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Variations of air content in Dasuopu ice core from AD 1570–1927 and implications fore climate change

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ABSTRACT

An ice core air content record that was recovered from the refrozen-recrystallization ice formation zone in the Dasuopu Glacier was investigated in this work, which showed that the air content in ice performed significant fluctuations both in the seasonal and long-time series. The air content was low in summer and high in winter, and fluctuated around the mean value of 5.025 cm^3 per 100 g ice from AD 1571 to AD 1927. The correlation of the air content in ice with the climatic and environmental factors was discussed combining with the dating results, which showed that over about 400 yrs from AD 1570 to AD 1927 the air content in ice from the refrozen-recrystallization ice formation zone in the Dasuopu Glacier was mainly dominated by the insolation intensity rather than the temperature and other environmental factors in the Southern Tibetan Plateau.

1. Introduction

The air bubbles trapped in ice offer a source of abundant climate information and could be used for the reconstruction of regional and global climate change (Brook, 2005). Based on studies of ice core air bubbles in polar and mid-low latitude regions (Barnola et al., 1987, 2008; Blunier et al., 1995; Chappellaz et al., 1997; Xu and Yao, 2001; Jouzel et al., 2007), the correlation between the concentrations of greenhouse gases (CO_2, CH_4 and N_2O etc.) and the temperature and precipitation over different time series had been reconstructed. Because the air content in ice is highly sensitive to the variation of physical character of ice and the transformation of ice formation zones which were both induced by climate and environment changes (Anderson and Benson, 1963; Martinerie et al., 1992; Paterson, 1994; Raynaud et al., 1997, 2007), it also could provide a feasible means to reconstruct the regional and global paleoclimate evolution.

Study of the air content in ice was pioneered by Langway (1958), and until now most of the studies were developed in the polar regions. Investigations on the air content in ice in the polar regions showed that the air content (represented by volume) in ice was mainly dominated by the atmospheric pressure and temperature in the dry ice formation zones. A coupled relationship among the ice sheet scale, sea level and climate change has been established (Martinerie et al., 1992; Raynaud et al., 1997; Delmotte et al., 1999; Krinner et al., 2000), which had provided significant databases to the reconstruction of the regional and global paleoclimate change and water cycle.

However, few studies have been done on the air content in ice in the Tibetan Plateau. Recently, only the East Rongbuk (ER) ice cores that were recovered from the percolation zone of East Rongbuk Glacier in Mt. Everest had been investigated for the air content in ice (Hou et al., 2007) which indicated that the air content in ER ice cores was mainly correlated with the magnitude and frequency of snow melting on the glacier surface in summer. No investigations had been done on the ice core air content record in the refrozen-recrystallization ice formation zones in the Tibetan Plateau. The general variation trend and its implications to the climate and environment changes were unknown.

This work used an ice core which was recovered from the refrozen-recrystallization ice formation zone in the Dasuopu Glacier to reveal the variations of the air content in ice and its implications to the climate and environment changes in the Tibetan Plateau. This will provide available approach to the reconstruction of paleoclimate and paleoenvironment changes in the Tibetan Plateau.

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2. Material and methods

2.1. Material

Dasuopu glacier (28° 23′ N; 85° 43′ E) (Fig. 1) is located at the northern slope of Mt. Xixiabangma, central Himalayas. The glacier terminates at about 5600 m a.s.l. and the snowline of this glacier is at about 6000 m a.s.l. According to the automatic weather station at an altitude of 6800 m a.s.l. on this glacier, the mean annual temperature was only −18.1 °C. The maximum and minimum mean daily temperatures were −5 °C and −33.5 °C respectively during the summer of AD 2006. The annual glacial accumulation is about 1000 mm per year which allows for a high resolution record of the climatic and environmental information in the ice. There is a 4 km long and 1 km wide refrozen-recrystallization ice formation zone on the top of the glacier between the altitudes of 7000–7200 m a.s.l. (Yao et al., 1998; Xu and Yao, 1999). Borehole temperature here at the depth of 10 m is −16 °C and −13.8 °C at bedrock, which indicate a suitable condition for the recrystallization of the fallen snow (Paterson, 1994; Yao et al., 1998; Qin and Ren, 2001). In AD 1997, three ice cores were recovered from this wide recrystallization ice formation zone at an altitude of ~7100 m a.s.l. Core 2, 149.8 m long, was used for the analyses of the air content in ice.

Pretreatment of the ice core samples were performed in the Laboratory of Ice Core and Cold Region Environment (LICCRE) and all the ice samples for the air content detection were selected below the firn close-off depth (47 m, Xu and Yao, 1999). From the depth of 49.82 m–52.41 m the ice core was uninterruptedly partitioned at length intervals of 5–10 cm to investigate the seasonal variation characters of the air content. Another 169 ice samples were selected from the depth interval of 49–148 cm to investigate the long-term variations of the air content. Each sample is about 75 g and 5 cm in length. This study only used the ice samples from the depth interval of 49–118 cm for the discussion of air content in ice. The deeper part of the Dasuopu ice core was not used because of the relatively long sampling intervals and low time resolution.

2.2. Measurement methods

Measurements of the Dasuopu ice core 2 were performed both in the Laboratory of Ice Core and Cold Region Environment (LICCRE), Chinese Academy of Sciences and the Laboratoire de Glaciologie et Géophysique de l'Environnement (LGGE) in France. The melting–refreezing method (Xu et al., 2002) was used to extract the air bubbles trapped in ice in LICCRE, and similar technique as described in reference (Chappellaz et al., 1997) were also performed for the extraction of the air bubbles in LGGE. The ice core air content value was obtained during the measurement of atmospheric methane in the ice core. First, before melting–refreezing of the ice, the quality of each ice core sample was weighted up, by which the volume of the pure ice after refreezing could be calculated. Then, during the measurement of atmospheric methane in the ice, a capacitive pressure sensor was used to detect the air pressure of each gas injection to the Gas Chromatograph. Therefore, combining with the pressure of the sample loop that had reached air balance, the volumes of the sample loop and the stainless steel container that had already been measured, the air volume of each ice core sample by the standard atmospheric pressure (1013 mbar) and standard temperature (273 K) can be calculated. The calculation equation is given below:

$$\frac{PsVs}{Ts} = \frac{Po(Vc - Vi)}{Tc} + \frac{PoVg}{Tg} \qquad (1)$$

With:

Ps and *Ts*: the standard atmospheric pressure and temperature (1013 mbar, 273 K),

Po and Tc: the atmospheric pressure and temperature when the ice core air reaches balance in the stainless steel container and the sample loop,

Vs, Vc, Vi and Vg: the air volume by the standard condition (1013 mbar, 273 K), the volumes of the stainless steel container, pure ice, and sample loop.

Finally, the air content of each ice sample is obtained by dividing the air volume with the ice core quality.

According to Xu et al. (2002) only 0.1%–0.3% of the total air volume is obtained from the repeating melting–refreezing processes, which indicates that the melting–refreezing method is applicable for the measurement of the air content in ice. The system measurement error on air content in Dasuopu ice core in LICCRE is ~3%. Meanwhile, according to Chappellaz et al. (1997), the experimental error on the air content in Dasuopu ice core in LGGE is 5%, which is mostly due to the uncertainty on the gas temperature inside the sample container. Therefore, both the measurement results of air content in Dasuopu ice core from the LICCRE and LGGE were reliable and could be used for the further discussion of its variation trend and implications.

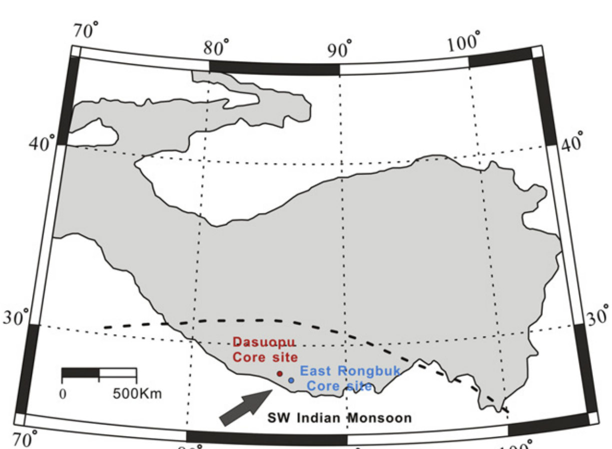

Fig. 1. Locations of the ice core drilling sites, with the shaded region presenting the Tibetan Plateau.

2.3. Data

Because a portion of air would be lost from cut-bubbles at the surface of the ice sample (Raynaud et al., 1982) and more air would be lost from the shallower ice samples due to their bigger bubble diameter than that in deeper ice samples (Hou et al., 2007), this should be carefully considered during the revision of the air content results in ice. For ice samples taken from polar dry snow zones, Raynaud et al. (1982) had established an air volume revision system according to their investigations both on the bubble diameter and ice quality. On the other hand, Hou et al. (2007) had also mentioned an air volume revision system for ice samples taken from the percolation ice formation zones in the Tibetan Plateau. However, for Dasuopu ice core which was recovered from the refrozen-recrystallization ice formation zone, no data revision system for the air volume lost during the cut-off process had been established. Therefore the data revision for the air content results in Dasuopu ice core should be seriously considered.

Fig. 2 shows the densification process of snow at Dasuopu core site. From Fig. 2a, the pores in the firn are gradually enclosed during the firn–ice transition. Besides, the ice density in Dasuopu glacier

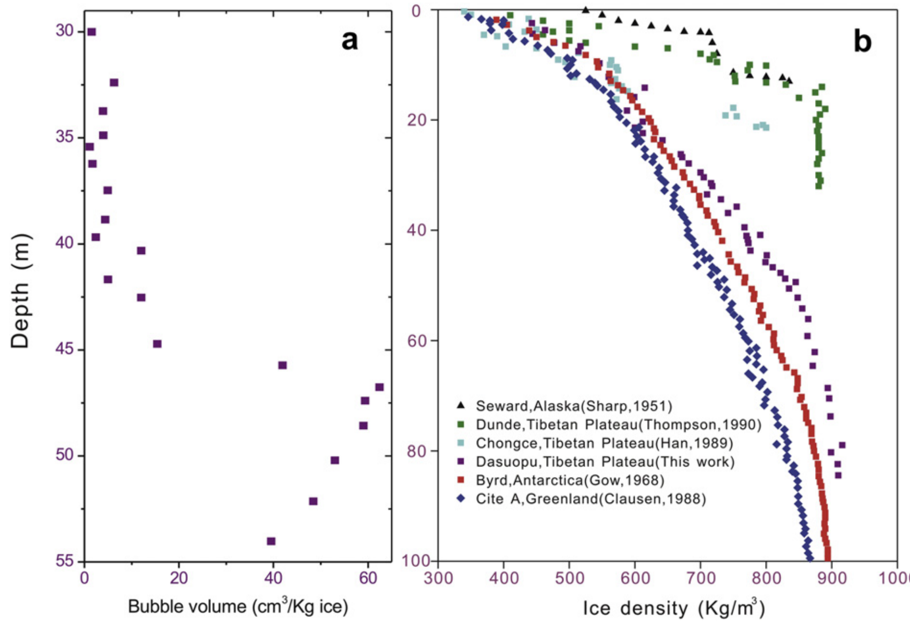

Fig. 2. Bubble volume as a function of depth in Dasuopu ice core (a), densification processes of the firn (b) at different ice core sites.

(Fig. 2b) increases steadily and gradually with depth, which is similar to polar dry glaciers (Gow, 1968; Clausen et al., 1988) and unlike the densification curves of Dunde ice cap (Thompson and Mosley-Thompson, 1990), Chongce ice cap (Han et al., 1989) and Seward glacier (Sharp, 1951) that represent percolation ice formation. However, field investigations (Xu and Yao, 1999) also showed that there were thin ice layers in some parts of the firn, measuring from 3 to 10 mm. These ice layers represent about 4%–13% of the annual layer thickness, which indicates that the ice formation is also influenced by limited snow melting at Dasuopu core site. Therefore, neither the air volume correction systems in the polar snow zones nor the percolation ice formation zones in the ER glacier could be used directly for the air volume correction in Dasuopu ice core. Because the ice formation process at Dasuopu core site is between the ice formation processes in a polar dry snow zone and an ER glacier percolation snow zone, the air volume correction grade for Dasuopu ice core should be between the grades of those two systems.

Fig. 3a shows the data revision results for air content in Dasuopu ice core using both the polar (Raynaud et al., 1982) and the ER glacier correction systems (Hou et al., 2007). There is a relatively deviation of air content on the upper half part of Dasuopu ice core. However for the deeper half part of Dasuopu ice core, air content deviation is very limited. The overall variation trends of air content in Dasuopu ice core using those two data correction systems have no obvious difference. Therefore according to the ice formation process at Dasuopu core site, a middle correction grade between the polar and ER air volume correction grades was taken in this work for the air volume correction of Dasuopu ice core. The final air content results after data correction as a function of depth in Dasuopu ice core are shown in Fig. 3b.

2.4. Dating

The air content in ice is the volume of the air trapped in each gram of ice, which represents the physical character (density) of the ice (Stauffer et al., 1985; Paterson, 1994; Qin and Ren, 2001). When the air content of the ice is high, it means a low density of the ice, and vice versa. No matter the year of the trapped gas, the volume of the gas only relates to the density of the ice in the same stratum. As the physical character of the ice has no age difference with the ice itself, the air content in ice should have no age difference with the surrounding ice. The ages of the ice core are also the ages of the air content in ice. Therefore, the air contents in the Dasuopu ice core used in this work were dating by the ice chronology of the Dasuopu ice Core 2 which had already been established by the pronounced seasonal signals of multi-parameters, such as the $\delta^{18}O$, ion concentration, and ice accumulation model (Thompson et al., 2000; Yao et al., 2002; Duan et al., 2004). The air content samples which are selected from the depth of 49–118 m of the ice core cover a time extent of approximately 400 yrs ranging from AD 1570–1927. The age error for the ice chronology is about 5 yrs for the past 400 yrs, less than one year for the past 100 yrs and negligible for the past 40 yrs (Thompson et al., 2000; Yao et al., 2002).

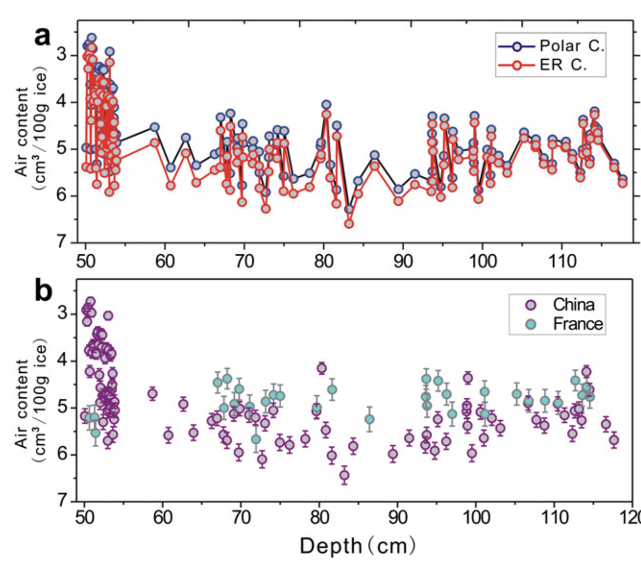

Fig. 3. Air content records as a function of depth in Dasuopu ice core using the Polar and ER glacier air volume correction systems (a), and the finally correction result of air content in Dasuopu ice core (b).

3. Results and discussion

The air content in ice is dominated by various factors in different ice formation zones (Kalesnik, 1982; Martinerie et al., 1992; Paterson, 1994; Qin and Ren, 2001; Raynaud et al., 2007). In polar dry snow zones, the air content in ice is dominated by the pore volume and the ice temperature at the close-off depth, the atmosphere pressure (Martinerie et al., 1992) and also the local insolation (Raynaud et al., 2007). In percolation ice formation zones, the air content of ice is dominated by the magnitude and frequency of the snow melting (Martinerie et al., 1992; Paterson, 1994; Hou et al., 2007). However, in the refrozen-recrystallization ice formation zones, local insolation, atmosphere pressure, ice temperature and snow melting should all be considered to explain the variation of the air content in ice (Kalesnik, 1982; Paterson, 1994; Delmotte et al., 1999; Raynaud et al., 1997, 2007). In comparison with the polar ice cap, the area of Dasuopu glacier is very small. Taking into account the very high altitude of the core site on Dasuopu Glacier, the elevation variations of the ice sheet surface over the past millennium were comparatively limited and could be neglected. Therefore, the atmosphere pressure at Dasuopu core site could be considered relatively stable over the past millennium and could not contribute to the variations of the air content in Dasuopu ice core.

Fig. 4 shows the air content measurement results of the Dasuopu ice core from the depth interval of 49.82 m–52.41 m. This high resolution sampling analyses showed a significant fluctuation of the air content in Dasuopu ice core in a very short-term scale. The air content was compared to the $\delta^{18}O$ of Dasuopu ice core (Fig. 4), which showed an obvious positive correlation between the air content of ice and the $\delta^{18}O$ of the Dasuopu ice core. When the $\delta^{18}O$ value is high, the air content is high. As the Dasuopu Glacier is located in the region dominated by the South-West Indian monsoon (Fig. 1), the seasonal variability of the ice core $\delta^{18}O$ is influenced by the "precipitation amount effect" (Hoffmann and Heimann, 1997; Araguás-Araguás et al., 1998) which means that the ice core $\delta^{18}O$ shows a low value in summer and a high value in winter. Therefore, the air content in Dasuopu ice core had low values in summer and high values in winter, which might indicate a negative seasonal variation of the air content with local temperature and/or insolation.

Long-term scale air content in Dasuopu ice core is shown in Fig. 5, in which the air content in Dasuopu ice core fluctuated around the mean value of 5.025 cm^3 per 100 g ice over about 400 yrs from AD 1571 to AD 1927. The $\delta^{18}O$ of Dasuopu ice core, the temperature reconstruction in Southern Tibetan Plateau (Yang et al., 2003) and the global solar irradiation reconstruction (Lean, 2004) from AD 1570–1930 are also shown in Fig. 5, which provides the basis for the discussion of the correlation of air content

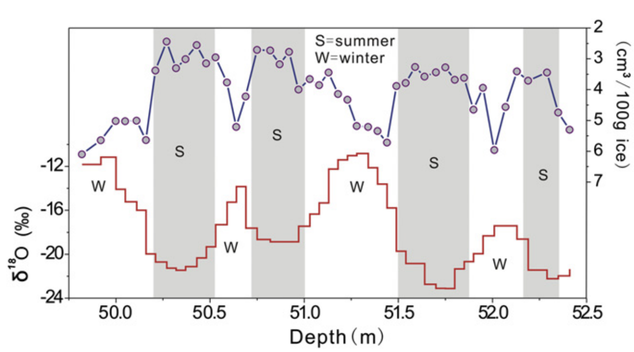

Fig. 4. Comparisons of air content with the seasonal variations of the $\delta^{18}O$ of Dasuopu ice core.

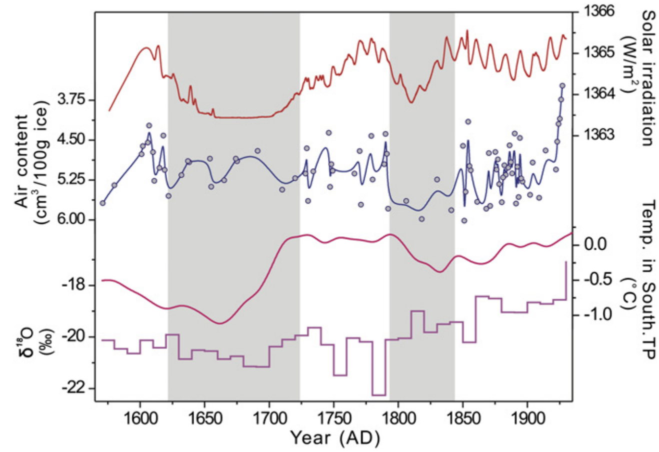

Fig. 5. Air content records in Dasuopu ice core (gray spots with blue line as the B-Spline results) compared to the $\delta^{18}O$ of Dasuopu ice core (Yao and Thompson, 1996, purple vertical line), the temperature reconstruction in Southern Tibetan Plateau (TP) (Yang et al., 2003, pink line) and the global solar irradiation reconstruction (Lean, 2004, red line).

in Dasuopu ice core with other climatic and environmental proxies. The long-term scale $\delta^{18}O$ value of the Dasuopu ice core is used in this study to represent the past local annual temperature variations at Dasuopu Glacier (Thompson et al., 2000; Yao et al., 2002). Comparisons of these four parameters showed that the annual temperature at the Dasuopu Glacier, the temperature in Southern Tibetan Plateau and the solar irradiation all presented general increasing trends from AD 1570 to AD 1930, which were negatively consistent with the general variation trend of the air content in Dasuopu ice core over the same period.

During periods of AD 1570–1620 and AD 1720–1790, two low value stages were present in the air content in Dasuopu ice core, which were consistent with the variations of solar irradiation during the same two periods. However, the relatively stable annual temperature during AD 1570–1620 and the decreasing trend of the annual temperature during AD 1720–1790 that indicated by the $\delta^{18}O$ of Dasuopu ice core did not correlate with these two parameters. Although the high value stage of the temperature in Southern Tibetan Plateau during AD 1720–1790 could correlate with the variations of the solar irradiation and the air content in ice, the low value stage of the regional temperature during AD 1570–1620 did not correspond with the variations of these two parameters. During AD 1620–1720 and AD 1790–1840, there were two increasing stages of the air content in Dasuopu ice core which were consistent with the decreasing trends of solar irradiation variation during the same two periods. The annual temperature at Dasuopu Glacier also presented a consistent low stage during AD 1620–1720, whereas the relatively increasing trend of the local annual temperature from AD 1790–1840 did not correlate with the other two parameters. The variations of the temperature in the Southern Tibetan Plateau were relatively related to the variations of the air content in ice during these two periods, whereas the variation amplitudes and phases of the temperature were not consistent with the variations of the air content in ice. From AD 1850 to AD 1890, the air content in Dasuopu ice core showed a gradually increasing trend which was consistent with the decreasing trend of the solar irradiation, but did not correlate with variations of the local and regional temperature. A significant decreasing trend of the air content in ice occurred around AD 1890, which might relate with the increasing trends of the local annual temperature and solar irradiation and was not consistent with the variations of the regional temperature in the Southern Tibetan Plateau during the same period.

The statistical analysis of the air content in Dasuopu ice core with the solar irradiation, local and regional temperature showed that the correlation coefficient (R) of the air content with the solar irradiation was 0.595, while both the correlation coefficients (R) of the air content with the local and regional temperature were less than 0.1.

Variations of the air content in Dasuopu ice core from AD 1571 to AD 1927 indicated the variations of physical character (crystal form, grain size and the density etc.) of ice in the refrozen-recrystallization ice formation zone. Combined with the negatively relationship of the air content with the solar irradiation, the variation of the irradiation strength on the glacier surface might influence the crystal from and the grain size of the firn particles and caused the variations of the pore volume in the firn during the firn–ice transition process in the refrozen-recrystallization ice formation zone in the Dasuopu Glacier, which is similar with the conclusion of Raynaud et al. (2007) on the air content record in Antarctic ice.

4. Conclusion

The air content in Dasuopu ice core had been measured with a relatively high precession both in the LICCRE and LGGE. Reconstructions of this ice core air content record showed that the air content was low in summer and high in winter. The air content fluctuated around the mean value of 5.081 cm^3 per 100 g ice from AD 1571 to AD 1890, and has a pronounced decreasing trend since AD 1890. Based on the comparisons of the seasonal and long-term variations of the air content in Dasuopu ice core to the $\delta^{18}O$ of Dasuopu ice core, regional temperature in the Southern Tibetan Plateau and the global solar insolation reconstruction, the ice core air content was negatively correlated with solar insolation over about 400 years from AD 1571 to AD 1927. Although general negative correlations were indicated between the local and regional temperature with the air content in Dasuopu ice core, the detailed variation trends of these two parameters were not consistent with the variation trend of the air content. The analyses indicate that the variations of the air content in Dasuopu ice core was mainly dominated by the irradiation strength rather than other climatic and environmental factors. Therefore, the air content in Dasuopu ice core which was recovered from the refrozen-recrystallization ice formation zone could be used as a proxy to reconstruct the past solar irradiation changes and also the paleoclimate evolution history.

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