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Distribution of Borehole Temperature at Four High-altitude Alpine Glaciers in Central Asia

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Abstract: The distribution of borehole temperature at four high-altitude alpine glaciers was investigated. The result shows that the temperature ranges from -13.4°C to -1.84°C, indicating the glaciers are cold throughout the boreholes. The negative gradient (i.e., the temperature decreasing with the increasing of depth) due to the advection of ice and climate warming, and the negative gradient moving downwards relates to climate warming, are probably responsible for the observed minimum temperature moving to lower depth in boreholes of the Gyabrag glacier and Miaoergou glacier compared to the previously investigated continental ice core borehole temperature in West China. The borehole temperature at 10 m depth ranges from -8.0°C in the Gyabrag glacier in the central Himalayas to -12.9°C in the Tsabagarav glacier in the Altai range. The borehole temperature at 10 m depth is 3~4 degrees higher than the calculated mean annual air temperature on the surface of the glaciers and the higher 10 m depth temperature is mainly caused by the production of latent heat due to melt-water percolation and refreezing. The basal temperature is far below the melting point, indicating that the glaciers are frozen to bedrock. The very low temperature gradients near the bedrock suggest that the influence of geothermal flux and ice flow on basal temperature is very weak. The low temperature and small velocity of ice flow of glaciers are beneficial for preservation of the chemical and isotopic information in ice cores.

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Introduction

The temperature within glaciers is not only an important intrinsic physical parameter, but also of considerable importance for a number of temperature dependent ice properties (Lange 1985). The ice temperature reflects the conditions of climate, environment and dynamics for developing of glaciers (HUANG 1999). The temperature of glaciers strongly determines their behavior (Blatter 1987). The borehole temperature profile can be used either to measure directly the past temperature history of the ice, or to calibrate the measured borehole isotopic variations (Johnsen et al. 2001). Therefore, an accurate knowledge of the thermal regime of glaciers is necessary for understanding their dynamics and response to climate changes. The temperature down through the ice core boreholes depends on the surface temperature, geothermal heat flux, ice flow pattern, solar radiation, wind, accumulation rates, percolation and refreezing of melt-water and other parameters (Haeberli and Alean 1985, Salamatin 2000, Zagorodnov et al. 2006).

Four ice cores have been recently recovered since 2005 from the Gyabrag glacier, Shule Nanshan glacier, Miaoergou glacier and Tsambagarav glacier in Central Asia. These glaciers are located in different geographic areas and influenced by different atmospheric circulation system. The study of these ice cores records is important for understanding the past climatic and environmental changes on regional scale in Central Asia. The understanding of the thermal regime of these glaciers is crucial for interpretation of their records (Salto et al. 2004), which will rely on the assumption of always cold ice. The aims of this paper are to describe the distribution features of borehole temperature in these four high-altitude alpine glaciers and to attempt a preliminary analysis for explaining the observed temperature features. Also, the study points a possible effect of the global warming on temperature of these glaciers.

1 Borehole Temperature Measurement

The four ice cores, recovered from the Gyabrag glacier (28°10' N, 86°38' E) on the north slope of Mt. Cho Oyu, in the central Himalayas, Shule Nanshan glacier (38°42' N, 97°16' E) on the west Mt. Qilian, Miaoergou glacier (43°03' N, 94°19' E) on the east Mt. Tienshan and Tsambagarav glacier (48°38' N, 90°57' E) on the Mt. Altai in the west Mongolia, respectively (Figure 1). The drillings of these cores were completed between 2005 and 2008. Table 1 gives the detailed information of these drilling sites. These drilling sites were selected due to their highest elevation to reduce the role of melting and flat topography to reduce the influence of ice flow. These conditions are necessary for acquiring good records of ice cores. These ice cores (about 9.4 cm in diameter) were drilled in dry holes using electromechanical drill developed by Cold and Arid Regions Environmental and Engineering Institute, Chinese Academy of Sciences (CAREEI, CAS). All the cores except the Tsambagarav core reach the glacier bed.

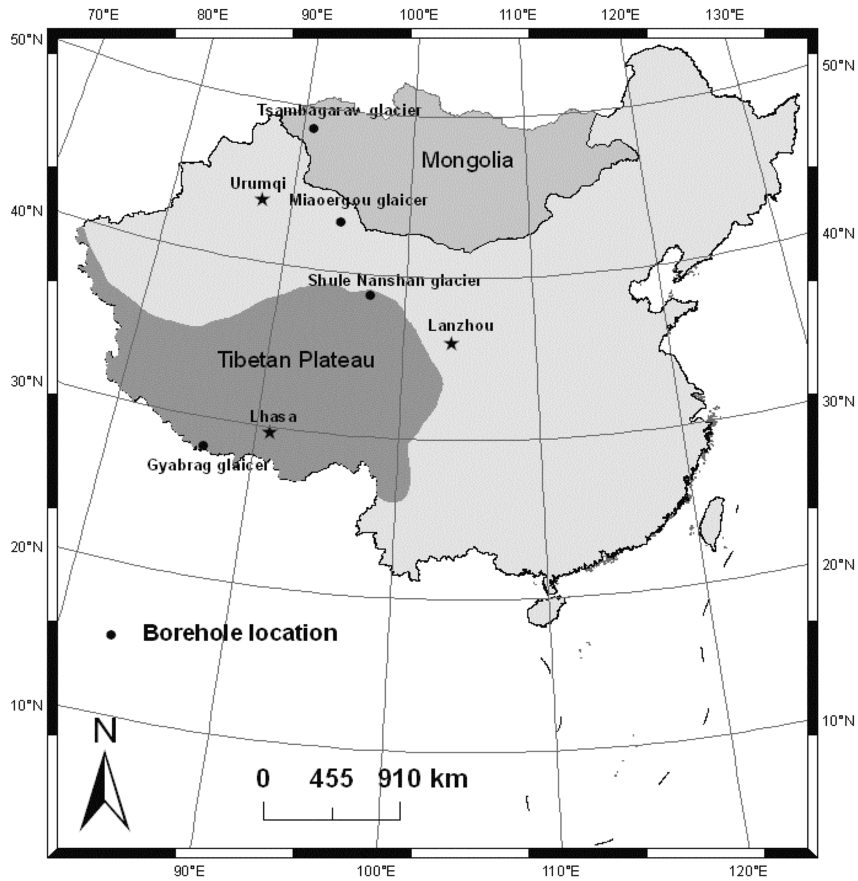

Figure 1 Location map of ice core boreholes

The temperature of the borehole was measured 24 h after completing the drillings in order to eliminate the disturbance of drilling on the natural glacier temperature (Haeberli and Funk 1991). The borehole temperature was measured by putting a standard platinum thermometer with electrical resistance into borehole at different depths. The intervals of measurement are 1~2 m at the upper part and 5~10 m at the low part of the boreholes. The thermometer was soldered to one conductor cable and calibrated at several reference temperature in a bath at the laboratory in CAREEI. The accuracy of thermometer is ±0.01°C over the temperature range from -20°C to 0°C (PU et al. 2002). However, this accuracy could not be maintained during the measurements *in situ* and the accuracy of the temperature measurements in our boreholes is estimated to be better than ±0.05°C. The thermometer was put out of a cylindrical container with a diameter about 9 cm, insuring the thermometer was kept in direct touch with the wall of borehole. The time of temperature susceptibility for each measured point was 40 minutes which is accordant with the designed time (20 minutes) for this kind of thermometer. The resistance reading was made by using Fluke True RMS 189 digital multimeter with an accuracy of 0.25 % (WU et al. 2003). The measured resistance was converted to temperature according to standard regression for the thermometer. This method was proved to be reliable under the temperature condition of the glacier (LIU et al. 2006).

2 Results and Discussions

All the four ice cores were drilled from the accumulation areas and their locations belong to the percolation zone of the glaciers. The borehole temperature profiles were presented in Figure 2. The shape of these profiles shows some similar characteristics despite of different elevation, latitude, longitude and topography of the drilling sites and measured time (Table 1). For example, the temperature changes quickly within the upper 20 m, especially within upper 10 m. Below 20 m, the temperature presents slight change.

It is clear from Table 1 that the temperature for each glacier is far below 0°C throughout the

Table 1 The parameters and characteristic temperature (°C) of ice core boreholes

Range	Altai	Tienshan	Qilian	Himalayas
Glacier	Tsambagarav	Miaoergou	Shule Nanshan	Gyabrag
Latitude (N)	48°38'	43°03'	38°42'	28°10'
Longitude (E)	90°57'	94°19'	97°16'	86°38'
Altitude (m)	3815	4512	5356	6303
Depth (m)	40.0	59.5	92.1	68.5
Measure time	2008.06	2005.08	2007.06	2005.10
Minimum temperature	-13.4	-8.3	-9.8	-9.0
Maximum temperature	-1.8	-2.9	-5.6	-4.3
Mean temperature	-11.3	-6.6	-8.4	-7.4
10 m temperature	-12.9	-7.2	-8.6	-8.0
Bottom temperature		-8.2	-8.2	-9.0

boreholes. The mean temperature ranges from -6.6°C at the Miaoergou glacier to -11.3°C at the Tsambagarav glacier, indicating that these glaciers are cold type ones. The low temperature is beneficial for preservation of the chemical and isotopic profiles due to lack of major disturbance by melt-water percolation. Among the four glaciers, the lowest mean temperature was observed in the Tsambagarav glacier with lowest elevation, while relatively higher mean temperature was found in the Gyabrag glacier with highest elevation. This phenomenon indicates the influence of latitude on glacier temperature. As to each borehole, the variation ranges of temperature are from several degrees (Gyabrag glacier) to more than ten degrees (Tsambagarav glacier) between their corresponding maximum and minimum temperature. This large temperature difference was mainly caused by rapid temperature change within the upper part of borehole due to seasonal air temperature change.

2.1 Temperature gradients and minimum temperature

Figure 2 also shows the temperature gradients as a function of depth. The gradients are computed by dividing the difference between two adjacent temperature values against the respective distance between the measuring points. The upper parts of the profiles show a steep negative gradient. Further below, the profiles show a relatively uniform positive or negative gradient, with a decreasing trend of absolute values of temperature gradients. For example, the temperature gradients of the Miaoergou glacier were -0.67°C·m^{-1} between 1 and 8 m depth, 0.11°C·m^{-1} between 8 and 20 m depth, -0.07°C·m^{-1} between 20 and 50 m depth and 0.011°C·m^{-1} from 50 m to bedrock. This indicates that the change in glacier temperature tends to be weak from the near surface to deep layers.

It was suggested that the minimum temperature of a continental glacier appeared at the bottom of active layer with a depth range of 5~20 m (HUANG et al. 1982, REN et al. 1994). However, the minimum temperature of -9.0°C appeared at the bedrock (68.5 m) for the Gyabrag glacier, and for the Miaoergou glacier the minimum temperature of -8.3 °C appeared at 50 m depth close to the bedrock (59.5 m). This phenomenon was also observed at Muztag Ata borehole temperature (LI et al. 2003), East Pamir, with a minimum temperature of -26.17 °C at 55 m depth at the altitude of 6250 m, and at Cerro Tapado glacier (Ginot et al. 2006), in Chilean Andes, with a minimum temperature of -12.4 °C at the bedrock (36 m) at 5536 m.

Figure 2 shows the unique profiles of negative temperature gradients in most cases. Below the

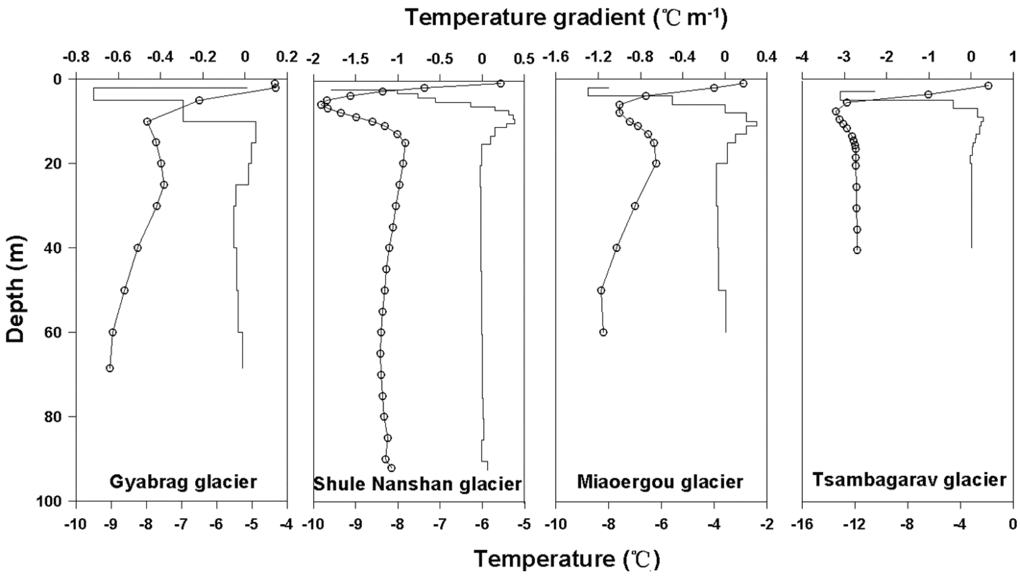

Figure 2 The profiles of temperature and temperature gradients. The lines with cycles stand for the temperature and the other lines for temperature gradients.

10~20 m depth, the negative gradient is popular in the infiltration zone of a continental glacier (REN et al. 1994). The negative temperature gradient of near surface is mainly caused by summer heat transport from surface down into deep ice and the refreezing of melt water resulting in the subsurface production of heat. However, the negative temperature gradient in deep ice can be owing to the following factors. First, the advection of ice has to be taken into account. On the one side, the ice at the drilling site might come from area of higher altitude with a cooler ice than that at drilling site (Blatter 1987, Johnsen et al. 2001); on the other side, the deeper ice at the drilling site derived from higher altitude ice resulting in lower temperature (LIU et al. 2006). Second, global warming over the last 100 years (1906~2005) has been universally recognized, especially for the last 50 years (Trenberth et al. 2007). High mountain glaciers are sensitive to warming (Beniston 2003). The surface ice responds quickly to warming. However, the deep ice retains still its cold condition of the past (Kotlyakov et al. 2004). The climatic warming increases the summer melting at the surface of glaciers (Nagornov et al. 2006) and reduces the depth of snow and firn. The thermal conductivities of snow and firn are considerably smaller than that of ice (Lange 1985). Thus, both move the negative gradient downwards because the heat from surface warming flows easily to underlying layers.

2.2 Near surface temperature and 10 m temperature

The upper parts of temperature profiles (Figure 2) present a summer season warm type of temperature distribution due to the influence of high air temperature.

The thermal regime of active layer is determined by the solar radiation, surface temperature variation, melting water percolation and thermal conductivity (Paterson 1994). Seasonal temperature variations occur in the glacier active layer about 15~20 m below the surface, while the glacier temperature below active layer depends on the long-term surface condition. Information of the past short-duration events has been lost from the borehole temperature profiles because of diffusion (Alley 2000). Hence, measured temperature of ice near the surface relates directly to short period perturbation of surface temperature. This perturbation propagating downwards from the surface weakens quickly with depth, which is probably responsible for the observed quick temperature change and large temperature gradient near the surface.

With the climatic warming, the melting of snow and ice is obviously one of the main reasons that determine the distribution of borehole temperature. The intensity of melting during summer is proportional to the third power of the mean air temperature (Nagornov et al. 2006). Model calculations show that the thermal regime of ice reacts very sensitively to variation in the amount of melt water refreezing in the firn (Patterson and Clarke 1978). Thus, small change of summer air temperature can produce significant changes in near surface snow and firn temperature. Ohmura (2001) suggests that long-wave atmospheric radiation and sensible heat flux are the dominant (75%) heat sources responsible for melting. It expected therefore that warming should be pronounced in the high altitude glaciers of the Central Asia. However, the quantitative information for the production of latent heat due to this process is not available for our studied glaciers.

10 m depth is often used as the low boundary of the active layer. 10 m depth temperatures (T_{10}) is important for studying the spatial T_{10} temperature changes induced by climatic variations, melt-water migrations, and aiding in the selection of new ice core drilling sites (Zagorodnov et al. 2006). From Table 1, T_{10} of boreholes ranges from -7.2°C at the Miaoergou glacier to -12.9°C at the Tsambagarav glacier. T_{10} is lower than their respective mean temperature and close to minimum temperature (Table 1).

The general relationships between the mean annual air temperature (T_a) and T_{10} concluded by Zagorodnov et al. (2006) are: $T_a=0.8T_{10}-5.8$, where T_a ranges from -60 °C to -7 °C; in high-latitude glaciers, sensible surface melting occurs when mean annual air temperature (T_a) is above -17 °C and results in 10 m depth temperature (T_{10}) rise of up to 5~16 °C above T_a; on tropical and low-latitude glaciers a noticeable surface melting occurs when $T_a>-10$°C, which can cause a 5°C increase in ice temperature (T_{10}) above T_a. Thus, latent heat from percolating water has an effect on the difference between T_a and T_{10}.

The calculated T_a is about -12°C from Zagorodnov's relationship of $T_a=0.8T_{10}-5.8_a$ for the Gyabrag glacier and Miaoergou glacier, -13°C for the Shule Nanshan glacier and -16°C for the Tsambagarav glacier, i.e., about 3~4 degrees lower than T_{10} (Table 1), suggesting that the melting water has influenced the formation of temperature profiles by infiltration and refreezing process. This situation can be verified by characteristic melt-layer content observed in our ice cores.

2.3 Basal temperature

Temperature profiles (Figure 2) of boreholes show that the basal temperature (Table 1) is well below melting point. Thus, the glaciers are frozen to bedrock. The basal temperature excludes the possibility of sliding and temperate ice at the bottom of glaciers. Considering the flat topography and ice-thickness of the glaciers, it is reasonable to conclude that the glaciers flow mainly in terms of ice deformation, resulting in low surface velocity.

Two principal processes govern the glacier temperature regime: the outward flow of heat from the geothermal flux and temperature perturbations at the surface propagating downwards into the interior. The latter typically varies in time scales of seasons, years and centuries, whereas there is a constant heat supply from the former (HUANG 1999). Hence, the thermal regime at the bottom of the glacier is close to steady state. The geothermal flux can be directly calculated by using the measured temperature gradient near the bedrock (Kotlyakov et al. 2004). The very small temperature gradients at the bottom of our studied glaciers suggest a relatively small geothermal flux. To the other side, it also indicates that the influence of ice flow on interior temperature is very weak. Assuming that the influence of ice flow on basal temperature can be neglected, we use $\left(\partial T/\partial z\right)_B=-G/K$ (Paterson 1994) to calculate the geothermal flux at the bedrock of our studied glaciers, where G is the geothermal flux, K is thermal conductivity and subscript B denotes the interface between ice and the bed. The calculated geothermal flux is about 23 $mW\cdot m^{-2}$ and 30 $mW\cdot m^{-2}$ for the Miaoergou glacier and Shule Nanshan glacier, respectively. No value of geothermal flux for the Gyabrag glacier can be calculated due to its negative gradient near the bedrock. In principle, the geothermal fluxes should be less than the calculated values due to the existence of deformation and advection of ice.

3 Conclusions

The temperature distribution of ice core boreholes in the four high altitude alpine glaciers in Central Asia was presented. We focused on the general features of temperature gradients, minimum temperature, near surface temperature, 10 m temperature and basal temperature in these boreholes. The results show that the glaciers are cold with a temperature ranging from -13.4°C to -1.84°C and the mean temperature from -11.3°C to -6.6°C. The negative gradients result in the relatively low depth of minimum temperature for the Gyabrag glacier and Miaoergou glacier. The near surface temperature changes quickly with a large temperature gradient due to melt-water percolation and refreezing and summer warming. The calculated mean annual air temperature is lower than the 10 m depth temperature, suggesting a low surface temperature condition on the glaciers. The low temperature and small temperature gradients near bedrock indicate the weak geothermal flux and low ice flow velocity.

The results indicate the possible effect of the global warming over the last 100 years on the thermal regime of glaciers through heat conductivity and latent heat released by melt-water percolation and refreezing. It was suggested that a continuation or even acceleration of warming trend would raise glacier temperature in the future (Haeberli and Alean 1985, Zagorodnov et al. 2006).

An important issue is the representativeness of a single borehole relative to a given glacier. Hence, more boreholes and long-term temperature investigations are expected for a better understanding of thermal regime of glaciers. Moreover, the present discussion of the measured vertical temperature profiles is based on assumed steady-state condition. Thus, non-stationary numerical model analysis is necessary in future under the background of climate warming. A coupled heat and ice flow model to extract the climatic information from the measured temperature profile is also the future object.

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References

Alley R. B. 2000. The Younger Dryas Cold Interval as Viewed from Central Greenland. Quaternary Science Reviews **19**: 213-226.

Beniston M. 2003. Climatic Change in Mountain Regions: A Review of Possible Impacts. Climate Change **59**: 5-31.

Blatter H. 1987. On the Thermal Regime of an Arctic Valley Glacier: A Study of White Glacier, Axel Helberg Island, N.W.T., Canada. Journal of Glaciology **33**(114): 200-211.

Ginot P., Kull C., Schottere U., et al. 2006. Glacier Mass Balance Reconstruction by Sublimation Induced Enrichment of Chemical Species on Cerro Tapado (Chilean Andes). Climate of the Past **2**: 21-30.

Haeberli W. and Alean J. 1985. Temperature and Accumulation of High Altitude Firn in the Alps. Annals of Glaciology **6**: 161-163.

Haeberli W. and Funk M. 1991. Borehole Temperatures at the Colle Gnifetti Core-drilling Site (Monte Rosa, Swiss Alps). Journal of Glaciology **37**(125): 37-46.

HUANG Maohuan, WANG Zhongxiang and REN Jiawen. 1982. Ice Temperature of Glaciers in China. Journal of Glaciology and Geocryology **4**(1): 20-28. (In Chinese)

HUANG Maohuan. 1999. Forty Year'S Study of Glacier Temperature Distribution in China: Review and Suggestions. Journal of Glaciology and Geocryology **21**(4): 310-316. (In Chinese)

Johnsen S. J., Dahl-Jensen D., Gundestrup N., et al. 2001. Oxygen Isotope and Palaeotemperature Records from Six Greenland Ice-core Stations: Camp Century, Dye-3, GRIP, GISP2, Renland and NorthGRIP. Journal of Quaternary Science **16**(4): 299-307.

Kotlyakov V. M., Arkhipov S. M., Henderson K. A., et al. 2004. Deep Drilling of Glaciers in Eurasian Arctic as a Source of Paleoclimatic Records. Quaternary Science Review **23**: 1371-1390.

Lange M. A. 1985. Measurements of Thermal Parameters in Antarctic Snow and Ice. Annals of Glaciology **6**: 100-104.

LI Zhen, YAO Tandong, TIAN Lide, et al. 2004. Borehole Temperature at the Ice-core Drilling Site in the Muztag Ata Glacier, East Pamirs. Journal of Glaciology and Geocryology **26**(3): 284-288. (In Chinese)

LIU Yaping, HOU Shugui, REN Jiawen, et al. 2006. Distribution Features of Borehole Temperatures in the Miaoergou Flat-topped Glacier, East Tianshan Mountains. Journal of glaciology and Geocryology **28**(5): 668-671. (In Chinese)

Nagornov O. V. Konovalov Y. V. and Tchijov V. 2006. Temperature Reconstruction for Arctic Glaciers. Palaeogeography, Palaeoclimatology, Palaeoecology **236**: 125-134.

Ohmura A. 2001. Physical Basis for the Temperature-based Melt Index Method. Journal of Appllied Meteorology **40**(4): 753-761.

Patterson W. S. B. and Clarke G. K. C. 1978. Comparison of Theoretical and Observed Temperature Profiles in Devon Island Ice Cap, Canada. Geophysical Journal of the Royal Astronomical Society **55**(3): 615-632.

Paterson W. S. B. 1994. The Physics of Glaciers. UK: Pergamon Press. Pp. 204-237.

PU Jian zhen, YAO Tandong, WANG Ninglian, et al. 2002. The Distribution of 80-m Ice Temperature in Purougangri Ice Field on the Tibetan Plateau. Journal of Glaciology and Geocryology **24**(3): 283-286. (In Chinese)

REN Jiawen, ZHANG Jinhua and HUANG Maohuan. 1994. A Study of the Ice Temperature in No. 1 Glacier in the Urumqi River Headwaters, Tianshan. Journal of Glaciology and Geocryology **7**(2): 141-151. (In Chinese)

Salamatin A. N. 2000. Paleoclimate Reconstructions Based on Borehole Temperature Measurements in Ice Sheets: Possibilities and Limitations. In: Hondoh T. (eds), Physics of ice core records. Sapporo: Hokkaido University Press. Pp. 243-282.

Saito F. and Abe-Ouchi A. 2004. Thermal Structure of Dome Fuji and east Dronning Maud Land, Antarctica, Simulated by a Three-demensional Ice-sheet Model. Annals of Glaciology **39**: 433-438.

Trenberth K. E., Jones P. D., Ambenje P., et al. 2007. Observations: Surface and Atmospheric Climate Change. In: Solomon S. et al. (eds.), Climate Change 2007: The Physical Science Basis. New York, USA: Cambridge University Press, Pp. 235-336.

WU Guanjian, YAO Tandong, XU Baiqin, et al. 2003. Ice-core Borehole Temperature in the Muztag Ata, East Pamirs. Journal of Glaciology and Geocyology **25**(6): 676-679. (In Chinese)

Zagorodnov V. Nagornov O. and Thompson L. G. 2006. Influence of Air Temperature on a Glacier's Active-layer Temperature. Annals of Glaciology **43**: 285-291.