JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 114, D17115, doi:10.1029/2008JD011611, 2009

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Observations of near-surface wind and temperature structures and their variations with topography and latitude in East Antarctica

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Received 10 December 2008; revised 30 March 2009; accepted 5 June 2009; published 15 September 2009.

[1] The first multiyear surface meteorological observations over Dome A, the highest ice feature in the entire Antarctica continent, are analyzed to understand the surface wind, temperature, and stability climatology over Dome A and how it differs from the surface climatology at two lower-latitude/lower-elevation sites along similar longitude in East Antarctica. The climatology is also compared with that over Dome C. In contrast to the surface winds at lower sites, where moderate to strong northeasterly winds prevail with a distinct diurnal oscillation in wind speed in response to the diurnal change in katabatic forcing, summertime surface winds over Dome A are very weak, are variable in direction, and show little diurnal variation. Although both temperature and temperature gradient oscillate diurnally, the gradient over Dome A remained positive all day long, indicating a persistent surface inversion, while at the two lower sites, as well as over Dome C, sufficient insolation leads to the breakup of inversion and the development of a convective boundary layer in the afternoon. Wavelet analysis of near-surface stability revealed that besides the strong diurnal signal, the near-surface stability also exhibits annual, semiannual, and interseasonal (period ~50 days) oscillations at all locations. These oscillations in near-surface stability are linked to the same peaks in the 500-hPa geopotential height spectra and therefore are believed to be caused by variations of synoptic conditions.

Citation: Zhou, M., Z. Zhang, S. Zhong, D. Lenschow, H.-M. Hsu, B. Sun, Z. Gao, S. Li, X. Bian, and L. Yu (2009), Observations of near-surface wind and temperature structures and their variations with topography and latitude in East Antarctica, *J. Geophys. Res.*, *114*, D17115, doi:10.1029/2008JD011611.

1. Introduction

[2] Antarctica is covered by ice on over 94% of its surface and has the coldest climate on Earth. However, observations over Antarctica have revealed recent deglaciation and rapid retreat of ice shelves in some areas of Antarctica, particularly west Antarctica and the Antarctic Peninsula, which is attributed in part to ice shelf collapses, and in part to regional ocean warming [*Vaughan and Doake*, 1996; *Rignot et al.*, 2004; *van den Broeke*, 2005]. Although recent studies [*Steig and Schneider*, 2008; *Steig et al.*, 2009] using ice core–based West Antarctic temperature reconstruction have clearly linked the climate change observed in Antarctica to the changes in the rest of the Southern Hemisphere, Antarctic climate change has been a complex issue due primarily to the relatively short and sparse observations and the strong decadal variability. More observations, especially in regions with few data, are important for improving our understanding of climate and climate change in Antarctica.

[3] Because of their pivotal role in determining the momentum and energy exchange between the earth's surface and the atmosphere, the near-surface wind and temperature structures over Antarctica have long been a subject of many scientific investigations. Using surface observations and numerical models, a number of investigators [e.g., *Sorbjan et al.*, 1986; *King and Turner*, 1997; *Parish and Cassano*, 2003] have studied near surface winds in different regions in Antarctica and their results have revealed strong and persistent near-surface winds that tend to follow the topography as would be expected of katabatic flow. On the basis of observations from either radiosonde soundings or 10-m towers, several studies [e.g., *Schwerdtfeger*, 1984; *Hudson and Brandt*, 2005] have shown the presence of surface-based temperature inversions, which at many locations, exist throughout the year. These persistent temperature inversions have been attributed primarily to the greater emissivity of snow covered surfaces compared to that of the atmosphere. *Neff* [1999] analyzed four-decade upper-air sounding and surface weather data

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0148-0227/09/2008JD011611$09.00

from the Amundsen-Scott South Pole station and showed that winds over the interior of Antarctica do not occur as a simple response to radiative cooling of slope ice surface; instead, they are controlled to a large extent by the large-scale circulation and that the wind speed is inversely proportional to the strength of the temperature inversion.

[4] Majority of previous studies, including those in recent years [e.g., *King et al.*, 2004; *Orr et al.*, 2008] have focused on locations at lower elevations such as the Antarctic Peninsula and other coastal areas. The difficulty in collecting data, especially long-term data in the harsh environment at high elevation, is a major factor in the current lack of understanding of the structure and evolution of atmospheric surface layer properties at high elevations typified by the vast East Antarctic Plateau that has an average elevation of about 3000 m above mean sea level (MSL) with peaks rising up to more than 4267 m MSL. The combination of high altitude and latitude of this region results in some of the lowest temperatures on Earth. The persistent southerly winds make the conditions even more inhospitable.

[5] Few studies have examined climate over the high plateau in the interior of Antarctica. In a recent study, *Renfrew and Anderson* [2002] compared wind observations at several coastal stations at low altitude with those at higher elevations, but their highest station is only at 1650 m MSL. *Wendler and Kodama* [1984] analyzed 3-year surface observations from an Automated Weather Station (AWS) over Dome C (~75°S, 123.0°E, 3300 m MSL), a flat top dome in the interior of East Antarctica and compared them with surface observations in the coastal region. *King et al.* [2006] compared observed surface energy budget and boundary layer structure over Dome C with those over Halley, a costal station with similar latitude as Dome C. These studies have revealed significant differences in the near-surface meteorological variables and boundary layer structure and evolution between Dome C and coastal regions and attributed these differences to the differences in insolation, altitude, terrain slope, and surface heat properties.

[6] This paper reports on observations from a recently installed AWS station over Dome A, the highest (4093 m) region of Antarctica and one of the most inhospitable environments on Earth. Three year observations of near-surface wind, temperature, and stability and their variability over Dome A are compared to those observed at two other AWS stations located along similar longitude but at lower latitude and elevation. The Dome A climatology is also compared to that of Dome C.

2. Station Locations and Instrumentation

[7] The observations used in the current study are from three sites shown in Figure 1. All three stations are located near the 77°E longitude line, but separated by approximately 5° latitude with significantly different elevation. The southernmost station is at Dome A on top of the Antarctic Plateau at 80.37°S, 77.35°E, and 4093 m MSL. The next station, referred to as Eagle, is located at 76.25°S, 77.02°E at an elevation of 2825 m MSL. Finally, the third station, identified as LGB69 (70.50°S, 77.04°E), is farther north from Eagle and closer to the coast at an elevation of 1905 m. The topography is complicated around the stations, especially on the eastern side of 75°E, owing to the Lambert Glacier/Amery Ice Shelf.

[8] Similar instruments are installed at the three weather stations. Mean wind speed and direction were measured with R. M. Young 12170C 3-cup anemometers and Aanderaa 3590B wind vanes. FS23D thermistors in a radiometric circuit and Vaisala HMP35D probes are used for measurements of mean temperature and relative humidity. Pressure, hemispheric radiation and snow height are measured using Paroscientific digiquartz 6015A sensors and Middleton EP08 pyranometers and Campbell SR 50 acoustic range, respectively. Temperature and wind speed are measured at three heights (1, 2, and 4 m) above ground level (AGL), while relative humidity, wind direction and global radiation were measured at only 4-m level. The sampling rates are 1 Hz for all variables and 5-min mean data are archived in the data logger. The 5-min data are then averaged to 1 h in the analyses.

[9] In this study, hourly observations from the three stations from January 2005 to November 2007 are analyzed. In austral winter the wind direction data are often unreliable at Dome A because the extremely cold temperature froze the wind vane, while the data at the other two stations are usually fine. Consequently, we performed wind analyses only for the summer season. In addition, the analyses of diurnal temperature variation and statistical properties of vertical temperature gradient at LGB69 used data from a shorter period (January 2005 to April 2006) because of a failed temperature sensor after May 2006. The snow depth change owing to drifting was small and its effect on temperature gradient calculated using 2- and 4-m temperatures was neglected.

[10] In addition to the surface observations from the three AWS stations, data from routine rawinsonde soundings launched at stations Davis (68.58°S, 77.95°E, 22 m MSL), Dome C (75.01°S,123.38°E, 3280 m MSL), and Amundsen-Scott (90°S) are also analyzed to link the variability of surface meteorology to changes in large-scale conditions.

3. Results

3.1. Wind Roses

[11] The wind roses for austral summer (December–February) at the three stations are shown in Figure 2. At the two lower stations, Eagle and LGB69, winds are predominantly from northeast, flowing down the topographic gradient onto the Lambert-Amery Ice Shelf while turning slightly to the left of the topographic fall line by the Coriolis force. The northeasterly winds at the two sites are part of the large-scale, continent-wide surface wind pattern documented by *Parish and Bromwich* [1987] using a diagnostic wind model that takes into account terrain slopes and estimates of temperature structure over the Antarctic ice sheets. As suggested in the work of *van den Broeke and van Lipzig* [2003] on the basis of analyses of climate model momentum budget, these persistent northeasterly winds are driven by a combination of katabatic forcing owing to cooling of the sloping surfaces and large-scale pressure gradient force that result in a generally easterly large-scale winds. In the summer season, the large-scale forcing is more important than the local katabatic pressure gradient.

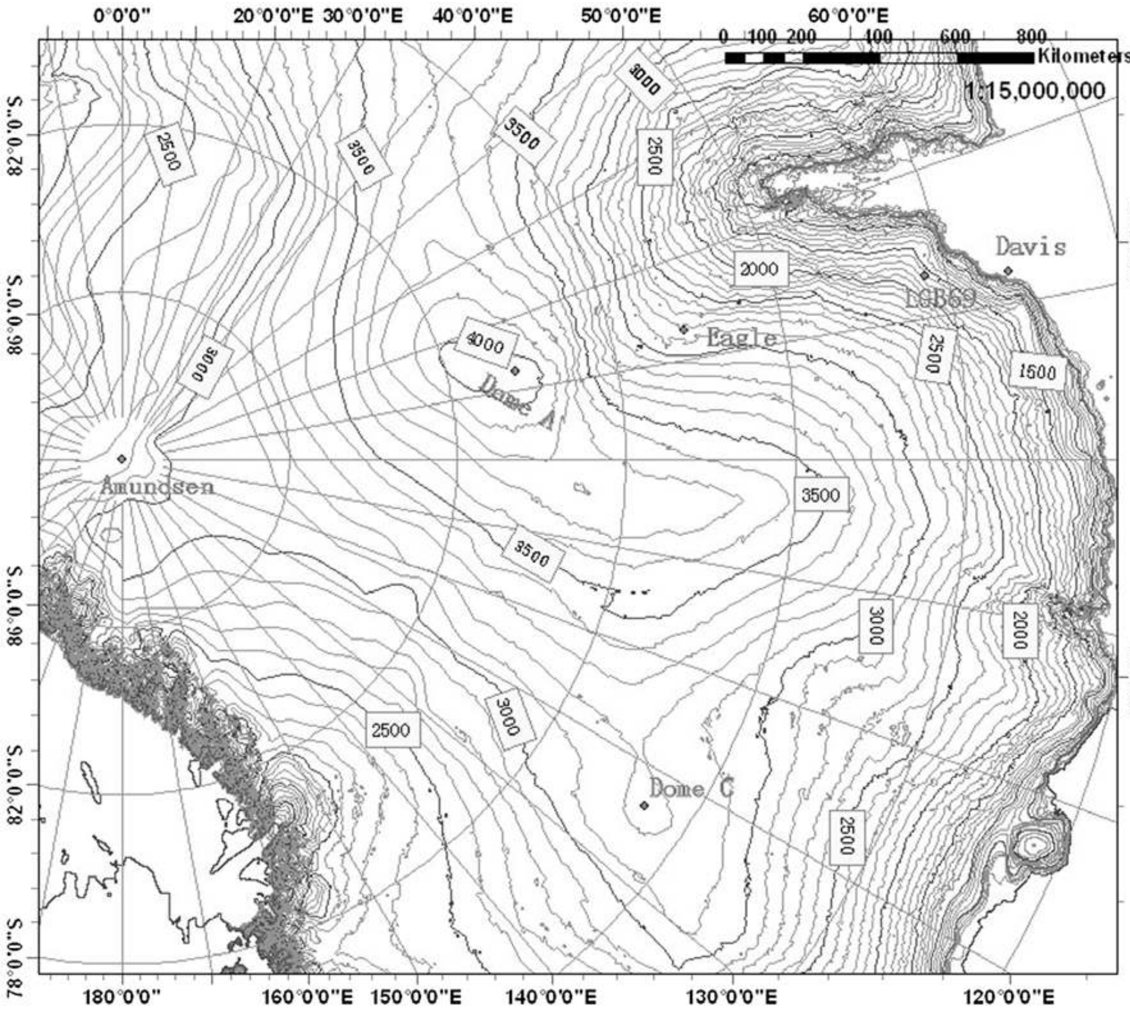

Figure 1. The topography in East Antarctica and the surface weather station locations for Dome A, Eagle, LGB69, and the upper-air sounding station locations for Davis, Dome C, and Amundsen-Scott. Topographic contours are shown at 100-m intervals.

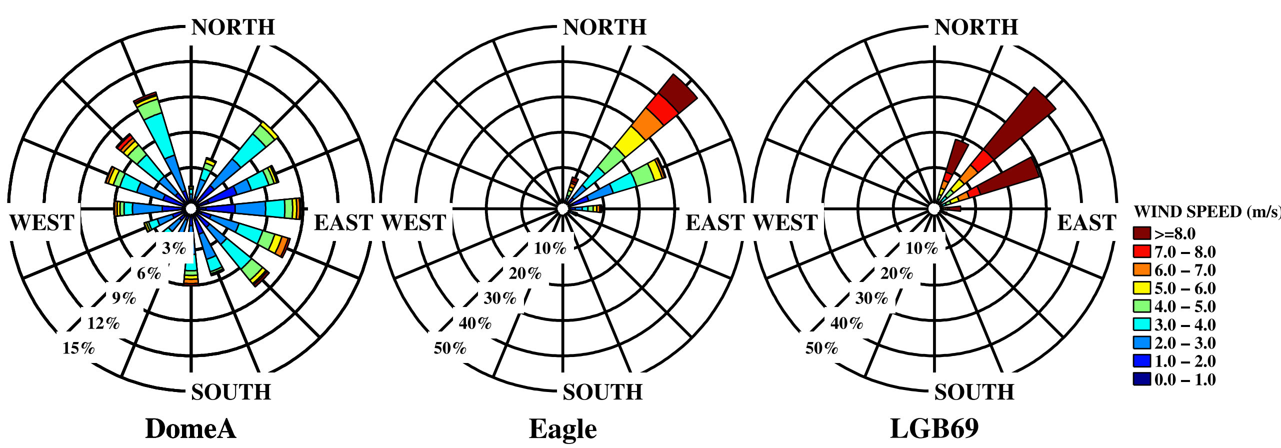

Figure 2. Wind roses at Dome A, Eagle, and LGB69 during austral summer (December–February). The wind directions are divided into 22.5° sectors and wind speeds into 1 m s^{-1} bins.

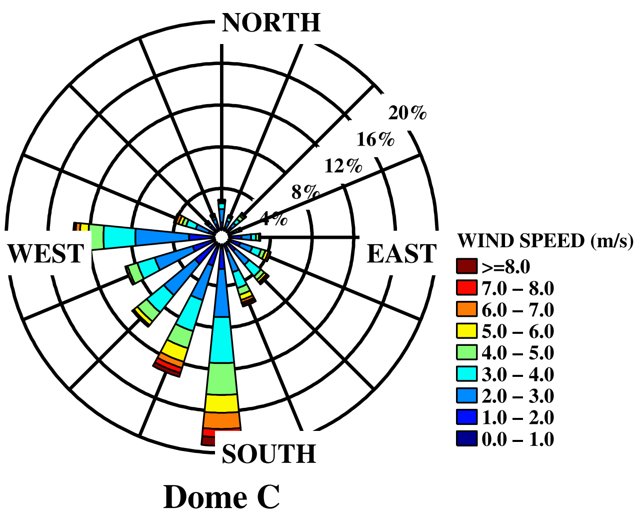

Figure 3. Wind rose at Dome C during austral summer (December–February) based on data dating 2005–2007. The wind directions are divided into 22.5° sectors and wind speeds into 1 m s^{-1} bins.

[12] In contrast to the two lower stations showing a single mode wind rose, the wind rose at Dome A displays a broad distribution with no more than 10% of frequency of occurrence for any wind direction. The lack of preferred wind direction at Dome A, which is distinctly different from those at Eagle and LGB69, indicates that the winds at the top of the Antarctic Plateau are not driven by katabatic forcing as they are at the lower elevations.

[13] The strengths of the wind at these three locations are quite different. At LGB69, the surface winds are strong with a summertime mean wind speed of 8.3 m s^{-1}. Moderate winds are found at Eagle with an average speed of 4.4 m s^{-1}, while at Dome A, winds are much weaker with mean speed only 3.0 m s^{-1}. The wind speed difference between LGB69 and the more interior Eagle site is consistent with the difference in topography that has a much steeper slope near LGB69 (0.4669°) compared to that at Eagle (0.2865°). This decrease of surface wind speed from the coastal perimeter toward the interior of Antarctica was also found in previous studies using observations, diagnostic flow models or climate models [e.g., *Ball*, 1960; *Wendler and Kodama*, 1984; *Parish and Bromwich*, 1987; *van den Broeke et al.*, 2002]. This phenomenon is unique to the Antarctic continent as winds are generally much stronger at high altitudes than those over coastal plains in other continents.

[14] Similar wind speed and direction differences were found between Dome C and a coastal station [*Wendler and Kodama*, 1984]. To compare winds over Dome A with those over Dome C, a wind rose for Dome C is also shown (Figure 3) using data from the same 3-year period. The hourly wind data were downloaded from http://www.climantartide.it. A common feature of winds over the two domes compared to those at lower-altitude/lower-latitude station is the weak wind speeds. Another feature shared by the two domes is the broader distribution in wind direction. However, compared to Dome C where winds are most frequently from the south to west quadrant, Dome A winds are much more spread in direction. To examine whether these differences are caused by different exposures to synoptic conditions, we show the monthly mean values of surface pressure in Figure 4. No systematic annual variation of the pressure is observed. The correlation coefficients of the pressure between these two stations for the 3-year period and for summer (December–February) are 0.74 and 0.88, respectively. The high correlation suggests that Dome A and Dome C are often under the influence of the same synoptic systems and the differences in wind direction distribution between them are unlikely to be caused by different synoptic exposures. Instead, the difference may be attributed to the higher elevation of Dome A and the local topography surrounding Dome C that is lower to the north and east.

3.2. Diurnal Variation

[15] The diurnal variations of the mean summer season (December–February) temperature and wind speed at the 4-m level are shown in Figure 5 for Dome A, Eagle, and LGB69. Also shown in Figure 5 is the vertical temperature difference between the 2- and 4-m levels (T4-T2). As expected, the summer season temperatures clearly display a diurnal cycle. The phase of the diurnal temperature oscillation is similar among the three stations with a maximum temperature occurring at 1000–1100 UTC (1500–1600 local standard time or LST) and a minimum at 2200–2300 UTC (0300–0400 LST). The amplitude of the diurnal temperature oscillation is somewhat smaller at LGB69 (5.9°C) compared to that at Eagle (7.8°C) and at Dome A (6.9°C), which may be a result of the stronger winds at LGB69 that mix the effects of surface heating or cooling over a greater depth. Similar differences in the

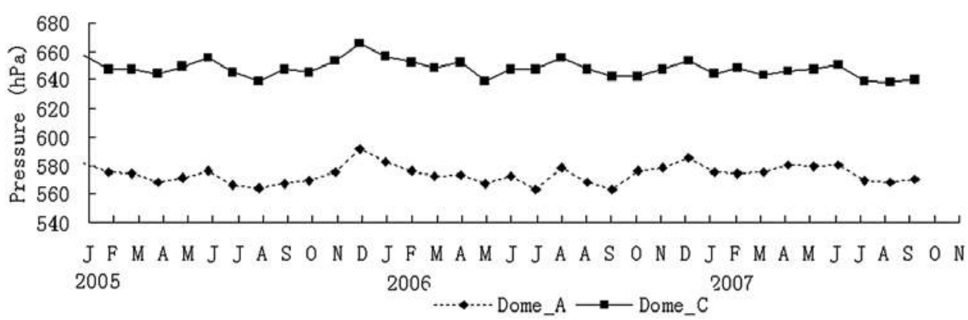

Figure 4. Monthly mean surface pressure at Domes A and C.

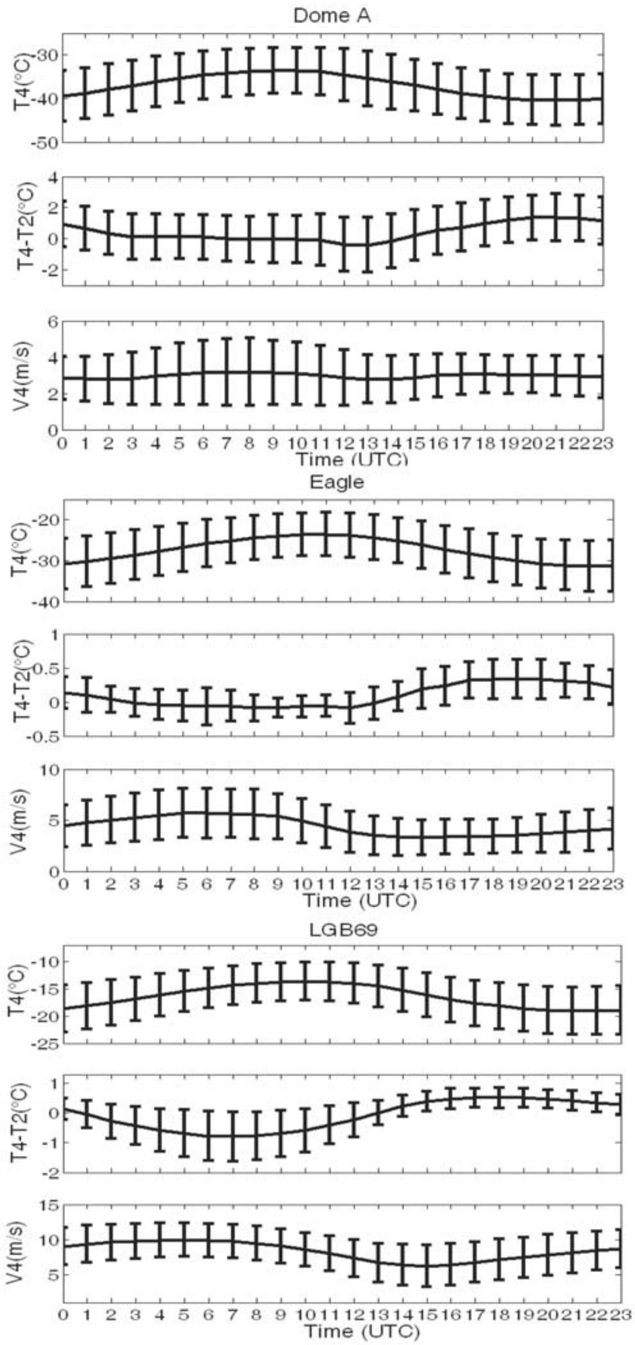

Figure 5. Mean diurnal variations of air temperature and wind speed at 4 m and the temperature difference between 4 and 2 m at Dome A, Eagle, and LGB69 during austral summer (December–February). Error bars represent standard deviation.

amplitude of diurnal temperature variation between Dome C and a costal site were also documented by *Wendler and Kodama* [1984] and *King et al.* [2006].

[16] Wind speeds at Eagle and LGB69 exhibit clear diurnal oscillation. The maximum wind speed at the two stations appears at 0500–0600 UTC (1000–1100 LST) and the minimum around 1500 UTC (2000 LST). The lower wind speed in the afternoon is likely a result of frequent break up of surface inversion (shown below) at these sites, which lead to a weakening of the katabatic forcing in the afternoon. The maximum and minimum wind speeds (9.9 and 6.2 m s^{-1}) at LGB69 are both considerably higher than the corresponding maximum and minimum at Eagle (5.7 and 3.3 m s^{-1}), indicating a decrease of wind speed from the coast toward the interior of the continent. Little diurnal variation in wind speed was observed at Dome A. The wind speeds there remain nearly constant over the diurnal cycle, varying between 2.8 and 3.2 m s^{-1}. The lack of diurnal oscillation in wind speed over Dome A further suggests that winds there are not driven by katabatic forcing that vary diurnally in response to diurnal cycle of insolation.

[17] The differences in lower atmosphere stability and its diurnal variation at the three sites during summer are revealed by the 4- and 2-m level temperature difference (T4-T2) in Figure 5. At LGB69 the near-surface atmosphere is stable (T4-T2 > 0) in the evening and nighttime, while it is unstable (T4-T2 < 0) during daytime with maximum instability occurring around local noon (0600–0800 UTC). A similar pattern of the diurnal variation of vertical temperature gradient is also found at Eagle with slightly weaker instability during daytime. At Dome A there is also a diurnal variation in the vertical gradient of temperature, but the gradient is nearly always positive, indicating the existence of a persistent surface inversion layer over Dome A.

[18] The lack of development of unstable stratification in the afternoon even during the summer season over Dome A is different from the conditions found over Dome C over which a convective boundary layer can develop in the afternoon [*King et al.*, 2006]. Although both sites have very low temperature allowing almost all available energy to be partitioned into sensible heat, the major difference is in the amount of insolation received at the two sites; at ~80 S, the solar insolation received over Dome A is in general insufficient to produce enough sensible heat to break the surface inversion, although a shallow unstable layer may develop for a short period in summer. *Neff et al.* [2008] observed a shallow mixed layer of less than 50 m over South Pole on the basis of observations from late November to the end of December in 2003. The lack of development of convective boundary layer over Dome A may also explain the lack of wind speed oscillation compared to that over Dome C where a distinct diurnal wind speed oscillation occurs with higher wind speed occurring in early afternoon as a result of convective boundary layer growth allowing downward mixing of high momentum air aloft.

3.3. Statistical Properties of the Near-Surface Inversion

[19] The oscillation of the near surface inversion is examined by applying wavelet analysis to the T4-T2 data. Figure 6 shows the periods of oscillation for the three stations. As expected, a clear signal of diurnal oscillation appears in the warm season at all three locations. In addition, an intraseasonal variability with a periodicity of 5–50 days is also found at all three stations. A relatively strong oscillatory signal with period of approximately 10 days appears in the austral winter season at Eagle, but no such signal is found at Dome A and LGB69.

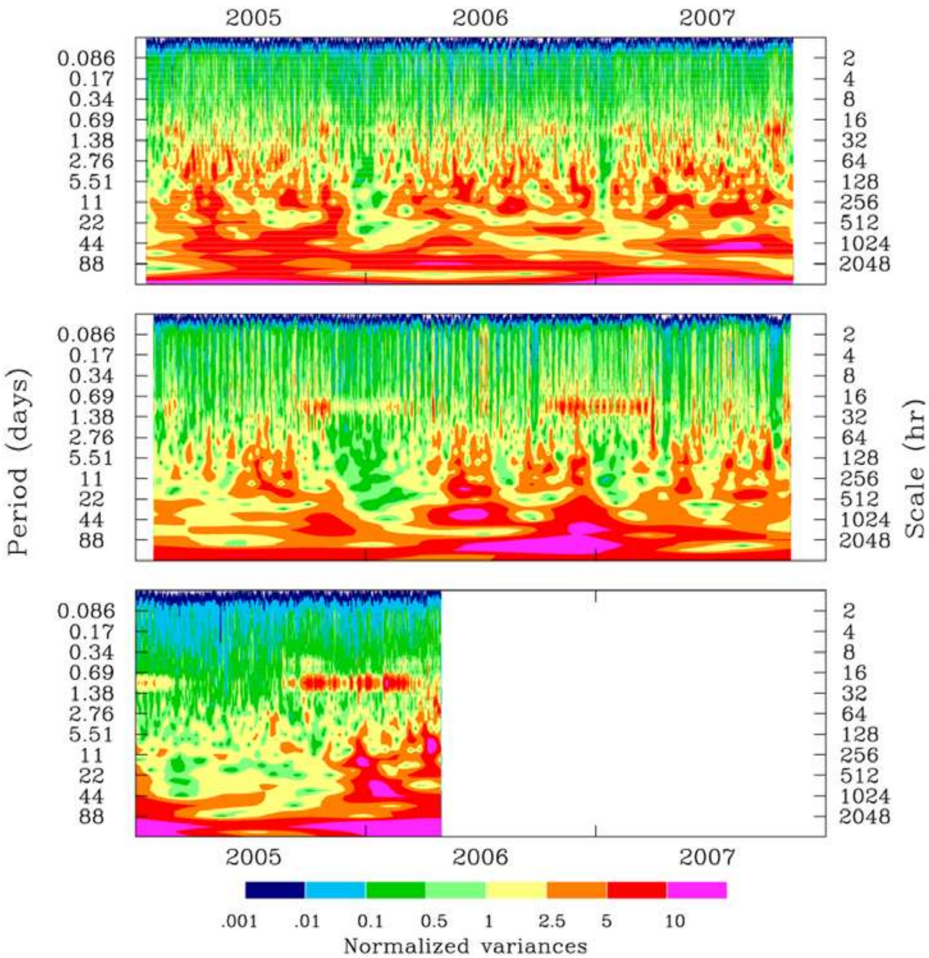

Figure 6. Wavelet spectra for the temperature difference between the 4- and 2-m levels at (top) Dome A, (middle) Eagle, and (bottom) LGB69. Data from January 2005 to November 2007 are used for Dome A and for Eagle, and data from January 2005 to April 2006 are used for LGB69.

[20] A classical spectrum can be constructed by averaging wavelet spectra over time. Similar to the original work by *Mather and Miller* [1966] showing a power spectral analysis of wind speed at four stations from the coast inland to Vostok station, Figure 7 illustrates the globally averaged spectrum normalized with the mean standard deviation for the wavelet spectrum in Figure 6 at the three station along longitude 77°E. Also shown in Figure 7 are the spectra of the 500-hPa geopotential heights calculated using the rawinsonde sounding data from three stations: Davis, Dome C and Amundsen-Scott. Besides the strong diurnal peak (1 cycle/day) at all three surface stations, an annual (0.0027 cycle/day) and a semiannual (0.0055 cycle/day) peak also appear clearly at Dome A and Eagle, but they are less obvious at LGB69 possible owing to the shorter period of data at LGB69. In addition, a spectral peak around 50 days representing an interseasonal oscillation appears at all three surface sites. Similar intraseasonal variation was also found in the surface wind observations at Mizubo (70.70°S, 44.33°E, 2230 m MSL) [*Yasunari and Kodama*, 1993]. The intraseasonal peak and the semiannual and annual peaks are also found in the 500-hPa geopotential height spectra at the three upper-air station sites. The consistency of the spectral peaks in the surface stratification and the 500-hPa geopotential heights suggests that the variations of synoptic-scale conditions are responsible for the observed longer than diurnal periods of oscillations observed in the near-surface stability, which is consistent with the results of *Neff* [1999] about synoptic control of surface variables.

[21] Figure 8 shows the time series of the T4-T2 at Eagle in winter (July–August) of 2005; the time series for 2006 and 2007 are similar to 2005. An unstable stratification tends to appear for short periods of time separated by a period of 10 or more days of stable stratification. The percentage of times when an unstable stratification occurred in winter at Eagle is shown in Figure 9 together with the percentages at the two other stations. At Dome A and LBG69, an unstable condition rarely occurred in the winter season. However, at Eagle, the near-surface atmosphere could become unstable in winter, with the value of T4-T2 even exceeding −1°C at times, although the probability is small (<2%). The strongest inversion appears at Dome A where the inversion strength reached 8°C. It is not clear what would cause the formation of an unstable surface layer at Eagle during austral winter; numerical

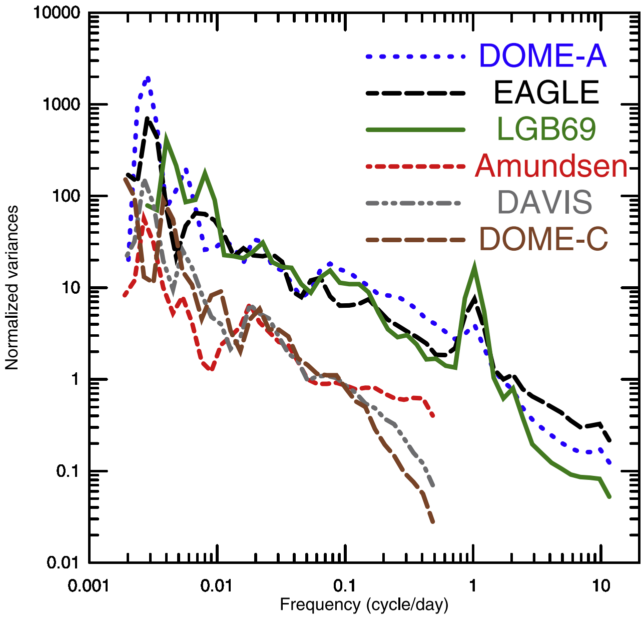

Figure 7. Global spectra for the temperature difference between 4 and 2 m at Dome A, Eagle, and LGB69 and global spectra for the 500-hPa geopotential heights at Davis, Dome C, and Amundsen-Scott. Sounding data were from January 2005 to December 2007.

simulations may be able to help explain this interesting observation.

4. Conclusions

[22] The newly obtained meteorological observations from an AWS at Dome A, the highest elevation in the entire Antarctic continent, are analyzed to understand the mean and the temporal variation of the near surface wind, temperature, and stability and how they differ from the observations at stations with similar longitude, but lower latitude and elevation, and observations from Dome C.

[23] The observations revealed that in contrast to the stations at lower elevation and latitude where strong northeasterly katabatic winds dominant in the summer season, the summer season surface winds over Dome A are much weaker with a mean speed of 3 m s^{-1} and are much more variable in direction. Unlike at lower stations where wind speeds exhibit a diurnal oscillation with weaker winds in the afternoon in response to the weakening of katabatic forcing, wind speeds over Dome A show little diurnal variation. The weak wind speed, the lack of consistency in wind direction, and the absence of diurnal wind speed oscillation all suggest that winds over Dome A are not driven by katabatic forcing.

[24] There is a clear diurnal cycle in near-surface temperature at all locations, although the amplitudes of the diurnal cycle are different. At lower stations, the vertical temperature gradients also exhibit a diurnal oscillation, with development of a convective surface layer around noon and in the afternoon. Over Dome A, however, the near-surface temperature gradient remained positive all day long despite the weakening of the gradient during the day, suggesting the existence of a persistent surface inversion over Dome A even in summer.

[25] The nonkatabatic nature of winds over Dome A is consistent with that found over Dome C where wind speeds are also much weaker and more variable compared to lower stations. However, Dome C is different from Dome A in that the sufficient solar insolation together with the near zero latent heat at very low temperature allows the development of a convective boundary layer in the afternoon during summer, which then leads to an increase in afternoon wind speed and therefore a diurnal wind speed oscillation that is absent from Dome A.

[26] Spectral analysis of vertical temperature gradient using a wavelet transform confirmed a strong diurnal oscillation in near-surface stratification. The spectral analysis also revealed an interseasonal oscillation with period near 50 days in addition to a semiannual and annual oscillation. These variable periods of oscillations in near-surface stability are clearly linked to synoptic variations as the same peaks also appear in the 500-hPa geopotential height spectra.

[27] Finally, although during austral winter, the near-surface atmosphere is almost always stable, short periods of unstable stratification may occur from time to time at Eagle and it is unclear what might have caused this. A more complete understanding of this and other features may be obtained by combining the observations with numerical modeling.

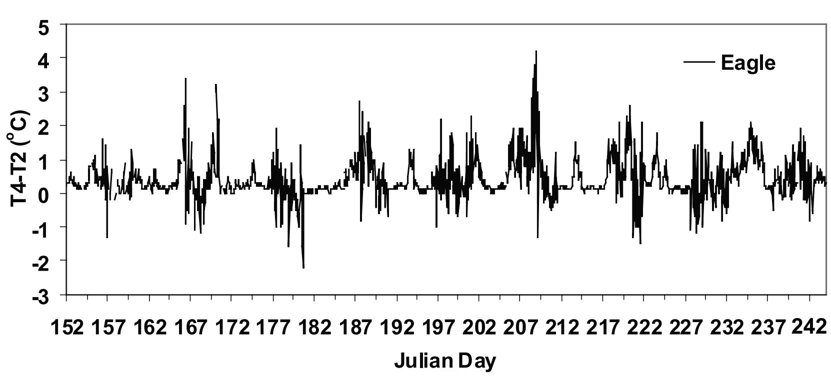

Figure 8. Time series of the temperature difference between the 4- and 2-m levels at Eagle during austral winter (June–August 2005).

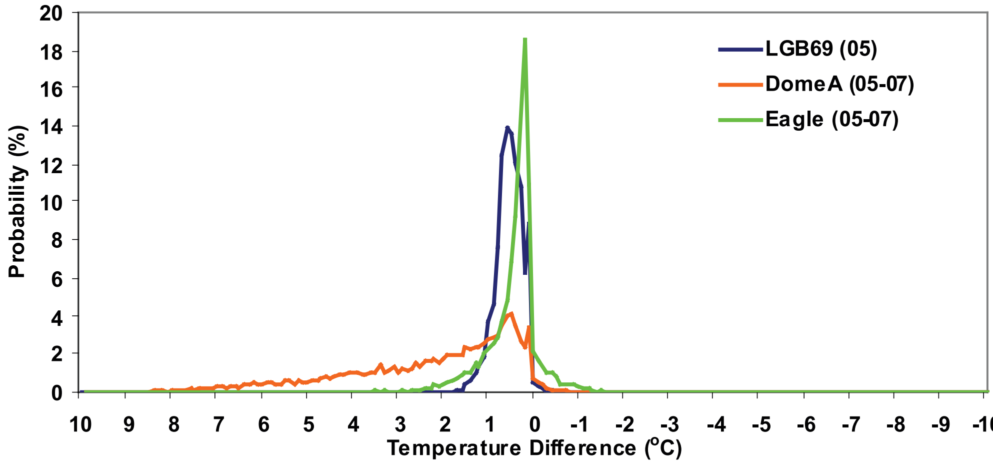

Figure 9. Probability distribution of the temperature difference between the 4- and 2-m levels during austral winter (June–August 2005–2007) at Dome A, Eagle, and LGB69.

[28] Antarctic climate is of critical importance from a global perspective, but the observations in this hostile region are extremely difficult to obtain. Although the data presented here are limited and some of the observed features (e.g., the formation of the unstable layers at Eagle) are not fully understood, the observations provide a basis for validating weather and climate models applied to this region.

[29] **Acknowledgments.** This study was supported by the National Natural Science Foundation of China (40233032) and Ministry of Science and Technology of China (2006BAB18B03 and 2006BAB18B05). Donald Lenschow and Hsiao-Ming Hsu are affiliated with the National Center for Atmospheric Research (NCAR), and M. Zhou was supported by the NCAR Visiting Science Program to spend a summer at NCAR to work on the manuscript. NCAR is sponsored by the National Science Foundation of the United States.

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