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Snowdrift effect on snow deposition: Insights from a comparison of a snow pit profile and meteorological observations in east Antarctica

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Abstract A high-frequency and precise ultrasonic sounder was used to monitor precipitated/deposited and drift snow events over a 3-year period (17 January 2005 to 4 January 2008) at the Eagle automatic weather station site, inland Antarctica. Ion species and oxygen isotope ratios were also generated from a snow pit below the sensor. These accumulation and snowdrift events were used to examine the synchronism with seasonal variations of $\delta^{18}O$ and ion species, providing an opportunity to assess the snowdrift effect in typical Antarctic inland conditions. There were up to 1-year differences for this 3-year-long snow pit between the traditional dating method and ultrasonic records. This difference implies that in areas with low accumulation or high wind, the snowdrift effect can induce abnormal disturbances on snow deposition. The snowdrift effect should be seriously taken into account for high-resolution dating of ice cores and estimation of surface mass balance, especially when the morphology of most Antarctic inland areas is similar to that of the Eagle site.

Keywords Snowdrift process, Air-snow interaction, Ice core dating, Ultrasonic sounder, Post depositional process

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1. Introduction

Among the proxies used for paleoclimate reconstruction, ice cores have become increasingly attractive due to their high temporal resolution, the variety of environmental information they provide, and most importantly, the historical greenhouse gas record that can be extracted from them. Since the mid-20th century, glaciologists have conducted numerous ice core studies in Antarctica, Greenland, and on mountain glaciers, including the Vostok Ice Core Project (Petit et al., 1999), the EPICA (The European Project for Ice Coring in Antarctica) Dome C project (EPICA Community Members, 2004) in Antarctica, and the NEEM (The North Greenland Eemian Ice Drilling) project in Greenland (Neem Community Members, 2013).

In contrast to loess and stalagmites, moisture that forms glaciers comes from ocean and is transported towards continent where it is permanently added to the underlying snow cover after condensation and precipitation through adiabatic cooling (Bromwich, 1988; Groot Zwaaftink et al., 2013). The post-depositional process occurring during/after snowfall (Frezzotti et al., 2002; Eisen et al., 2008) and influenced by thermodynamics (during firnification) and wind (snowdrift) (Fierz and Lehning, 2001) may lead to a misinterpretation of climate records.

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Many studies have discussed the post-depositional effect driven by wind. Watanabe (1978) described the deposition-erosion processes at Mizuho Plateau, Antarctica, and divided it into four regions on the basis of the regional characteristics of the surface condition. Frezzotti et al. (2004, 2007) estimated the role of surface slope along the prevailing wind direction (SPWD) in the snow erosion near Talos Dome and found the SPWD has a considerable impact on the spatial distribution of snow over short (tens of metres) and medium (kilometre) spatial scales. Petit et al. (1982) suggested the local erosion could be on the same order of magnitude as precipitation in Dome C. Groot Zwaaftink et al. (2013) simulated event-driven deposition of snow and found that the precipitation is not the driving force behind non-temporary snow height changes. The modelling of drifting snow by Lenaerts and van den Broeke (2012) found that although drifting snow erosion can be neglected on a continent-wide-scale, it is significant locally for surface mass balance, which corroborates the results of Lenaerts et al. (2010), who estimated that snow drift sublimation could remove approximately 16%±8% of the accumulated snow from the surface of the Ekström ice shelf in Eastern Antarctica, etc. However, few of these studies could give an accurate estimation of post depositional processes, in part because drifting and blowing snow events are difficult to observe.

Significant snow layers can be lost during the strong wind season in Antarctica (e.g., Bintanja, 2001; Frezzotti et al., 2002; Scarchilli et al., 2011; Groot Zwaaftink et al., 2013). Sublimation can also be increased by wind (e.g., Smith, 1995; Gallée, 1998; Bintanja, 1998a, 2001; Gallée et al., 2013). For example, Ren (1995) found there were inconsistencies among δ^{18}O dating results, snow physical characteristics, and stake records and suggested that the original deposition might be changed; at Mid Point site (MdPt, 75°32′S, 145°51′E, 2510 m a.s.l.), deposition could reach up to 0.4–0.6 mm w.e. per day (Scarchilli et al., 2008). To understand the snowdrift process, a few studies have been carried out over polar ice sheets to establish empirical functions and models (e.g., Pomeroy and Jones, 1996; McConnell et al., 1997; Bintanja, 1998a, 1998b; Mann et al., 2000; Scarchilli et al., 2010; Groot Zwaaftink et al., 2013). For example, Winther et al. (2001) and van de Berg et al. (2006) found that the firn layer can be completely removed by snowdrift erosion and/or sublimation, exposing the glacier ice at the surface in regions with active katabatic winds. Van den Broeke et al. (2006, 2008) simulated the snow accumulation distribution under the influence of wind and suggested that surface sublimation and snowdrift erosion may exceed the solid precipitation flux, resulting in areas with a negative surface mass balance. Ding et al. (2015) evaluated the variability of snow accumulation and found that at least 12 and 20 sites are needed for local and regional studies on surface mass balance, respectively. Most of these studies only described the phenomenon, focused on mass loss processes by wind, or studied how to eliminate this type of error, of which none has given an overall estimation, especially the misinterpretation of the snow layer.

Here, we present a case study of a typical Antarctic inland area and attempt to explore the snowdrift process by sampling the snow profile under an ultrasonic sounder of an automatic weather station (AWS) and investigating its influence on the accuracy of annual signal estimation.

2. Location and method

Since 1997, the Chinese National Antarctic Research Expedition (CHINARE) began its traverse to the inland Antarctic area and installed 5 AWSs along the Zhongshan Station to Dome A route (Figure 1) (Xiao et al., 2005). The Eagle AWS (76°25′S, 77°01′E; 2852 m a.s.l.) was deployed on 27 January 2005 as part of a cooperative effort between China and Australia. This AWS is ~800 km distant from coast and ~450 km from Dome A. Eagle was designed by the Australian Antarctic Division, calibrated before being placed in the field, and has made continuous observations since its deployment. It measures the air temperature (~1, ~2, and ~4 m above the snow surface), wind speed (1, 2, and 4 m), wind direction (4 m), atmospheric pressure (4 m), global radiation (4 m), and firn temperature (−0.1 m, −1 m, −3 m, and −10 m (at the time of installation)). The snow surface height (SSH) is also observed by an ultrasonic sounder (Figure 2). Hourly data are collected and transmitted in real time through the Data Collection System of the ARGOS supporting satellite. In Antarctica, there are approximately 30 AWSs of this type (http://aws.acecrc.org.au/datapage.html; e.g., Allison et al., 1993; Allison, 1998; Ma et al., 2010).

On 4 January 2008, 50 snow samples were collected at ~3 cm resolution from a 166 cm snow pit profile at the Eagle site, and the density profile was measured using the tube method (Ding et al., 2011). The stable oxygen isotopic composition and major ions were analysed using a stable isotope ratio mass spectrometer (Finnigan MAT252) and an Ion Chromatography System (Dionex ICS-3000) at the State Key Laboratory of Cryospheric Sciences, Chinese Academy of Sciences. All procedures, such as preparation, fieldwork, sealed transportation, and analytical testing, were carried out very carefully to prevent adverse environmental impacts and contamination. The oxygen isotopic composition was reported in terms of the standard δ^{18}O value, representing the difference in the ^{18}O/^{16}O ratios between the sample and the standard V-SMOW. The accuracy was estimated to be ±0.15‰ (1 standard deviation).

3. Results

3.1 The climatology of Eagle

The Eagle AWS is located within the “Extremely Flat Area”

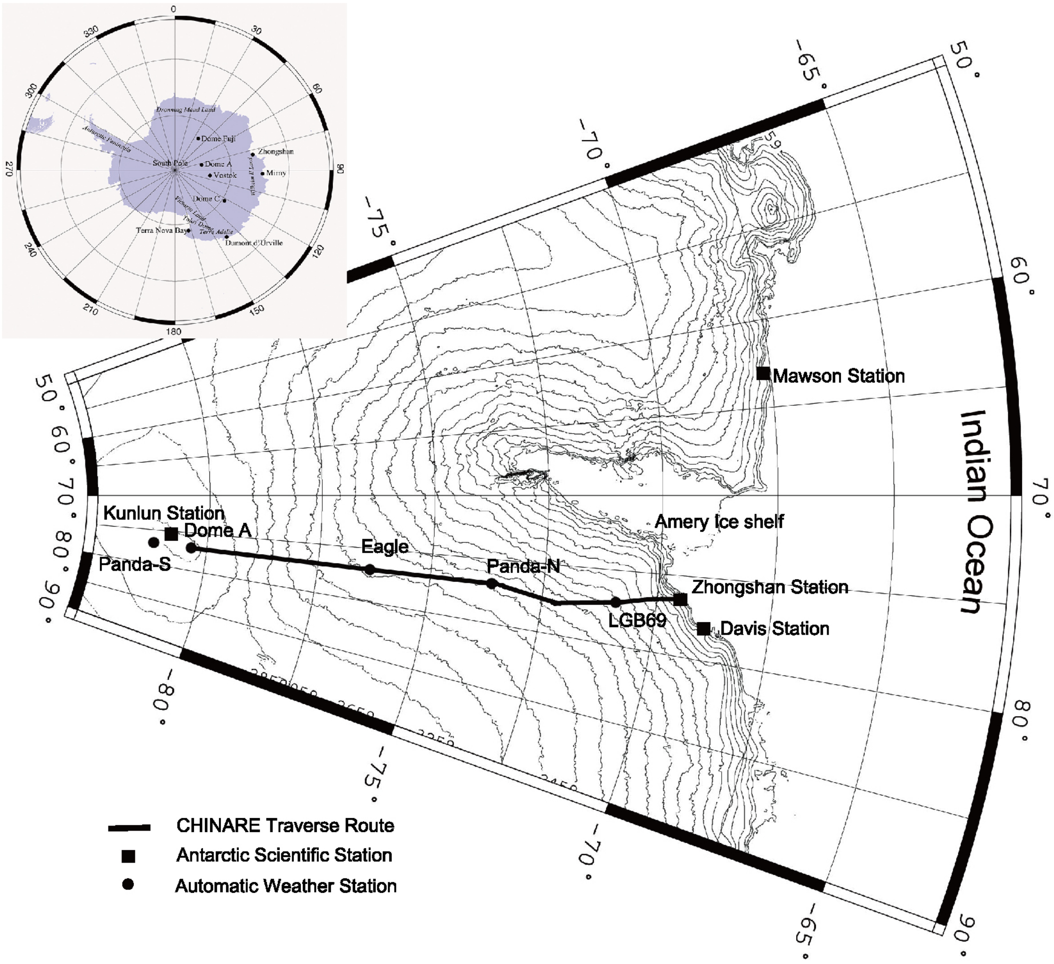

Figure 1 Locations of AWSs deployed by CHINARE in east Antarctica.

of inland Antarctica, with a hard surface crust (Ding et al., 2011, 2015, 2016) and an average slope of ~3.40 m km^{-1} (calculated with a diameter of 30 km from the Digital Elevation Model developed by the US National Snow and Ice Data Center; DiMarzio et al., 2007). Its prevailing aspect is northwestward at the eastern side of the Lambert Glacier Basin, but the prevailing wind direction is NE (56.3%; see Figure 2). The annual average 4 m wind speed is 4.17 m s^{-1} (Zhou et al., 2009; Ma et al., 2010). The observed annual average temperature, relative humidity, air pressure, and snow accumulation are −40.80°C, 77.32%, 683.52 hPa, and 30.33 cm snow, respectively (Figure 3).

Considering the low temperature and snow accumulation, the surface morphology of Eagle is relatively polished because of its location in the typical wind-glazed area, and the interaction between wind and topography creates a continuum of snow erosional/depositional effects. Wind-glazed areas are far more extensive on the East Antarctic Ice Sheet than previously considered, as Scambos et al. (2012) showed using a combination of satellite remote sensing and field-gathered datasets. Areas with similar surface morphology and climate occupy 11% of the total extent above 1500 m of the East Antarctic Ice Sheet, including most of areas explored by the Japanese Antarctic Research Expedition every year since 1975 and Victoria Land investigated by the Italian Antarctic Programme (Motoyama et al., 2008; Frezzotti et al., 2002). In other words, studies carried out at Eagle are of great significance in Antarctica.

According to the AWS records, only ~95 cm of snow accumulated during January 2005 to January 2008, so this paper will describe only the top 100 cm of the vertical profile of the Eagle snow pit.

3.2 Dating the snow pit

As Figure 4 shows, the δ value ranges from −40.30‰ to −52.75‰, with an average of −47.86‰, and the standard deviation is 3.42‰. In contrast to previous studies (Ding et al., 2010; Xiao et al., 2012), this result captures the same level of the local stable oxygen isotopic composition.

As many studies have noted (e.g., Qin, 2001; Hezel et al., 2011), the Na^+ and Cl^- in polar snow are characterised by high concentrations during winter, and MSA also shows high concentration because of the seasonal variation of sea ice extent

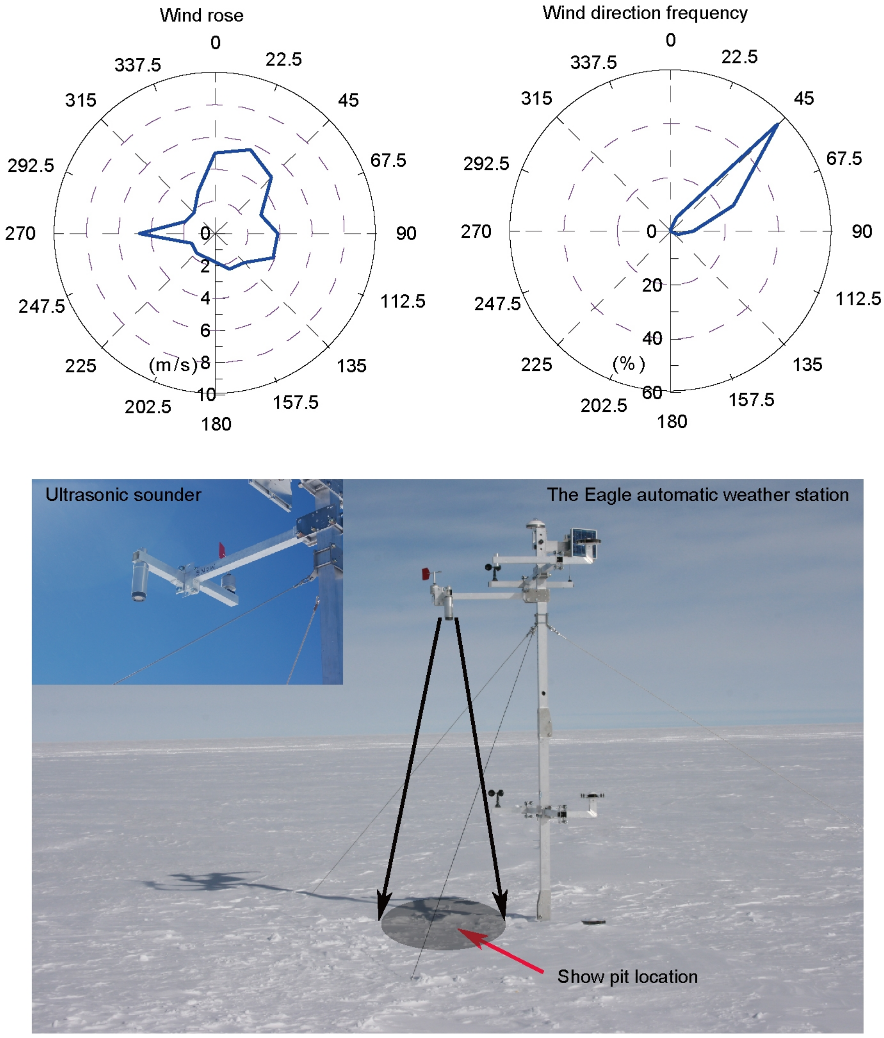

Figure 2 Wind speed/direction and wind direction frequency analyses for the Eagle AWS during January 2005–January 2008 (top) and the Eagle AWS and snow pit diagram (bottom).

(Curran et al., 2003). Due to the heavy diffusion around the snow surface and the stable input from upper atmosphere, respectively, the NO_3^- and $nssSO_4^{2-}$ might not show obvious variability (Legrand and Mayewski, 1997). Thus, we used $\delta^{18}O$, Na^+, Cl^- and MSA for dating, and the results showed good consistency with each other (Figure 4).

Physical stratigraphic profiles can also be used for dating, as many researchers have done (e.g., Ren, 1995; Ren et al., 2004). However, the credibility of this method is restricted in area with low accumulation or heavy wind because the hard scour by solar radiation would smoothed or the firn might be too compact (e.g., Ren et al., 2004). Eagle is a typical "wind glaze" area: its surface and the firn are very hard. Therefore, it is difficult to identify the solar-scoured layer, and we cannot use this method here.

The metamorphism related to movement of vapour between firn and snow, based on the vertical gradient of temperature, might have a large impact on water isotope redistribution. Annual layering of the water isotope near the surface of the ice sheet can be modified by this process in a heavy sublimation area, as indicated by the work of Steen-Larsen et al. (2011, 2013). That is also a reason we used both isotopes and chemicals for dating.

Nonetheless, the variations of Na^+ and Cl^- do not seem to be correlated with $\delta^{18}O$ in the bottom of snow pit due to the contamination by the installation of the AWS in January 2005.

3.3 The post-depositional process in Eagle

General speaking, the post-depositional processes include densification, firnification, snowdrift, and sublimation. In the densification process, as the density of snow stratification increases with the new precipitation deposits on snow surface (e.g., Gow, 1969; Goodwin, 1991), the increase of the snow height is suppressed at the same time. Our measurements show that the density gradient along the Eagle snow pit remains relatively stable (Figure 4), partly due to the wind crust structure created by a high annual mean wind directional

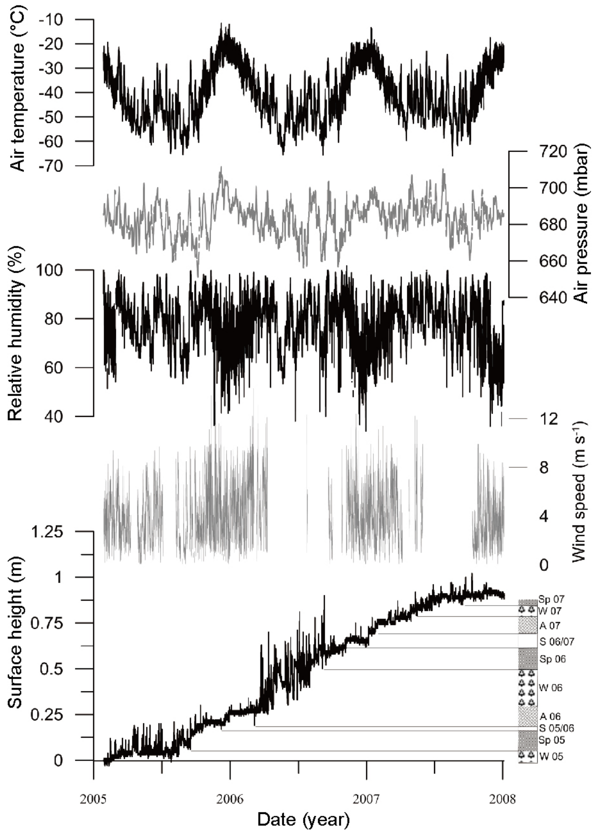

Figure 3 Dating of the snow profile by the record of the ultrasonic sounder, the wind speed, relative humidity, air pressure and air temperature (4 m) during January 2005 and December 2007 (top) at the Eagle AWS (Sp: spring; S: austral summer; A: autumn; W: winter).

constancy of 0.91 (Figure 2). The firnification process is a type of destructive metamorphism, such that when the densification process occurs, physical properties such as particle size and transmittance will change until the snow becomes ice (e.g., Paterson, 1994; Williams et al., 2000); thus, firnification has no direct connection with snow height. The wind-driven sublimation process (controlled by SPWD) has a large impact (up to 85% of snow precipitation) on surface mass balance and is significant in terms of past, present, and future surface mass balance evaluations in the katabatic area (Frezzotti et al., 2004, 2007), but this process can be recorded by ultrasonic sounder because it happens at the snow surface. It has also been shown that the net mass loss by sublimation on the Antarctic surface is no more than 5% of the precipitation (Qin, 2001), so we consider this process part of the snowdrift process in this study. In the snowdrift process, the surface snow can be transported from the original location and re-deposited at a new location as a result of wind (Groot Zwaaftink et al., 2013). This effect is regularly neglected in studies of environmental records and will be the emphasis in section 4.

3.4 The ultrasonic sounder record

By reconstructing the snow height variation, we found that accumulations mainly occurred during certain precipitation or snowdrift events, as illustrated in Figure 3 and listed in Table 1.

(1) The spring of 2005 had continuous snow accumulation. The snow layer that precipitated from January to July 2005 was lost because of the snowdrift process. (2) The 2005/06 austral summer received stable precipitation, but most of it drifted away as the result of occasionally strong winds. (3) The strong average wind speed in 2006 (4.8 m s^{-1} in 2006 versus 3.7 m s^{-1} in 2005 and 4.0 m s^{-1} in 2007) repeatedly blew away and brought in snow, layers as indicated by the numerous sharp decreases and increases in Figure 3 (the standard deviations of wind speed were 54.8%, 51.7%, and 53.4% in 2005, 2006, and 2007, respectively). However, there was a relatively large snow accumulation. (4) Although 7 cm of snow accumulated during the 2006/07 summer, its depositional time was during 6 January and from 24 January to 4 February 2007. (5) The autumn and winter of 2007 had a stable snow accumulation of 15 cm. (6) The snow samples in our study were collected on 4 January 2008, but the surface snow was deposited during October 2007, which is also implied by the value of Na^+, Cl^-, and MSA concentrations in Figure 4.

Additionally, there is a visible seasonal variability of snow accumulation (Figure 3): the austral summer receives less mass than the other seasons. For example, the summer accumulation was only ~2 cm of snow (no more than 6% of the yearly accumulation) during the 2005/06 austral summer. The possible reason could be sublimation during polar day.

Table 1 Summary of snow events at the Eagle AWS site based on the record of the ultrasonic sounder

Deposition time of snow layer	Thickness of snow layer (cm)	Cumulative height of snow surface (cm)
~20–30 July 2005	3	3
~10 August 2005	3	6
~10–20 September 2005	5	11
20 September–25 October 2005	6	17
~10–20 December 2005	2	19
~1–10 March 2006	8	27
~10–20 April 2006	2	29
~20–30 April 2006	1	30
June–August 2006	20	50
~1–10 September 2006	2	52
14 September–2 October 2006	7	59
~1–10 November 2006	3	62
~1–10 January 2007	7	69
~1-10 February 2007	3	72
~10–20 March 2007	3	75
~20–30 April 2007	3	78
~20 May–10 July 2007	6	84
~20–30 November 2007	4	88

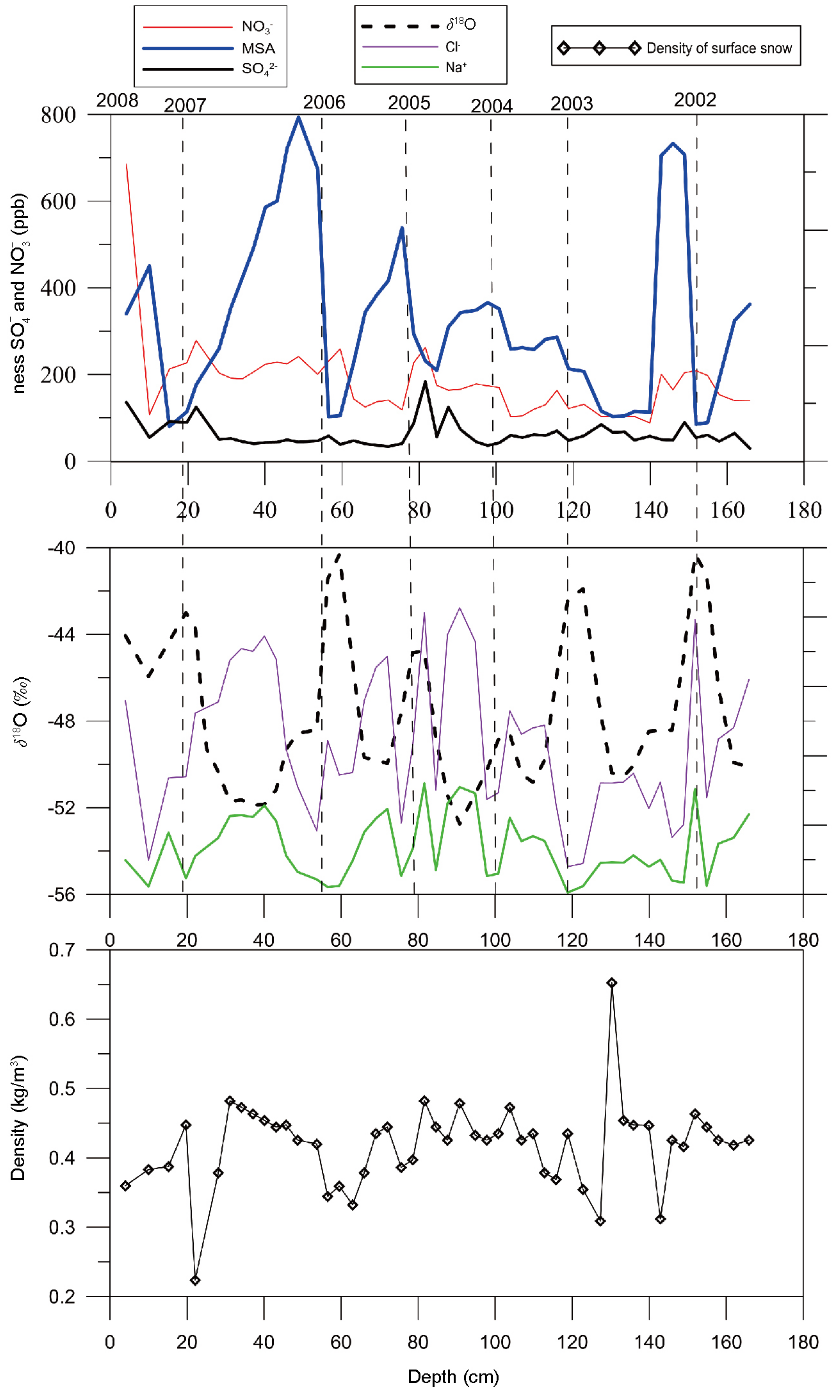

Figure 4 The dating results of the Eagle pit by marine aerosol and $\delta^{18}O$ cycles (top and middle) and snow density along the Eagle snow pit profile (bottom).

4. Discussion

4.1 The factor of wind

Unfortunately, the Eagle AWS did not continuously record wind speed/direction data because of the extreme environment of the Antarctic inland (Figure 3). Therefore, we choose specific periods for detailed analysis.

In Figure 5, we illustrated an accumulated record from stable to heavy snow drift and deposition during midwinter (1 June to 4 July 2005). The air temperature and pressure kept increasing because of the invading warm air mass (Figure 6). This synoptic process brought precipitation inland, as also reflected by the increasing relative humidity in Figure 5. The wind speed was also becoming stronger (Figure 5), and the wind direction changed from ~40° during 1–20 June to ~60° during 21–25 June then to ~80° during 28 June–3 July, so the new precipitation was blown away.

During austral summer, the atmospheric general circula-

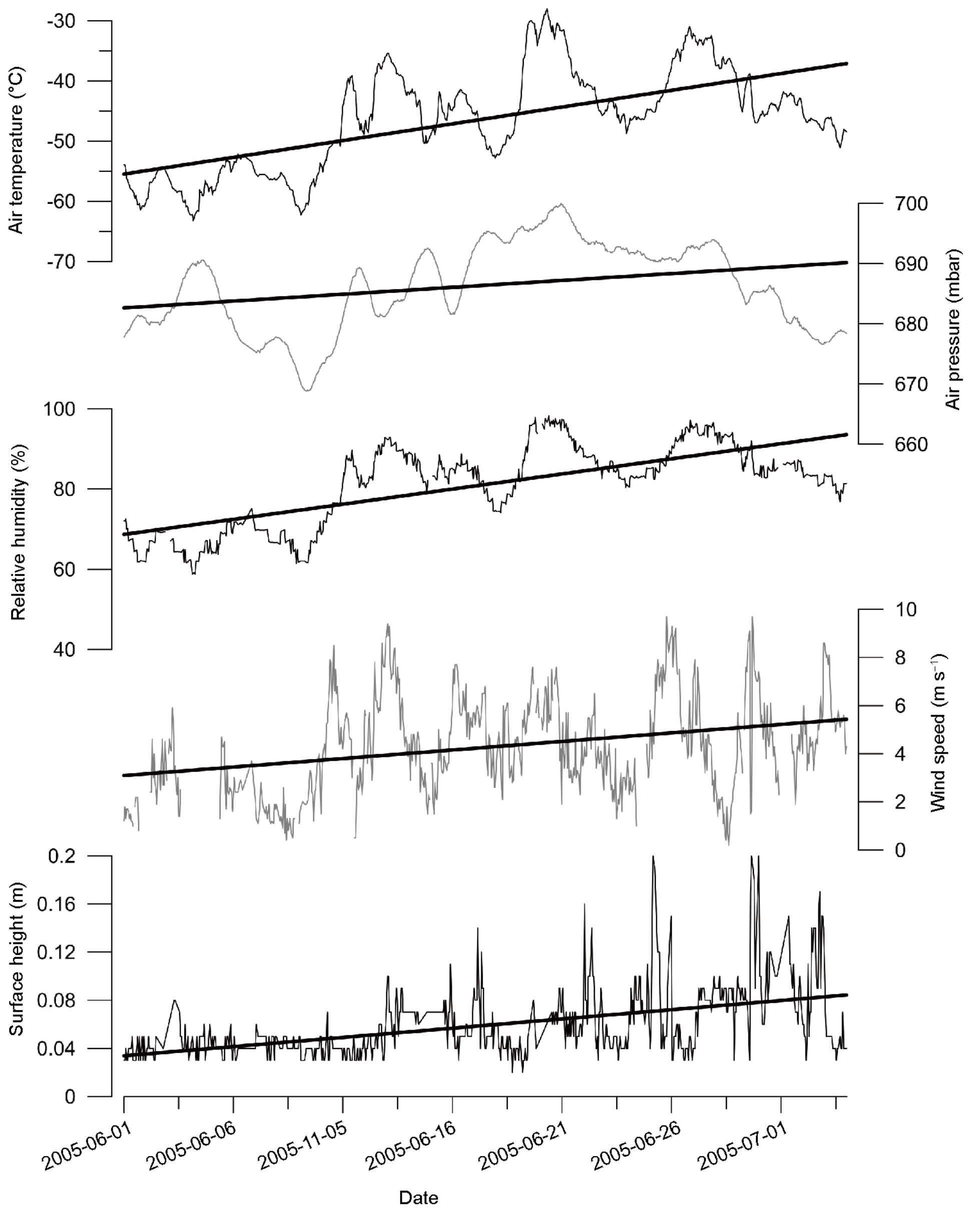

Figure 5 The snow height record, wind speed, relative humidity, air pressure and air temperature (4 m) during 1 June and 4 July 2005 at the Eagle AWS.

tion field is relatively stable. Because of the smaller temperature difference between Antarctica and the Southern Ocean, less moisture is transported inland, and weaker wind was observed at Eagle (Figures 7 and 8). The slight decrease of the snow surface during December 2007 should be attributed to the low precipitation and the surface sublimation (which might be more than 0.2 mm d^{-1}, according to the estimation in MdPt (Scarchilli et al., 2008), where the surface is ~350 m lower, 52' northerly, and much flatter than at Eagle).

We speculate that wind is the key factor in snowdrift, as many other researchers have also noted (e.g., Frezzotti et al., 2004; Scarchilli et al., 2010; Groot Zwaaftink et al., 2013), not only because the process primarily occurs during winter when the surface sublimation is weaker but also because the AWS recorded quick decreasing and increasing at the snow surface when extremely heavy wind gusts were detected.

To estimate the different effects of weak wind and strong wind and between different wind directions, we distinguished the surface decreasing as snow loss and surface increasing as snow deposition, then compared them with wind speed and direction (Figure 9). Under the presupposition that all losses are caused by wind and all depositions are from precipitation or blowing snow, the snow loss tended to happen in a slightly northerly wind direction compared to the snow deposition (Figure 9a and b), which implies that wind from a low to high attitude would induce more mass loss. For the analysis of wind speed and snow loss/gain, most of the loss and the greatest loss happened around 4–6 m s^{-1}, partially because the average annual wind speed was 4.17 m s^{-1}, but it was very significant that heavy winds over 10 m s^{-1} did not cause

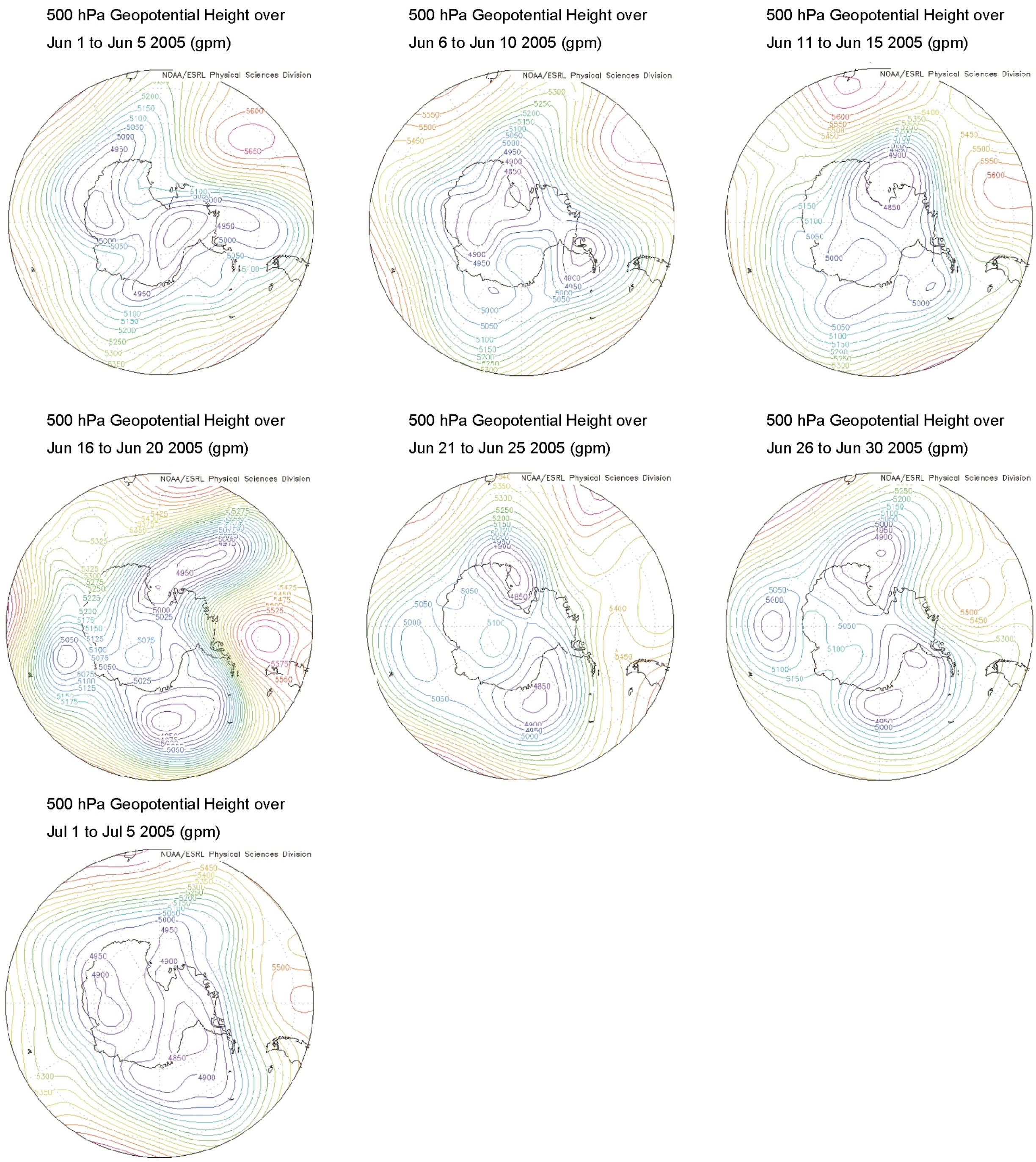

Figure 6 The 500 hPa geopotential height over 1 June and 4 July 2005, derived by NCEP reanalysis (http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.derived.html) and spanning 45°S to 90°S.

heavy loss (we suggest that this result is because the snow has been blown away before the wind accelerated up to 10 m s^{-1}) (Figure 9c and e). Figure 9d and f showed no obvious relation between snow deposition and wind speed.

4.2 Estimation of the snowdrift process

As many studies have shown, stable isotopic snow compositions have a linear relationship with the precipitation temperature (e.g., Dansgaard, 1964; Jouzel et al., 1997). Ding et al. (2010) and Xiao et al. (2012) provided an empirical formula for $\delta^{18}O/\delta D$-temperature in this area ($\delta^{18}O=0.842T-9.118$, $R=0.945$).

To compare the differences between our dating results from chemical proxies and the real depositional date from the AWS record, we illustrate the variations of both methods along the snow depth in Figure 10a. The $\delta^{18}O$ variation is generally consistent with temperature and has a good correlation in the

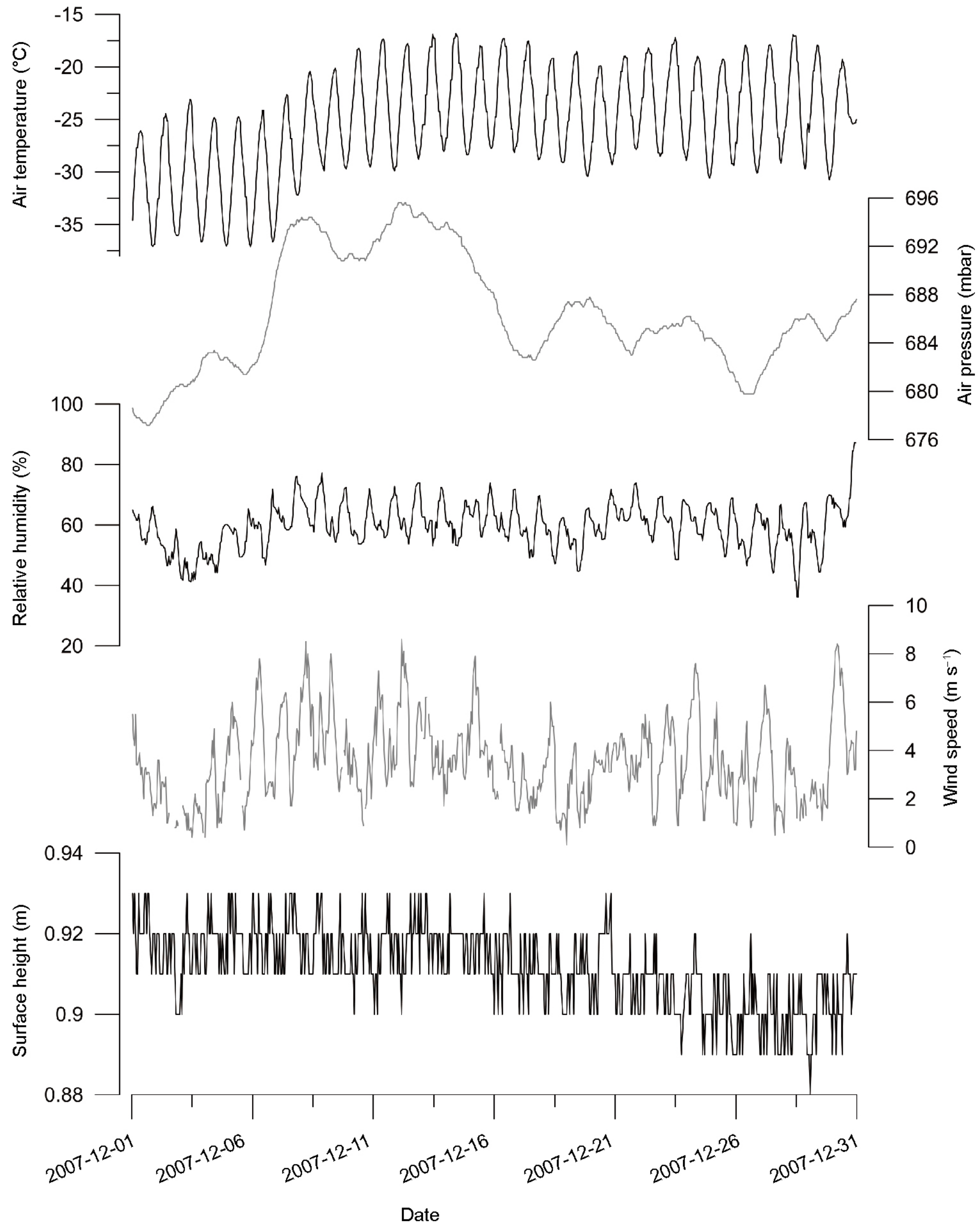

Figure 7 The snow height record, wind speed, relative humidity, air pressure and air temperature (4 m) during 1 December and 31 December 2007 at the Eagle AWS.

top ~50 cm. This result implies that during spring 2007 and spring 2006, the snowdrift was weak, as also shown in Figure 3. Farther down, however, the dating difference starts increasing for heavy snowdrift during March–October, 2006, when too much of the snow layer has been exchanged. At ~90 cm, the difference can be as large as 12 months (27.8 cm).

Based on the reconstruction of the snow deposition layer shown in Figure 3 and Table 1, we calculated the real air temperature during the snow deposition events. The δ^{18}O-temperature relationship is given in Figure 10b, which should show a linear equation as the fractionation of the stable water isotopes is related to temperature. Instead, we find that the correlation coefficient is quite low (R=0.33), suggesting that although the snow layers were dated precisely by the AWS record, the original precipitation time and locations of these layers (before the snowdrift process) are more important for short-term studies (which cannot be observed at present).

It can be concluded that the snowdrift process has a significant impact on surface snow accumulation. Wind drift, redistribution, and sublimation effects could induce abnormal loss/accumulation of the annual/seasonal layer, disturbing the climate signals. In other words, the credibility of short-term records of the snow profile in windy areas may be limited. However, in areas where wind is weak and temperature is low, such as Law Dome, snowdrift is weak, and most of the snow layers are from original snowfall.

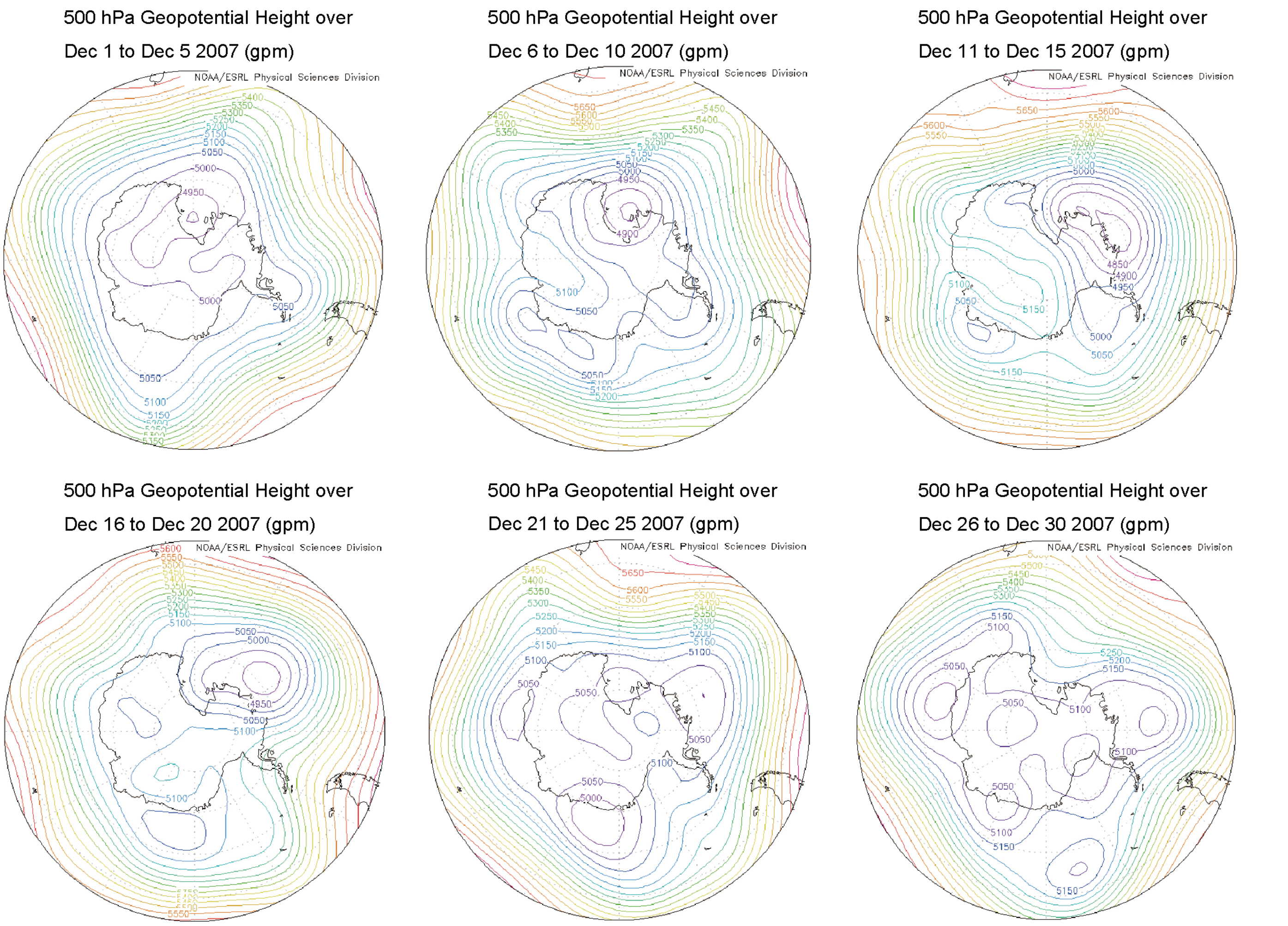

Figure 8 The 500 hPa geopotential height over 1 December and 31 December 2007.

5. Conclusion

By comparing snow chemical/isotopic layers with the precise snow accumulation records of the AWS ultrasonic sounder, we evaluated the influence of the snowdrift process on dating the snow profile. A maximum 12-month difference between the 3-year chemical dating results and the actual deposition time was illustrated. The variance of the dating depth at the bottom reached up to 28 cm, which accounts for 31% of the complete snow pit. Wind-driven processes controlled by wind speed along the surface slope have a significant effect not only on surface mass balance evaluation but also on ice core dating. These results contrast to the studies carried out by McMorrow et al. (2002, 2004), who found that the annual cycles of ion species and oxygen isotope ratios were preserved very well near Law Dome. This pattern should be attributed to high snow accumulation (120 cm) and the absence of high wind gusts (Adams, 1996), both of which minimise surface mixing and redistribution. The summer temperature is also low at that site and precludes melt and sublimation (Allison et al., 1993). In summary, the snowdrift effect should be taken carefully in low accumulation or windy areas, such as the 'wind glaze' areas described by Scambos et al. (2012) or the katabatic wind region suggested by Furukawa et al. (1996).

During austral winter, the warm air mass from the ocean may bring more precipitation inland, but strong winds and changeable wind direction could push it away. In summer, the atmospheric general circulation field is relatively stable, along with wind speed and direction; thus, the snow height is less affected by snowdrift.

More importantly, snow layers may be deposited by certain precipitation/snowdrift events, leading to a non-continuous climate record in the Antarctic inland region. This phenomenon has also been observed in Droning Maud Land (Reijmer and van den Broeke, 2003) and Dome Fuji (Fujita and Abe, 2006; Kameda et al., 2008) previously, and judging snow layers or historical records requires caution. Near the coastal area, the high precipitation could smooth/cover the disturbing signal. Nevertheless, the snowdrift process is not explicitly included in numerical weather forecasting and general circulation models (e.g., Krinner et al., 2006), although some one-

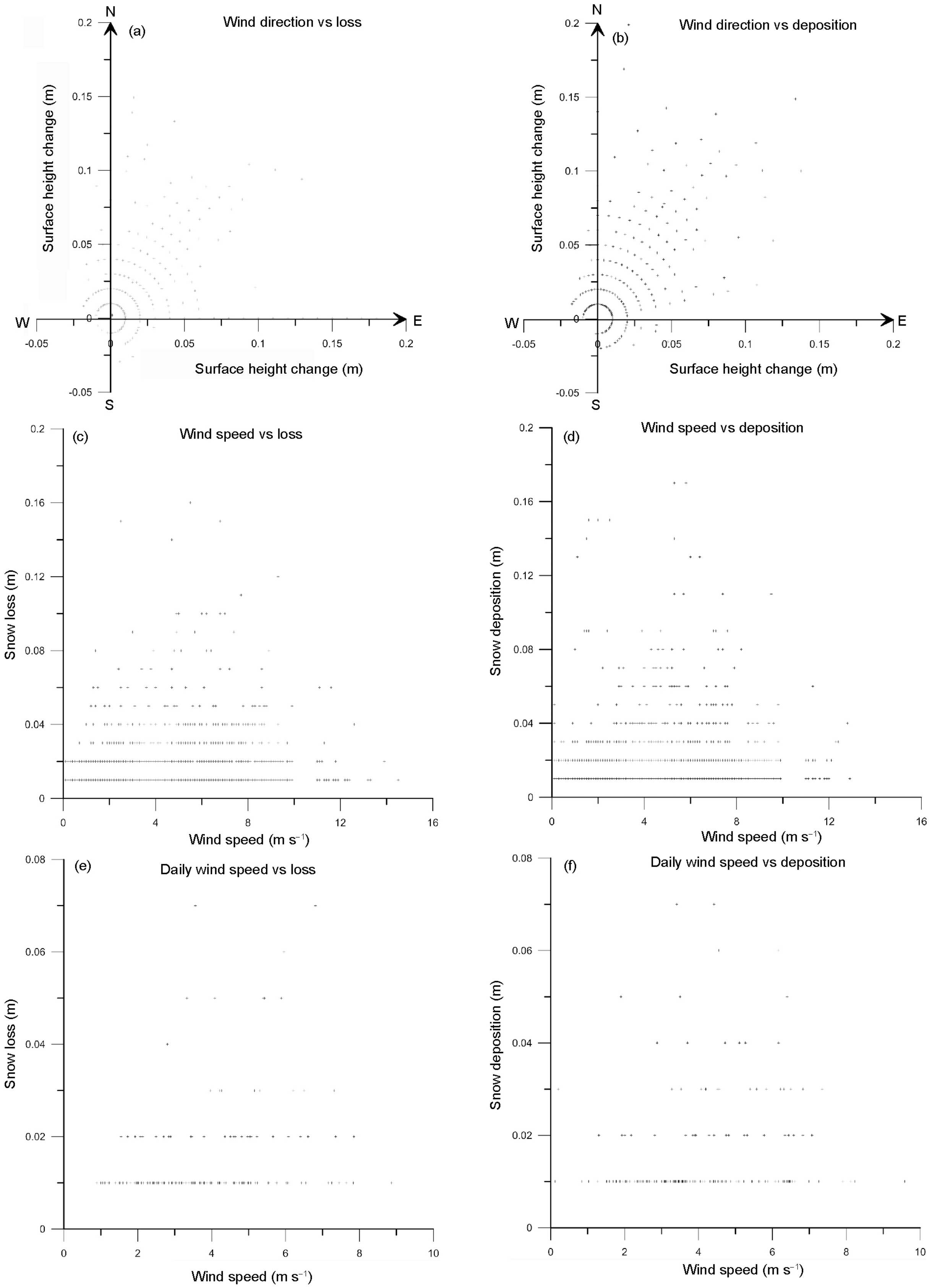

Figure 9 Snow loss/deposition versus wind direction, wind speed and daily wind speed.

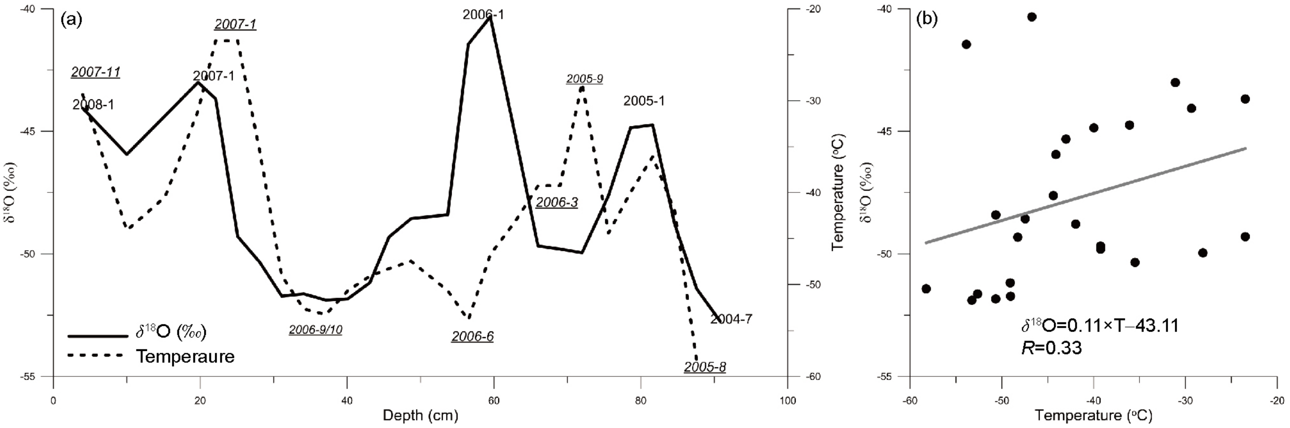

Figure 10 Comparison of $\delta^{18}O$ records from the snow pit vs. air temperature records from the AWS. (a) The difference in the dating depths between the $\delta^{18}O$ method and the ultrasonic sounder records. (b) Correlation analysis between $\delta^{18}O$ and air temperature. The italicised dates in (a) represent the real date of the depth; the other dates represent the dating results from the $\delta^{18}O$ method.

dimensional models have considered the effect (e.g., Fierz and Lehning, 2001; Vionnet et al., 2012), one of which was included in the regional climate model RACMO 2.3 (Wang et al., 2016).

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