Development of depth hoar and its effect on stable oxygen isotopic content in snow–firn stratigraphy on Ürümqi glacier No. 1, eastern Tien Shan, China

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ABSTRACT. We report on the development of depth hoar and its relation to stable oxygen isotopic content in snow–firn stratigraphy in the percolation zone of Ürümqi glacier No. 1, eastern Tien Shan, China, during the period September 2004–August 2006. The essential condition for the development of depth hoar in the snow–firn pack is the temperature gradient. When the temperature gradient of the snow–firn pack reaches a maximum value of 13.0°C m^{-1} in mid-October, depth hoar begins to develop. By the end of March, the depth hoar might account for 25% of the total snow–firn pack depth. From April to June, as the weather becomes warm, the transport of water vapor diminishes and melting–regelation metamorphism replaces metamorphism caused by the temperature gradient. As a result, the depth hoar turns into coarse-grained firn. Fractionation of the oxygen isotopic content also occurs during formation of the depth hoar. The bottom 15 cm of the depth-hoar δ^{18}O values were depleted in the lighter isotopic species as the snow sublimated from the lower to the upper crystals, and the δ values increased from –9.4‰ to –7.0‰ from 8 September 2004 to 25 January 2005. The upper 10 cm of the depth-hoar δ^{18}O values were enriched in the lighter isotopic species and the δ values decreased from –6.8‰ to –9.3‰ during the same period.

1. INTRODUCTION

Depth hoar is a type of snow with distinctive crystal shapes (Akitaya, 1974). It forms in snow with densities less than about 0.3 g cm^{-3} at temperature gradients of about 10–25°C m^{-1} (Akitaya, 1974; Armstrong, 1980; Colbeck, 1982). If the gradient is weak, the grains will still grow, but depth-hoar characteristics may be less conspicuous or absent (Sturm and Benson, 1997). The high rate of vapor transport forced by the temperature gradient causes the snow to recrystallize in a few days. The snow crystals under these conditions exhibit the skeletal forms characteristic of high growth rates (Hobbs, 1974). Mass redistribution associated with depth-hoar formation can change concentrations of isotopic species, altering atmospheric signals prior to archivation in ice. Depth hoar has long been studied for its role in producing avalanches on steep slopes (Bader and others, 1954; Yosida and others, 1955). The influence of sublimation on the isotopic composition of snow is also documented (Sommerfield and others, 1991; Stichler and others, 2001), but restricted to a snow depth of 7 cm (Stichler and others, 2001). However, the development of depth hoar and its relation to stable oxygen isotopic content in snow–firn stratigraphy have received little attention.

In the Tien Shan, northwest China, well-developed depth hoar is one of the most important features in the snow–firn pack. In order to better understand the depth-hoar features, a multi-year campaign was launched in July 2002 to investigate the seasonal changes in characteristics of the snow–firn pack on Ürümqi glacier No. 1 (UG1) in eastern Tien Shan. The research was a component of the Program for Glacier Processes Investigation (PGPI) carried out by the Tien Shan Glaciological Station (TGS), Chinese Academy of Sciences (CAS), since July 2002 (Li and others, 2006).

2. SITE DESCRIPTION AND DATASETS

UG1 is a small valley glacier consisting of an east and west branch located at the headwaters of the Ürümqi river, in the eastern Tien Shan (43°05′ N, 86°49′ E). From 1959 to 2003, the annual equilibrium-line altitude (ELA) of the glacier averaged approximately 4055 m a.s.l. An observation and experimental site was carefully chosen in a percolation zone of the east branch of UG1 (where the ice surface slopes about 6°) above the ELA at 4130 m a.s.l. During the sampling period, the mean annual air temperature was approximately –9.1°C, and the precipitation, i.e. snowfall, was 700 mm w.e. (Li and others, 2006; Wang and others, 2006). The depth of the snow–firn pack at the site typically ranged from 1.5 m in late summer to 3 m in late spring and incorporated 3–4 years of net snow accumulation. The floor of the snow–firn pack was composed of superimposed ice, a clear and impermeable opaque ice with spherical bubbles approximately 1–5 mm in diameter.

The data used in this analysis were obtained mainly from September 2004 to August 2006. Snow–firn stratigraphy was recorded every 7 days; the observations were made according to the international classification for seasonal snow on the ground (Colbeck and others, 1990) and included snow-pack depth, grain size and type, density and temperature. The pit was sampled from top to bottom at 10 cm increments on a weekly basis for 11 years. After each session, the pit was refilled and the same procedure was followed 7 days later.

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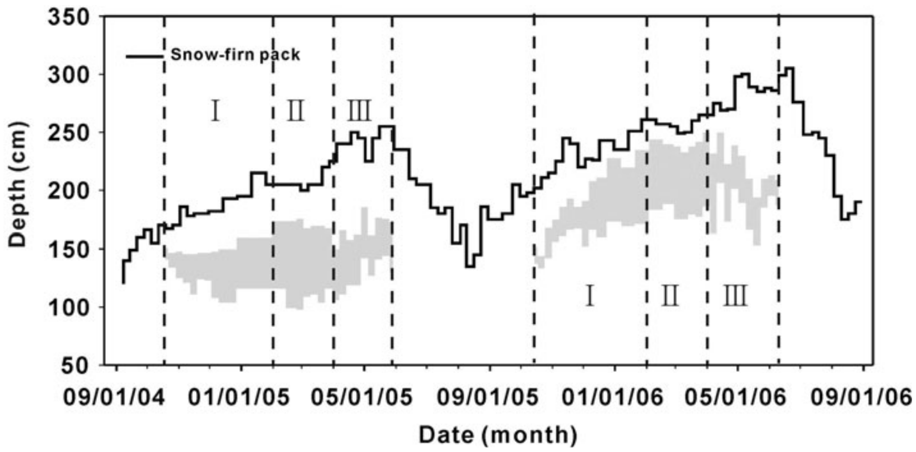

Fig. 1. The development of snow–firn pack and depth hoar from August 2004 to August 2006 (dates are mm/dd/yy). The shaded gray is the position of the depth hoar, and the *y* axis presents the height (cm) above the surface of the superimposed ice.

The wall was scaled back by at least 50 cm before the next collection round. A strict protocol was followed during this procedure to prevent contamination, including the use of disposable polyethylene gloves, masks and pre-cleaned polyethylene sample containers. All the samples were transported in insulated boxes to the laboratory, and kept frozen until analysis.

The $\delta^{18}O$ values of the samples were determined at the State Key Laboratory of Cryosphere Science, CAS, using MAT-252 and DeltaPlus mass spectrometers, with a precision of ±0.2‰.

3. RESULTS AND DISCUSSION

3.1. Development of depth hoar in the snow–firn pack

Depth hoar is formed by sublimation and can only develop in unconsolidated snow. Conditions are especially favorable when the snow lies on top of much denser material such as ice (Paterson, 1994). According to our observations, the depth hoar usually develops above the coarse-grained firn layers (density ~0.73 g cm^{-3}) in the snow–firn pack on UG1. The essential condition for the development of depth hoar in the snow–firn pack is the temperature gradient, which is dependent on the snow–firn pack depth, air temperature and snow–firn pack temperature regime (Ma and Hu, 1990). Generally speaking, the lower the air temperature and the temperature gradient are in the snow cover, the longer the negative temperature lasts, especially with low temperatures, and the thicker the depth hoar will be.

Figure 1 shows the development of the snow–firn pack and depth hoar from August 2004 to August 2006. As was noted, the depth hoar is located in the upper layers of the snow–firn pack. The maximum snow–firn pack depth usually appears in late spring (May) or early summer (June). The development process of the depth hoar is divided into three periods: 15 October–31 January (period I), 1 February–31 March (period II) and 1 April–30 May 2005 and 1 April–10 June 2006 (period III).

Figure 2 shows the seasonal changes in depth-hoar thickness, the mean air temperature and the temperature gradient in the snow–firn pack from August 2005 to June 2006. The temperature gradient is assumed to be vertical and linear and is defined by $(T_i - T_s)/Z_s$, where T_i is the snow/ice interface temperature, T_s is the snow-surface temperature and Z_s is the thickness of the snow–firn pack. Notice that since the temperature gradient of the snow–firn pack is weaker during the period from August to October, none of the snow–firn packs developed depth hoar.

During period I, the snow–firn pack depth increased from 198 to 251 cm. The daily mean air temperature decreased

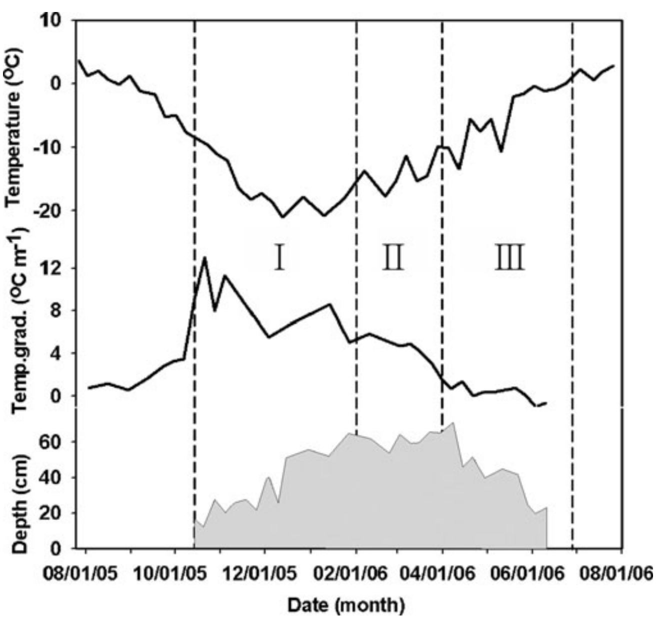

Fig. 2. Seasonal changes in depth-hoar thickness, mean air temperature and the temperature gradient in the snow–firn pack from August 2005 to June 2006 (dates are mm/dd/yy).

Table 1. Changes in temporal $\delta^{18}O$ values at the bottom and top of the depth hoar on different dates

Depth cm	8 Sept. 2004	2 Nov. 2004	25 Jan. 2005
33–43	–6.8	–8.3	–9.3
78–93	–9.4	–7.6	–7.0

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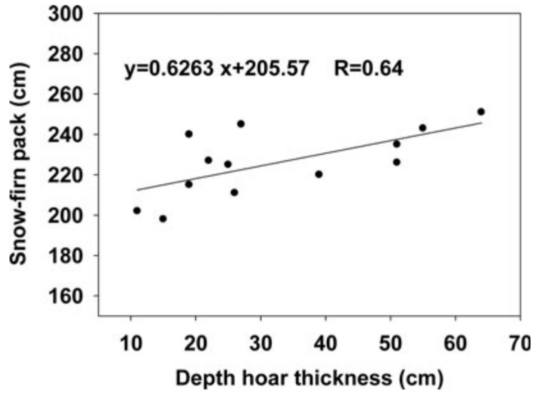

Fig. 3. The relationship between snow–firn pack and depth-hoar thickness during period I.

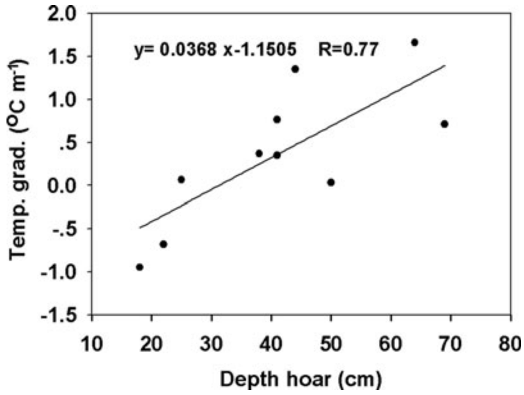

Fig. 4. The relationship between temperature gradient and depth-hoar thickness during period III.

from –5 to –21°C and the temperature gradient reached a maximum value of 13.0°C m^{-1} in mid-October. Generally, this is the active period for vapor transport and depth-hoar development. The depth hoar increased from 15 to 64 cm and the mean thickness accounted for 15% of the total snow–firn pack depth. An obvious linear relationship ($R = 0.64$, two-tailed, $p = 0.01$, $N = 13$) between the snow–firn pack and the depth-hoar thickness was found during this period (see Fig. 3).

During period II, the air temperature increased slowly and snow precipitation was scarce, which resulted in the decrease of the temperature gradient from 5.8 to 1.6°C m^{-1}. Therefore, the snow–firn pack and depth-hoar thickness was relatively stable. The mean depth-hoar thickness was 60 cm, and accounted for 25% of the total snow–firn pack depth.

During period III, the temperature of both the air and the snow–firn pack increased, resulting in a drop in the temperature gradient in the snow–firn pack. This caused the speed of the development of the depth hoar to decrease, along with the relative thickness of depth hoar. The temperature gradient and depth-hoar thickness are obviously correlated ($R = 0.77$, two-tailed, $P = 0.01$, $n = 12$; see Fig. 4). This suggests that the impact of the temperature gradient on depth-hoar thickness overcomes the effect of the snow–firn pack thickness. The mean depth-hoar thickness was 36 cm, and accounted for 15% of the total snow–firn pack depth.

From 1 April to mid-May, the weather alternated between cold and warm with a slight warming trend, which caused the temperatures of the bottom and surface of the snow–firn pack to increase gradually. According to the observations, the temperature gradient in the snow–firn pack decreased to 0.6°C m^{-1} by mid-May. During this period, the transport of water vapor diminished, and a regime of melting–regelation metamorphism discontinuously replaced the temperature gradient for metamorphism in the snow. In early summer (June), as air temperature rose to ~0°C, the upper section of the snow layer began to melt, leading to a rapid thinning of the snow–firn pack. The depth hoar turned completely into coarse-grained firn when the meltwater infiltrated the underlying firn layers by mid-June.

3.2. Effect of depth hoar on stable oxygen isotopic content

3.2.1. Isotopic results for the snow–firn pack

Three $\delta^{18}O$ profiles of the snow–firn pack were selected to investigate the isotopic changes during the development process of depth-hoar formation (Fig. 5). Two of them (2 November 2004 and 25 January 2005) were subjected to strong temperature gradients and developed a typical depth hoar; another (8 September 2004) did not.

Clearly, fractionation of the oxygen isotopic content occurred during formation of the depth hoar. The $\delta^{18}O$ values in the bottom 15 cm (78–93 cm) of the depth hoar increased by 19.1% from 8 September to 2 November 2004 and by 7.9% from 2 November 2004 to 25 January 2005. However, in the upper 10 cm (33–43 cm), $\delta^{18}O$ values of the depth hoar decreased by 22.1% from 8 September to 2 November 2004 and by 12.0% from 2 November 2004 to 25 January 2005 (see Table 1).

3.2.2. Isotopic fractionation effect

Fractional condensation of water vapor (produced by sublimation of the snow) on growing snow crystals as the vapor moves vertically through the snow–firn pack results in isotopic fractionation (Friedman and others, 1991). The

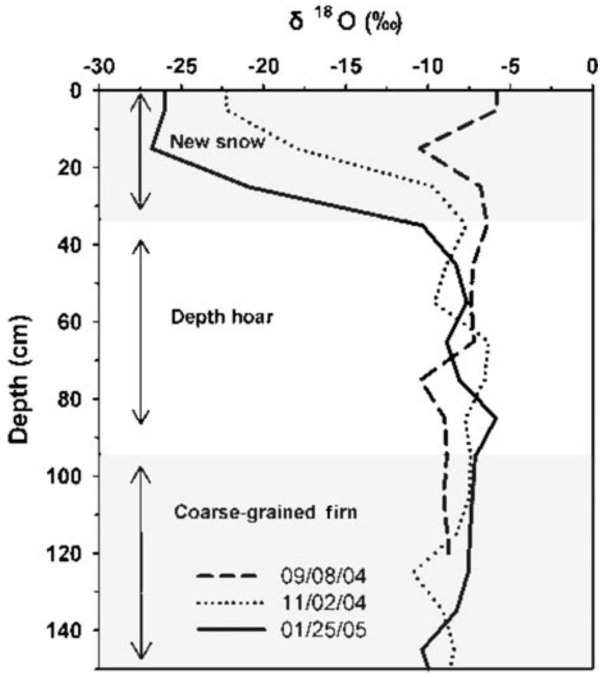

Fig. 5. The $\delta^{18}O$ profiles of the snow–firn pack at different times (dates are mm/dd/yy).

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vapor pressure of the lighter isotopic molecule ($H_2{}^{16}O$) is higher than that of the heavier isotopic molecules (HDO and $H_2{}^{18}O$); therefore, the vapor is enriched in the light molecules in equilibrium with the solid.

Fractionation of vapor within the bottom layer of the depth hoar resulted in the loss of 'light' vapor upward under the influence of temperature gradients. Therefore, the bottom of the snow was depleted in the lighter species, resulting in the increase of the δ value. The 'light' vapor appeared to have traveled up to the top of the pack where some or all of it condensed, resulting in the decrease of the δ value of the snow–firn pack.

4. SUMMARY

Long-term data were used to determine the development of depth hoar and its relation to stable oxygen isotopic content in snow–firn stratigraphy on UG1. Direct observations show that depth hoar formed during mid-October and early June at the observation site. It began to form when the temperature gradient reached a maximum value of 13.0°C m^{-1} during mid-October. From February to the end of March, it was fully developed and accounted for 25% of the total snow–firn pack depth. After April, as the weather became warmer and meltwater percolated downward, the depth hoar turned rapidly into coarse-grained firn. Fractional condensation of water vapor (produced by sublimation of the snow) on growing snow crystals as the vapor moved vertically through the snow–firn pack resulted in isotopic fractionation. The bottom 15 cm of the depth hoar show an increase in $\delta^{18}O$ associated with mass loss, and the upper part shows a decrease associated with mass gain.

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REFERENCES

Akitaya, E. 1974. Studies on depth hoar. *Contrib. Inst. Low Temp. Sci., Ser. A,* 26.

Armstrong, R.L. 1980. An analysis of compressive strain in adjacent temperature-gradient and equi-temperature layers in a natural snow cover. *J. Glaciol.,* **26**(94), 283–289.

Bader, H., R. Haefeli, E. Bucher, J. Neher, O. Eckel and C. Thams. 1954. Snow and its metamorphism. *SIPRE Transl.* 14. [Translated from *Beitr. Geol. Schweiz.* 3 [1939].]

Colbeck, S.C. 1982. An overview of seasonal snow metamorphism. *Rev. Geophys. Space Phys.,* **20**(1), 45–61.

Colbeck, S.C. *and 7 others*. 1990. *The international classification for seasonal snow on the ground*. Wallingford, Oxon, International Association of Scientific Hydrology. International Commission on Snow and Ice.

Friedman, I., C. Benson and J. Gleason. 1991. Isotopic changes during snow metamorphism. *In* Taylor, H.P., Jr, J.R. O'Neill and I.R. Kaplan, *eds. Stable isotope geochemistry: a tribute to Samuel Epstein*. Washington, DC, Geochemical Society, 211–221. (Special Publication 3.)

Hobbs, P.V. 1974. *Ice physics*. Oxford, etc., Clarendon Press.

Li, Z. *and 9 others*. 2006. Seasonal variability of ionic concentrations in surface snow and elution processes in snow–firn packs at the PGPI site on Ürümqi glacier No. 1, eastern Tien Chan, China. *Ann. Glaciol.,* **43**, 250–256.

Ma, W. and R. Hu. 1990. Relationship between the development of depth hoar and avalanche release in the Tian Shan Mountains, China. *J. Glaciol.,* **36**(122), 37–40.

Paterson, W.S.B. 1994. *The physics of glaciers. Third edition.* Oxford, etc., Elsevier.

Sommerfeld, R.A., C. Judy and I. Friedman. 1991. Isotopic changes during the formation of depth hoar in experimental snowpacks. *In* Taylor, H.P., Jr, J.R. O'Neill and I.R. Kaplan, *eds. Stable isotope geochemistry: a tribute to Samuel Epstein*. Washington, DC, Geochemical Society, 205–209. (Special Publication 3.)

Stichler, W., U. Schotterer, K. Fröhlich, P. Ginot, C. Kull and H.W. Gäggeler. 2001. The influence of sublimation on stable isotope records recovered from high altitude glaciers in the tropical Andes. *J. Geophys. Res.,* **106**(D19), 22,613–22,620.

Sturm, M. and C.S. Benson. 1997. Vapor transport, grain growth and depth-hoar development in the subarctic snow. *J. Glaciol.,* **43**(143), 42–59.

Wang, F. *and 6 others*. 2006. Seasonal evolution of aerosol stratigraphy in Ürümqi glacier No. 1 percolation zone, eastern Tien Shan, China. *Ann. Glaciol.,* **43**, 245–249.

Yosida, Z. *and 6 others*. 1955. Physical studies on deposited snow. I. Thermal properties. *Contrib. Inst. Low Temp. Sci., Ser. A,* 7, 19–74.