a modern PC weather system was installed beginning the modern PC/Macintosh or workstation-level computing capability that South Pole continues to have today. Through the 1990s, ceilometers were problematic, with the Qualimetrics instrument working intermittently during the 1993 and 1994 seasons. A new ceilometer was installed in 1995, but was removed in 1997 for maintenance and was unable to be made operational again. The end of the decade saw the installation of the fourth radiosonde upperair system — a Vaisala MARWIND MW12 portable system, with a full replacement completed by August, 2001.

Table 1
The equipment list for South Pole Station in use by South Pole Meteorology Office for the 1991–1992 field season.

Sensor/equipment	1991/1992 instrumentation	1999 instrumentation
Temperature (at 2 m)	• Two Omega temperature probes • Platinum RTD probe • Rosemount/Esterline Angus system	• Omega display (model DP41-RTD) with Omega temperature probe
Pressure	• Kollsman aneroid barometer and altimeter setting indicator • Princo mercurial barometer • Belfort microbarograph • Two Omega pressure sensors	• Setra 270 Pressure sensor
Wind (at 10 m)	• UMQ-5 with chart recorder • Two RM Young 05103	• M-Tek model 2802 chart • RM Young Wind Tracker 06201
Ceilometer	• Qualimetrics model 8329-A	• Not installed
Datalogger	• Omega OM-272 (the "Watcher" system), updated every minute	• Handar 555 datalogger with inputs to a PC computer with Analog to Digital input card.

2.6. 2000s

Visibility markers were installed in December of 2001 at azimuths of 350, 110 and 270 (grid) degrees, replacing the existing single line at 280°. The new 1.2 by 2.4 meter (4 by 8 ft) sheets of plywood were painted black to be more easily seen by observers. In November of 2002, these markers were improved with 2.4 by 2.4 meter (8 by 8 ft) plywood. The markers along the skiway were installed at 1.6, 2.4, 4.8, and 6.4 km (1, 1.5, 2, 3, and 4 mi) out from the standard observing location. In March, 2003, the new South Pole elevated station was occupied. For the 2003–2004 field season, a new meteorological suite of instruments (Coastal Engineering Systems FMQ-19) was installed in the vicinity of the new elevated station, and a full year of side by side testing on the old and new instrument towers was performed (Keller et al., 2009). This new system included optical visibility, ambient light meters, and a ceilometer deployed at the skiway tower during the austral summer only. Wind speed and direction are reported from the skiway tower. Temperature, pressure, wind speed and wind direction are recorded at the instrument tower (called the Clean Air tower) near the new station, but only temperature and pressure are reported. This system became the primary observing system as of February 2005. Fig. 1 depicts the locations of the historical and current stations and meteorological towers. A National Aeronautics and Space Administration (NASA) LIDAR system was installed in the 2001–2002 field season and was used in the following winter for cloud detection and determination. A ceilometer was tested and failed in the 2002–2003 field season. The 2000s saw the installation of a Vaisala DigiCORA III MW21 radiosonde/upper air system. Also, transmission of meteorological data to the Global Telecommunication System (GTS) was changed from an Aeronautical Fixed Telecommunications Network (AFTN) relay via McMurdo Station to an Iridium multi-channel system transmission via e-mail directly to the National Oceanic and Atmospheric Administration (NOAA) gateway to the GTS.

3. Data, corrections, and methods

The data for this study come from the station records at South Pole. As the station history shows, several different agencies have been responsible for meteorological observations at South Pole Station. For some groups, the main focus was on providing observations for aviation operations. The meteorological records were sent to the National Climatic Data Center (NCDC) as well as maintained on station which proved invaluable when tracing and correcting problems that were uncovered during this project's data analysis.

A primary issue uncovered during this project was that the observation time was recorded in Coordinated Universal Time (UTC) for some years and New Zealand Standard Time (NZST) for others. Data records were analyzed by matching daily means calculated from synoptic observations with means reported in the Local Climate Data (LCD) in order to standardize the reporting time for the entire climate record. Data from NCDC were noted as being in UTC. Analysis revealed that this was correct for January 1957 through December 1958. Starting in 1959, the data were "converted to UTC", but as the observations were already in UTC, the times became 12 h offset. This offset continued through 9 December 1968. After that time, the observations were taken in NZST which meant that the conversion to UTC was correct, and no offset was found. After 1985, observations were recorded in UTC except for the years 1994–1996, which were again reported in NZST.

The next major correction involved the calculation of the daily mean temperatures. Originally, the daily means for the LCDs were calculated as the maximum plus the minimum divided by 2. While this is often an acceptable method in the mid-latitudes, it is not appropriate at the South Pole (and other Antarctic stations) where diurnal cycles are generally absent. It was decided to recalculate the means using the full number of daily observations. The observation day starts with the first observation after 0000 UTC (i.e. 0100 or 0300 or 0600 depending on the number of observation times). The number of observations in a day can vary from 4 to 24 with 24 being the standard since 1988. With the exception of September 1957 to February 1961 and February 1973 to January 1974 which had 24 observations per day, there were 8 observations per day from November through January or February and four observations per day for March through October.

Although the means were recalculated, it was not possible to determine the actual time of the maximum and minimum values for the variables reported for the early years. The decision was made to leave the reported values as they were found on the original LCDs. The final modification to the data involved correcting the obvious transcription errors in the digital observation data set. After all the corrections and modifications were made, the entire set of LCDs was reprocessed and sent to both NCDC and AMRC with a copy remaining at South Pole Station. For this study, the data from February 1957 through January 2011 will be used. This extensive time period allows for three different 30-year climatology sets (World Meteorological Organization (WMO) standard) to be calculated as well as a 50-year long-term climatology.

Once the data were corrected, the daily means were recalculated from the observations available for each day. Daily means were calculated for temperature, pressure, and wind speed. Daily resultant (vector) winds were calculated from the observed wind speed and direction. All mean wind speeds and resultant wind speeds have been converted from knots or miles per hour to meters per second. In addition, the daily extremes (maximum and minimum) for temperature and the monthly extremes for temperature, pressure and wind speed were extracted from the LCD reports.

Other South Pole data sets are available. For example, the British Antarctic Service (BAS) maintains a South Pole monthly mean data set as part of the Reference Antarctic Data for Environmental Research (READER) project (Turner et al., 2004). The BAS is collaborating with the AMRC to update their data holdings to include the corrections to the data that were found during this study. The NOAA Global Monitoring Division (GMD) maintains a separate observing system at the Atmospheric Research Observatory (ARO) located 500 m east-northeast of the new South Pole station. The ARO dataset begins in 1977 and has been compared with the South Pole Meteorological Office data set during the overlapping period. A 30-year climatology (1981–2010) of the ARO data was created for comparison with the SP climatology for that period. The variability and trends of the various time series are quite similar, especially in the later years, but the magnitudes are somewhat different. The ARO pressure is approximately 1.5 hPa lower than the SP pressure, but the ARO pressure is not corrected for elevation whereas the SP data are. The temperatures are less than 1 °C different in the 30 year mean but can be up to 3–4 °C different for monthly means, especially during the early 1980s when there are only 4–8 observations per day from the South Pole Meteorology Office. Winds speeds are within about 0.5 m s^{-2} in the mean with the ARO speeds slightly higher than the SP wind speeds even though both are measured at 10 m, but this difference is within the accuracy of the instruments.

Given the shorter time records for the ARO data, only the South Pole Meteorology Office data set was used to calculate the monthly means, seasonal means, annual means, three sets of 30 year climatological means (1961–1990, 1971–2000, and 1981–2010) and a 50-year climatological mean (1957–2006). The thirty year means are calculated to conform with the standards set by the WMO, but they are not always the most suitable way of describing a changing climate (Arguez and Voss, 2011; Livesey et al., 2007); hence, other methods of examining the climate at the South Pole are explored here. Means were also calculated for the daily extremes of temperature, pressure, and maximum wind speed.

It was intended that the 50-year climatological mean would be a good proxy to use to calculate anomalies, but that proved not to be the case due to the high variability of the daily means during the winter. Various methods for smoothing and filtering were tested, and the best representation of the overall pattern for the year came from generating the fourth harmonic of the observed daily mean data (Trenberth and Olson, 1989). The fourth harmonic curve also highlights the coreless winter aspect of the temperature (von Hann, 1909; Schwerdtfeger, 1970), as well as the differences between early and late winter for the temperature, pressure and wind speed (e.g., Fig. 2). This led to a redefinition of the seasons from four to five: December and January constitute summer; February–March and October–November are the fall and spring transition seasons, respectively; April–June are considered early winter; and July–September comprise late winter. These definitions will be used throughout the rest of the paper.

4. Results

4.1. 50 and 30 year climatology

4.1.1. Temperature

The 50-year climatology for daily mean temperatures and fourth harmonic fit to the data are shown in Fig. 2. The mean temperatures vary from the middle −20s °C in the summer

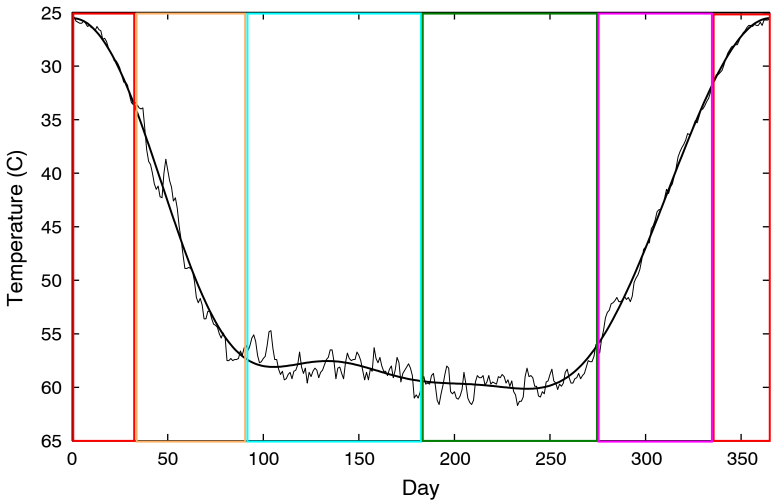

Fig. 2. Daily mean temperatures for 50-year climatology (1957–2006) (thin solid line) and fourth harmonic fit to the data (thick solid line). Season definition: summer (red box), autumn (gold box), early winter (cyan box), late winter (green box), spring (magenta box).

to around −60 °C in the winter. The extreme maximum and minimum temperatures, shown in Fig. 3, can be as much as 15–20° different from the mean in the winter, but only about 5–10° different in the summer. Fig. 3 also shows that the highest extreme temperatures occur in December. As this paper was being prepared, a new temperature maximum of −12.3 °C was set on 26 December 2011 breaking the old record of −13.6 °C set on 27 December 1978. The minimum temperature record at South Pole station is −82.8 °C on 23 June 1982. The average annual temperature is −49.4 °C. The extreme maximum temperatures average in the middle to lower −30s °C while the extreme minimum temperatures for most of the winter are below −73.3 °C (−100 °F). Even though the South Pole can see wide variations in temperatures, the actual daily temperature ranges are much smaller. The mean daily temperature range (Fig. 4) is around 3° in the summer, increasing to 8–9° in the winter. The larger temperature range in the winter again points out the greater degree of variability in that season. The variability of the temperature in winter can be caused by clouds and/or the horizontal advection of air by synoptic systems that penetrate into the interior or by a change in wind speed which mixes the inversion layer (Stone and Kahl, 1991).

As 50 years is not the standard WMO climatological period, 30-year mean daily climatology sets were calculated for the three periods spanning the data record. If there were no trends over the 50 years of data, the climatologies would not be significantly different from each other in the statistical sense, and the 50-year mean daily climatology could be used as a proxy for the shorter climatologies. Using the nonparametric Wilcoxon signed rank test, the 1961–1990 and 1971–2000 daily climatology sets are significantly different from the 1957–2006 climatology at the 5% level. In addition, the 1961–1990 climatology is significantly different from the 1971–2000 and

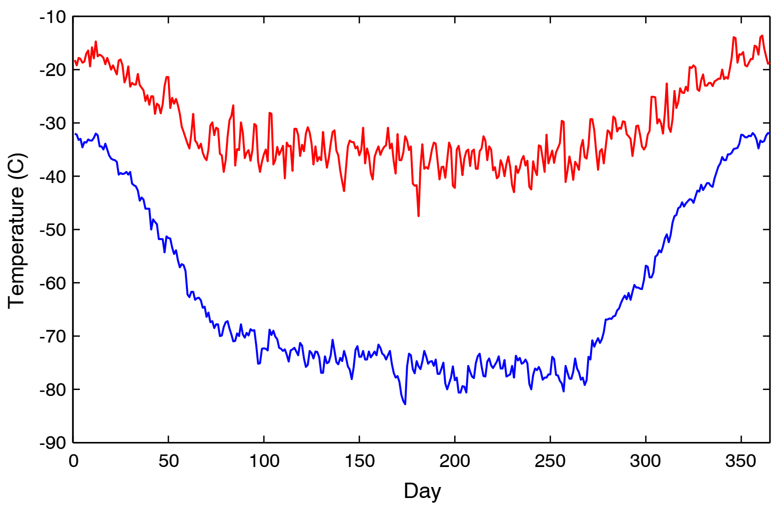

Fig. 3. Daily extreme maximum (red) and minimum (blue) temperatures for the 50-year climatology (1957–2006).

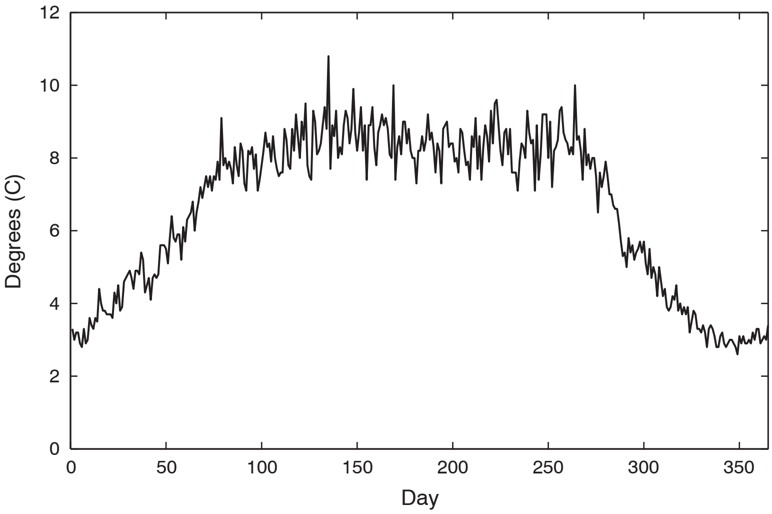

Fig. 4. Mean daily temperature range for the 50-year climatology (1957–2006).

1981–2010 climatologies (Fig. 5). This indicates that the data has a trend or a periodic signal, and decadal time scales may be more appropriate.

Fifty-four years of annual mean temperatures are shown in Fig. 6. The mean annual temperature is −49.3 °C ± 0.7 °C. A trend line fitted using the linear least squares method has a slope of −0.058 ± 0.96 °C decade^{-1} which is not significant at the 5% level. Monaghan et al. (2008) estimated +1.0 °C decade^{-1} trend for 1992–2005 for the South Pole, Turner et al. (2005) estimated −0.17 °C ± 0.21 decade^{-1} for 1958–2000, and the reconstruction by Steig et al. (2009) showed a trend of −0.1 °C decade^{-1} for 1957–2006. The year to year variations in annual temperatures indicate a possible quasi-biennial influence (Trenberth and Olson, 1989). Since half of the year is winter (early and late combined), the variability in winter will have a greater effect on the annual mean temperature than any of the other seasons. A ten-year running mean is also shown in Fig. 6 to highlight the decadal variability. Due to the obvious increase in variability after the early 1980s in Fig. 6, a Student's t-test was performed on the time series to check for equal means. The time series was split into two equal partitions using years 1957–1982 and 1983–2008 for the test, and the means were significantly different at the 5% level (the variances were not assumed to be equal). An F-test was performed on the variances using the same two periods, and it showed the variances were also significantly different at the 5% level.

There are several possibilities which could explain the change in variance. There was a significant change in the climate of the North Pacific in 1976–1977 (e.g., Trenberth, 1990) that may be linked to an increase in the Southern Hemisphere variability. From the early 1980s on, there has been increased variability and delay in the time of the polar

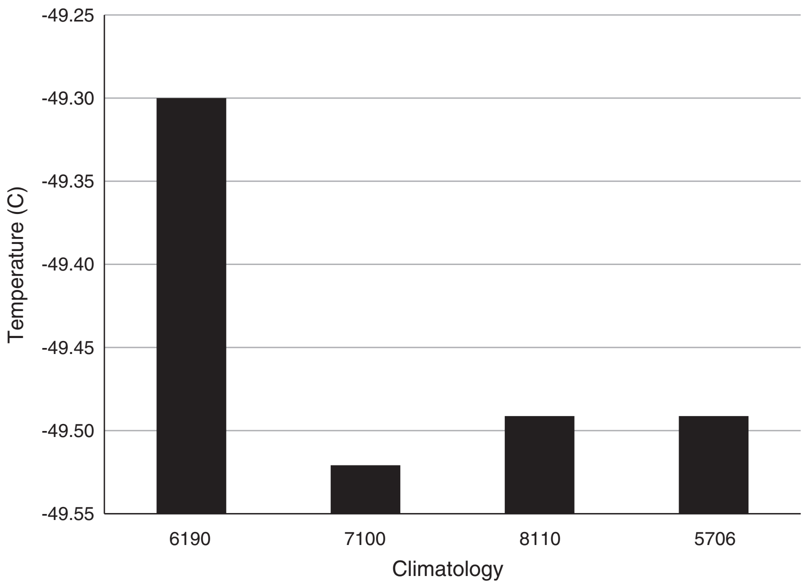

Fig. 5. Mean temperature for the 30-year climatology sets (1961–1990, 1971–2000, and 1981–2010) and for the 50-year climatology (1957–2006).

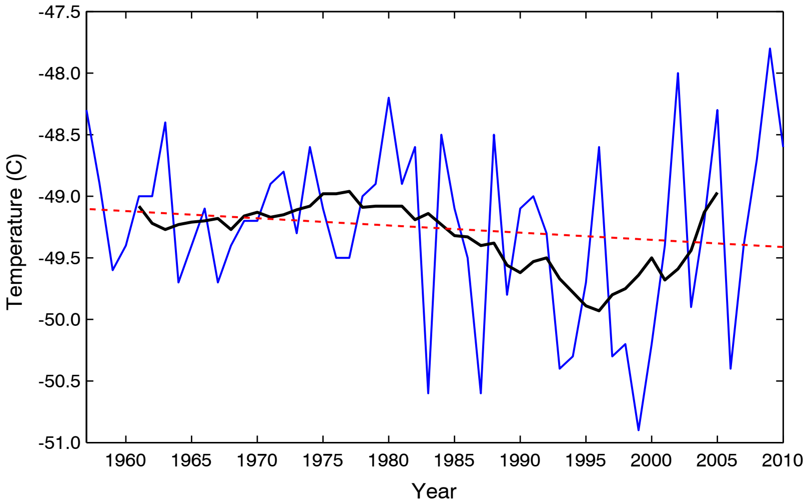

Fig. 6. Annual mean temperatures for 1957–2010 (blue), 10 year running mean (black), and least squares linear regression line (dashed, $r^2 = 0.017$).

vortex breakup in the spring, possibly due to ozone depletion events as well as changes in the planetary wave geometry and downward wave coupling (Neff, 1999; Harnik et al., 2011). However, a study by Neff et al. (2008) found no signal in the South Pole geopotential heights related to ozone depletion. The time of the final stratospheric warming (another indication of the polar vortex breakup) has also become more variable, and the trend is for later dates into December rather than early to mid-November (Black and McDaniel, 2007). Further examination of these interconnected changes is beyond the scope of this study.

There are other indirect measures of the climate at the South Pole. One measure, which is very much on the minds of the forecasters and pilots, is how early the first flight can get in and how late the last flight can get out. These dates are dependent on the temperature due to the adverse effects on the aircraft and ground-based aircraft operations, especially the hydraulics and the consistency of the fuel (the limits for acceptable risk are −50 °C on the ground, −55 °C in flight, −54 °C for the hydraulics, and −58 °C for the fuel (Doll, M., Air National Guard-National Science Foundation liaison, pers. comm.)). Using −50 °C as a conservative estimate for safety, the length of the winter season can be defined as the number of days between the first occurrence of −50 °C in the fall and the last occurrence of −50 °C in the spring. For the last 10–15 years the length of the winter season has been decreasing (Fig. 7). The longest winter using the −50 °C standard occurred in 1995 (264 days), and the shortest winter occurred in 1972 (236 days). From Fig. 7, the longest winters are clustered between the mid-1980s to the mid-1990s.

4.1.2. Pressure

The 50 year mean surface pressure exhibits many of the same patterns as the temperature. The fourth harmonic was again created to depict a smoothed annual cycle (Fig. 8). The early winter shows an increase in pressure from the autumn transition season, and then late winter settles into the lowest pressures of the year. The early winter behavior reflects the

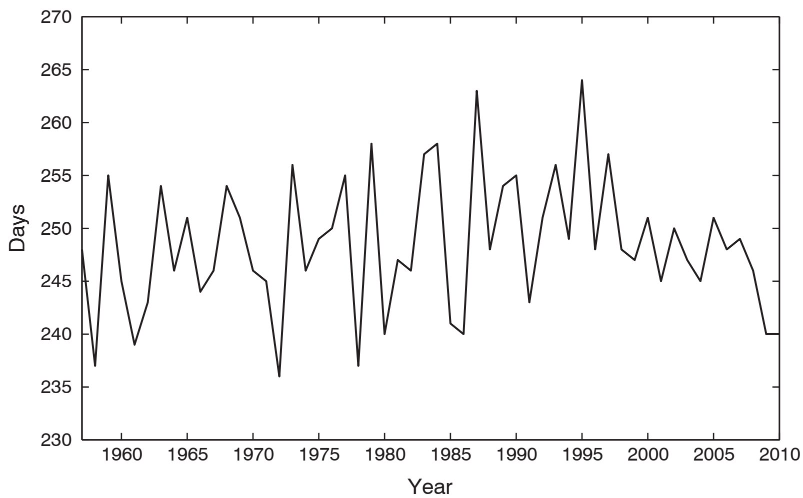

Fig. 7. Length of the winter season defined as the number of days between the first occurrence of −50 °C in the fall and the last occurrence of −50 °C in the spring, over the years 1957 to 2010.

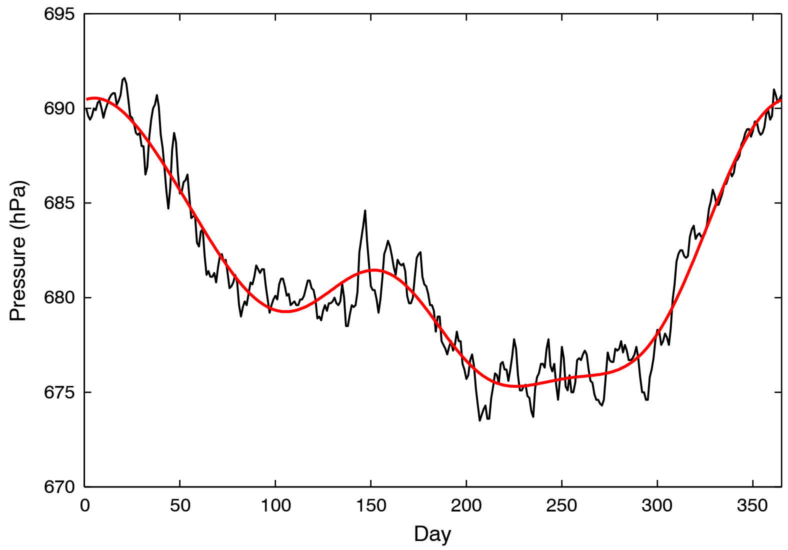

Fig. 8. Daily mean pressure for 50-year climatology (1957–2006) (thin solid line) and fourth harmonic fit to the data (red solid line).

reorganization of the pressure belt and amplification of the wavenumber 3 pattern as the strong polar vortex builds in the autumn (van den Broeke, 2000). Unfortunately, no daily maximum and minimum pressures were recorded as part of the official record, so only monthly extremes can be examined. The mean pressure extremes vary from just under 700 hPa for the maximum values to 660 to 680 hPa for the minimum values over the year. The maximum pressure of 719.0 hPa occurred on 24 and 25 August 1996 and the minimum pressure of 641.7 hPa occurred on 25 July 1985. The mean annual pressure is 681.2 hPa ± 6.2 hPa.

The 30-year mean pressure climatology sets only vary by about 0.5 hPa from lowest to highest mean. Again using the Wilcoxon signed rank test, the 30- and 50-year climatologies are statistically significantly different at the 5% level for all comparisons except for the 50-year climatology (1957–2006) and the 1971–2000 thirty year climatology. The decadal mean pressures suggest the 30-year climatologies should be different with the alternating decades of lower and higher pressure (Fig. 9). The annual mean pressures show a slight downward trend (a slope of -0.14 ± 1.89 hPa decade^{-1}) over the fifty-four year period which is not statistically significant (Fig. 9). By comparison, Turner et al. (2005) found the annual trend to be -0.03 ± 0.60 hPa decade^{-1}.

4.1.3. Wind speed

The Polar Plateau is known for its low wind speeds because of the lack of steep topography. The mean resultant (vector) wind speeds from the 50-year climatology show daily mean wind speeds of around 2 m s^{-1} in the summer rising to around 4–5 m s^{-1} in the spring, autumn, and early and late winter seasons (Fig. 10). The annual mean wind speeds show a decrease throughout the period of -0.28 ± 0.74 m s^{-1} decade^{-1}, which is statistically significant at the 5% level

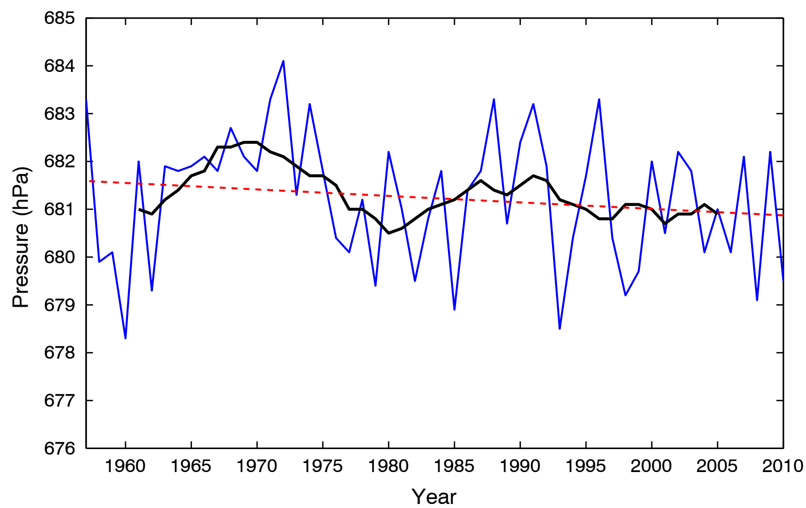

Fig. 9. Annual mean pressure for 1957–2010 (blue), 10 year running mean (black), and least squares linear regression line (red dashed, $r^2 = 0.024$).

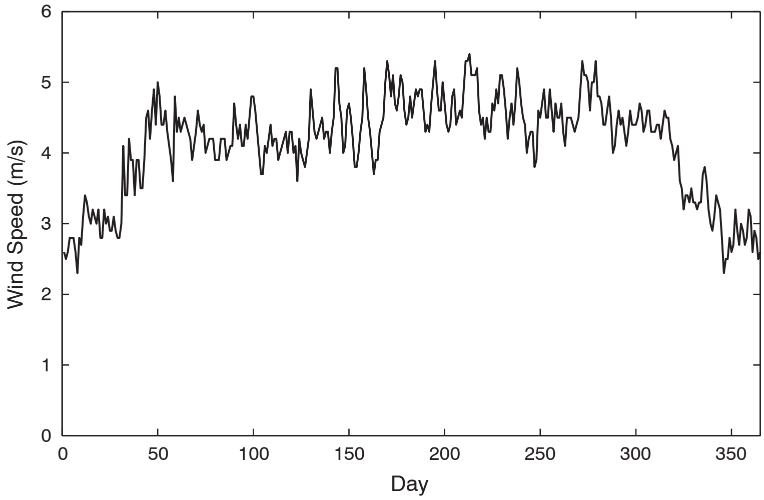

Fig. 10. Daily mean resultant (vector) wind speed for 50-year climatology (1957–2006).

(Fig. 11). There is a prolonged period from around 1987 to 1997 where the wind speeds are relatively higher. The mean annual wind speed is 4.1 m s^{-1} ± 0.7 m s^{-1}. The maximum wind speeds for each month are between 20 and 25 m s^{-1} while the lowest maximum speeds are between 7 and 10 m s^{-1} with the higher values more prevalent in the winter seasons. The standard deviations are between 2 and 3 m s^{-1}. The highest wind speed ever recorded was 25.9 m s^{-1} from 020° on 27 September 2011. Wind speeds for the 1961–1990 climatology are slightly higher than the later 30 year climatologies (not shown). The averages for the first two decades are around 1 m s^{-1} higher than all the following years with the 1997–2006 decade having the lowest average at 4.5 m s^{-1}. The wind speeds are higher for the last four years of the record; however, the winds are measured at the skiway tower from 2005 to present, so the relocation of the reporting tower could be an explanation.

4.2. Seasonal values

While the annual, decadal, or full climatological time series has information to contribute to the understanding of the behavior of the long-term South Pole climate, seasonal time series provide information on the intra-annual variability. Using the seasons defined above, the temperature, pressure and resultant wind are examined for seasonal variations over the last 54 years.

4.2.1. Temperature

The non-stationarity of the seasonal temperature time series precludes the investigation of possible trends over the time period studied. Instead, a ten year running mean was utilized to illustrate the behavior of the time series for each season. The time series of summer mean temperatures shows

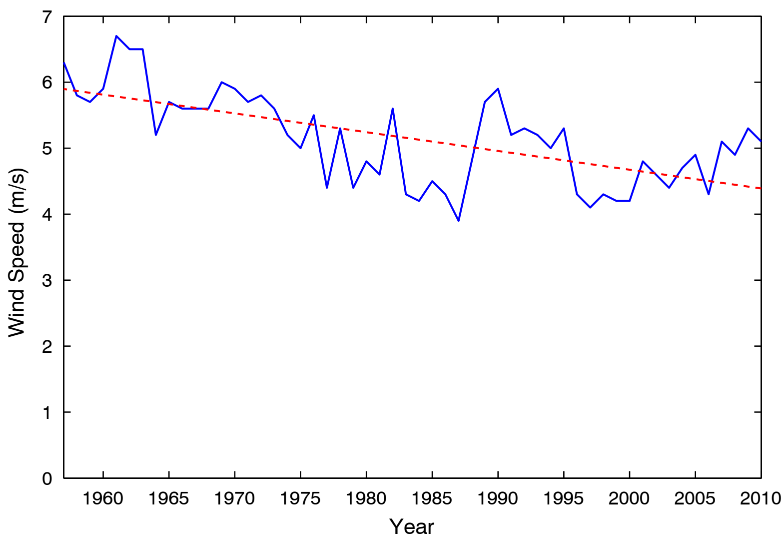

Fig. 11. Annual mean wind speeds for 1957–2010 (blue line) and least squares linear regression line (red dashed, $r^2 = 0.416$).

the longer term oscillating nature of the interannual variability with warmer temperatures in the late 1960s and 1970s and cooler temperatures in the latter half of the 1990s (Fig. 12a). A large interannual variability is also evident. The autumn transition season (not shown) has an almost opposite oscillation with cooler temperatures in the late 1960s and early 1970s, slightly warmer temperatures in the late 1970s to late 1980s, cooling again in the early 1990s and more warming in the late 1990s to early 2000s. Early winter resembles the summer pattern except the warm and cool periods are shifted a few years earlier (not shown). Late winter has less of an oscillation to the pattern, but there are two extended warm periods — one in the late 1960s and one in the late 1990s (not shown). Finally, the spring transition season is also fairly flat in terms of any oscillatory pattern, but it does have a pronounced low–high–low triplet from 1981–1983 (Fig. 12b). Interestingly, the slightly negative slope for the spring temperature time series stands in marked contrast to the warming reported in West Antarctica (e.g., Schneider et al., 2012). Table 2 lists the three top maximum and minimum temperatures for each month as well as the lowest maximum and highest minimum occurrences. The extremes are examined by month because of the change in temperature ranges over the year. The highest temperatures occur in December while the lowest occur in August and September.

4.2.2. Pressure

Seasonal mean pressure also shows a great deal of interannual variability over the 54-year period. In addition, the summer and transition months show longer term oscillations. The summer season has low pressures in the early 1960s, higher pressure in the late 1960s through the 1970s, and then lower pressure in the mid to late 1990s (Fig. 13a). The autumn season is similar to the summer (not shown). The early and late winter seasons do not show the longer term oscillations seen in the other seasons (not shown). The early winter has a downward trend of −0.031 hPa per year, which is not statistically significant (not shown). Late winter has no trend or long term oscillation, but the mean seasonal pressure can vary as much as 10 hPa between years (not shown). The spring season (October,

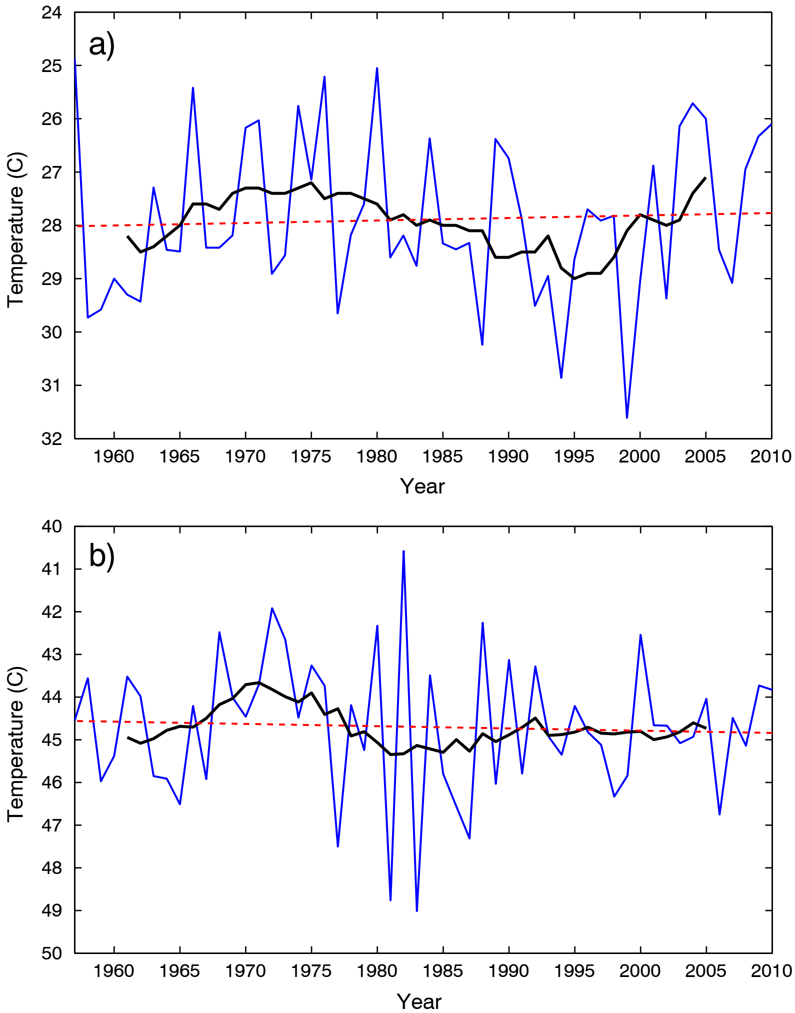

Fig. 12. a. Summer (December–January) annual mean temperatures (blue), 10 year running mean (black), and least squares linear regression line (red dashed, $r^2 = 0.0023$), over the period 1957–2010. b. Spring (October–November) annual mean temperatures (blue), 10 year running mean (black), and least squares linear regression line (red dashed, $r^2 = 0.0026$), over the period 1957–2010.

Table 2
The three top maximum and minimum temperatures for each month as well as the lowest maximum and highest minimum occurrences.

Month	Maximum temperature (C)	Minimum temperature (C)	Lowest maximum temperature (C)	Highest minimum temperature (C)
December	−12.9, Dec. 2011	−42.0, Dec. 1999	−26.4, Dec. 1962	−29.7, Dec. 1957
	−13.6, Dec. 1978	−41.1, Dec. 2002	−24.6, Dec. 1999	−30.3, Dec. 2009
	−13.9, Dec. 2005	−38.9, Dec. 1965, 78, 83	−24.5, Dec. 2000	−30.6, Dec. 1976
January	−14.7, Jan. 1958	−41.4, Jan. 1974	−24.3, Jan. 1995	−30.6, Jan. 2011
	−14.8, Jan. 2001	−41.1, Jan. 1965	−24.1, Jan. 1992	−31.1, Jan. 1958
	−15.8, Jan. 1984	−40.2, Jan. 2008	−24.0, Jan. 2000	−32.4, Jan. 2007
February	−20.8, Feb. 1984	−59.4, Feb. 1984	−35.5, Feb. 1994	−46.8, Feb. 1986
	−21.4, Feb. 1958	−57.8, Feb. 1978	−34.8, Feb. 1962	−46.9, Feb. 2004
	−22.8, Feb. 1982	−57.6, Feb. 2000	−34.4, Feb. 1969	−49.0, Feb. 1991
March	−26.7, Mar. 1975	−75.8, Mar. 1998	−46.1, Mar. 1961	−62.6, Mar. 1980
	−28.3, Mar. 1964	−74.2, Mar. 1999	−45.2, Mar. 1997	−62.6, Mar. 2010
	−29.5, Mar. 1988	−73.2, Mar. 1997	−44.5, Mar. 1980	−62.8, Mar. 1988
April	−28.1, Apr. 1968	−75.2, Apr. 1982	−51.0, Apr. 1999	−63.9, Apr. 1971
	−30.2, Apr. 1991	−74.8, Apr. 1995	−49.4, Apr. 1975	−65.0, Apr. 1978
	−31.1, Apr. 1992	−73.7, Apr. 2010	−48.6, Apr. 1958	−65.4, Apr. 1986
May	−30.8, May 1981	−78.1, May 1982	−47.4, May 1986	−65.9, May 2007
	−31.2, May 2009	−76.9, May 1995	−46.3, May 1992	−66.1, May 1969
	−31.7, May 1969	−75.8, May 1998	−45.9, May 1958, 1962	−66.3, May 2009
June	−30.9, Jun. 1963	−82.8, Jun. 1982	−50.9, Jun. 1967	−67.8, Jun.1961
	−32.1, Jun. 1997	−77.1, Jun. 1989	−48.3, Jun. 1971	−67.8, Jun. 1965
	−33.9, Jun. 1969	−77.0, Jun. 1986	−47.5, Jun. 1973	−67.8, Jun. 1974
July	−33.7, Jul. 1967	−80.6, Jul. 1964	−55.5, Jul. 2004	−68.6, Jul. 1984
	−33.7, Jul. 1986	−80.0, Jul. 1968	−50.0, Jul. 1976	−69.1, Jul. 1995
	−34.0, Jul. 1995	−78.9, Jul. 1963	−49.4, Jul. 1974	−69.2, Jul. 1978
August	−32.5, Aug. 1963	−80.0, Aug. 1987	−52.5, Aug. 1987	−68.0, Aug. 1981
	−34.2, Aug. 1961	−77.8, Aug. 1959	−50.2, Aug. 2004	−68.8, Aug. 2003
	−34.4, Aug. 1974	−77.6, Aug. 1978, 1993	−50.2, Aug. 2005	−69.4, Aug. 1963
September	−29.3, Sep. 1994	−80.4, Sep. 1997	−50.1, Sep. 1995	−66.6, Sep. 2005
	−29.6, Sep. 1983	−79.2, Sep. 1986	−49.7, Sep. 1957	−67.2, Sep. 1963
	−32.5, Sep. 1969	−78.9, Sep. 1959	−49.1, Sep. 1986	−67.7, Sep. 2008
October	−25.1, Oct. 2002	−72.0, Oct. 2007	−44.7, Oct. 1983	−58.9, Oct. 1962
	−28.8, Oct. 2005	−71.3, Oct. 2005	−43.1, Oct. 1964	−59.1, Oct. 2004
	−29.8, Oct. 1961	−71.1, Oct. 1983	−42.9, Oct. 2006	−61.0, Oct. 1988
November	−19.2, Nov. 1957	−55.1, Nov. 1983	−33.8, Nov. 1983	−40.2, Nov. 1982
	−19.5, Nov. 1990	−54.9, Nov. 1981	−33.1, Nov. 1959	−42.8, Nov. 1972
	−22.5, Nov. 1980, 2010	−54.8, Nov. 1987	−32.2, Nov. 1977	−43.1, Nov. 1973

November) has a shorter cycle of oscillations with lower pressure in the early 1960s, late 1970s and early 1980s, and trending downward again in the late 2000s. Higher pressure is reported in the late 1960s and early 1970s and the 1990s (Fig. 13b). Table 3 lists the top three maximum and minimum pressures for each month.

4.2.3. Wind speed and Wind roses

The seasonal mean wind speed over the 54-year period shows a consistent pattern of decreasing speed for all seasons. The only long period of higher wind speeds occurred in the late 1980s and early 1990s and appears in all the seasons. The decrease is significant at the 5% level for all seasons except summer. The steepest declines occur in early winter (-0.47 ± 1.0 m s^{-1} $decade^{-1}$) (not shown) and late winter (-0.47 ± 0.99 m s^{-1} $decade^{-1}$, Fig. 14). Spring and autumn decreases were -0.38 ± 1.2 m s^{-1} $decade^{-1}$ and -0.24 ± 0.97 m s^{-1} $decade^{-1}$, respectively (not shown). It was expected that the wind speeds would decrease after 2005 due to the new instrument tower location near the skiway. The prevailing winds blow across the station before they reach the tower, and the increased surface roughness should slow the wind speed. In fact, summer and the transition seasons show increases in wind speed, although these increases appear to have started before the tower relocation.

Wind roses were constructed for each month to examine the prevailing wind direction and the direction of the highest mean wind speeds. Grid wind direction is used at the South Pole, such that winds from the south follow the 180-degree meridian, winds from the east follow the 90-degree meridian, etc. As all the months follow one of two patterns, only two months will be shown as examples. The February pattern (Fig. 15a) has the prevailing wind direction more or less equally out of the northeast and east which is a downslope wind generally associated with surface temperature inversions. Analyses by Neff (1999) and Stone and Kahl (1991) showed that these downslope winds are also prevalent during radiational cooling due to clear skies and decreased wind speeds associated with synoptic scale events with the upper level winds (300 hPa) out of the southeast. The strongest wind speeds for February are from the north and northeast, with the air moving across Queen Maud Land. The August late winter pattern (Fig. 15b) has the prevailing wind primarily centered on 30° (i.e. 15–45°). The highest wind speeds, however, now are out of the west, northwest, and northerly directions. These wind directions are more related to synoptic situations bringing warm, moist air from the direction of the Weddell Sea with the accompanying increase in cloud cover and wind speed. Instead of downslope winds, the direction of flow of the highest wind speeds indicates along-slope flow.

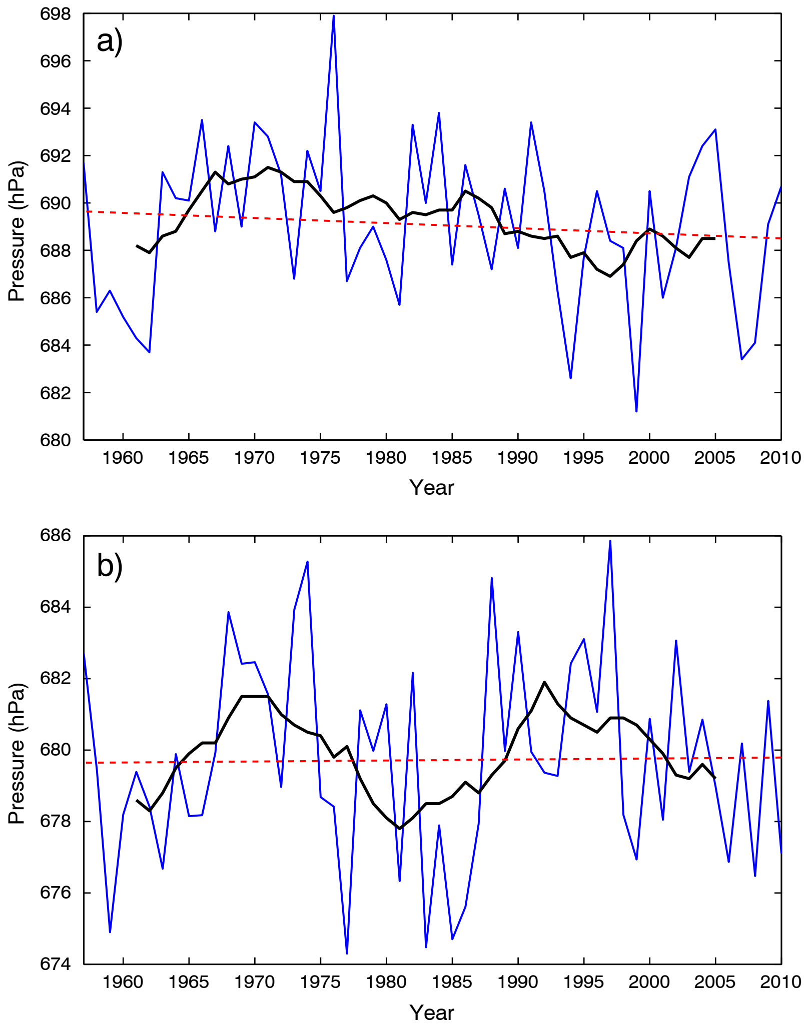

Fig. 13. a. Summer (December–January) annual mean pressure (blue), 10 year running mean (black), and least squares linear regression line (red dashed, $r^2 = 0.010$), over the years 1957 to 2010. b. Spring (October–November) annual mean pressure (blue), 10 year running mean (black), and least squares linear regression line (red dashed, $r^2 = 0.0002$), over the years 1957 to 2010.

The maximum wind speeds by month are confined to the northwest to northeast quadrants with a secondary area around 110°. No maximum wind speeds are recorded between 150 and 250° (southeast to southwest quadrants). The maximum wind speeds are increasing over the period of record during the summer and transition months. Specifically, November, December, January, March, and April show statistically significant positive trends over the 54 years with November (0.7 ± 3.7 m s^{-2} decade^{-1}) (Fig. 16a) and April (0.5 ± 3.1 m s^{-2} decade^{-1}) (Fig. 16b) having the largest increases. The other seven months have no significant trend in the maximum wind speed. This is directly opposite to what was seen with the mean wind speed, which is decreasing over most of the record.

4.3. Sunshine duration

Sunshine data are reported in hours per day. Mean monthly hours of sunshine for 1969–2010 were calculated from the monthly reports of total number of hours of sunshine in the LCDs. Before 1969 the data were incomplete, and all of 1976 is missing as well as parts of 1975 and 1977. Only the months of October through March are analyzed since September has many missing values. Total sunshine hours can be reduced by clouds, ice fog, and snow and blowing snow, for example. October is a month of extremes with either much less sunshine than average (late 1970s, early 1980s, and 2000) or much more than normal sunshine (1997 and 2006). November and December are close to average for the entire record with a tendency for more sunshine than normal in November from 2002 on. January has tended to have more than normal sunshine from the mid-1990s except for 2010 (Fig. 17). February is another month of extremes with greater than normal hours of sunshine in 1994, 1997, and 2006 and less than normal hours in 1993 and 1996. March has the most consistent trends with more total sunshine in the early 1970s, less total hours from the late 1970s to the early 1990s (except for large

Table 3
The top three maximum and minimum pressures for each month.

Month	Maximum pressure (hPa)	Minimum pressure (hPa)
December	709.6, Dec. 2010	667.6, Dec. 2008
	706.7, Dec. 2003	670.0, Dec. 1999
	706.1, Dec. 1991	670.5, Dec. 1973
January	708.9, Jan. 2002	669.6, Jan. 1974
	708.7, Jan. 1986	672.1, Jan. 1980
	708.6, Jan. 1983	672.9, Jan. 1962
February	712.0, Feb. 1991	665.4, Feb. 1970
	706.1, Feb. 1986	667.4. Feb. 1993
	705.0, Feb. 1965	668.8, Feb. 2009
March	706.2, Mar. 1987	660.0, Mar. 1960
	703.0, Mar. 1975	660.2, Mar. 1982
	702.2, Mar. 1986	662.4, Mar. 1964
April	716.2, Apr. 1990	653.0, Apr. 1981
	707.5, Apr. 1981	655.4, Apr. 1982
	704.7, Apr. 1996	656.7, Apr. 1995
May	713.2, May 1957	654.1, May 1964
	710.6, May 1983	654.7, May 1998
	708.0, May 1990	654.9, May 1989
June	714.2, Jun. 1964	649.9, Jun. 1982
	712.7, Jun. 1999	654.5, Jun. 2004
	708.1, Jun. 1997	655.3, Jun. 2006
July	708.8, Jul. 2007	641.7, Jul. 1985
	706.5, Jul. 1995	642.4, Jul. 2004
	706.4, Jul. 1964	643.4, Jul. 1972
August	719.0, Aug. 1996	650.3, Aug. 1992
	716.4, Aug. 1974	651.9, Aug. 1993
	707.8, Aug. 1989	652.4, Aug. 1978
September	704.1, Sep. 1991	643.1, Sep. 1960
	704.1, Sep. 2000	648.0, Sep. 1986
	702.8, Sep. 1970	648.3, Sep. 1992
October	706.7, Oct. 1970	647.4, Oct. 1983
	704.9, Oct. 2002	652.6, Oct. 1977
	702.7, Oct. 1977	653.4, Oct. 2001
November	708.9, Nov. 1996	657.0, Nov. 1986
	708.0, Nov. 1976	661.7, Nov. 1976
	704.6, Nov. 2009	662.4, Nov. 1970

peaks in 1984 and 1992), and more sunshine hours from 2006 to 2010 (not shown). The sun goes below the horizon on March 22–23, so there is a very low sun angle at this time of year.

4.4. Snow stake field

For this study, the snow accumulation measurements recorded in the LCD report for each month are being taken at a site 0.4 km (one-quarter mile) grid east of the station. There was a snow stake field set up during the years of the original station (1963–1974), but measurements during this time were sparse and without a documented procedure. In 1974, the official snow stake field was moved to the grid east side of the dome so as to keep drifting within the field due to man-made structures and objects to an absolute minimum. This field contains a total of 50 snow stakes that are reset to a standard value twice a year. This sample size of the current snow stake field is also designed to negate the effects of any drifting/sastrugi within the field. The annual accumulation is only examined for the years 1983–2010 because that period has continuous reports for each month. The results in Mosley-Thompson et al. (1995, 1999) indicate that there was an increase in accumulation of 30% between the 1960s and the 1990s. For the period 1983–2010 in the current study, the average annual snow accumulation is 274.83 mm year^{-1}, and there is a statistically significant downward trend of $-2.9\pm$ 6.7 mm year^{-1} (Fig. 18). The results from Monaghan et al. (2006) for 1985–2005 confirm this decreasing trend. Looking at the individual months, only February has a significant downward trend (-0.876 ± 1.8 mm year^{-1}). Seven other months have downward trends that are not statistically significant. Four months have upward trends which are also not significant. The years with the most accumulation are 1988

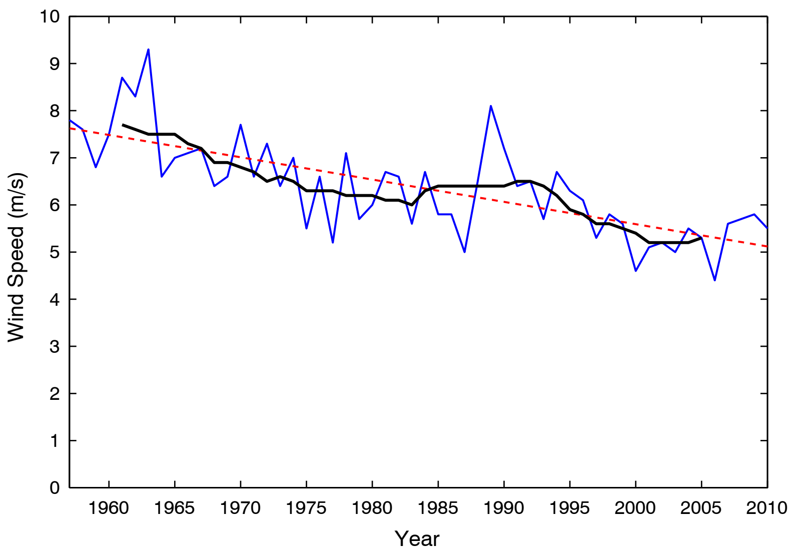

Fig. 14. Late winter (July–September) annual mean wind speed for 1957–2010 (blue), 10 year running mean (black), and least squares linear regression line (red dashed, $r^2=0.519$).

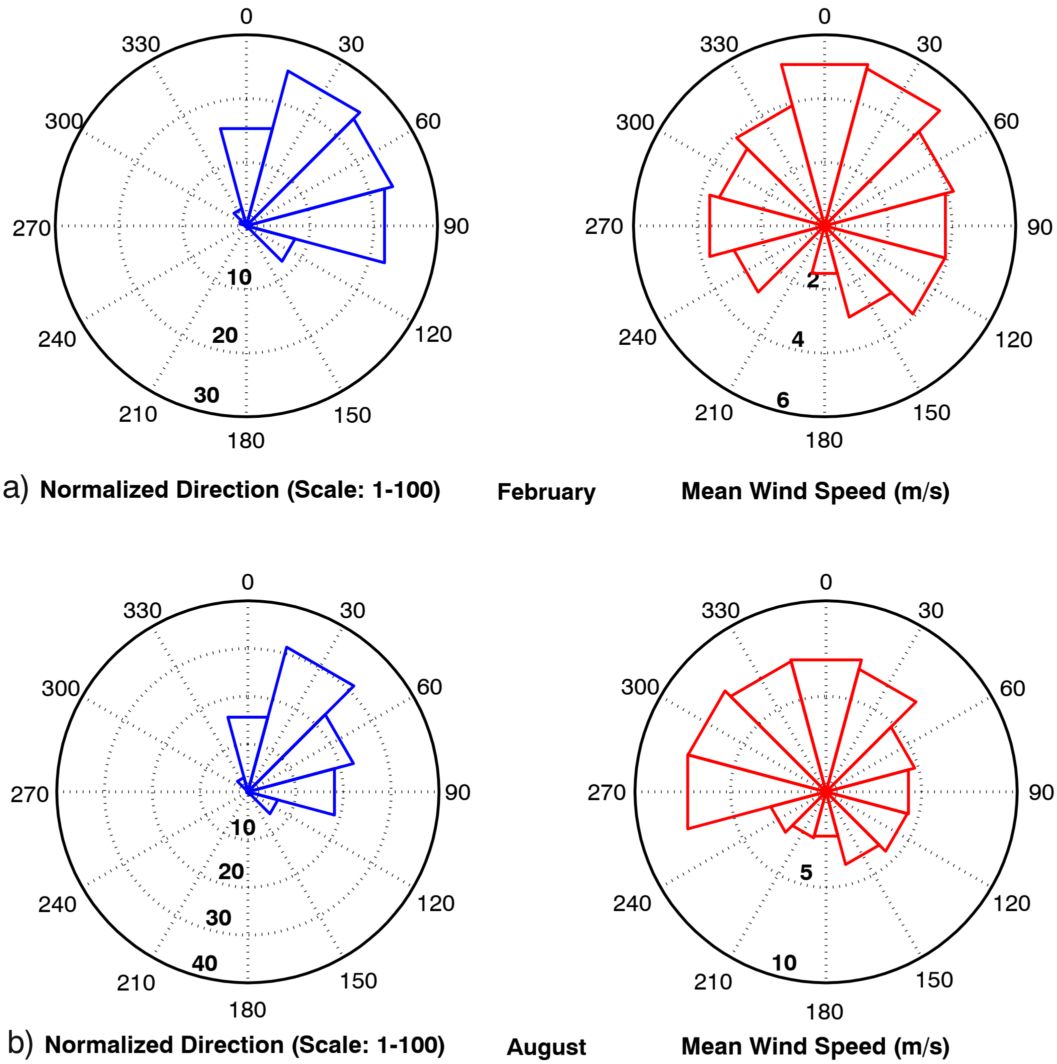

Fig. 15. Prevailing wind direction (as percent of total observations) and the direction of the highest mean wind speeds, (a) February, (b) August, over the years 1957 through 2010.

(419.61 mm) and 1984 (350.52 mm). The least accumulation was in 2003 (185.45 mm). The maximum accumulation for one month was 81.3 mm for May, 1981, and the minimum accumulation (or maximum reduction) was −58.4 mm for November, 1987. The accumulation for each year between 2003 and 2008 was below 254 mm.

5. Discussion

5.1. Change points and trends

Long-term trends and change points or discontinuities in the data are revealing characteristics of a climate time series. A move in the station location or change in the instruments or gradual changes such as urbanization are usually the source of discontinuities in station time series. One solution is to perform pairwise comparisons between stations in close proximity so that a discontinuity in one report should be reflected in the paired station report if it is real (Menne and Williams, 2009). Unfortunately, there are no other stations with 50 year records near the South Pole, so this method cannot be used for the entire length of the time series. The ARO time series does confirm the trends and changes in the last thirty years of the SP data set. As noted above, there have been many instrument changes, but the only testing on the possibility of a discontinuity occurring with such changes was performed on the new instrument suite installed in 2004 (Keller et al., 2009). The major change for this instrument upgrade was that the wind speed and direction were now reported from a tower on the southwest side of the station near the skiway instead of the northeast side of the station near the Clean Air sector. This study concluded that there were differences in the reported observations between the old and new instruments, especially for the wind speed, but these differences were within the accuracy of the instruments themselves.

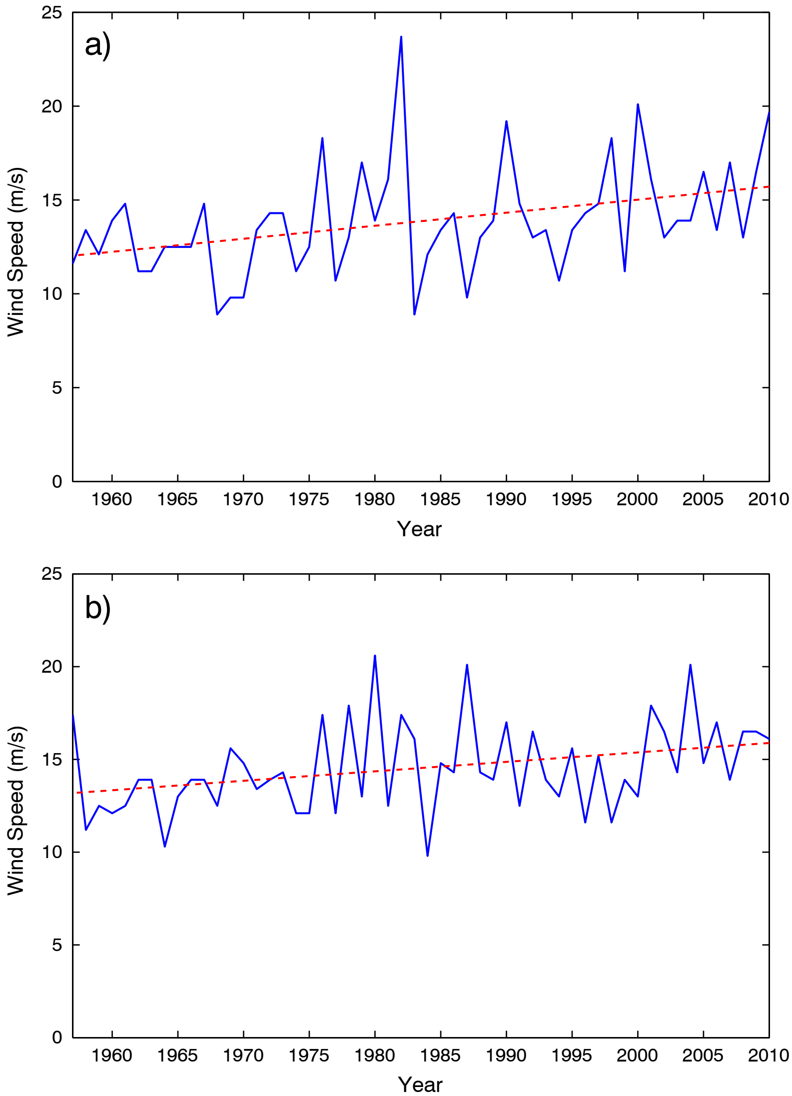

Fig. 16. a. November annual maximum wind speed for (blue) and least squares linear regression line (red dashed, $r^2=0.139$) over the years 1957 to 2010. b. April annual maximum wind speed for (blue) and least squares linear regression line (red dashed, $r^2=0.110$) over the years 1957 to 2010.

Several different methods of detecting change points have been developed based on regression methods (Easterling and Peterson, 1995; Lund and Reeves, 2002; Wang, 2003; Lund et al., 2007) or robust, nonparametric methods (Lanzante, 1996). Gerard-Marchant et al. (2008) reviewed both of these methods and found that the regression methods are more skillful at identifying trends while the robust methods are better at identifying true discontinuities. The robust methods have a disadvantage in that they will identify the middle of a trend as a change point. Both methods were tested on the temperature time series presented here (e.g., Fig. 12a). While change points were detected, none of them proved to be significant. The possibility of a discontinuity in the wind speed due to the change in wind observation location could not be tested because it was too close to the end of the time series.

5.2. Other influences

The existence of trends in the data is evident in the short term (again see Fig. 12a), but the long-term trends in temperature and pressure are not significant as reported above. The short-term trends in Fig. 12a illustrate the caution that must be used in picking the time period to be studied (Liebmann et al., 2010). The longer term oscillations suggest that forcing by other influences is also at work. The main candidates for the longer-term influences are the Southern Annular Mode (SAM) (Marshall, 2003) and the Interdecadal Pacific Oscillation (IPO) (Salinger et al., 2001). Shorter fluctuations may be related to El Niño-Southern Oscillation (ENSO) (Kidson, 1999; Grainger et al., 2011; Fredericksen and Zheng, 2007), the Pacific-South America pattern (Mo, 2000), and the Southern Annular Oscillation (van den Broeke, 1998). Kidson (1999, Fig. 17) used the 300 hPa

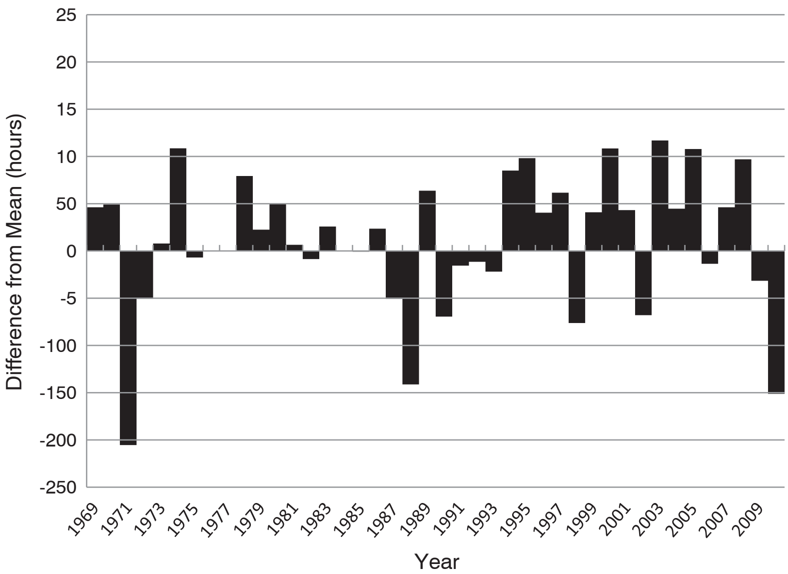

Fig. 17. January anomaly for sunshine hours as a difference from the observed mean for 1969–2010.

stream function from the NCEP-NCAR reanalysis dataset to associate the principal Southern Hemisphere modes of variability with time scales from 10 days to 20 years. Recent research indicates that SAM is the leading mode of intraseasonal variability (Gillett et al., 2006; Fredericksen and Zheng, 2007; Monaghan et al., 2008; Fogt and Bromwich, 2006; Fogt et al., 2011; Grainger et al., 2011) and is coupled to the variability of ENSO events. The SAM index has increased since the 1960s (Marshall, 2003, 2007) but has leveled off since the mid-1990s. A positive SAM index is related to cooling over the continent (van den Broeke and van Lipzig, 2004), and strongest positive SAM trends have been in the summer and autumn (Marshall, 2007; Monaghan et al., 2008). An examination of Fig. 12a shows warming of the summer annual temperatures until the mid-1970s with cooling occurring from then until the end of the 1990s. Another warming trend has been occurring since then (up until 2010). Autumn temperatures are more complicated as the cycle of warming and cooling seems to occur on a slightly faster time scale with cooling until 1970, warming until the mid-1980s, cooling again until the 1990s, and finally warming until the end of the time series. Early summer exhibits a warming trend from the 1990s onward, but late winter and spring have no real trend throughout the time series.

Anomalies of mean monthly temperature, maximum and minimum monthly temperature, mean monthly pressure and maximum and minimum monthly pressure were created for all the months from 1957 through 2010 and tested for correlation against the various indices of forcings known to be operative in the Southern Hemisphere (i.e., SAM, IPO, the sea surface temperature in region Niño 3.4, and the Southern

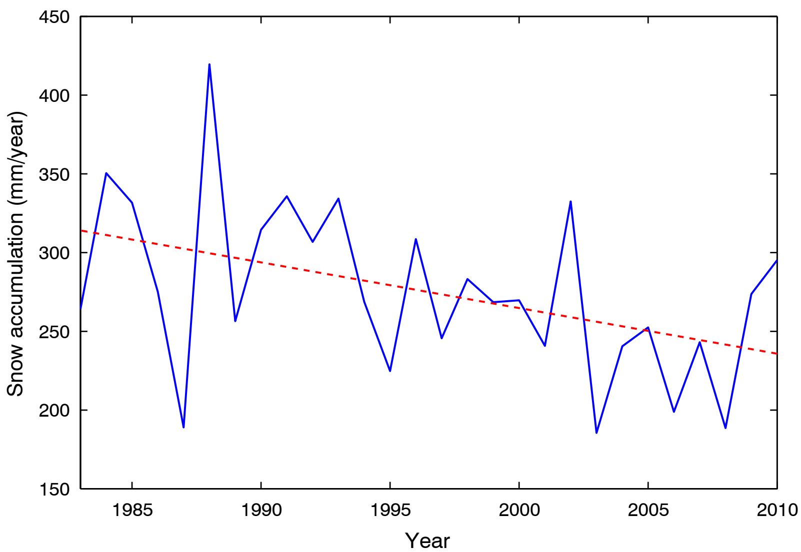

Fig. 18. Annual snow accumulation (1983–2010) from South Pole snow stake field (blue) and least squares linear regression line (red dashed, $r^2=0.189$).

Oscillation Index (SOI)). Only SAM was significantly correlated with each of the anomaly time series. In spite of the lack of a significant relationship with ENSO related indices, there are indications of some ENSO influence in extreme events (Fogt and Bromwich, 2006). For example, Fig. 19 shows the number of days in the last 54 years that the South Pole station has reported minimum temperatures at or below −73.3 °C (−100 °F). The two highest peaks (1982 and 1997–1998) correspond to the two strongest El Niño events in the last 50 years. Using a simple definition of an ENSO event as an anomaly of ±0.5 °C in the Niño 3.4 region sea surface temperature (Trenberth, 1997), all the instances of minimum temperatures below −73.3 °C in April and May and the greatest number for one year in June (1982) correspond to ENSO event years. Finally, over half of the temperature extremes in Table 2 are associated with ENSO events, and the maximum temperatures and highest minimum temperatures are more likely to occur with the negative SAM phase while the minimum temperatures and lowest maximum temperatures are more likely to occur with the positive phase of SAM. From Table 3, 86% of the maximum pressures occur doing the negative phase of SAM while 78% of the minimum pressures occur during the positive phase of SAM. One other signature is associated with the 1982 El Niño event. Fig. 12b shows the cold–warm–cold triplet in temperature that has been seen in temperature series from other Antarctic stations for this particular event (Keller and Weidner, 1999). These examples agree with the findings in Fogt and Bromwich (2006) that ENSO and SAM must be coupled without interference from the Pacific-South America pattern (Rossby wave activity) in order to have a strong teleconnection between the Tropics and the South Pacific.

6. Conclusions

With more than fifty years of observations available, a comprehensive climatology of the Amundsen–Scott South Pole station was undertaken. In addition to the climatology, the station meteorological history has been included to aid in the examination of possible discontinuities due to station moves and instrument changes. Significant discontinuities were not discovered, and the only known test on instrument changes (Keller et al., 2009) showed that differences were within the accuracy of the instruments. The station history did reveal that a variety of agencies performed observations, which led to the discovery that the observation times were not standardized into one time zone. In addition, the mean temperature had been calculated as the average of the maximum and minimum temperature, which provides inaccurate results where there is no diurnal cycle. An extensive effort was required by the South Pole Meteorology Office personnel to standardize the time zone and recalculate all the daily temperature means. This experience provides a cautionary experience to anyone using an observational data set with no metadata, especially since the records for South Pole station were fairly well cared for. This effort emphasizes the critical importance of data stewardship.

Three 30-year climatologies were computed for temperature, pressure, and wind speed using the WMO standard years along with a 50-year climatology for 1957–2006. For mean temperature, the coreless winter is well defined with larger variability in the daily means during winter than summer. Statistical tests showed that the two earliest 30-year climatology sets (1961–1990 and 1971–2000) were significantly different from the 50-year climatology, and the 1961–1990 climatology was significantly different from the other two 30-year climatologies. A breakdown of the temperature means into decades provided the explanation that the mean temperatures in the early decades were warmer than the later decades. However, the last four years of the record (2007–2010) show a tendency toward even warmer temperatures. Regarding mean pressure, the highest pressures are in the summer and reach their lowest point in late winter. The slight upward movement of mean pressure in the early winter is associated with the reorganization of the pressure belt and amplification of the wavenumber 3 pattern as the strong polar vortex builds in the autumn. The 50-year climatology is significantly different from the first and last 30-year climatologies. The decadal mean pressures offer an explanation for these differences, with alternating decades of

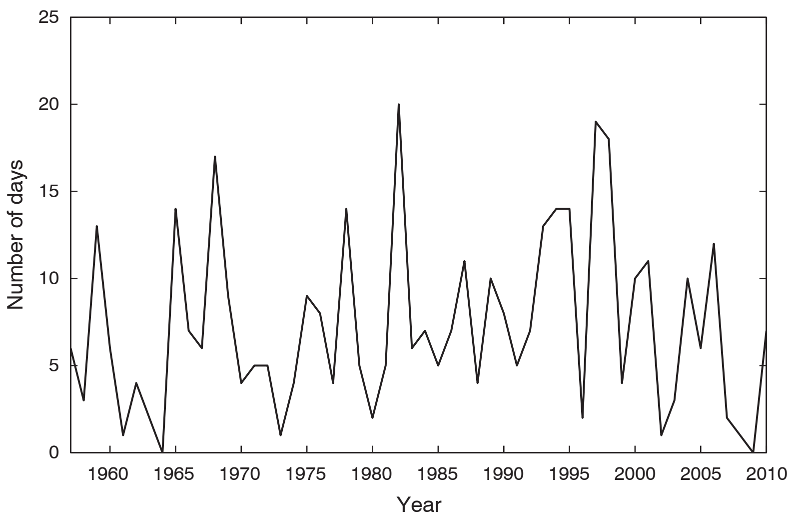

Fig. 19. Annual number of days for 1957–2010 that the South Pole station has reported minimum temperatures at or below −73.3 °C (−100 °F).

lower and higher pressure. Finally, the mean wind speeds for the 50-year climatology illustrate the low wind speed conditions found at South Pole with a mean wind speed of 2 m s^{-1} in the summer rising to 4–5 m s^{-1} in the winter.

Annual monthly means for the 54-year record in this study were examined to determine the trend (or lack thereof) in the temperature, pressure, and wind speed. The mean annual temperature trend was -0.058 ± 0.96 °C decade^{-1}, which is not statistically significant. Comparisons with other studies showed that the period of record used changed the trend estimates from negative to positive in some cases. The non-stationary behavior of a time series is a serious problem when attempting to detect linear trends. The annual mean pressure trend was -0.14 ± 1.89 hPa decade^{-1}, which was also not significant. The annual mean wind speed has a significant downward trend of -0.28 ± 0.74 m s^{-1} decade^{-1}, with most of the decrease occurring before 1987.

Based on the 50-year climatologies of temperature and pressure, the seasons were redefined to better capture the behavior of the seasonal variability. The seasonal time series of temperature and pressure highlighted the influence of the long (e.g., SAM) and short (ENSO) term Southern Hemisphere modes of variability. While the seasonal anomalies, especially in summer, were significantly correlated with the SAM, there are also indications that ENSO can modulate that influence. This topic is beyond the scope of the report presented here, and there are studies which have focused on understanding this interaction (e.g., Fogt et al., 2011). The increased warming in the spring in West Antarctica reported by several studies (e.g., Schneider et al., 2012; O'Donnell et al., 2011; Steig et al., 2009; Monaghan et al., 2008; Chapman and Walsh, 2007) does not appear to reach the South Pole.

Mean wind speeds show a decline over all seasons, with the steepest decline in the early and late winter ($-0.47\pm$ 1.0 m s^{-1} decade^{-1}). All the decreasing trends are significant except for the summer season. In contrast to the mean wind speeds, the maximum wind speeds are increasing for the summer and transition seasons. These increases are statistically significant and reach 0.7 ± 3.7 m s^{-2} decade^{-1} for November. Wind roses constructed for each month indicate the prevailing wind direction is from the east. However, the maximum wind speeds are generally associated with wind directions from the northeast to northwest.

An analysis of the hours of sunshine indicates that October and February are the most variable months while November and December are the least variable. January and March have recorded greater than average sunshine hours over the last 5–10 years. The increase in sunshine hours somewhat corresponds to the significant decrease in annual snow accumulation, with some of the lowest accumulations occurring from 2003 to 2008.

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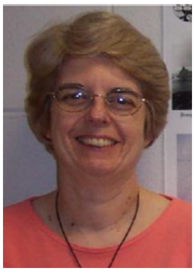

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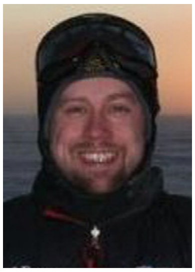

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