Record low surface air temperature at Vostok station, Antarctica

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[1] The lowest recorded air temperature at the surface of the Earth was a measurement of −89.2°C made at Vostok station, Antarctica, at 0245 UT on 21 July 1983. Here we present the first detailed analysis of this event using meteorological reanalysis fields, in situ observations and satellite imagery. Surface temperatures at Vostok station in winter are highly variable on daily to interannual timescales as a result of the great sensitivity to intrusions of maritime air masses as Rossby wave activity changes around the continent. The record low temperature was measured following a near-linear cooling of over 30 K over a 10 day period from close to mean July temperatures. The event occurred because of five specific conditions that arose: (1) the temperature at the core of the midtropospheric vortex was at a near-record low value; (2) the center of the vortex moved close to the station; (3) an almost circular flow regime persisted around the station for a week resulting in very little warm air advection from lower latitudes; (4) surface wind speeds were low for the location; and (5) no cloud or diamond dust was reported above the station for a week, promoting the loss of heat to space via the emission of longwave radiation. We estimate that should a longer period of isolation occur the surface temperature at Vostok could drop to around −96°C. The higher site of Dome Argus is typically 5−6 K colder than Vostok so has the potential to record an even lower temperature.

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1. Introduction

[2] The near-surface air temperature of −89.2°C measured at the Russian Vostok station (78.5°S, 106.9°E, 3488 m above sea level (asl)) on the plateau of East Antarctica (Figure 1) on 21 July 1983 is acknowledged as the lowest temperature ever recorded at the surface of the Earth [*Marshall*, 2007]. Although this record is widely quoted in books, popular articles, and on the World Wide Web, there is very little in the scientific literature on this climatic event. The actual recording of this record low temperature was announced in a Russian publication soon after the event [*Budretsky*, 1984]. However, there has been no investigation into the mechanisms behind its occurrence.

[3] The high, cold plateau of East Antarctica is the major heat sink in the Southern Hemisphere, with the large Equator to pole temperature difference being responsible for the extensive synoptic activity over the Southern Ocean [*King and Turner*, 1997]. While there has been a major surface warming over the Arctic in recent decades [*Overland et al.*, 2008], across the Antarctic the observations show that only the Antarctic Peninsula has warmed significantly over the last 50 years [*Turner et al.*, 2005]. The remainder of the continent has experienced little change in near-surface temperature [*Monaghan et al.*, 2008].

[4] At upper levels, analysis of the 50 years of radiosonde data from the Antarctic suggests that the midtroposphere above the continent has warmed more than anywhere else on Earth during the winter [*Turner et al.*, 2006]. The mechanisms behind this change are not fully understood at present, although it has been suggested that the increase in polar stratospheric cloud that has occurred as stratospheric temperatures have dropped may have played a role [*Lachlan-Cope et al.*, 2009].

[5] While the bulk of the Antarctic has not yet exhibited the large near-surface changes seen in the Arctic, over the next century there is expected to be a substantial surface warming and loss of sea ice as a result of greenhouse gas emissions and reduced springtime ozone loss [*Bracegirdle et al.*, 2008]. Understanding meteorological processes on the Antarctic plateau is therefore important in terms of the broadscale climate of the Southern Hemisphere, since changes in the atmospheric conditions here can have far-reaching climatic consequences. In addition, understanding the meteorology of the plateau is important for the interpretation of the climate signals locked into ice cores, which can provide detailed insight into climatic changes for most of the last million years [*EPICA Community Members*, 2004].

[6] In this paper we present an analysis of the meteorological conditions that led to the record low surface temper-

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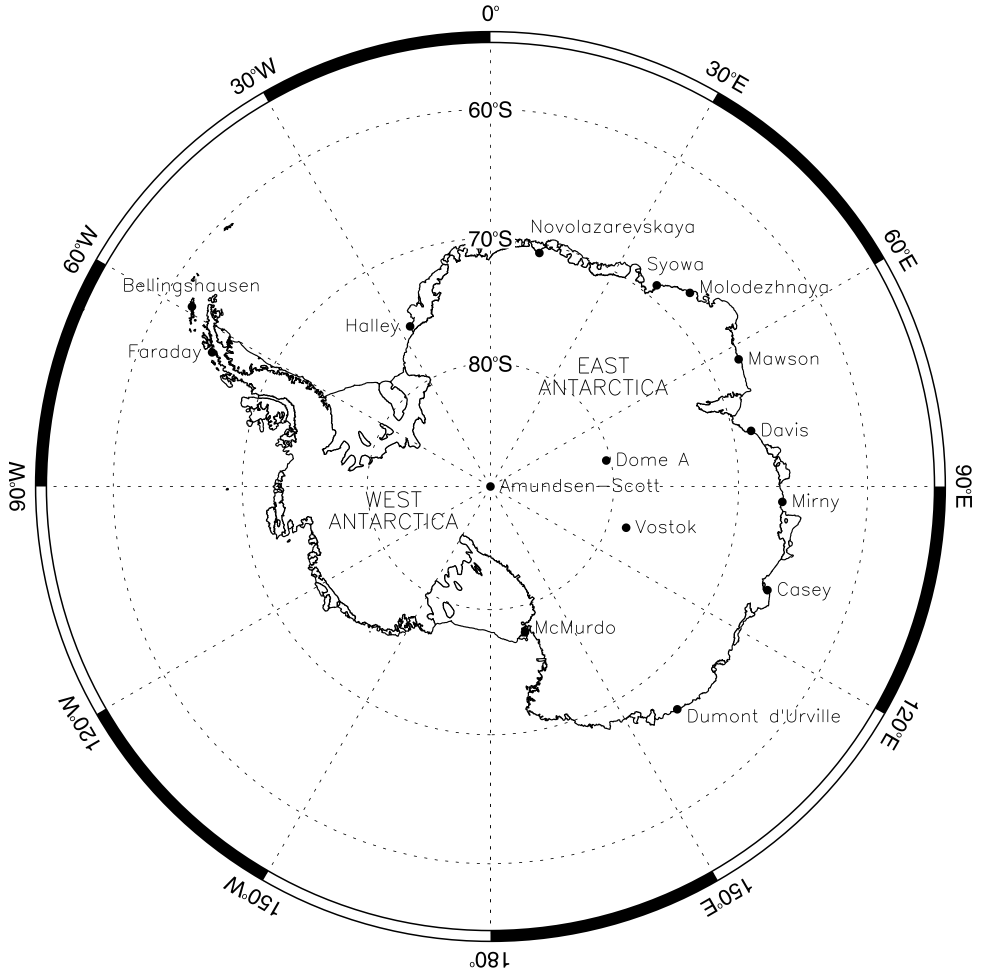

Figure 1. A map of the Antarctic showing the locations referred to in the text.

ature at Vostok and investigate the mechanisms involved that allowed the temperature to drop so low. We first document the data that are available for the region and then provide some background to the climatic conditions at Vostok. We then discuss in detail the atmospheric conditions that led up to the record low temperature and consider how much lower temperatures can get on the high plateau of East Antarctica.

2. Data Availability

[7] Vostok station was established in 1958 during the International Geophysical Year, and surface meteorological observations have been made on a near continuous basis ever since. The measurements were brought together as part of the Scientific Committee on Antarctic Research's Reference Antarctic Data for Environmental Research (READER) project, with the original data being digitized and quality controlled [*Turner et al.*, 2004]. It is these 6 hourly surface meteorological reports of temperature, station pressure, and wind speed and direction, and the daily radiosonde ascents that form the basis of this study. Monthly mean temperature, surface pressure, and wind data have been computed from these observations and are available online via the READER Web site at http://www.antarctica.ac.uk/met/READER/.

[8] There are some gaps in the Vostok climate record. No surface temperature, pressure, and wind speed data are available for the whole of 1962, and there are an increasing number of gaps after 1994. Prior to 1997, wind directions are only available for about 50% of the years. However, we are fortunate in that they are available for 1983. The upper air radiosonde program stopped at the end of 1991.

[9] The original Vostok meteorological register for 1983 was obtained by the Russian Arctic and Antarctic Research Institute, St. Petersburg, and it provided the past and present weather observations, along with the subjective estimates of total, high, medium, and low cloud amount.

[10] The reanalysis data used consist of the 6 hourly fields from the ECMWF 40 year [*Uppala et al.*, 2005] and National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP-NCAR) [*Kistler et al.*, 2001] reanalyses that start in 1957 and 1948, respectively. We are fortunate here in that the record low temperature occurred in the period when satellite sounder data were available, since the analyses before 1979 have been shown to be of poor quality at high southern latitudes because of lack of satellite data [*Marshall and Harangozo*, 2000]. The reanalysis fields over the plateau will not be as reliable as

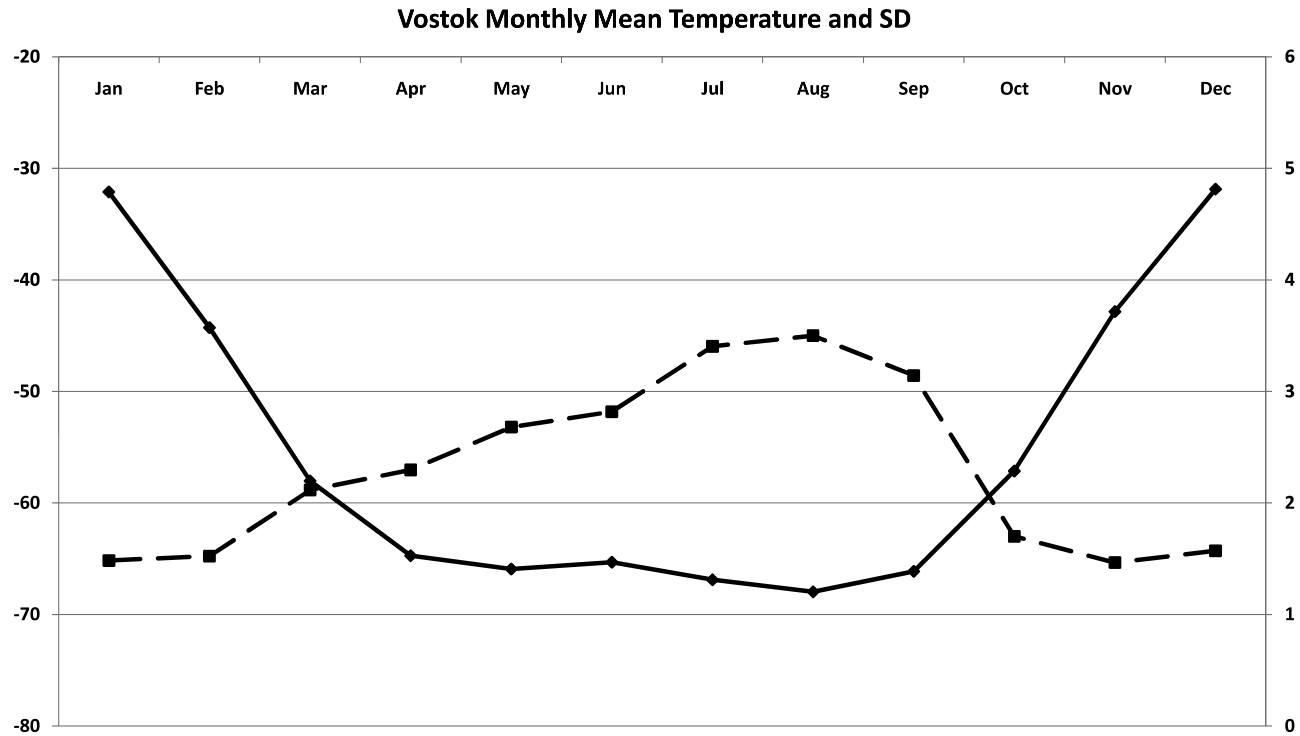

Figure 2. The monthly mean surface temperature (solid line) and standard deviation (dashed line) for Vostok over 1958–2007.

those over the Southern Ocean because of the problems in using satellite sounder data over an ice surface and the high elevation, meaning that a number of the channels will be seeing the surface rather than the atmosphere. However, the Vostok and South Pole radiosonde data were used in the reanalysis process, along with the ascents from the coastal stations. The fields should, therefore, be acceptable to investigate the broadscale atmospheric circulation.

3. Mean Conditions and Variability of Temperature at the Station

[11] With its location high on the plateau of East Antarctica remote from the ocean, Vostok experiences an extremely cold, continental polar climate. Mean temperatures are highest in January and December at about −32°C but drop rapidly through the autumn as a result of the "coreless winter" [*van Loon*, 1967], reaching nearly −65°C by April (Figure 2). Mean temperatures then stay close to this value through the winter, being −66.9°C in July and −68.0°C in August.

[12] Considering the two coldest months of July and August, the highest temperature ever recorded was −34°C on 31 July 1977. Such warm events are associated with amplified Rossby waves [*Sinclair*, 1981] with ridges extending southward into this sector of the Antarctic bringing relatively warm air to the station. An analysis of all July and August temperatures at the station indicates that warm events are more common than exceptionally cold conditions (16% of reports are warmer than 1 standard deviation compared to 11% that are colder by the same amount) (Figure 3), since high temperatures can occur with a short-lived intrusion of warm air, while cold conditions require isolation from maritime air for an extended period.

[13] The standard deviation of the monthly mean temperatures (Figure 2) varies from a minimum of 1.5°C in January to 3.5°C in August. The largest standard deviation is in winter because the temperature difference between the Antarctic plateau and midlatitudes is greatest at this time of year, and changes in the amplitude of the Rossby waves can thus have a major impact on temperatures [*Yasunari and Kodama*, 1993]. In addition, the stronger surface temperature inversion in winter gives a greater potential for large variability in temperature.

[14] The surface wind speed at Vostok is fairly constant over the year with a minimum in December of 4.5 m/s and a semiannual cycle over the year with maxima of 5.5 m/s in April and 5.1 m/s in October. The station is located on a slope, and throughout the year the winds are predominantly from a southwesterly to westerly direction as air flows down the orographic gradient from around the highest part of the plateau at Dome Argus (4083 m asl) (Figure 1). In winter stronger winds are found during intrusions of warm, maritime air when the amplified Rossby waves increase the pressure gradient.

[15] The interannual variability of surface temperatures is large (Figure 4), with July mean temperatures varying from −56.7°C in 1995 to −73.8°C in 1983. The center of the midtropospheric vortex has a climatological position over the Ross Ice Shelf (Figure 5a), and the mean flow toward Vostok is down the slope from the highest part of the Antarctic Plateau. The interannual variability of winter temperatures at Vostok is strongly dependent on the amplitudes and locations of the Rossby waves in the sector of

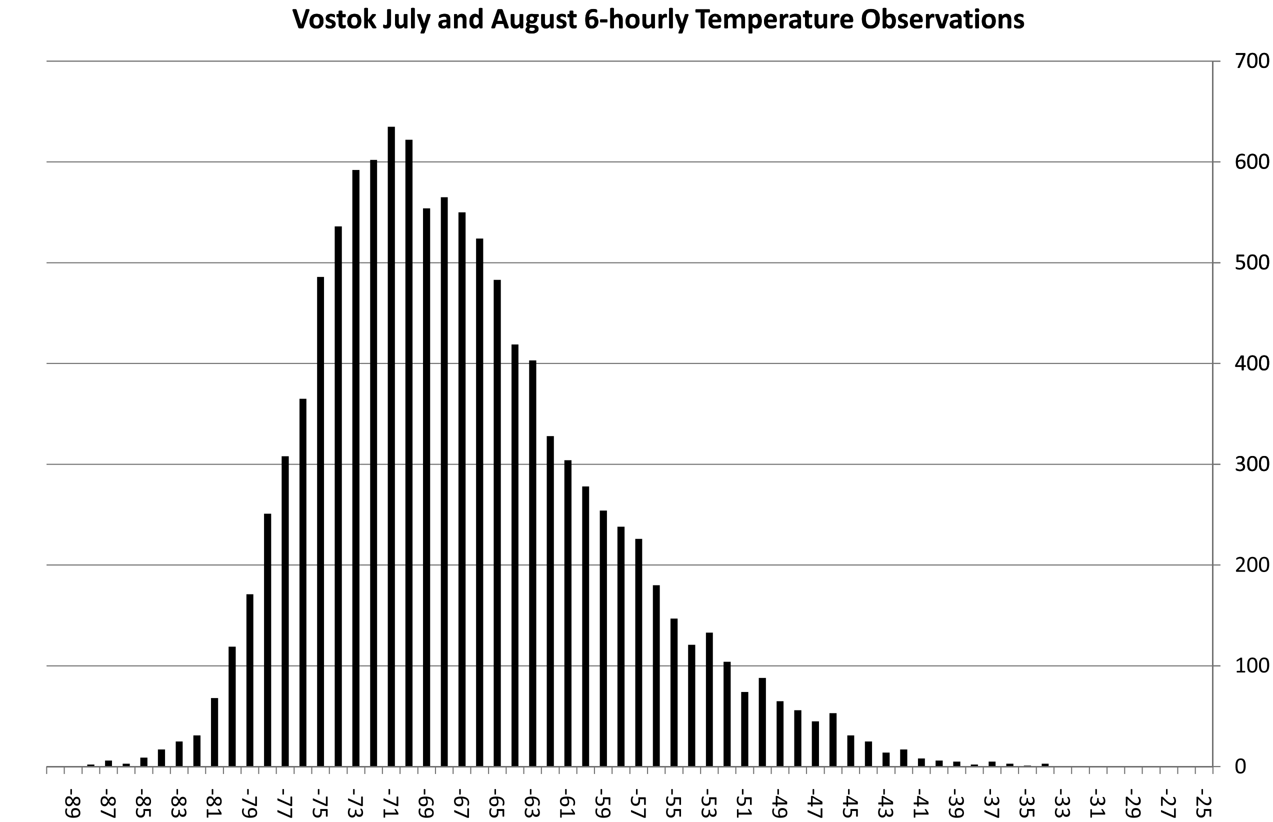

Figure 3. A histogram of Vostok 6 hourly July and August near-surface air temperature observations for 1958–2006.

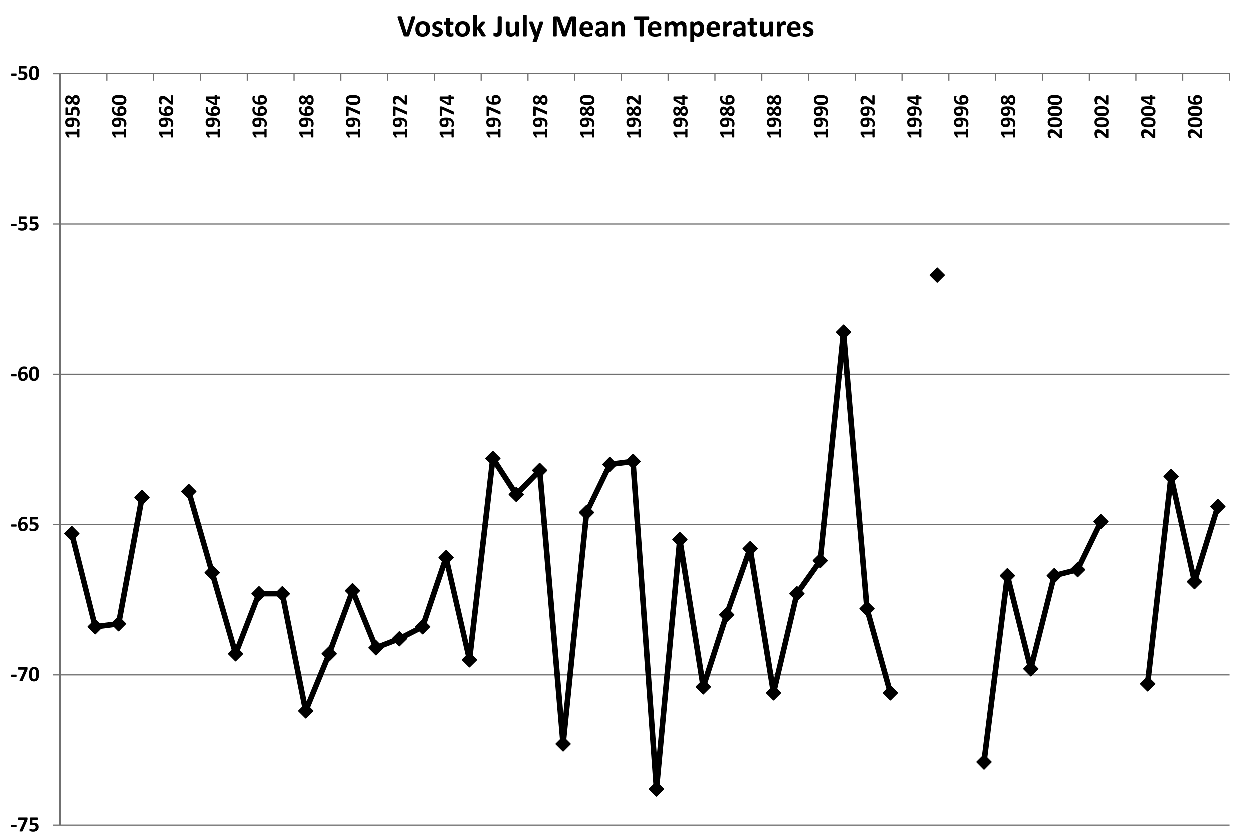

Figure 4. Vostok monthly mean temperatures in July for 1958–2007.

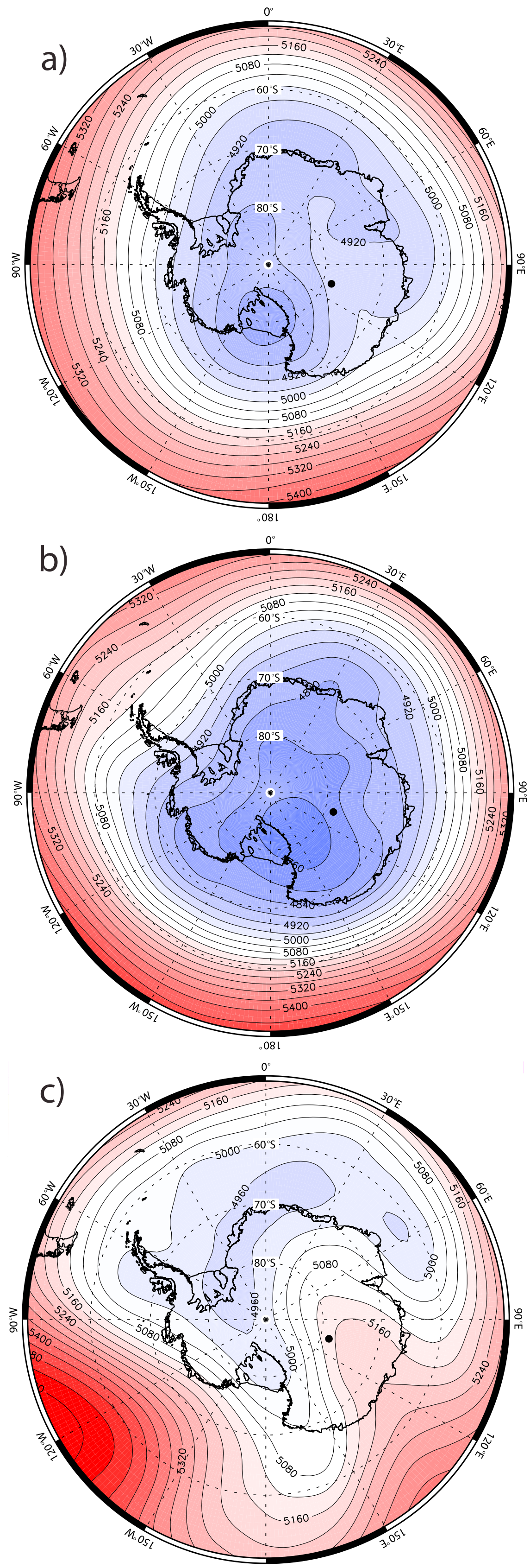

Figure 5. Mean 500 hPa geopotential height fields. (a) Long-term (1979–2007) July mean, (b) July 1983 mean, and (c) July 1995 mean. Contour values are in meters.

East Antarctica from approximately 0–120°E. In 1983 the center of the midtropospheric vortex was displaced toward a location between Vostok and the Ross Ice Shelf, and the Rossby wave pattern around East Antarctica was markedly dampened, minimizing the advection of warm air into this sector of the continent (Figure 5b). The warm conditions in 1995 were a result of an amplified Rossby wave pattern with a ridge over East Antarctica that fed warm air toward Dome Argus and then to the station (Figure 5c).

4. Event of July 1983

4.1. In Situ Data

[16] The Vostok mean monthly temperature for June 1983 was over 3 K warmer than the long-term mean for that month (−65.3°C, Figure 2), and there is no indication of any preconditioning of the atmospheric or surface conditions in the months leading up to the record minimum temperature.

[17] The record low temperature occurred at the end of a near-linear drop in temperature, with 2 m screen temperatures falling by 30.8 K over a 10 day and 6 h period from −58.0°C at 1800 UT on 10 July to −88.8°C at 0000 UT on 21 July (3.48×10^{-5} °C s^{-1}) (Figure 6). This was a large drop in temperature for a location on the Antarctic plateau but by no means the largest in the Vostok record. In August 2001 temperatures at the station fell by 38.2°C in 9 days 6 h, a drop of 4.78×10^{-5} °C s^{-1}, although the final temperature was "only" −79.8°C.

[18] According to the official meteorological register, the lowest temperature of −89.2°C was recorded at 0245 UT on 21 July with the minimum temperature observed via the 6 hourly measurements being −88.8°C at 0000 UT 21 July. This was over a degree colder than the previous lowest temperature in the 6 hourly record of −87.6°C measured at 0600 UT on 24 August 1960.

[19] Over the 10 day period leading up to the minimum temperature the mean wind speed was 5.5 m/s, which is close to the July monthly mean wind speed of 5.3 m/s. However, the wind speed dropped over the 24 h leading up to the minimum temperature, with the speed being only 3.9 m/s at 0000 UT 21 July when the temperature was −88.8°C, which is within the lowest 5% of July wind speed observations (Figure 7).

[20] The station launched one radiosonde each day at 0000 UT. The 500 hPa temperatures from the ascents during July 1983 are shown in Figure 6. During the middle of the Austral winter there is a very strong surface temperature inversion, which the *Phillpot and Zillman* [1970] analysis suggests is of the order of 25 K at Vostok. During the event described in this paper the temperature difference between the surface and 500 hPa at Vostok increased from 20.9 K at 0000 UT on 11 July to 34.7 K at 0000 UT on 21 July. During the period of the surface cooling in July 1983, temperatures at 500 hPa fell from −41.1°C at 0000 UT on 9 July to −55.3°C at 0000 UT on 23 July 1983, with this latter temperature being the fourteenth coldest observation during the period from 1958 to 1991.

[21] The Vostok present weather observations (Figure 8) indicate that there was clear-sky precipitation (diamond dust) intermittently over the period 10–16 July, but that between 1800 UT 16 July and 1200 UT 21 July the observers reported only "sky unchanged," indicating that

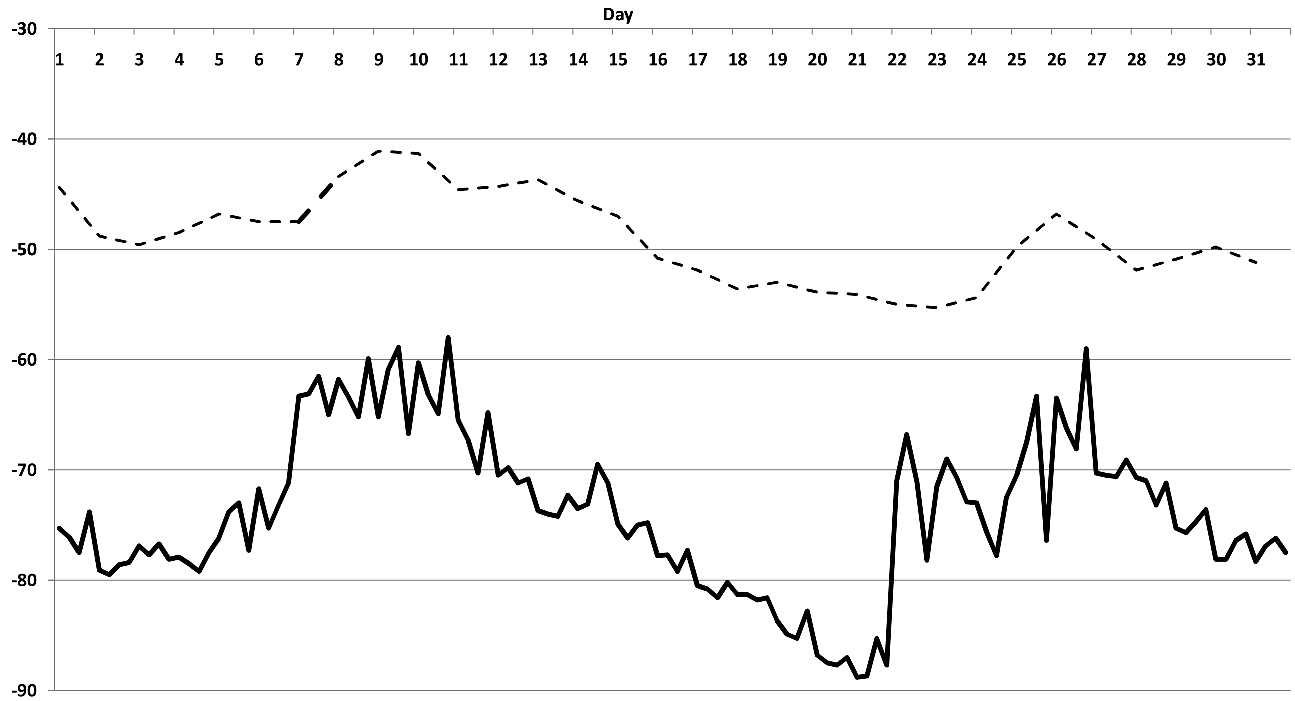

Figure 6. The Vostok surface (solid line) and 500 hPa (dashed line) temperature records for July 1983.

there were no hydrometeors. In addition, the total cloud cover fell to zero tenths over the period from 1200 UT on 16 July to 1800 UT on 21 July (Figure 8).

[22] After the record minimum temperature in the early hours of 21 July, the temperature was still very low at −88.7°C at 0600 UT but rose steadily over the next 24 h to −66.8°C at 0600 UT 22 July, which is close to the monthly mean. During this period the wind speed increased to almost 8 m/s, the cloud cover increased rapidly to 10 tenths, and blowing snow was reported.

4.2. Broadscale Synoptic Environment

[23] Prior to the record low temperature there was a progressive drop in station surface pressure from 625.3 hPa

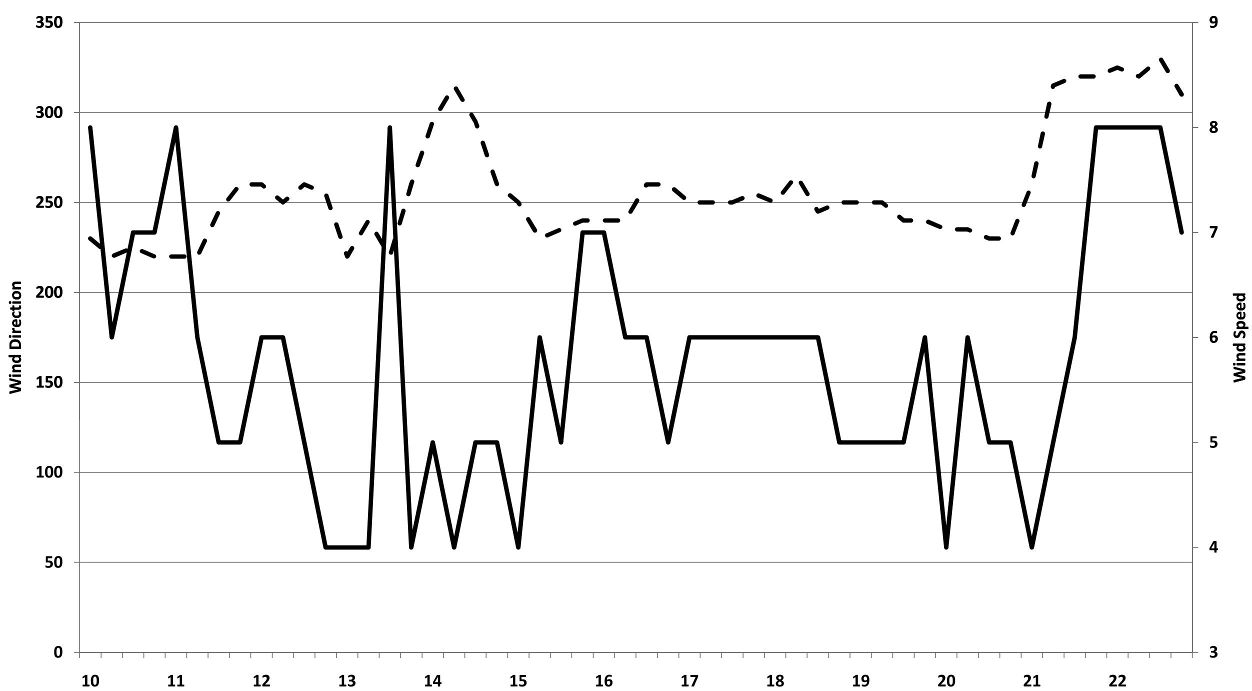

Figure 7. The Vostok surface wind speed (m s^{-1}) (solid line) and wind direction (dashed line) for 10−23 July 1983.

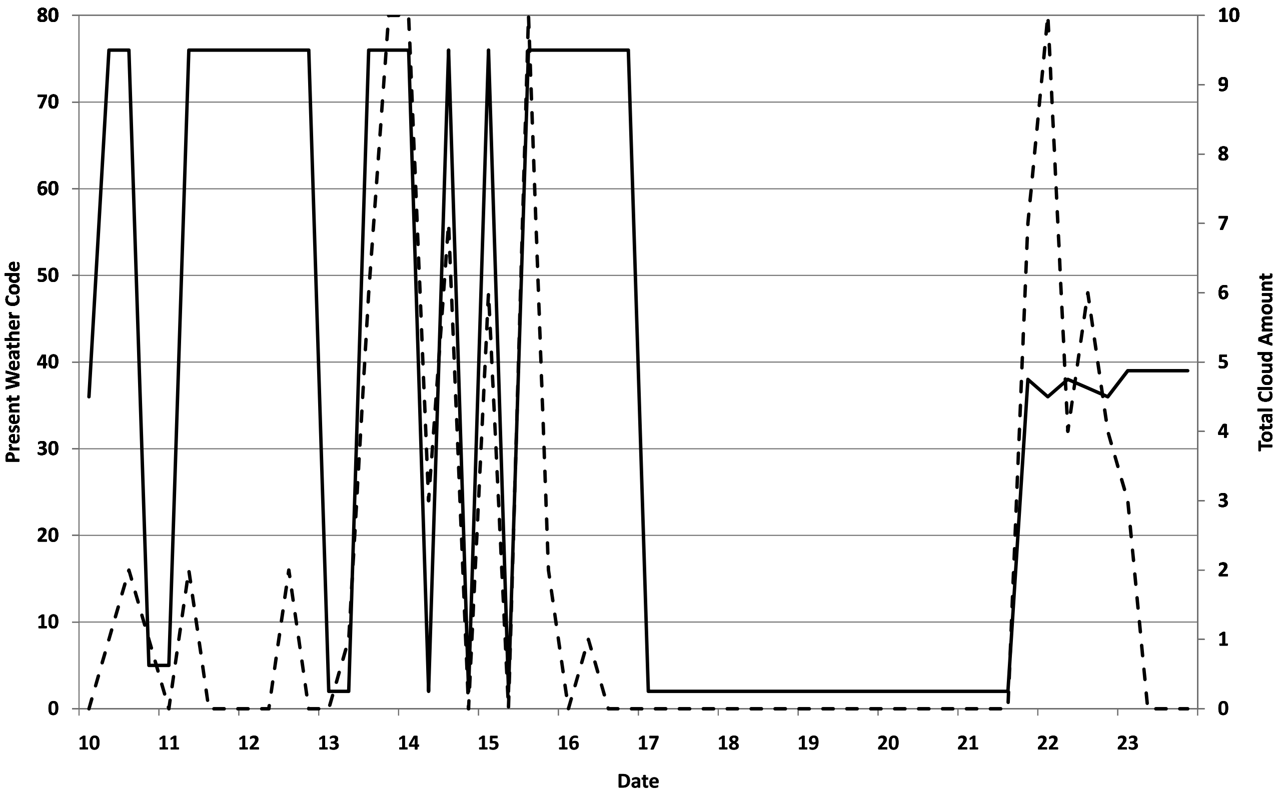

Figure 8. Vostok present weather codes (solid line) and total cloud amounts (tenths) (dashed line) for 10–23 July 1983. The present weather codes are 0 (cloud development not observed or not observable), 2 (state of sky on the whole unchanged), 5 (haze), 36 (slight to moderate drifting snow, generally low (below eye level)), 37 (heavy drifting snow, generally low (below eye level)), 38 (slight to moderate blowing snow, generally high (above eye level)), 39 (heavy blowing snow, generally high (above eye level)) and 76 (diamond dust (with or without fog)).

at 1200 UT, 12 July to 603.0 hPa at 1800 UT, 20 July, before the pressure rose through the time of the minimum temperature and the subsequent period of increasing surface wind speed and blowing snow. The reanalysis fields show that pressure fell at Vostok as the center of the midtropospheric vortex moved from close to its climatological position over the Ross Ice Shelf on 12 July to near to the South Pole, before moving toward Vostok, arriving over the station on 15 July.

[24] The center of the vortex was associated with very cold air and the reanalysis fields suggest that cold air advection at the 500 hPa level over the area of Vostok played a part in the development of the very low temperature at the station, a topic that is discussed in section 4.4. The fields show that 500 hPa temperatures in the vortex core fell from close to −50°C on 12 July to about −56°C on 20 July when the vortex core was close to Vostok (Figure 9).

[25] The radiosonde data from Vostok are in good agreement with the reanalysis fields and reflect the cooling in depth that took place above the station, although the radiosonde temperatures were often a couple of degrees warmer than the analyses since the coldest air was always slightly poleward of the station (Figure 9).

[26] During the 24 h following the minimum temperature event the midtropospheric vortex moved toward Dome Argus so that the air arriving at Vostok came from a north to northwesterly direction. Amplification of a trough close to 150°W played a part in the increase of temperature as it fed mild, maritime air into this sector of the Antarctic, which also led to the increase in cloud cover.

4.3. Interpretation of the Satellite Imagery

[27] Meteorological satellite imagery for this study was obtained from the NOAA Polar Pathfinder Project, with level 1b data of the advanced very high resolution radiometer (AVHRR) on board of NOAA 7 providing coverage throughout the event. This so-called global area coverage data, provided by the NOAA Satellite and Information Service, have a horizontal resolution of approximately 4 km. Around 130 passes cover the area during the period under investigation (up to 10 passes per day). Priority though was given to the passes that had Vostok and Dome Argus toward the center of the passes limiting the number of useful images to only one per day. All results presented in this section are based on measurements at a wavelength of 11 μm.

[28] Figure 10a shows the pass of AVHRR brightness temperatures for 1702 UT on 20 July 1983 draped across a digital topographic representation acquired using satellite radar (1994–1995) and satellite laser (2003–2006) altimetry of the Antarctic [*Bamber et al.*, 2009]. The image shows clearly the very low temperatures experienced at that time on the plateau, with the coldest temperatures shown as dark blue. An enlargement of the area around Vostok is

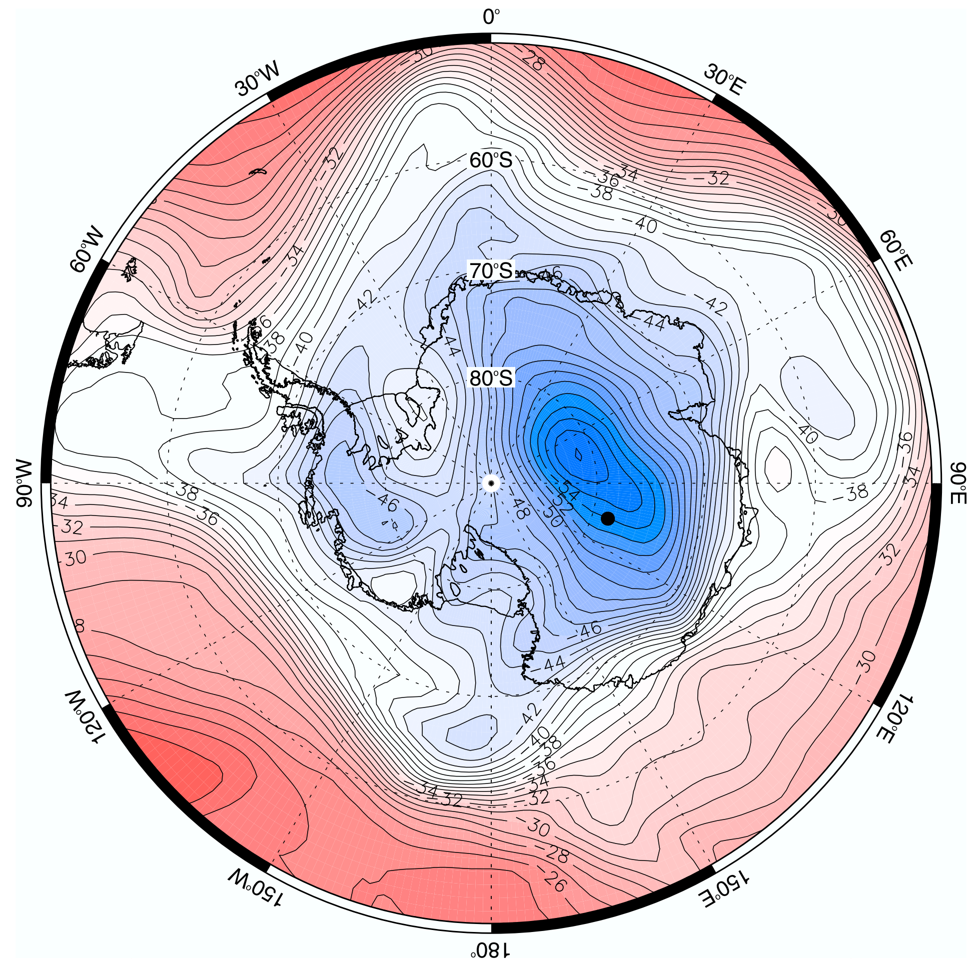

Figure 9. The 500 hPa temperature analysis for 20 July 1983 from the ECMWF reanalysis.

shown in Figure 10b. This shows clearly the surface signature of Lake Vostok [*Oswald and Robin*, 1973], which is the largest of the Antarctic subglacial lakes. The lake is apparent as a "ledge" on the slope down from Dome Argus, which was detected in satellite radar altimeter data [*Ridley et al.*, 1993] and is visible in the Antarctic digital topography. In the thermal infrared imagery it appears as a striking, elongated cold signature extending right from the location of Vostok station. As air descends down the slope from Dome Argus, there is turbulent mixing resulting in relatively higher temperatures on the slope compared to the "ledge." However, as the air encounters the gentler topographic gradient, it slows down, and the reduced mixing leads to lower skin temperatures.

[29] The satellite imagery confirms that during the low temperature event no clouds were present in the immediate vicinity of Vostok station, which is in agreement with the subjective in situ observations. In addition to visual inspection of the 11 μm brightness temperatures, the difference between the 11 and 12 μm data was examined, which is a good test for the presence of semitransparent cirrus [*Yamanouchi et al.*, 1987]. This also indicated cloud-free conditions at Vostok. However, to the west of the cold ledge signature in Figure 10b the red linear feature corresponds to cloud.

[30] To examine the skin temperatures during the event in more detail, the spatial mean of the surface temperature in a 40 km $\times$ 40 km area around Vostok was extracted. These are shown in Figure 11, along with the temperatures at the pixels closest to Vostok and Dome Argus, and the 2 m screen temperatures from Vostok. We obviously have no in situ temperature observations for Dome Argus.

[31] Generally, the in situ 2 m air temperatures and the brightness temperatures measured by the satellite agree very well. The good agreement between the spatial mean of the brightness temperature and the values retrieved for the respective pixels closest to Vostok shows that these individual pixels are valid representations of the area. For most of the time the observed air temperature was higher than the temperature measured by AVHRR. This reflects cloud-free situations in which the satellite actually "sees" the surface. Under such conditions the actual surface as "seen" by the satellite is 2°C–4°C colder than the 2 m air temperature. In cases where the temperature derived from the satellite measurements is higher than the in situ measurement, clouds were present, so satellite measurements represent the cloud top temperature rather than the surface skin temperature.

[32] Over the days leading up to the extreme event on the 21 July the satellite-derived surface temperatures show a

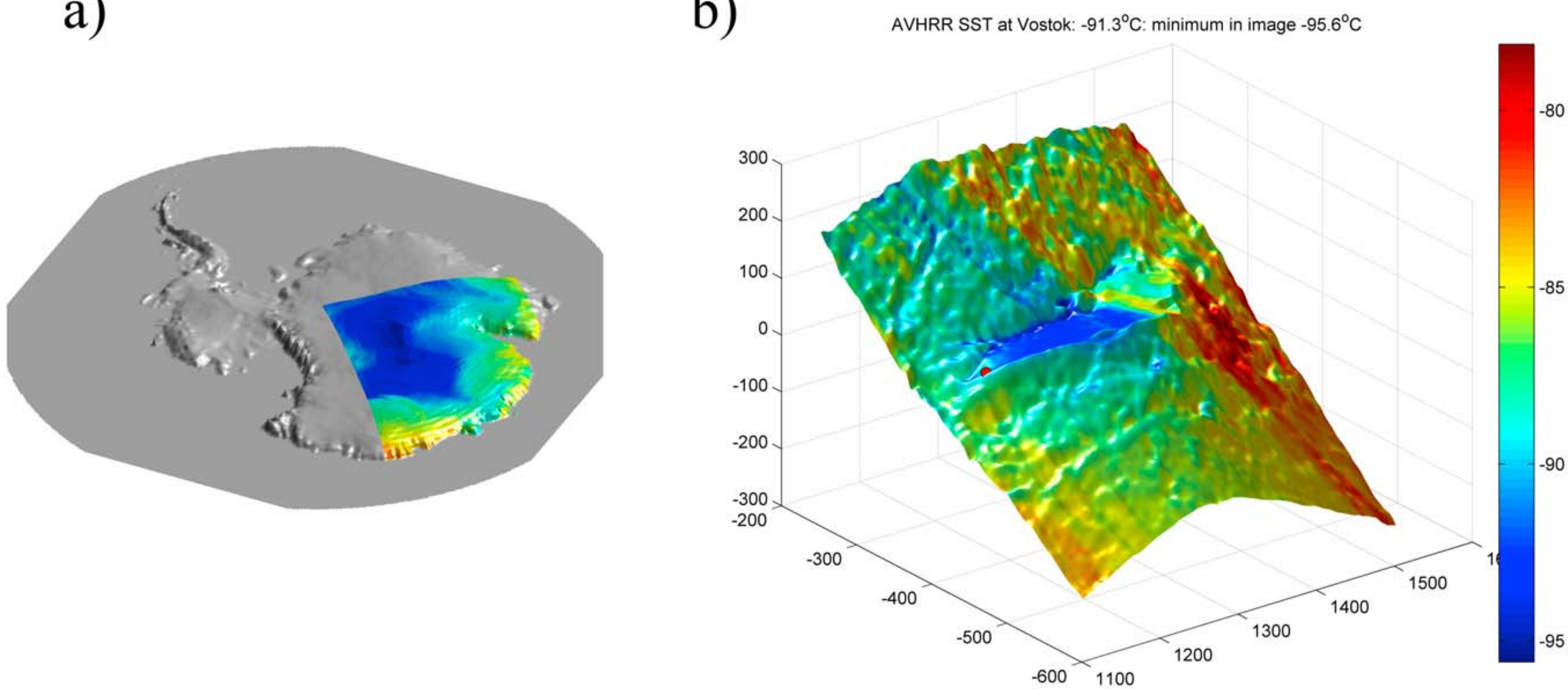

Figure 10. NOAA 7 AVHRR 11 μm brightness temperatures at 1702 UT on 20 July 1983 draped across a high resolution digital orography for (a) East Antarctica and (b) the area around Vostok. Note the imagery for the limited area has been enhanced to highlight the regional temperature variations. The horizontal scale is given in kilometers and vertical scale in meters. The temperature scale is degrees C. The location of Vostok Station is marked by a red dot, and the area of ice sheet floating on the Vostok Lake appears as a near-horizontal ledge on the ice sheet surface. The coldest temperatures appear to occur within the flatter portions corresponding to the Vostok Lake area, with the actual minima within pockets at the southern side of the lake where the descending ice-flow generates a dip before readjusting to the zero-shear zone over water. In these zones, surface wind shear would be minimal, with associated minima in sensible heat flux.

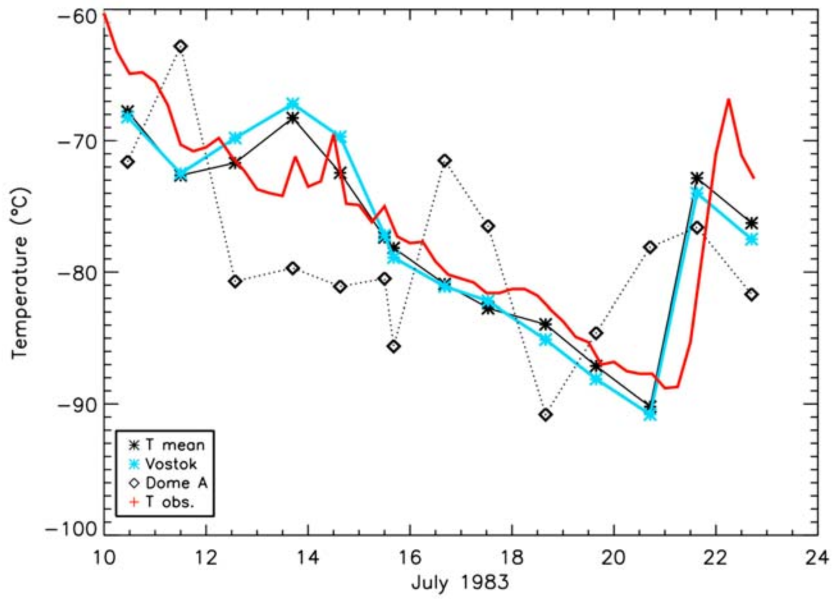

Figure 11. Temperatures at Vostok and Dome Argus over the period 10–23 July 1983. Vostok in situ 2 m screen temperatures (red line). Satellite skin temperatures for a 40 km × 40 km area around Vostok (black solid line). The satellite skin temperature at the closest pixel to Vostok (blue line). Satellite skin temperatures for a 40 km × 40 km area around Dome Argus (black dotted line).

very similar cooling rate to the in situ air temperature. Between midday 14 July and midnight of 21 July the 2 m air temperature dropped by 19.3 K, a cooling rate of 2.9 K d^{-1}. The brightness temperature around Vostok decreased by 17.7 K between the afternoon satellite passes on 14 and 20 July. The beginning and end of this period of steady cooling were flanked by the occurrence of low clouds, as can be seen in the records of cloud observations (Figure 8). This presence of cloud also explains the relatively higher temperatures measured by the satellites prior to the onset of the cooling.

[33] Despite the generally very similar environmental conditions, temperature values retrieved for pixels close to Vostok and Dome Argus differ largely due to the influence of the regionally inhomogeneous cloud cover. This is especially the case on 15 and 16 July, when persistent clear sky led to a further decrease in surface and air temperature at Vostok, while cloud in the area of Dome Argus resulted in an increase of 14 K in the temperature measured by satellite.

[34] Over the cloud-free period leading up to the minimum temperature event the average difference between the satellite-derived surface temperature and measurements of the 2 m temperature was 2.7 K. This agrees well with results of *Comiso* [2000] who found a standard deviation of about 3°C between in situ air temperature measurements and surface temperatures derived from infrared satellite data.

[35] Cloud-free situations allow a comparison between satellite-derived temperature data at Dome Argus and Vostok, but the period analyzed in this study is too short to reflect any long-term conditions since cloud at one site or the other prohibit a meaningful intercomparison. However, cloud-free conditions at both Vostok and Dome Argus on 15 and 18 July suggest that the skin temperatures at the two locations differ by about 5–6 K, which corresponds very well with the temperature difference to be expected given the elevation difference assuming a dry adiabatic lapse rate of 9.8 K km^{-1}.

4.4. Mechanisms Responsible for the Very Low Temperature at Vostok

[36] Temperature changes at the height of the standard meteorological observation (2 m) can be considered via two key equations: the surface energy balance (SEB) equation

$$H + H_\lambda + L\downarrow + L\uparrow + S\downarrow + S\uparrow + G = 0, \qquad (1)$$

and the prognostic equation for atmospheric temperature,

$$\frac{\partial \theta}{\partial t} = -\frac{\nabla \cdot \mathbf{L}}{\rho C_p} - \frac{\nabla \cdot \mathbf{H}}{\rho C_p} - \mathbf{u} \cdot \nabla \theta. \qquad (2)$$

In equation (1), H is the sensible heat flux, H_λ is the latent heat flux, G is the snow heat flux, L is the longwave radiation, S is the shortwave radiation, with arrows denoting the direction of radiative fluxes, and all referring to the vertical component of the flux. The sign convention is downward positive for all terms; that is, $L\uparrow$ and $S\uparrow$ are necessarily negative. Note that only the vertical components of the fluxes are considered, as the horizontal gradients of these fluxes are assumed to be relatively small.

[37] In equation (2) θ is the potential temperature; t is time; $\mathbf{L}$ is the longwave heat flux vector, in W m^{-2}; $\mathbf{H}$ is the sensible heat flux vector, in W m^{-2}; ρ is the air density; C_P is the heat capacity of air at constant pressure; and $\mathbf{u}$ is the wind vector. The first two terms on the right-hand side are the heat flux divergence terms, and the third term is the thermal advection term. Note that this last term includes horizontal and vertical advection.

[38] Generally, the literature assumes that the observed 2 m temperature is identical to the surface temperature; hence, station temperature is governed solely by the SEB equation. We highlight the need for the prognostic equation for three reasons. (1) The thermal link between the surface and the 2 m temperature is via turbulent heat exchange, and the possibility of a temperature change at the 2 m level being due to advection cannot be instantly discarded. (2) Within the SEB equation, $L\downarrow$ is governed by the optical depth and absolute temperature of the overlying air mass, and achieving a very small $L\downarrow$ requires a low temperature aloft. (3) Low absolute temperatures throughout the overlying air mass can be achieved by either longwave heat loss, sensible heat loss, horizontal advection of cold air, or vertical ascent of a stable stratified column. In summary, equation (2) governs $T(z)$ and therefore $L\downarrow$. $L\downarrow$ then governs the evolution and partitioning of the SEB, and the SEB then links to T(2 m) via equation (2) again.

[39] Considering first the conditions in the air mass over Vostok, we note that the Vostok radiosonde data for 500 hPa show a decrease in temperature of 12.8 K (1.16 K d^{-1}) for the 11 day period 10–21 July. The ERA-40 reanalysis fields indicate that at the same level above the location of the station the temperature fell by 11.6°C over the same period and are therefore in reasonable agreement with the Vostok radiosonde ascents. This is not surprising since the Vostok ascents were assimilated into the reanalysis scheme.

[40] **H** is governed by the turbulent exchange of air parcels, and in the free atmosphere above the boundary layer (and especially under stable stratification), such parcel exchange is minimal. We, therefore, assume that the divergence in **H** will be negligible.

[41] The divergence of radiation within the column, $\nabla \cdot \mathbf{L}$, was determined from the radiosonde temperature profile and a radiative transfer model, [*Key and Schweiger*, 1998]. This indicated that throughout the period, there was cooling of the air column of $\sim\!-1$ K d^{-1} between 1 and 10 km.

[42] The horizontal thermal advection, $\mathbf{u} \cdot \nabla_h \theta$, was derived from the ERA-40 500 and 300 hPa surfaces and indicates that there was initial warming of the air column above Vostok of ~2 K d^{-1}. Reducing with time until after 16 July, there is near constant cooling of $\sim\!-2$ K d^{-1}.

[43] The mean ERA-40 wind fields for the 10 days preceding 21 July 1983 show vertical velocity, $w(z) = \mathbf{k} \times \mathbf{u}$ to be small over Vostok at all levels, except near the surface, in comparison to general descent observed over sloping terrain toward South Pole or toward the coast. The 10 day average $w(z)$ at 500 hPa was less than 1 cm s^{-1}, but this is at the limit of the resolution of the model. The radiosonde data show that during the 10 days prior to 21 July 1983, the mean vertical potential temperature at this level, $\partial\theta/\partial z$, was fairly constant at 6.7 ± 1.5 mK m^{-1}. With uncertainty in the sign of the vertical wind, but assuming a maximum of 1 cm s^{-1}, this gives a maximum warming or cooling rate of 7 K d^{-1}.

[44] The magnitude in the uncertainty in the vertical advection term therefore swamps the other terms in equation (2), due to the strong stability of the atmosphere over Vostok in winter and the uncertainty in vertical winds. A thorough analysis of the ERA-40 diagnostics may explain the exact mechanism for the initial formation of the unusually cold vortex core, but this is outside the scope of this paper. For our analysis of the observed surface cooling, only the radiative behavior of the air column above the station is required, which is well restrained from the radiosonde data.

[45] As discussed in section 4.2, the center of the vortex moved from over the Ross Ice Shelf to close to the station during the period preceding the record low temperature. An analysis of the ERA-40 temperatures shows that the lowest temperature in the vortex core was −57.4°C, which occurred at 0600 UT on 20 July. At this time the vortex core was close to Vostok but not exactly over the station; hence, the lowest temperature recorded by the radiosonde ascents was a couple of degrees higher. Nevertheless, the 500 hPa temperature of −57.4°C was the fifteenth coldest in the 1979–2001 segment of the ERA-40 data set. It should be noted that the core of the vortex became colder immediately after the end of the 1983 event, with −57.9°C occurring at 0000 UT on 23 July, which is the eighth coldest temperature in the ERA-40 record. The coldest 500 hPa temperature in the period 1979–2001 was −59.4°C and occurred at 0000 UT on 23 June 1982.

[46] Regarding the temperature actually recorded at the surface, we again refer to the right-hand side components of equation (2), but in this case concentrating on the advective and divergence terms close to the surface. Throughout the event the surface winds at Vostok were mainly from a direction of 250° (Figure 6) and therefore down the slope from Dome Argus. The role of advection in lowering the temperatures at Vostok was considered via the cross section of satellite-derived skin temperatures along the line from Dome Argus to Vostok. This shows that while the temperatures increased down the slope, the potential temperature had no overall trend, indicating that advection played no significant part in the surface cooling at Vostok, which for the 10 days preceding the record low temperature, decreased at a rate of 3.0 K d^{-1} (3.47×10^{-5} K s^{-1}).

[47] With the advective term negligible, the observed surface cooling must be solely due to changes in components of the surface energy balance. Some simplifications may be made. The temperature was recorded on 21 July 1983 during the polar winter when S was 0. H_λ can be neglected because of the very low temperatures encountered; even at saturation ($RH_{\rm ice}$ = 100%) the associated saturated vapor pressure ensures minimal evaporation rates [*King and Anderson*, 1994]. Because of the near unity of the snow emissivity in the infrared, outgoing longwave radiation can be accurately inferred from the snow surface temperatures:

$$L\uparrow = -\sigma T^4. \tag{3}$$

The snow heat flux at the surface, $G_{z=0}$, can be estimated from

$$G = -k_s \left.\frac{\mathrm{d}T}{\mathrm{d}z}\right|_{z=0}, \tag{4}$$

where k_s is the thermal conductivity of snow and dT/dz is the temperature gradient at the surface. An estimate of dT/dz in the snow can be derived from the time series of the snow surface temperature and a one-dimensional (1-D) thermal diffusion model, and assuming typical values of surface

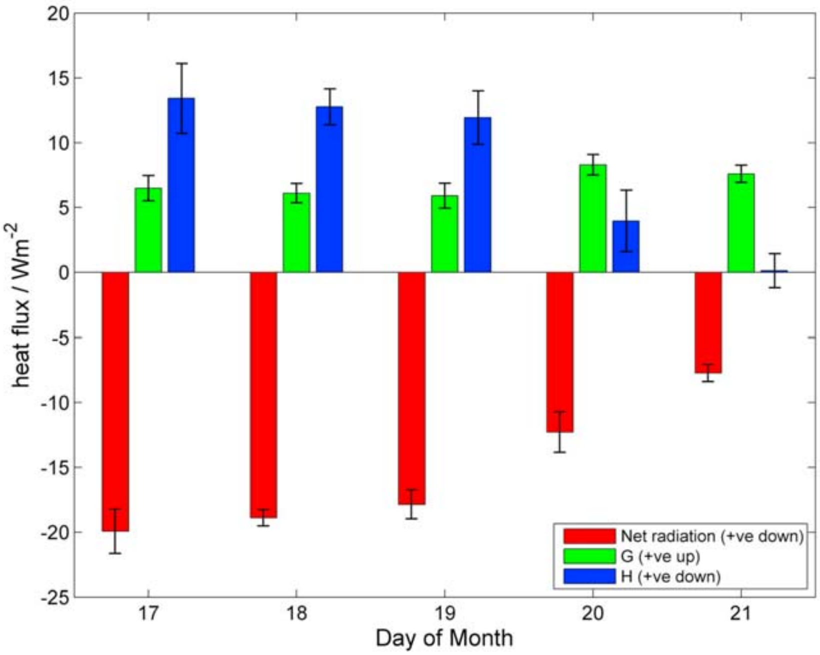

Figure 12. Surface energy balance components for the 5 days preceding the record event. The net radiation gradually decreased due to a cooling snow surface, while the snow heat flux was constant until 20 July 1983. On 20 July 1983 and subsequently, stratification of the boundary layer, coupled to the flat terrain, generates lamination of the flow, and sensible heat flux collapsed. Surface cooling was maintained for a further 2 days. Extrapolation by eye indicates cooling would have ceased by 22 July 1983 in any event.

thermal diffusivity, κ_s, of 6.8×10^{-7} m^2 s^{-1} [*Weller and Schwerdtfeger*, 1968]. The snow surface temperature is assumed to be identical to the 2 m air temperature obtained from the meteorological register. There will inevitably be some errors in the estimate of G due to gradients in the temperature over the lowest 2 m of the atmosphere.

[48] The downward longwave radiation was computed from the daily radiosonde ascents made at 0000 UT each day using the Streamer radiative transfer model [*Key and Schweiger*, 1998]. In accordance with the surface observations for the period 17–21 July the model was set up to assume no cloud cover. With no turbulence sensors, or even thermal gradients measured, the sensible heat flux, H, has been computed as the residual of the other terms.

[49] The three components H, G, and the net radiation (Rn) are shown on Figure 12 as a comparative bar plot, with an estimate of uncertainty overlaid as error bars. The behavior of the magnitudes and partitioning are now apparent.

[50] The main external forcing of the surface energy balance was the downwelling longwave radiation. During the 5 days, the overlying atmosphere close to the core of the vortex was very cold and cloud free and hence provided minimal radiative heat to the surface. Although the snow was also cold, the radiation from the snow exceeded that absorbed from the sky, and the snow, therefore, cooled. The cold and cooling surface also extracted heat, via the sensible heat flux term, from the near-surface atmosphere. In the absence of horizontal advection, this cooling would result in the development of a surface temperature inversion; that is, the boundary layer would become stratified. This situation, of cooling surface and cooling air, progressed through 16, 17, and 18 July. However, this trend could not be sustained; the snow was gradually tending toward radiative equilibrium with the sky. With heat arriving at the surface via the sensible heat flux, the snow should eventually reach equilibrium at some temperature in excess of the effective sky temperature. An estimate based on the fluxes from 16–18 July would give this equilibrium snow surface temperature as approximately −83°C (assuming heat fluxes of L↓ = 55 W m^{-2}, H = 12 W m^{-2}, and G = 6 W m^{-2}). The cause of the final cooling during 20 and 21 July can be inferred from the behavior of the snow heat flux, which increased for these last 2 days even though the magnitude of Rn was getting smaller. It would appear that the sensible heat flux collapsed on these final days, due, we presume, to the "laminarization" of the boundary layer. This term refers to the effect of stratification reducing the strength of the turbulence for a given wind shear (which is the vehicle for sensible heat flux). The subsequent reduction in heat flow to the surface enhanced surface cooling, and this positive feedback resulted in enhanced turbulent suppression, conceptually to the point where all turbulence ceases, and the flow is laminar. In reality, there remains residual, if sporadic, turbulence, which maintains the vertical temperature structure near the surface [*Anderson*, 2009], and H becomes small (~1 W m^{-2}) but not actually 0.

[51] With the suppression of turbulence, the surface continued to cool, and by the 21 July, H was near zero; extrapolation by eye implies that, within another 24 h, Rn would also be 0, at which point surface cooling would cease, at an equilibrium temperature of just above −96°C. There would be a residual temperature gradient within the snow for some time, even without further cooling, which could maintain the surface perhaps a few Kelvin elevated from the effective sky temperature.

[52] This behavior of the SEB partitioning, with a near collapse of the sensible heat flux behavior, is only possible on flat terrain; were the area to be sloping, drainage currents set up by the cooling and densification of the near-surface air would generate katabatic winds, which would maintain the turbulence and, hence, *H*.

5. Discussion

[53] The record low temperature at Vostok station occurred in near-optimum conditions for cooling at the station. A cold air mass with little cloud cover had moved over the area bringing near-record low temperatures at the 500 hPa level, resulting in strongly reduced downwelling longwave radiation. Importantly, the almost circular flow pattern around the station for an extended period minimized the thermal advection toward the station so that the heat lost to space by longwave emission was not replaced.

[54] It is interesting to consider further how low the surface temperature could get at the station with a colder air mass and a more extended period of isolation from maritime air. The Vostok radiosonde record includes 13 observations of 500 hPa temperatures that were lower than during the event in July 1983. However, none of these was associated with the vortex center being located over the station, so during all these events there was significant thermal advection toward the station. The ERA-40 fields indicate that over the period 1979–2001 the core of the midtropospheric vortex was on one occasion about 2 K colder than during the 1983 event. This gives a reasonable indication of how much colder conditions could be above the station if the vortex core was located directly above and there was the same degree of isolation from maritime air masses as in 1983. However, the radiosonde ascents from the Antarctic stations and the reanalysis data sets have shown that the midtropospheric temperatures above the Antarctic in winter have increased more than anywhere else on Earth over the last 30 years [*Turner et al.*, 2006]. The conditions suitable for very low temperatures have therefore diminished slightly in recent years.

[55] It is instructive to consider how low the near-surface temperatures could get at other locations on the Antarctic plateau. Figure 10b shows that Vostok station is located toward the eastern end of the orographic "ledge" above Lake Vostok. On the day of the record low temperature, the satellite infrared brightness temperatures indicate that skin temperatures were 1°C–2°C colder further to the west of the station. This suggests that temperatures could be slightly colder than at Vostok even in the immediate vicinity of the station.

[56] The domes that are at higher elevations than Vostok Station are also locations where temperatures could potentially fall lower. The Japanese Dome Fuji Station, (77.31°S, 39.70°E 3810 m asl) has been making in situ observations for a number of years. The mean annual temperature at Dome Fuji is slightly warmer at −54.4°C, compared to −55.5°C at Vostok, despite its higher altitude [*Yamanouchi et al.*, 2003]. This could be a result of other climatological factors, such as cloud cover.

[57] Recently the Chinese Antarctic program has established a new station on Dome Argus. Being some 595 m higher than Vostok, we can expect the station to on average record lower temperatures than Vostok. Assuming a dry adiabatic lapse rate of 9.8 K km^{-1} Dome Argus will be 5.8 K colder than Vostok. However, as discussed in section 4.3, Vostok is on a ledge that results in temperatures at the site being lower than at comparable sites at the same elevation. If the same conditions had prevailed above Dome Argus as occurred in the vicinity of Vostok on 21 July 1983 then the location would have recorded a temperature of about −95°C. On the day of the record low temperature at Vostok the AVHRR satellite-derived skin temperatures at Dome Argus are within a fraction of a degree of that at Vostok. With a more extended period of isolation from maritime air surface temperatures may fall even lower.

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References

Anderson, P. S. (2009), Measurement of Prandtl number as a function of Richardson number avoiding self-correlation, *Boundary Layer Meteorol.*, *131*, 345–362, doi:10.1007/s10546-009-9376-4.

Bamber, J. L., J. L. Gomez-Dans, and J. A. Griggs (2009), A new 1 km digital elevation model of the Antarctic derived from combined satellite radar and laser data–Part 1: Data and methods, *Cryosphere*, *3*, 101–111.

Bracegirdle, T. J., W. M. Connolley, and J. Turner (2008), Antarctic climate change over the twenty first century, *J. Geophys. Res.*, *113*, D03103, doi:10.1029/2007JD008933.

Budretsky, A. B. (1984), *New Absolute Minimum of Air Temperature (in Russian)*, *Inf. Bull. of Sov. Antarct. Exped.*, vol. 105Hydrometeoizdat, Leningrad, Russia.

Comiso, J. C. (2000), Variability and trends in Antarctic surface temperatures from in situ and satellite infrared measurements, *J. Clim.*, *13*, 1674–1696, doi:10.1175/1520-0442(2000)013<1674:VATIAS>2.0.CO;2.

EPICA Community Members (2004), Eight glacial cycles from an Antarctic ice core, *Nature*, *429*, 623–628, doi:10.1038/nature02599.

Key, J., and A. J. Schweiger (1998), Tools for atmospheric radiative transfer: Streamer and FluxNet, *Comput. Geosci.*, *24*, 443–451, doi:10.1016/S0098-3004(97)00130-1.

King, J. C., and P. S. Anderson (1994), Heat and water-vapor fluxes and scalar roughness lengths over an Antarctic Ice Shelf, *Boundary Layer Meteorol.*, *69*, 101–121, doi:10.1007/BF00713297.

King, J. C., and J. Turner (1997), *Antarctic Meteorology and Climatology*, 409 pp., Cambridge Univ. Press, Cambridge, U. K.

Kistler, R., et al. (2001), The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and documentation, *Bull. Am. Meteorol. Soc.*, *82*, 247–267, doi:10.1175/1520-0477(2001)082<0247:TNNYRM>2.3.CO;2.

Lachlan-Cope, T. A., W. M. Connolley, J. Turner, H. K. Roscoe, G. J. Marshall, S. R. Colwell, M. Hopfner, and W. J. Ingram (2009), Antarctic winter tropospheric warming—The potential role of Polar Stratospheric Clouds, a sensitivity study, *Atmos. Sci. Lett.*, in press.

Marshall, G. J. (2007), Temperature, in *Encyclopedia of the Antarctic*, edited by B. Riffenburgh, pp. 986–988, Routledge, New York.

Marshall, G. J., and S. A. Harangozo (2000), An appraisal of NCEP/NCAR reanalysis MSLP viability for climate studies in the South Pacific, *Geophys. Res. Lett.*, *27*, 3057–3060, doi:10.1029/2000GL011363.

Monaghan, A. J., D. H. Bromwich, W. L. Chapman, and J. C. Comiso (2008), Recent variability and trends of Antarctic near-surface temperature, *J. Geophys. Res.*, *113*, D04105, doi:10.1029/2007JD009094.

Oswald, G. K. A., and G. D. Robin (1973), Lakes beneath the Antarctic ice sheet, *Nature*, *245*, 251–254, doi:10.1038/245251a0.

Overland, J., J. Turner, J. Francis, N. Gillett, G. Marshall, and M. Tjernström (2008), The Arctic and Antarctic: Two faces of climate change, *Eos Trans. AGU*, *89*(19), doi:10.1029/2008EO190001.

Phillpot, H. R., and J. W. Zillman (1970), The surface temperature inversion over the Antarctic continent, *J. Geophys. Res.*, *75*, 4161–4169, doi:10.1029/JC075i021p04161.

Ridley, J. K., W. Cudlip, and S. W. Laxon (1993), Identification of subglacial lakes using ERS-1 radar altimeter, *J. Glaciol.*, *39*, 625–634.

Sinclair, M. R. (1981), Record-high temperatures in the Antarctic—A synoptic case study, *Mon. Weather Rev.*, *109*, 2234–2242, doi:10.1175/1520-0493(1981)109<2234:RHTITA>2.0.CO;2.

Turner, J., S. R. Colwell, G. J. Marshall, T. A. Lachlan-Cope, A. M. Carleton, P. D. Jones, V. Lagun, P. A. Reid, and S. Iagovkina (2004), The SCAR READER project: Toward a high-quality database of mean

Antarctic meteorological observations, *J. Clim.*, *17*, 2890–2898, doi:10.1175/1520-0442(2004)017<2890:TSRPTA>2.0.CO;2.

Turner, J., S. R. Colwell, G. J. Marshall, T. A. Lachlan-Cope, A. M. Carleton, P. D. Jones, V. Lagun, P. A. Reid, and S. Iagovkina (2005), Antarctic climate change during the last 50 years, *Int. J. Climatol.*, *25*, 279–294, doi:10.1002/joc.1130.

Turner, J., T. A. Lachlan-Cope, S. R. Colwell, G. J. Marshall, and W. M. Connolley (2006), Significant warming of the Antarctic winter troposphere, *Science*, *311*, 1914–1917, doi:10.1126/science.1121652.

Uppala, S. M., et al. (2005), The ERA-40 re-analysis, *Q. J. R. Meteorol. Soc.*, *131*, 2961–3012, doi:10.1256/qj.04.176.

van Loon, H. (1967), The half-yearly oscillations in middle and high Southern latitudes and the coreless winter, *J. Atmos. Sci.*, *24*, 472–486, doi:10.1175/1520-0469(1967)024<0472:THYOIM>2.0.CO;2.

Weller, G., and P. Schwerdtfeger (1968), Thermal properties and heat transfer processes of the snow of the central Antarctic plateau, *IAHS Publ.*, *86*, 284–298.

Yamanouchi, T., K. Suzuki, and S. Kawaguchi (1987), Detection of clouds in Antarctica from infrared multispectral data of AVHRR, *J. Meteorol. Soc. Jpn.*, *65*, 949–962.

Yamanouchi, T., N. Hirasawa, M. Hayashi, S. Takahashi, and S. Kaneto (2003), Meteorological characteristics of Antarctic inland station, Dome Fuji, *Mem. Natl. Inst. Polar Res., Spec. Issue*, *57*, 94–104.

Yasunari, T., and S. Kodama (1993), Intraseasonal variability of katabatic wind over east-Antarctica and planetary flow regime in the Southern Hemisphere, *J. Geophys. Res.*, *98*, 13,063–13,070, doi:10.1029/92JD02084.

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