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The snowdrift effect on snow deposition: insights from a comparison of a snow pit profile and meteorological observations

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Abstract

A high-frequency and precise ultrasonic sounder was used to record precipitated/deposited snow and drift events over a 3 yr period (17 January 2005 to 4 January 2008) at the Eagle automatic weather station (AWS) site. Through a comparison of the meteorological data with snow pit chemical/isotopic dating results, the snowdrift process effect during snow accumulation was assessed. We believe that ice/firn cores are the most important proxies of climate and the environment because of their high resolution and their preservation of historical greenhouse gas levels, although their limitations and measurement uncertainties must be taken into account, due to the event-driven snow dominates the snow deposition. This study found a difference between two dating results of up to 12 months for a ~ 95 cm snow pit, where the annual snow accumulation rate is 30.3 cm. A weakness is also indicated when simulating the surface mass balance in Antarctica.

1 Introduction

Ice cores, loess, and stalagmites are the most important proxies for paleoclimate studies. Among them, ice cores have become increasingly more 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 last century, glaciologists have conducted numerous ice core studies on Antarctica, Greenland, and mountain glaciers. These studies include the Vostok Ice Core Project (Ekaykin et al., 2010) and the EPICA Dome C project (EPICA Community Members, 2004) in Antarctica, the NEEM international project and the GNIP project in Greenland (Ren et al., 2008), and the Guliya ice core project on the Tibetan Plateau (Wu et al., 2004).

Different from loess or stalagmites, the sediment (precipitation) on glaciers and ice sheets primarily comes from the ocean surface in the form of snow, and sonw is

transported by the wind before it is permanently added to the underlying snow cover (Groot Zwaaftink et al., 2013). Furthermore, the post-depositional process occurs after/during snow events (Frezzotti et al., 2002; Esien et al., 2008), influenced by thermodynamics (during firnification) and wind (snowdrift) (Fierz and Lehning, 2001), which may lead to a misunderstanding of climate records.

Many studies have discussed the post depositional effect by wind. Such as: Watanabe (1978) described the deposition-erosion processes at Mizuho Plateau; Frezzotti et al. (2007) estimated the role of SPWD in the snow erosion near Talos Dome; Petit et al. (1982) suggested the local erosion could be on the same order of magnitude as precipitation; Groot Zwaaftink et al. (2013) simulated the the event-driven deposition of snow, and found that the precipitation is not the driving force behind non-temporary snow height changes. However, it still could not give an accurate estimation of post depositional processes, because but not only drifting and blowing snow events are hard to observe.

As part of the ongoing deep ice core project in Dome A, Antarctica, the 21st CHINARE drilled a 109.91 m shallow core and tried to obtain the primarily environmental characteristics of the Dome A area. However, it was quite surprising to learn that the two dating results of the core by Jiang et al. (2012) and Li et al. (2012) differed significantly. The former study obtained a 2840 yr record for the top 100.42 m and the latter a 4115 ± 150 yr record for the whole core, a difference of up to 1275 yr (a misinterpretation rate of 31 % to 45 %). One of the most likely reasons for this discrepancy is disturbance of the proxy by post-depositional processes.

How large, then, is the influence of the post-depositional process? Could it disturb the seasonal or even annual signal? Here, we will present a case study and attempt to explore the snowdrift process by sampling the snow profile under the ultrasonic sounder of an automatic weather station (AWS).

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 (Fig. 1). 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, when the 21st CHINARE first arrived at Dome A. Its distance to the coast is nearly 806 km. Eagle was designed by the Australian Antarctic Division and calibrated before being placed in the field, and it has made continuous observations since its deployment. Eagle measures the air temperature (1, 2, 4 m), wind speed (1, 2, 4 m), wind direction (4 m), atmospheric pressure (4 m), global radiation (4 m) and firn temperature (−0.1 m, −1 m, −3 m, −10 m). The snow surface height (SSH) is also observed by an ultrasonic sounder (Fig. 2). Table 1 lists the major sensors and their resolutions. The sampling frequency is set as 24 times per day, and the data are transmitted in real time through the Data Collection System of the ARGOS supporting satellite. These sensors make it possible to correct for the observation errors due to wind and air temperature (Eisen et al., 2008). In Antarctica, there are approximately 30 AWSs of this type (http://aws.acecrc.org.au/datapage.html), and they have been proven to have a high credibility (e.g. Allison et al., 1993, 1998; Ma et al., 2010).

On 4 January 2008, 50 snow samples were collected at a ∼ 3 cm interval from a 165.9 cm snow pit profile at Eagle, 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

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the difference in the $^{18}O/^{16}O$ ratios between the sample and the standard V-SMOW. The accuracy was estimated as ±0.15‰.

As Fig. 3 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 correct level of the local stable oxygen isotopic composition.

3   Discussion

3.1   The climatology of Eagle

The Eagle AWS is located within the "Extremely Flat Area" of inland Antarctica, with a hard surface crust (Ding et al., 2011) and an average slope of $\sim 3.40\,\mathrm{m\,km^{-1}}$ (calculated from the digital elevation model developed by the US National Snow and Ice Data Center). Its prevailing aspect is northwards at the eastern side of the Lambert Glacier Basin, but the prevailing wind direction is northeast (56.3 %, see Fig. 4). The annual average wind speed is $4.17\,\mathrm{m\,s^{-1}}$ because of the atmospheric circumfluence (Allison et al., 1993; 1998; Zhou et al., 2009; Ma et al., 2010). Although the ice divide of east Antarctica starts to increase in this area, katabatic wind has almost no influence, as the observations show. The observed annual average temperature, relative humidity, air pressure, and snow accumulation are 40.80 °C, 53.67 %, 683.52 hPa, and 30.33 cm, respectively (Ma et al., 2010).

According to the AWS records, only ~ 95 cm of snow accumulated during January 2005 to January 2007, so this paper will only describe the top 100 cm of the $\delta^{18}O$ vertical profile of the Eagle snow pit.

3.2 The post-depositional process

The post-depositional processes include densification, firnification, snowdrift, sublimation, and ice stretching processes etc. In the densification process, as the density of snow stratification increases with the new precipitation deposits on the snow surface
5 (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 stays relatively stable (Fig. 3), partly due to the wind crust structure (Fig. 2) by a high annual mean wind directional constancy of 0.91 (Fig. 4). In the firnification process, when the densification process occurs, physical properties such as particle size and
10 transmittance will change until the snow becomes ice (e.g. Paterson, 1994; Williams et al., 2000; Frezzoti et al., 2004), it has no direct connection with snow height. Although it is known that sublimation in Antarctica is not negligible (e.g. Stearns and Weidner, 1993; Bintanja, 1998a; Gallée, 1998; Gallée et al., 2001; van den Broeke et al., 2005) and that wind-driven sublimation processes (controlled by the surface slope along the
15 prevailing wind direction, SPWD) have an enormous impact (up to 85 % of snow precipitation) on SMB and are significant in terms of past, present, and future SMB evaluations in the katabatic area (Frezzoti et al., 2004, 2007), sublimation can still be recorded by an ultrasonic sounder (Scarchilli et al., 2008, 2010). It has been proved that the net mass loss by sublimation on the Antarctic surface is no more than 5 % of the precip-
20 itation (Qin et al., 2001), so we combined this process with the snowdrift process in this study. Ice stretching happens deep inside the ice sheet (e.g. Rignot et al., 2008; Anschutz et al., 2011). 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 on environmental
25 records.

However, the estimations of the snowdrift shows that it can lead to significant layer losses during the strong wind season (e.g. Bintanja, 2000; Frezzotti et al., 2002; Scarchilli et al., 2011; Groot Zwaaftink et al., 2013). Sublimation could also be

accelerated by wind (e.g. Smith 1995; Gallée, 1998; Bintanja 1998a; 2001; Gallée et al., 2013), with a maximum value of 0.1–0.2 mm d^{-1} around the Talos Dome (Scarchilli et al., 2008). A few studies on snowdrift have been carried out over polar ice sheets, and some empirical functions and models have been established (e.g. Pomeroy and Jones, 1996; McConnell et al., 1997; Bintanja, 1998a, b; Mann et al., 2000; Scarchilli et al., 2010; Groot Zwaaftink et al., 2013), but almost all of these studies focused on mass loss processes by wind and did not give an overall estimation of the snowdrift process, especially the misinterpretation of the snow layer. Therefore, we will provide a case study in the next section and attempt to determine how large the influence of the snowdrift process is on the snow depositional layer.

3.3 Dating the snow pit

First, we dated the snow pit by marine aerosols and δ^{18}O cycles (Fig. 5) (Legrand and Mayewski, 1997). The results show good seasonal variations along the profile, although some parts may be misunderstood due the weak signals of some proxies at certain depths, such as between 60 cm and 100 cm. Overall speaking, these proxies have good consistency.

3.4 Reconstructing the ultrasonic sounder record

We then traced the record using the Eagle AWS ultrasonic sounder and compared it with the vertical profile of the Eagle snow pit (Fig. 6). An obviously seasonal variability of snow accumulation (not for precipitation) can be found: 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.

By reconstructing the snow height change history, we found that accumulations mainly occurred during certain precipitation or snowdrift events, which is illustrated in Fig. 6 and is listed in Table 2. The snow samples in our study were collected on

4 January 2008, but the surface snow was deposited during Oct. 2007, which is also implied by the concentrations of Na$^+$ and Cl$^-$ and the δ^{18}O value in Fig. 5. The autumn and winter of 2007 had a stable snow accumulation of 15 cm. Although 7 cm of snow accumulated, its depositional time was during 6 January and from 24 January to 4 February 2007. The strong wind 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 a snow layer as indicated by the numerous sharp decreases and increases in Fig. 6. However, there was a relatively high snow accumulation. The 2005/06 austral summer received stable precipitation, but most of it drifted away as the result of occasionally strong winds. The spring of 2005 had continual snow accumulation. The snow layer that precipitated from January to July 2005 was lost because of the snowdrift process. Groot Zwaaftink et al. (2013) suggested that the snow might be added to the snow cover permanently only during periods of strong winds, due to the soft snow before would be drifted be strong wind. This assumption in the SNOWPACK model is consistent with our observation.

Unfortunately, the Eagle AWS did not continuously record wind speed/direction data because of the extreme environment of the Antarctic inland (Fig. 6). However, we can speculate that wind is the key factor in snowdrift, as many other studies 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 decreases and increases in the snow surface when extremely high winds were detected. Previous studies, such as Winther et al. (2001) and Van de Berg (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 the surface sublimation and snowdrift erosion may exceed the solid precipitation flux, resulting in areas with a negative surface mass balance. Frezzotti et al. (2004, 2007) noted that the wind-driven sublimation phenomena determined by the SPWD have a considerable impact on the spatial distribution of snow over in short (tens of metres)

and medium (kilometre) spatial scales. However, the slope, especially the SPWD in our study area, is low.

3.5 Estimating the snowdrift process

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

To compare the differences between our dating result from chemical proxies and the real depositional date from the AWS record, we illustrate the variations of both methods along the snow depth in Fig. 7b. The $\delta^{18}O$ variation is generally consistent with temperature and has a good correlation in the top ~ 50 cm. Farther down, however, the dating difference becomes increasingly larger. At ~ 90 cm, the difference can be as large as 12 months.

Based on the reconstruction of the snow deposition layer shown in Fig. 6 and Table 2, we calculated the real air temperature during the snow deposition events. The $\delta^{18}O$-temperature relationship is given in Fig. 7a, which shows a linear equation. However, the correlation coefficient is quite low ($R = 0.33$), which suggests that rather the snow layers have been 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 currently).

It can be concluded that the snowdrift process has a significant impact on surface snow accumulation. Wind drift, redistribution, and sublimation effects induce the 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.

4   Conclusions

By comparing snow chemical/isotopic layers with the highly precise snow accumulation records of the AWS ultrasonic sounder, we uncovered the disturbing effect of the snowdrift process on dating the snow profile. We found a maximum 12 month difference between the 3 yr chemical dating results and the actual deposition time. The variance of the dating depth at the bottom reached up to 27.8 cm, which accounts for 30.6 % of the whole snow pit. Wind-driven processes controlled by wind speed along/against the surface slope not only have a significant effect on surface mass balance evaluation but also on ice core dating.

More importantly, snow layers may be deposited by certain precipitation/snowdrift events and may not indicate a continuous climate record in the Antarctic inland, where the annual precipitation is low and the wind is relatively high. For the coastal area, the high precipitation could smooth/cover the disturbing signal. Furthermore, the snowdrift process is not explicitly included in numerical weather forecasting and general circulation models (e.g. Krinner et al., 2007), although some one-demension models have been well improved (e.g. Fierz and Lehning, 2001; Vionnet et al., 2012).

Dome A is one of the most attractive positions for recovering the oldest ice cores, as the International Partnerships in Ice Core Sciences noted (IPICS: http://www.pages-igbp.org/ipics/). Dome A is quite close to Eagle and may experience the same atmospheric circumfluence; furthermore, its snow accumulation rate is only ∼ 9 cm (Hou et al., 2007; Ding et al., 2011). CHINARE started a drilling project in January 2012. One of the greatest challenges is obtaining a reliable record of climate and biogeochemistry. Although we have carried out detailed survey and modelling work (e.g. Hou et al., 2007; Xiao et al., 2008, 2012; Sun et al., 2009; Ding et al., 2010, 2011; Wang et al., 2012), the post-depositional processes should not be neglected or misjudged.

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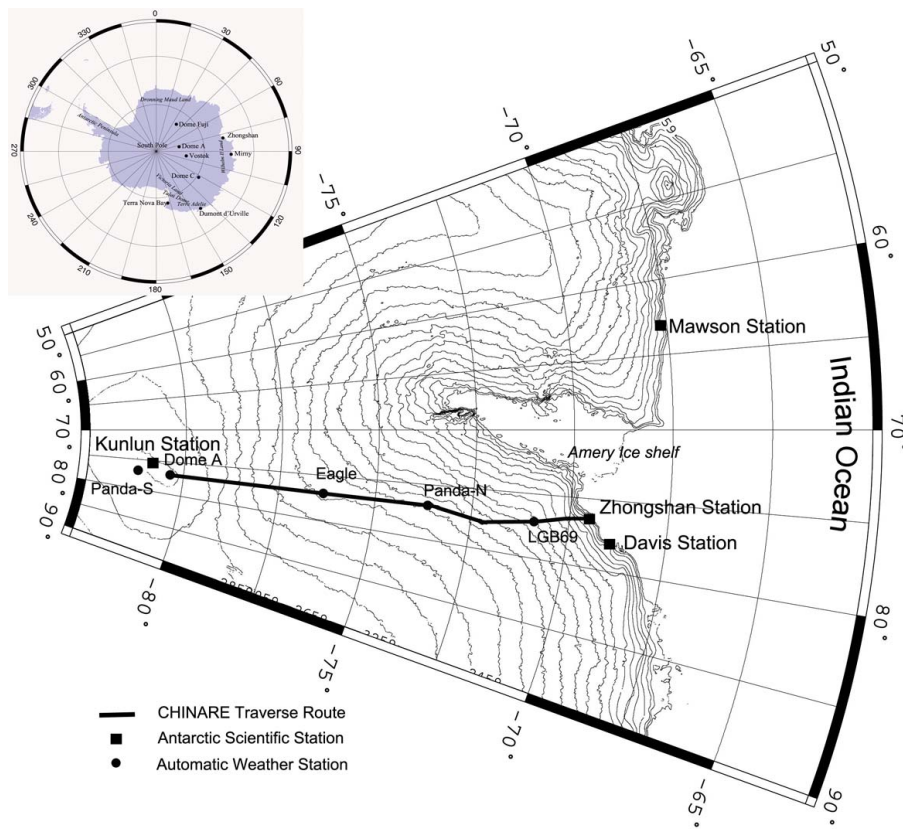Full Screen / Esc

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Table 1. Specifications of the Eagle AWS.

Sensor	Type	Range	Accuracy
Air thermometer	FS23D thermistor	-85–$65\,^{\circ}$C	$0.02\,^{\circ}$C
Hygrometer	Vaisala HMP45D	0–100 %	2 % (RH < 90 %)
			3 % (RH > 90 %)
Anemometer	Young P/L cup anemometer	0–51.1 m s^{-1}	0.1 m s^{-1}
Anemoscope	Aanderra 3590 vane	0–360°	6°
Ultrasonic sounder	Campbell Scientific SR50-45	0.5–10 m	0.01 m
Radiometer	Middleton EP08	0–204.8 MJ	0.1 MJ m^{-2}
Barometer	Paroscientific Digiquartz 6501A		0.1 hPa
Subsurface thermometer	FS23D thermistor	-85–$65\,^{\circ}$C	$0.02\,^{\circ}$C

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Table 2. 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 Jul 2005	3	3
~ 10 Aug 2005	3	6
~ 10–20 Sep 2005	5	11
20 Sep–25 Oct 2005	6	17
~ 10–20 Dec 2005	2	19
~ 1–10 Mar 2006	8	27
~ 10–20 Apr 2006	2	29
~ 20–30 Apr 2006	1	30
Jun–Aug 2006	20	50
~ 1–10 Sep 2006	2	52
14 Sep–2 Oct 2006	7	59
~ 1–10 Nov 2006	3	62
~ 1–10 Jan 2007	7	69
~ 1–10 Feb 2007	3	72
~ 10–20 Mar 2007	3	75
~ 20–30 Apr 2007	3	78
~ 20 May–10 Jul 2007	6	84
~ 20–30 Nov 2007	4	88

Fig. 1. Locations of AWSs deployed by CHINARE in east Antarctica.
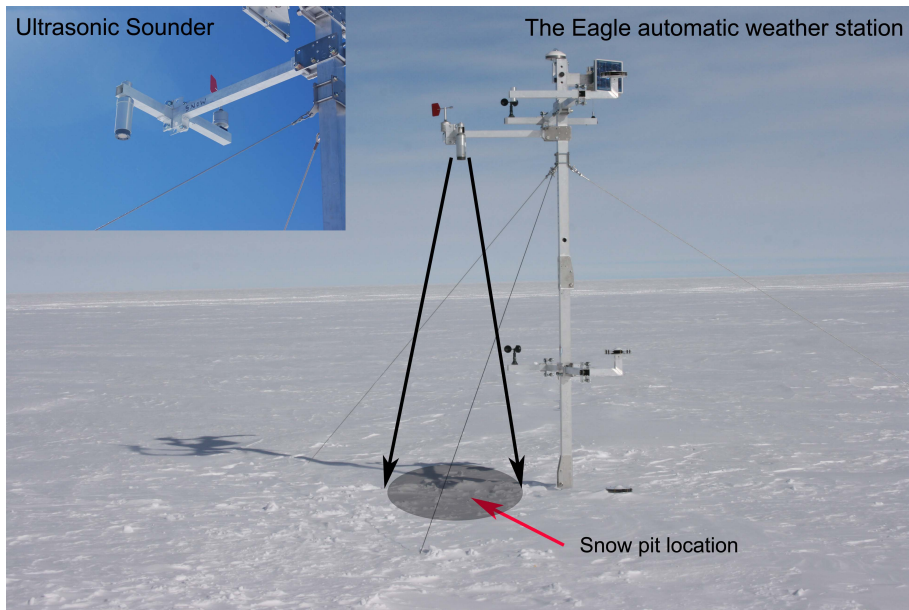
Fig. 2. The Eagle AWS and snow pit diagram.
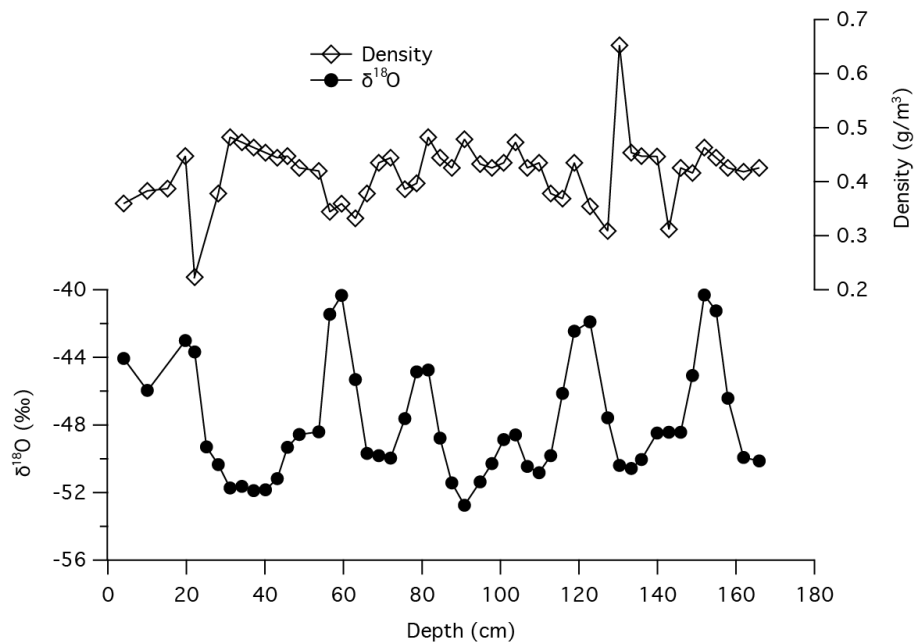
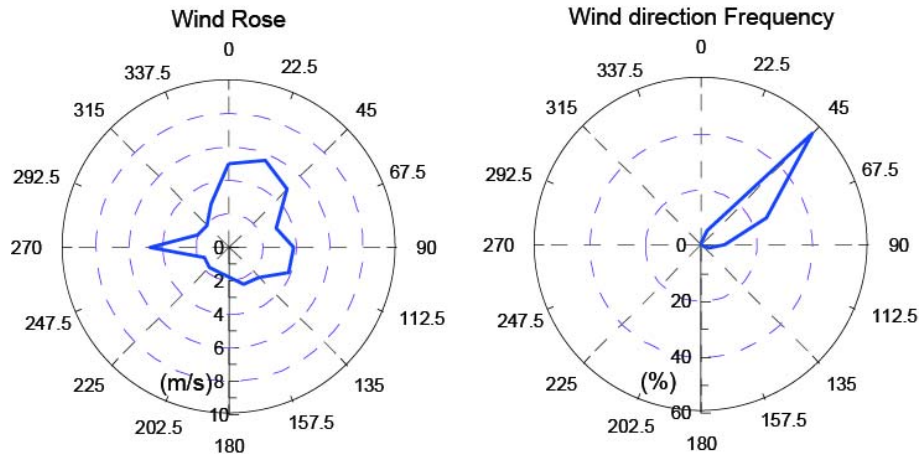**Fig. 3.** The variations of δ^{18}O values and snow density along the Eagle snow pit profile.

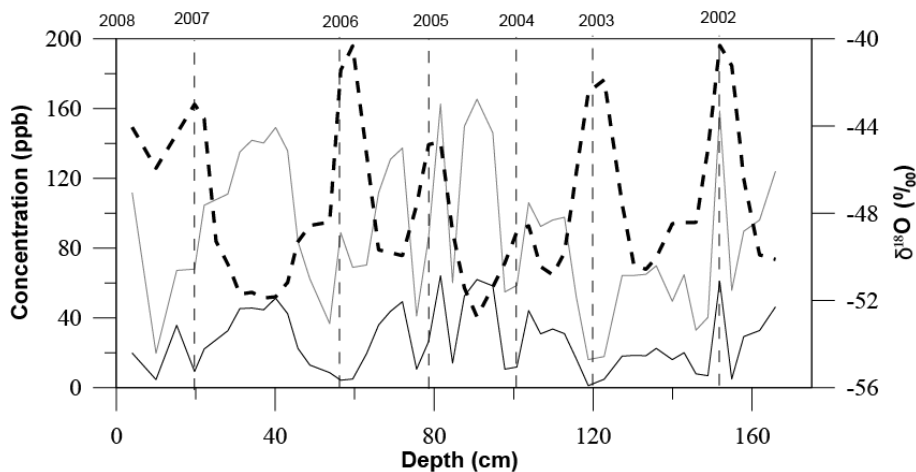**Fig. 4.** Wind speed/direction and wind direction frequency analyses for the Eagle AWS during January 2005–January 2008.

Fig. 5. The dating results of the Eagle pit by marine aerosol and $\delta^{18}O$ cycles (the solid black, solid grey, and dotted black lines represent Na^+, Cl^-, and $\delta^{18}O$, respectively).
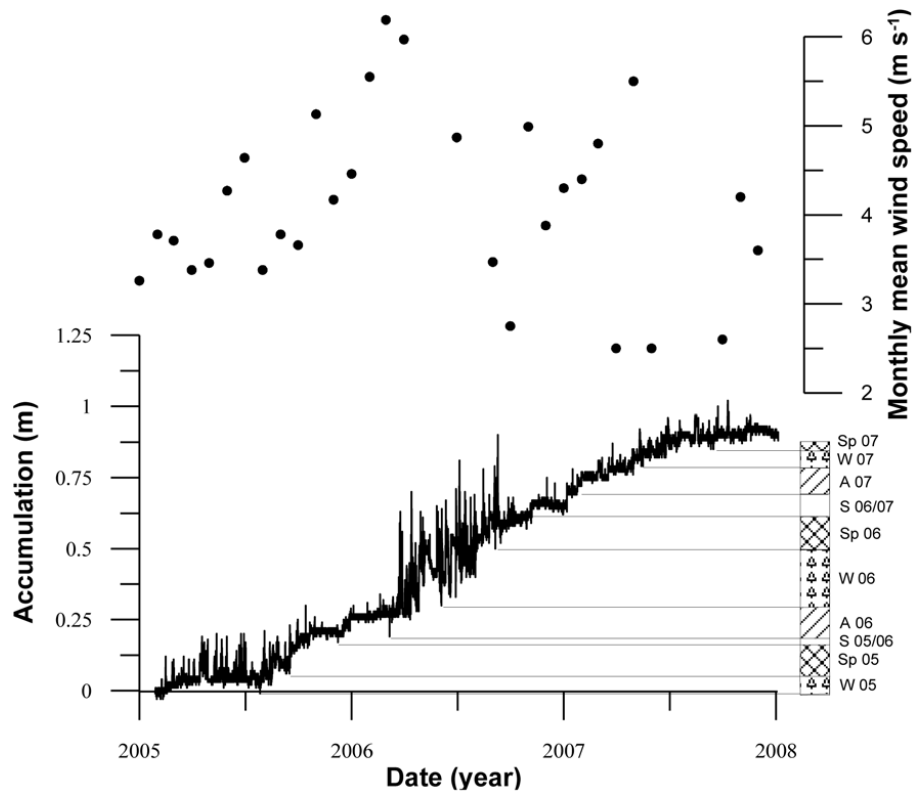
Fig. 6. Dating of the snow profile by the record of the ultrasonic sounder (bottom) and the monthly mean wind speed during January 2005 and December 2007 (top) at the Eagle AWS (Sp: spring; S: austral summer; A: autumn; W: winter).

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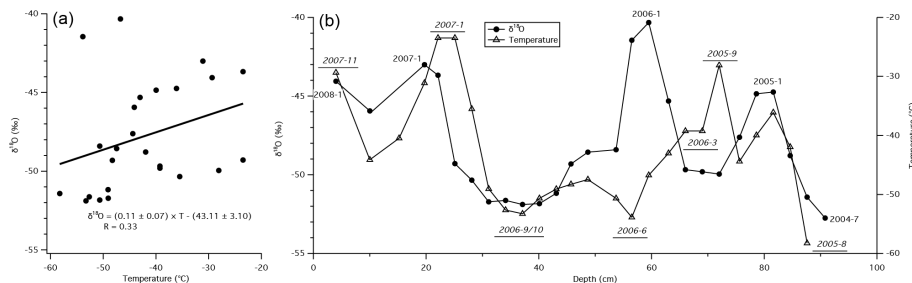Full Screen / Esc

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Fig. 7. Comparison of δ^{18}O records from the snow pit vs. air temperature records from the AWS. **(a)** Correlation analysis between δ^{18}O and air temperature. **(b)** The difference in the dating depths between the δ^{18}O method and the ultrasonic sounder records. The italic dates in **(b)** represent the real date of the depth; the other dates represent the dating results from the δ^{18}O method.