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Impacts of snow accumulation on air temperature measured by automatic weather stations on the Antarctic ice sheet

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Abstract The heights of automatic weather station (AWS) sensors over the Antarctic ice sheet are nominal and change with snow accumulation or ablation. Therefore, the measured data may not be used directly. In this study, we analyzed the impact of snow accumulation on AWS observations using continuous measurements from three AWS that were deployed on the traverse route from the Zhongshan Station to Dome A over East Antarctica. We then corrected the measured air temperature to account for changes in the sensor height relative to the snow surface to improve the authenticity and representativeness of the observation data from the AWS. The results show that (i) the annual mean snow accumulations at Dome A, Eagle and LGB69 were approximately 0.11 m, 0.30 m and 0.49 m, respectively, and the corresponding annual mean air temperature differences between the corrected and measured values at 1 m in height were 0.34℃, 0.29℃ and 0.35℃; (ii) the impact on air temperature from accumulation decreases with height from the surface; (iii) the air temperature difference between the corrected and measured values was not directly proportional to the snow accumulation but was related to the seasonal air temperature variations and the intensity of the local surface inversion; and (iv) the averaged corrected air temperature was higher than the measured values except during the summer when there were days without temperature inversion. The magnitude of the temperature difference between the corrected and measured was mainly determined by snow accumulation and the intensity of the local surface inversion.

Keywords **AWS, snow accumulation, temperature correction**

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0 Introduction

The Antarctic, 98% of which is permanently covered by snow and ice, plays a crucial role in global and climate changes. Due to the extreme climate conditions, most perennial meteorological stations are deployed along the coast, with very few stations in the interior. The lack of inland stations makes it somewhat difficult to study the interaction between snow/ice and the atmosphere in the Antarctica. The advent of automatic weather stations (AWS) makes it possible to provide long–term unmanned observations in remote areas and in areas where the weather is extremely adverse. Over the past two decades, about 100 AWS have been set up in different regions of Antarctica to investigate the near–surface weather, climate and micro−meteorological physical processes. These AWS provide large amounts of climatological data for Antarctica, and from these data, many important conclusions have been made[1–9]. The data gathered from AWS provide information that is extremely useful for the investigation of the interactions between ice/snow and the atmosphere and of the mass exchange.

AWS has become an optimal means of direct observation of near–surface meteorological conditions in the continental interior[10]. Due to the harsh climate

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conditions and the absence of servicing personnel, data from Antarctic AWS suffer from potentially large errors. Van den Broeke et al.[11] and Reusch and Alley [10] addressed the errors in the transducers themselves, the icing/riming of sensors, which caused errors in observations, and the manner in which to fill in data gaps. In these studies, they mentioned that the AWS sensor heights above the snow surface change with snow accumulation and ablation; thus, the given height of the sensor is only a nominal height rather than the height of the sensor. However, the effect of snow accumulation on the quality of AWS data has been ignored by many researchers. Uncorrected data, when applied to models for the surface energy balance over the Antarctic ice sheet, will cause certain errors in the simulated surface temperature and, accordingly, in the turbulent and longwave radiative fluxes. However, since snow accumulation is small and only temporary, the associated errors are expected to be small when the average fluxes over the entire measuring period are considered[3, 12]. For this reason, it is necessary to investigate the effects of accumulation on the quality of AWS observations.

Based on sequential datasets from January 2005 to December 2007 from three AWS (Dome A, Eagle and LGB69, see Figure 1) along the traverse route from the Zhongshan Station to Dome A, this work analyses the impact of snow accumulation on AWS observations, particularly on air temperature, and corrects the temperature data based on the difference between the nominal height and the real height relative to the snow surface. Correcting the data in this manner allows us to better study the time–space patterns of basic meteorological elements and the surface energy balance over the Antarctic ice sheet.

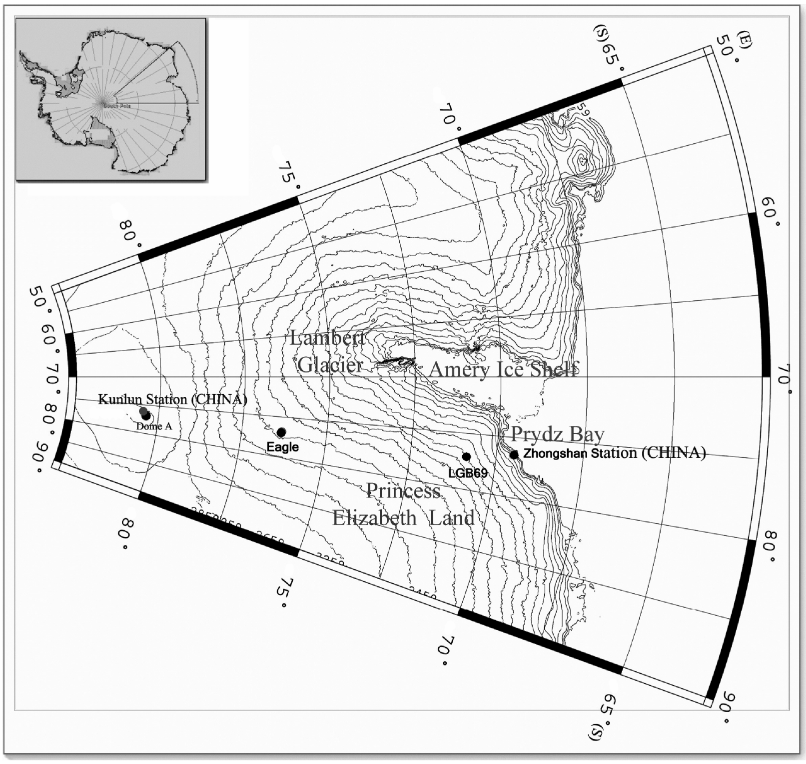

Figure 1 The topography and the AWS locations along the traverse route from the Zhongshan Station to Dome A.

1 Data and methods

The datasets used in this paper were based on datasets from three AWS over three years and were provided by the Chinese National Antarctic Research Expedition (CHINARE). Dome A and Eagle provided data from January 2005 to December 2007, and LGB69 provided data from January 2002 to July 2004. LGB69 is located on the Princess Elizabeth Land in East Antarctica (70°50′ S, 77°04′ E, 1 854 m above sea level (*a.s.l.*) and 160 km from the coast) and was built in January 2002 by the 18th CHINARE. Eagle (76°25′ S, 77°01′ E, 2 852 m *a.s.l.* and 787 km from the coast) and Dome A (80°22′ S, 77°22′ E, 4 093 m *a.s.l.* and 1 228 km from the coast) were deployed in late January 2005 by the 21st CHINARE. The three AWS have continuously recorded observations since establishment.

These AWS were designed by the Australian Antarctic Division (AAD) and were calibrated before assembly at the selected locations. They measure air temperature and wind speed at nominal heights of 1 m, 2 m and 4 m, wind direction and a vector wind speed at 4 m, and firn temperatures at nominal depths of −0.1 m, −1 m, −3 m and −10 m. The AWS also measure atmospheric pressure, global radiation and snow surface height (SSH). Table 1 lists the major sensors and their resolutions.

The nominal sensor height above the snow surface changes with variations in snow accumulation; thus, it is a variable height rather than a constant height. For this reason, we considered the accumulation effects and corrected the measured air temperature to account for changes in the actual sensor height relative to the snow surface. Before carrying out the temperature correction, a simple quality control measure for the data was performed in such a way as to (i) eliminate the obviously incorrect records and (ii) remove the early part of the dataset that was instable during the initial operating period of each AWS.

Table 1 Sensor type and resolution for the AWS discussed in this study

Sensor	Type	Range	Resolution
Air temperature	FS23D thermistor	− 85 — 65℃	0.02℃
Relative humidity	Vaisala HMP45D	0 — 100%	2% (RH< 90%) 3% (RH> 90%)
Wind speed	Young P/L three–cup anemometer	0 — 51.1 m/s	0.1 m/s
Wind direction	Aanderra 3590 wind vane	0° — 360°	6°
Snow height	Campbell Scientific SR50–45	0.5 — 10 m	0.01 m
Global radiation	Middleton EP08	0 — 204.8 MJ/m^2	0.1 MJ/m^2
Air pressure	Paroscientific Digiquartz 6501A		0.1 hPa
Snow temperature	FS23D thermistor	− 85 — 65℃	0.02℃

Notes: Dome A is slightly different, see Xiao et al. [13] .

2 Necessity of correction for AWS observations

Figure 2 presents the annual snow accumulation calculated from continuous records of SSH from the three AWS. For LGB69, the snow accumulation was 0.48 m and 0.50 m in 2002 and 2003, respectively. The average accumulation was 0.49 m, which is equivalent to 0.20 m water equivalents per year (w.e./a). For Eagle, the snow accumulation was 0.25 m, 0.39 m and 0.27 m in 2005, 2006 and 2007, respectively. The average accumulation was 0.30 m, which is equivalent to 0.10 m w.e./a. The snow accumulation at Dome A was 0.11 m, 0.05 m and 0.19 m in 2005, 2006 and 2007, respectively. The average accumulation was 0.12 m, which is equivalent to 0.03 m w.e./a, a figure that is slightly higher than that estimated from the snow pit at Dome A[14].

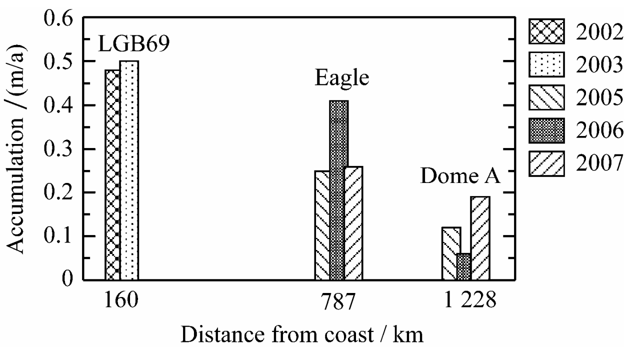

Figure 2 Annual mean snow accumulation for LGB69, Eagle and Dome A.

This result shows that the snow accumulation decreases with altitude and with distance from the coast. This is consistent with the common pattern of accumulation in Antarctica and is in agreement with the conclusion of mass balance in East Antarctica presented by Ren et al.[15].

Since the snow accumulates along with the time, the sensor heights relative to the snow surface change with snowfall and thaw. This means that the observations may fail to represent the meteorological parameters for the initial (nominal) height, especially when the snow is very thick. At LGB69, for instance, the snow accumulation exceeded 1 m in April 2004, and the 1 m level sensors became buried in snow. Because they were buried, the sensors did not provide accurate air temperatures, but now provides surface snow temperature. Therefore, to improve the authenticity and representativeness of the AWS observations, it is necessary to take into account the impact of snow accumulation on the primary meteorological observations and to correct the measured data to account for changes in sensor height relative to the snow surface. This correction is particularly important for the air temperature.

3 Correction of measured air temperatures

3.1 Introduction to the air temperature correction technique

Following the flux profile of the Monin-Obukhov similarity theory, a relation was derived using the assumption that the underlying surface is mainly in stable or neutral stratification over the Antarctic ice sheet. This relation can describe the relationship between the air temperature and the height above the snow surface. It can be expressed as

$$T = a \cdot \ln(z) + b \cdot z + c \tag{1}$$

The derivative process is as follows: The general flux–gradient relation for temperature is expressed in the form

$$\frac{kz}{\theta_*}\frac{\partial \bar{\theta}}{\partial z} = \phi_H(\zeta) \tag{2}$$

Integrating equation (2) from the surface to height z, we obtained the integral form of the flux profile relation

$$\theta - \theta_0 = \frac{\theta_*}{k}[\ln(\frac{z}{z_0}) + \psi_H(\frac{z}{L})] \tag{3}$$

where k (= 0.4) is the Von Karman constant; θ and θ_0 are the potential temperatures at height z and at the surface, respectively; ζ (=z/L) is a stability parameter; L is the Monin-Obukhov length; ϕ_H is universal function for the sensible heat flux; θ_* is the surface temperature scale; ψ_H is a function of the stability correction for the sensible heat flux; and z_0 is the surface roughness length.

Assuming the underlying surface to be mostly of stable or neutral stratification (i.e., $\zeta = z/L \geq 0$), we obtain $\psi_H = A\zeta = Az/L$, of which the typical values of A given by Businger et al.[16] and Dyer [17] are 4.7 and 5 (0.74 and 1) for a stable (near–neutral) stratification. Then, substituting ψ_H and the potential temperature $\theta = T(\frac{p_0}{p})^{0.286}$ into formula (3), we obtain function (1) and its three coefficients:

$$a = \frac{\theta_*}{k(p_0/p)^{0.286}} \tag{4}$$

$$b = \frac{A\theta_*}{kL}/(p_0/p)^{0.286} \tag{5}$$

$$c = T_0 - \frac{\theta_*}{k}\ln(z_0)/(p_0/p)^{0.286} \tag{6}$$

In these equations, T_0 is the surface temperature, p is surface air pressure, and p_0 is the standard atmospheric pressure. It is evident that equation (1) agrees with the temperature profile function of the boundary layer theory under neutral and stable stratification. Therefore, the air temperature can be found directly for a certain height when θ_*, z_0, T_0 and L are known. In this work, equation (1), the air temperature correction equation, was used to fit the synchronous temperature at different heights by using the least squares method. This fit gave us the hourly coefficients a, b and c. Putting z = 1 m, 2 m and 4 m into equation (1) then gave us the air temperature at the heights of 1 m, 2 m and 4 m relative to the snow surface.

3.2 Test of the temperature correction equation

The three-year temperature observations show that surface temperature inversion occurred nearly all year-round at LGB69, Eagle and Dome A, although with varying intensity. This phenomenon indicates that the area monitored by these three AWS had climate characteristics typical of the interior ice sheet. They had a stable stratification mainly in the near–surface layer, thus satisfying the basic assumptions for equation (1).

Considering the change in snow accumulation, the actual observed heights (i.e., the heights relative to the snow surface) for the three sensor levels should be $(1 - H)$, $(2 - H)$ and $(4 - H)$ m when the accumulated snow depth is H m. Equation (1) was used to fit the temperatures measured at the three heights by using the least squares method to find the hourly coefficients a, b and c. The calculated temperatures using equation (1) for the heights $(1 - H)$, $(2 - H)$ and $(4 - H)$ m agreed entirely with the raw observations at these three heights, and their squared correlation coefficients nearly reached 1.0. This high correlation illustrates that equation (1) is able to describe the relationship between the air temperature and the height in the near–surface layer over the Antarctic ice sheet and can thus be used to correct AWS–measured air temperatures.

3.3 Air temperature correction results

Using the hourly fitting coefficients a, b and c described in the previous section and putting z = 1 m, 2 m and 4 m into equation (1), we were able to calculate the temperatures at the heights of 1 m, 2 m and 4 m with respect to the actual snow surface. The resulting values are the corrected air temperatures that take into consideration the changes in snow accumulation. Figure 3 shows the relationship between the measured and corrected hourly temperatures at the three sensor heights for Dome A, Eagle and LGB69. The 1 m, 2 m and 4 m heights on the y− (x−) coordinate denote the actual (nominal) heights above the snow surface. The data presented in Figure 3 indicate that equation (1) is able to correct temperatures measured by AWS, with the squared correlation coefficients > 0.99 between the measured and corrected temperatures. The correlation coefficient for 1 m was smaller than those for 2 m and 4 m. Furthermore, the fitting expressions between the observed and corrected temperatures illustrate that the corrected and observed temperatures for the 2 m and 4 m heights differed by 0.1%—0.2%, whereas the difference between the observed and corrected temperatures for the 1 m height was 0.3%—0.7%. This suggests that the difference between the corrected and observed temperatures at 1 m was greater than the differences at 2 m and 4 m.

For LGB69, Eagle and Dome A, a temperature inversion occurred for most of the year and was much stronger during the winter than during the summer. The air temperature curve indicates that there was rapid warming at the beginning of the summer and rapid cooling at the end of the summer, preceded and followed by lower rates of temperature change at all observed heights for all of the AWS. These temperature observations display the typical “coreless” winter temperature feature of Antarctica[1−2]. As a result, the corrected temperatures are generally higher than the values measured during the winter but are only slightly higher or are lower during the summer.

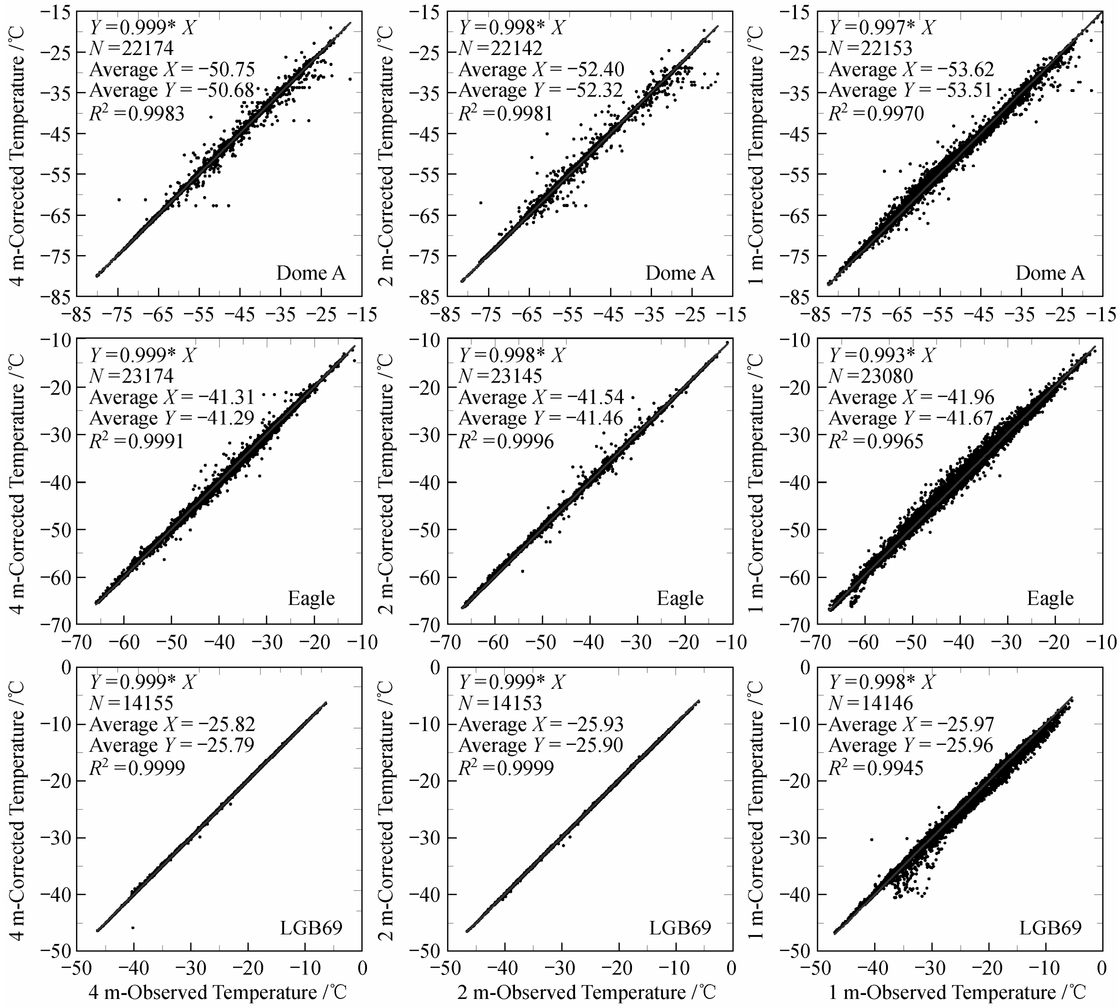

Figure 3 The relationship between the measured temperature and the corrected temperature calculated hourly using formula (1) at different heights at Dome A, Eagle and LGB69.

Figure 4 gives the time series of the monthly mean snow accumulation and TD_{CO} (i.e., the air temperature differences between the corrected and measured values) for the three heights (1 m, 2 m and 4 m) at Dome A, Eagle and LGB69. At Dome A, the monthly mean TD_{CO} values for the three heights all varied greatly during the periods of snow accumulation, with obvious changes and its magnitude can reached 1℃ (e.g., the 4th — 13th and 27th — 36th month), as compared to the stable periods (e.g., the 14th — 26th month). When there were slow changes in accumulation, TD_{CO} changed by lower rates. The monthly mean for TD_{CO} at Dome A was within 0.1℃, displaying a stable state similar to the feature of snow accumulation. For LGB69 and Eagle, TD_{CO} showed no remarkable fluctuation in response to increases or decreases in snow accumulation, thus indicating that the TD_{CO} values at these two sites were less sensitive to accumulation than at Dome A. This occurred because the near–surface inversion was distinctly weaker at Eagle and LGB69 than at Dome A, leading to a greater change in snow accumulation, which induced a smaller change in the air temperature. As the snow accumulation approached 1 m (> 0.95 m), the monthly mean TD_{CO} was below −1℃ in the 36th month for Eagle and the 25th to 26th month for LGB69, a value that is obviously lower than that of the preceding summer. The *in situ* observed temperature gradient (between 2 m and 1 m) was −1.8℃ for the 36th month, −0.1℃ for the 24th month and −0℃ for the 12th month at Eagle and was −0.5℃ —

−1.9℃ for the 25th — 26th months and −0.1℃ — −0.4℃ for the 10th — 13th months at LGB69. This suggests that the −1.9℃ TD_{CO} in the 36th month at Eagle and the < −1℃ TD_{CO} over the 25th — 26th months at LGB69 were the results from observations. However, the results of the corrected temperature values still agree well with the observed temperature gradient. For Eagle and LGB69, little or no inversion phenomenon happened during the summer, so the mean TD_{CO} for the summer was negative.

The above analysis shows that the air temperature correction equation (1) also works well for Eagle and LGB69 when the accumulated snow depths were close to 1 m Figure 4 shows that the TD_{CO} value was the highest at 1 m and was the lowest at 4 m for all three AWS (see also Table 2).

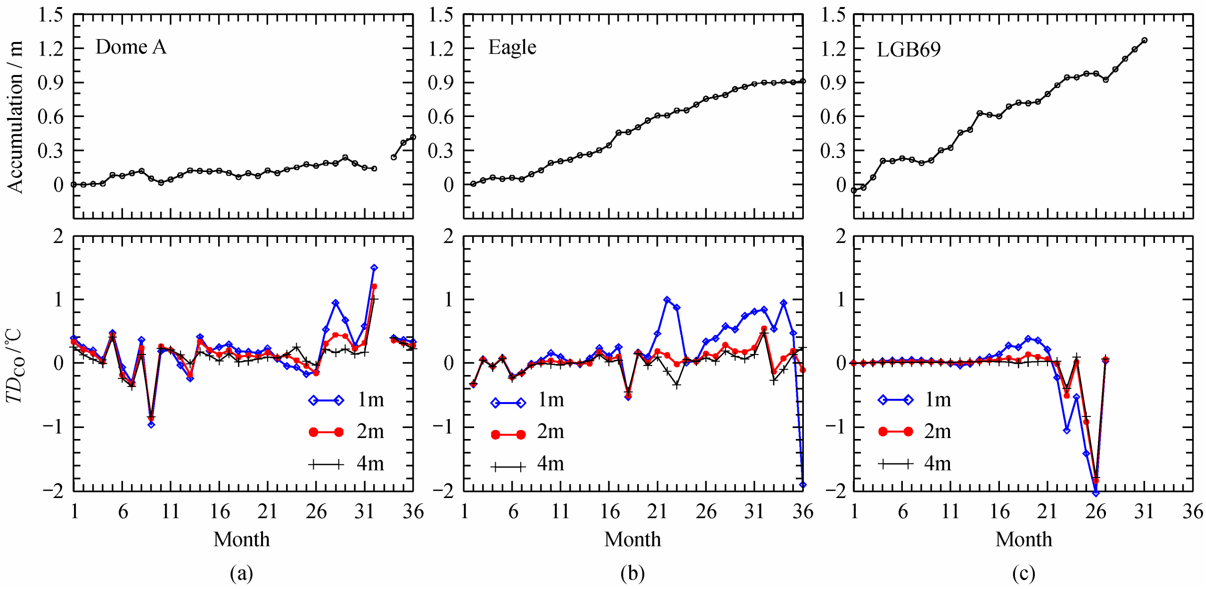

Figure 4 Time series of the monthly mean snow depths and differences between the corrected and measured air temperature (TD_{CO}) for the three heights (1 m, 2 m and 4 m) at Dome A (a), Eagle (b) and LGB69 (c) from January 2005 to December 2007.

The corrected results are reliable, as can be seen from the characteristics of seasonal variation in the air temperature itself and in the surface inversion.

Figure 5 presents the time series of the monthly means of the measured and corrected air temperatures at Dome A, Eagle and LGB69. The plots show that there were no obvious differences between the observations and the corrected values for the 2 m and 4 m levels. A slightly larger difference occurred at the 1 m level, especially during the winter, with corrected temperatures that were higher than the observed temperatures. The difference was the greatest between the 27th—32nd months (except for LGB69) because the snow accumulation was markedly higher during that time than it was during the previous two winters. During the summer, the corrected temperatures were marginally higher than the observed temperatures at Dome A, but they were either slightly higher or lower than observed temperatures at Eagle and LGB69, as shown in Figure 4. For LGB69 in particular, during the 24th through the 26th months (the summer of 2003), the corrected temperature was noticeably lower than the observed temperature due to the fact that the measured temperature decreased with height for both AWS Eagle and LGB69 during the summer, suggesting that there was no inversion. The results indicate that the magnitude of TD_{CO} is closely related to the existence of local inversions and the strength of those inversions.

Table 2 lists the annual mean accumulated snow depths, air temperatures and the TD_{CO} values for the three AWS. For Dome A, Eagle and LGB69, the 1 m level annual mean temperature were −53.19℃, −41.33℃ and −26.29℃, respectively, and the average snow accumulations were approximately 0.11 m, 0.30 m and 0.49 m per year, respectively. The corresponding annual mean TD_{CO} values at the 1 m height were 0.34℃, 0.29℃ and 0.35℃, respectively. The annual mean of TD_{CO} values at the 2 m and 4 m heights were markedly smaller than the value at 1 m, with values of < 0.1℃. The value at 2 m was larger than that at 4 m at all three AWS. The results show that the impact of snow accumulation on air temperature was the greatest at the height closest to the surface and declined gradually with increasing height. This is related to the existence of the nearly permanent surface inversion over the Antarctic ice sheet, which weakens the effects of surface cooling on the upper air. This led to snow accumulation having a greater impact on the air temperature at heights close to the surface (e.g., at 1 m), as compared to higher levels (e.g., 2 m and 4 m). Although the yearly mean accumulation was higher at Eagle and LGB69 than at Dome A, the annual mean TD_{CO} values were smaller than the

TD_{CO} value at Dome A. This is associated with the intensity of local near-surface inversion.

For Dome A, the near–surface inversion intensity (as shown by the difference in the air temperature between 4 m and 1 m) was the strongest, reaching an annual mean Eagle and LGB69, which were 0.62℃ and 0.2 ℃, respectively. A smaller change in snow accumulation at Dome A corresponds to a larger fluctuation in the near-surface air snow accumulation, the larger the TD_{CO} and that the value of TD_{CO} was larger at the height closest to the surface (1 m level)

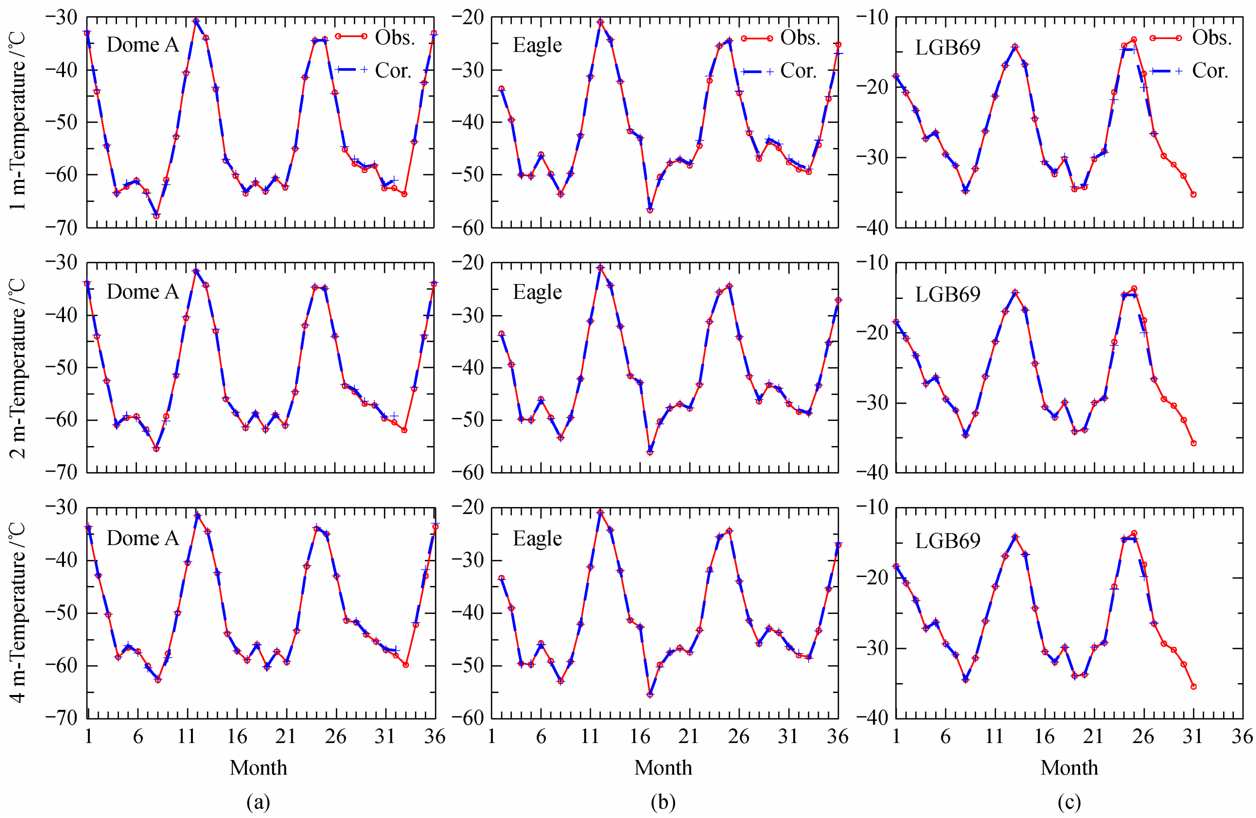

Figure 5 Time series of monthly mean measured and corrected air temperatures for the three levels (1 m, 2 m and 4 m) at Dome A (a), Eagle (b) and LGB69 (c). The dotted line represents the observed temperature, and the hatched line represents the corrected temperature.

Table 2 Annual mean accumulated snow depths, annual mean air temperatures and the differences between the corrected and measured temperatures (TD_{CO}) for the three levels (1 m, 2 m and 4 m) at Dome A, Eagle and LGB69

Site	Year	Annual Mean Snow Depth /m	1 m Air Temperature /℃		2 m Air Temperature /℃		4 m Air Temperature /℃	
			Annual mean		Annual mean		Annual mean	
			Observed	TD_{CO}	Observed	TD_{CO}	Observed	TD_{CO}
Dome A	2005	0.05	−53.95	0.06	−52.64	0.04	−50.98	0.03
	2006	0.11	−53.31	0.18	−52.26	0.07	−50.78	0.06
	2007	0.23	−52.3	0.77	−51.24	0.18	−49.42	0.16
Eagle	2005	0.1	−42.4	0.04	−42.15	0.01	−41.93	0
	2006	0.47	−41.29	0.27	−40.89	0.07	−40.71	0.01
	2007	0.84	−40.3	0.56	−39.97	0.1	−39.77	0.06
LGB69	2002	0.21	−26.22	0.2	−26.13	0.01	−26.03	0.01
	2003	0.73	−26.35	0.49	−26.28	0.05	−26.16	0.04

than in the upper air (2 m and 4 m levels). In addition, the magnitude of TD_{CO} also depended strongly on the strength of the local near-surface inversion, and it increased with the inversion intensity.

4 Summary

In this work, we used observations from three AWS to investigate the impacts of snow accumulation on the air temperature measured by the AWS located on over the Antarctic ice sheet. We also corrected the observed air temperatures to take into account differences between the nominal sensor heights and the actual heights relative to the snow surface. It was found that:

(1) The equation $T = a \cdot \ln(z) + b \cdot z + c$ that we derived was capable of describing the relationship between the near-surface air temperature and the height under stable or neutral stratification and could be used to correct the AWS-measured temperature over the Antarctic ice sheet. This expression was derived from the flux profile relation in the boundary layer, and thus, it has a physical meaning. It can only be used when the near-surface layer is under stable or neutral stratification. Therefore, it is recommended for use over the Antarctic ice sheet. However, in unstable conditions, the reliability of the correction requires further investigation.

(2) The annual mean air temperature at the 1 m level was −53.19℃, −41.33℃ and −26.29℃, and the average snow accumulation was 0.11 m, 0.30 m and 0.49 m per year for Dome A, Eagle and LGB69, respectively. The corresponding annual mean TD_{CO} values for the 1 m height were 0.34℃, 0.29℃ and 0.35℃, respectively. Although the yearly mean accumulation was higher at Eagle and LGB69 than at Dome A, the annual mean TD_{CO} values at the 1 m, 2 m and 4 m levels were nearly equal to or were smaller than the corresponding values at Dome A. This occurred because the surface inversion was considerably stronger at Dome A than at the other two AWS, a smaller change in snow accumulation corresponding to a larger fluctuation in near-surface air temperature. This illustrates that the magnitude of TD_{CO} not only depends on the snow accumulation but also on the local inversion strength-the stronger the surface inversion, the larger the TD_{CO}. The annual means of TD_{CO} at the 2 m and 4 m levels were less than 0.1℃ for the three AWS, indicating that the impact of snow accumulation was the greatest at the lowest sensor height and decreased gradually with increasing height.

(3) The averaged values of TD_{CO} were positive during the austral winter, but during the summer, the sign of the TD_{CO} values was determined by the existence of a local inversion (when an inversion occurred, the value of TD_{CO} was positive).

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