



# Dramatic loss of glacier accumulation area on the Tibetan Plateau revealed by ice core tritium and mercury records

S. Kang<sup>1,2</sup>, F. Wang<sup>3</sup>, U. Morgenstern<sup>4</sup>, Y. Zhang<sup>1</sup>, B. Grigholm<sup>5</sup>, S. Kaspari<sup>6</sup>, M. Schwikowski<sup>7</sup>, J. Ren<sup>1</sup>, T. Yao<sup>1,2</sup>, D. Qin<sup>1</sup>, and P. A. Mayewski<sup>5</sup>

<sup>1</sup>State Key Laboratory of Cryospheric Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China

<sup>2</sup>CAS Center for Excellence in Tibetan Plateau Earth Sciences, Chinese Academy of Sciences, Beijing 100101, China

<sup>3</sup>Centre for Earth Observation Science, Department of Environment and Geography, and Department of Chemistry, University of Manitoba, Winnipeg, MB R3T 2N2, Canada

<sup>4</sup>Institute of Geological and Nuclear Sciences, National Isotope Centre, Lower Hutt 5040, New Zealand

<sup>5</sup>Climate Change Institute and Department of Earth Sciences, University of Maine, Orono, ME 04469-5790, USA

<sup>6</sup>Department of Geological Sciences, Central Washington University, Ellensburg, WA 98926, USA

<sup>7</sup>Paul Scherrer Institute, 5232 Villigen, Switzerland

*Correspondence to:* S. Kang (shichang.kang@lzb.ac.cn), F. Wang (wangf@ms.umanitoba.ca)

Received: 30 October 2014 – Published in The Cryosphere Discuss.: 16 January 2015

Revised: 19 April 2015 – Accepted: 15 May 2015 – Published: 15 June 2015

**Abstract.** Two ice cores were retrieved from high elevations ( $\sim 5800$  m a.s.l.) at Mt. Nyainqêntanglha and Mt. Geladaindong in the southern and central Tibetan Plateau region. The combined tracer analysis of tritium ( $^3\text{H}$ ),  $^{210}\text{Pb}$  and mercury, along with other chemical records, provided multiple lines of evidence supporting that the two coring sites had not received net ice accumulation since at least the 1950s and 1980s, respectively. These results implied an annual ice loss rate of more than several hundred millimeter water equivalent over the past 30–60 years. Both mass balance modeling at the sites and in situ data from the nearby glaciers confirmed a continuously negative mass balance (or mass loss) in the region due to dramatic warming in recent decades. Along with a recent report on Naimona'nyi Glacier in the Himalayas, the findings suggest that the loss of accumulation area of glacier is a possibility from the southern to central Tibetan Plateau at high elevations, probably up to about 5800 m a.s.l. This mass loss raises concerns over the rapid rate of glacier ice loss and associated changes in surface glacier runoff, water availability, and sea levels.

## 1 Introduction

Data from remote sensing and in situ observations suggest that glacier shrinking has been prevailing over the Tibetan Plateau (including the Himalayas hereafter) in the past decades (e.g., Liu et al., 2006; Kang et al., 2010; Fujita and Nuimura, 2011; Bolch et al., 2012; Kääb et al., 2012; Yao et al., 2012; Neckel et al., 2014), raising major concerns over the impact on water supplies to some 1.4 billion people in Asia (Immerzeel et al., 2010), and on global sea level rise (Jacob et al., 2012; Gardner et al., 2013; Neckel et al., 2014). It has been estimated that glacier retreat has been occurring in more than 82 % of the total glaciers in the region (Liu et al., 2006), and since the 1970s, glacier areas have reduced by several percent (about 4.8 %) in the central Tibetan Plateau (Ye et al., 2006) and up to 20 % in the northeastern marginal regions of the Tibetan Plateau (Cao et al., 2010; Pan et al., 2012). In situ stake observations have also confirmed a continuously negative mass balance during the last decade in the region (Yao et al., 2012; Zhang et al., 2014). However, quantitative changes in the glacier ice volume, a key parameter for assessing retreating glaciers' impact on water supply or sea level rise, remain poorly known due to the lack of in situ measurements of glacier thickness through time. Although

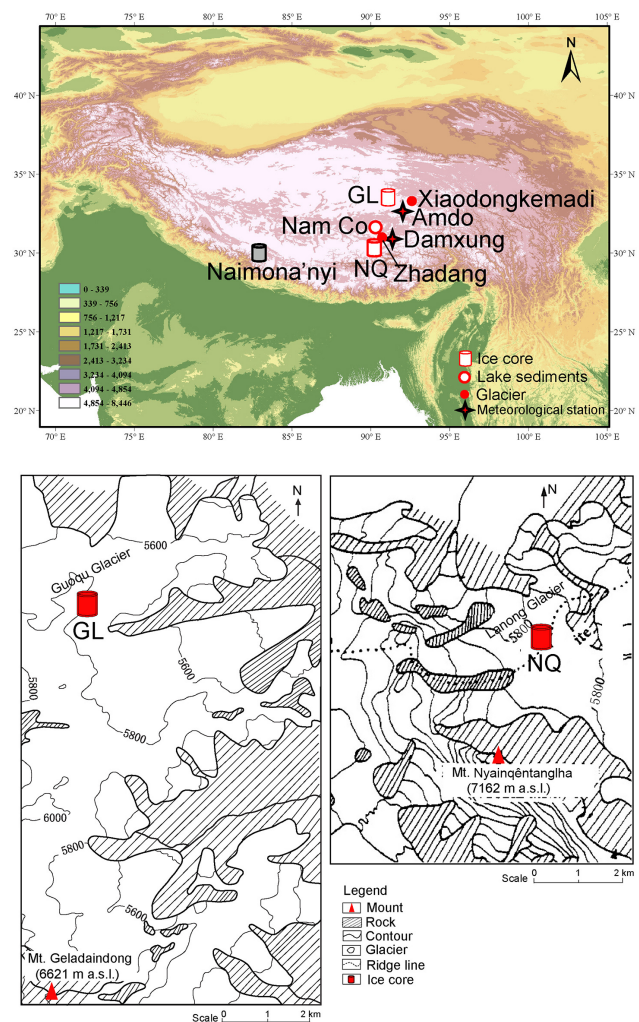
remote sensing techniques have provided some assessments of glacier thickness globally, especially in the last decade, the application of these techniques to the Tibetan Plateau region is rather limited, due to the complexity of the regional topography (Jacob et al., 2012; Kääb et al., 2012; Gardner et al., 2013; Neckel et al., 2014).

Based on the lack of distinctive marker horizons of atmospheric thermonuclear bomb testing (e.g., beta radioactivity,  $^{36}\text{Cl}$ , and tritium ( $^3\text{H}$ )) in an ice core retrieved from Naimona'nyi (6050 m a.s.l.) in the Himalayas, a recent study suggests that there might not have been a net accumulation of glacier mass at the site since at least the 1950s (Kehrwald et al., 2008). This thinning could be very significant, considering that the mass loss occurred at the upper part of the glacier which is normally considered to be the accumulation area (Shi et al., 2005). To test whether such loss of glacier accumulation area is occurring at high elevations over the Tibetan Plateau, here we report on two ice core records taken from high elevations ( $\sim 5800$  m a.s.l.) at Mt. Nyainqêntanglha and Mt. Geladaindong in the Tibetan Plateau. In addition to radioisotopes  $^3\text{H}$  and  $^{210}\text{Pb}$  and other geochemical tracers, the depth profile of mercury (Hg) is used as a new marker for the last century based on known atmospheric depositional histories.

## 2 Methodology

With an average elevation of over 4000 m a.s.l., the Tibetan Plateau is home to the largest volume of glacier ice outside the polar regions (Grinsted, 2013). The Tibetan Plateau blocks mid-latitude westerlies, splitting the jet into two currents that flow to the south and north of the plateau. The plateau is also a major forcing factor on the intensity of the Asian monsoons. The southern and central Tibetan Plateau is climatically influenced primarily by the Indian monsoon during the summer monsoon season, and the westerlies during the non-monsoon season (Bryson, 1986; Tang, 1998).

Two ice cores were retrieved as part of the Sino–US cooperation expedition (Fig. 1). The Nyainqêntanglha ice core ( $30^\circ 24.59' \text{N}$ ,  $90^\circ 34.29' \text{E}$ ; 5850 m a.s.l.) was collected in September 2003 from the Lanong glacier pass on the eastern saddle of Mt. Nyainqêntanglha (peak height: 7162 m a.s.l.) in the southern Tibetan Plateau, by drilling to the bedrock depth of 124 m. The Geladaindong core ( $33^\circ 34.60' \text{N}$ ,  $91^\circ 10.76' \text{E}$ ; 5750 m a.s.l.), 147 m in length (did not reach to the bedrock), was collected in October 2005 from the Guoqu glacier on the northern slope of Mt. Geladaindong (peak height: 6621 m a.s.l.), which is the summit of the Tanggula Mts. in the central Tibetan Plateau and the headwater region of the Yangtze river. Elevations of both ice coring sites are higher than the snow line altitudes (close to the equilibrium line altitudes (ELAs)) of around 5700 m a.s.l. in the Mt. Nyainqêntanglha region (Shi et al., 2005) and 5570 m a.s.l. in the Mt. Geladaindong region (Zhang, 1981). However, these ELAs

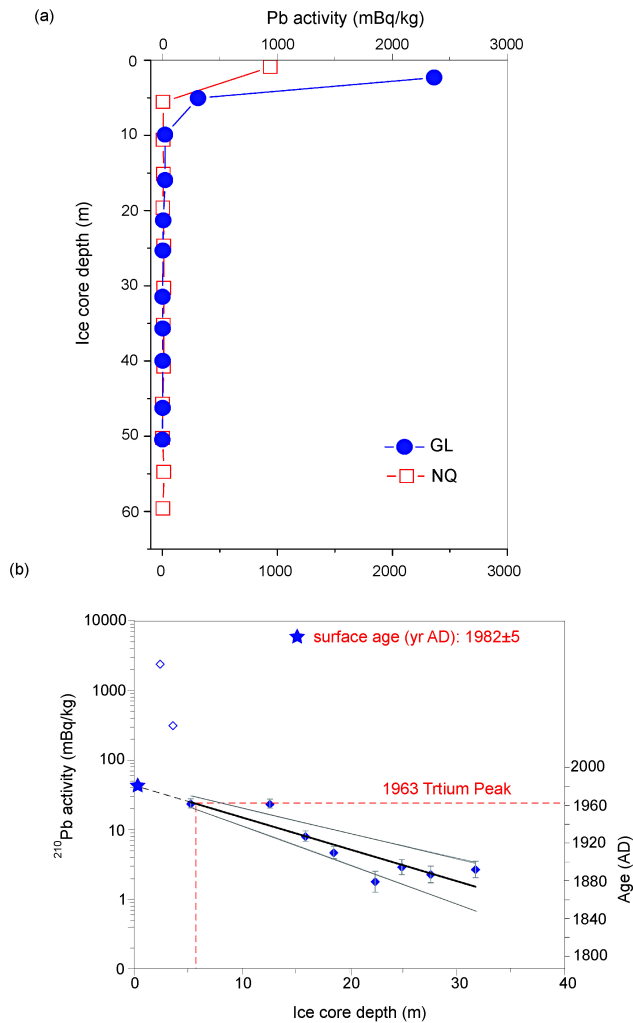


**Figure 1.** Location map of the glacier ice cores Geladaindong (GL) and Nyainqêntanglha (NQ) on the Tibetan Plateau. Also shown are the locations of the Naimona'nyi ice core by Kehrwald et al. (2008), Xiaodongkemadi glacier, Zhadang glacier, the meteorological stations, and Lake Nam Co.

were retrieved from the glacier area data obtained several decades ago (e.g., data in 1980s and 1970s for the Mt. Nyainqêntanglha and Mt. Geladaindong region, respectively), and may not reflect present-day ELAs. Snow pits, with a depth of 40 and 78 cm at the Nyainqêntanglha and Geladaindong coring sites, respectively, were also sampled at a 10 cm depth interval.

The Nyainqêntanglha ice core was transported in a frozen state to the Climate Change Institute at the University of Maine, USA, whereas the Geladaindong ice core was transported to the State Key Laboratory of Cryospheric Sciences of the Chinese Academy of Sciences, Lanzhou, China. The cores were sectioned at 3 to 5 cm intervals in a cold ( $-20^\circ$ ) room, with the outer sections (approximately 1 cm) scraped off using a pre-cleaned ceramic knife. The inner sections

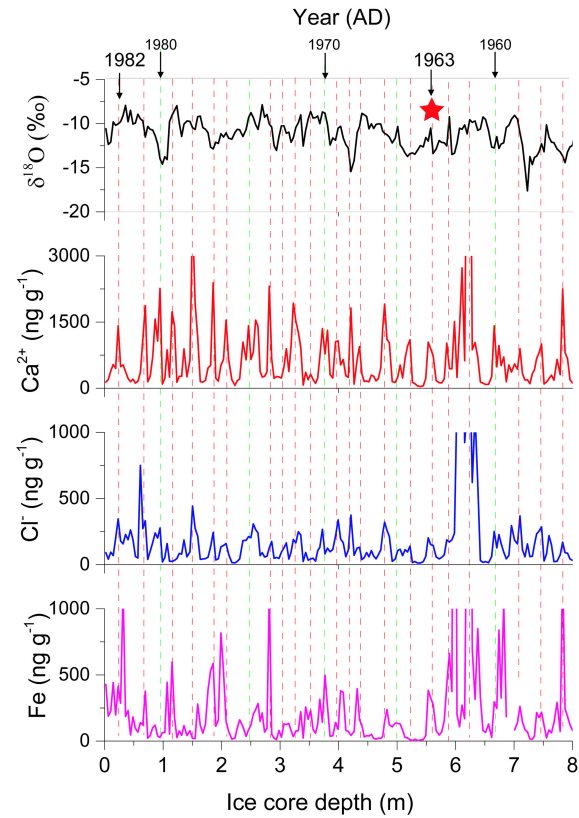




**Figure 3.** (a)  $^{210}\text{Pb}$  activity profiles of the Geladaindong (GL) and Nyainqêntanglha (NQ) ice cores; (b)  $^{210}\text{Pb}$  activity vs. depth for the GL core. The age–depth relationship was derived from an exponential regression of  $^{210}\text{Pb}$  activity against depth. The uppermost two samples (open diamonds) were excluded (enrichment due to melt). This age–depth relation was anchored using the known age and depth of the tritium horizon. Extrapolation of the age fit to the surface allows estimating the surface age (blue star). Error bars and the fine grey lines indicate the  $1\sigma$  uncertainty of the given ages.

2006). The  $^{210}\text{Pb}$  activity was  $940.5 \text{ mBq kg}^{-1}$  at the topmost sampling layer at a depth of 0–0.9 m; however, it decreased sharply to near the background level ( $7.6 \text{ mBq kg}^{-1}$ ) in the next sampling layer at a depth of 5.6 m (Fig. 3a). High  $^{210}\text{Pb}$  activity in the upper layer indicates enrichment due to the negative mass balance. Based on the extremely low  $^3\text{H}$  and  $^{210}\text{Pb}$  activities immediately beneath the surface layer, we conclude that there has been no net ice accumulation at the Nyainqêntanglha site since at least the 1950s.

In contrast, the Geladaindong ice core exhibited a classic  $^3\text{H}$  profile, with a sharp spike of up to 680 TU at a depth of



**Figure 4.** Dating of the Geladaindong ice core by annual layer counting based on the seasonal cycles of  $\delta^{18}\text{O}$ ,  $\text{Ca}^{2+}$ ,  $\text{Cl}^-$ , and Fe according to the anchor of the 1963 tritium peak (red star; dashed lines represent the annual boundaries).

5.22–6.23 m (Fig. 2), suggesting that the ice accumulated at this site during the AD 1963 thermonuclear bomb-testing era is still present. We assign the 5.74 m depth, which shows the highest  $^3\text{H}$  level, to the year AD 1963 when above-ground nuclear tests peaked just prior to the Nuclear Test Ban Treaty (Van Der Wel et al., 2011). Based on this  $^3\text{H}$  bomb test horizon, we establish the chronology of the Geladaindong ice core by counting annual layers according to the seasonal cycles of  $\delta^{18}\text{O}$ , major ions, and elemental concentrations upward to the top of the core (Fig. 4). The uppermost ice layer is designated as AD 1982 based on annual layer counting above the AD 1963  $^3\text{H}$  marker, and is further constrained by  $^{210}\text{Pb}$  estimation of  $1982 \pm 5$  years for the surface of the core (Fig. 3b).

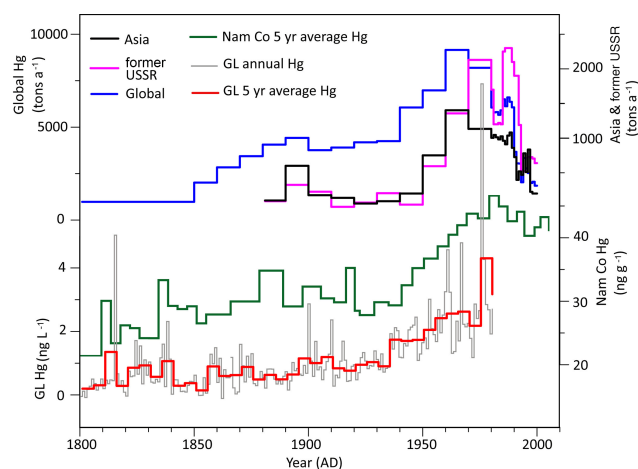
The Geladaindong ice core dating by counting annual layers is in agreement with previous work in the region. Based on snow pit records in the Guoqu glacier, Mt. Geladaindong, Zhang et al. (2007) reported that  $\text{Ca}^{2+}$  and other major ions in snow pits varied seasonally with higher values during the winter half year. At our coring site, there were firm layers (snow pit) with a depth of 78 cm. The bottom of the snow pit was glacier superimposed ice, indicating 1 year transferring from snow to ice. Thus, melt could happen during the

summer but seasonal signals were still preserved in ice layers. In other words, the meltwater (or percolation) should not disturb the layers deposited in previous years as suggested in other studies (Namazawa and Fujita, 2006; Eichler et al., 2001).

One assumption in dating by counting annual layers backwards from the AD 1963 nuclear bomb horizon to AD 1982 is that there was annual net ice accumulation during this period. Uncertainties in the chronology will thus rise should there be no net accumulation in one or some of the years due to ice melt. This does not appear to be the case for the Geladaindong ice core, as the annual variation patterns and amplitudes in the main ion concentrations were similar upward and downward from the AD 1963 layer, suggesting no occurrence of strong melt (Fig. 4). Furthermore, the air temperatures were much lower before the 1980s than those in the last 3 decades according to the data observed from the nearby meteorological stations such as Amdo. Indeed, the continuously deficit mass balance (cumulative negative mass balance) has only been reported since the 1990s in the central Tibetan Plateau (e.g., Xiaodongkemadi glacier, near to the Geladaindong region; Yao et al., 2012), as well as in the northern neighboring region (e.g., Glacier No. 1, Tianshan Mts.; Zhang et al., 2014), due to dramatic warming in recent decades. Therefore, we might suggest that the mass loss of the coring site occurred mainly from the 1990s in the central Tibetan Plateau.

To further investigate whether the lack of net ice accumulation at the Geladaindong site has occurred since the 1980s, we examined the profile of Hg in the ice core. Although naturally occurring in the Earth's crust, Hg emission (especially the gaseous elemental mercury) into the atmosphere has been greatly enhanced coinciding with the rise in anthropogenic activities (e.g., mining, burning of fossil fuels). Mercury has a lifetime of approximately 0.5–2 years (Holmes et al., 2010) and can be transported globally via atmospheric circulation. Hg profiles in ice cores from high (Fäin et al., 2008) and mid-latitude (Schuster et al., 2002) regions have matched the general chronological trends of global atmospheric Hg emissions or global industrial Hg use. As atmospheric transport is essentially the only transport pathway for anthropogenic Hg to the Tibetan Plateau, due to the region's high altitudes and minimal to nonexistent local industrial activities (Loewen et al., 2007), ice cores from the region could provide a useful indicator for atmospheric Hg concentrations, as demonstrated by Hg profiles in snowpacks overlying the glaciers across the plateau (Loewen et al., 2007; Zhang et al., 2012).

As shown in Fig. 5, the Hg profile in the Geladaindong ice core, with the uppermost layer dated to around AD 1982, matches the atmospheric Hg depositional chronology established from sediment records in Nam Co (Li, 2011), a large alpine lake (4710 m a.s.l.) on the Tibetan Plateau, as well as the history of regional and global Hg production (Hylander and Goodsite, 2006), showing low and stable background levels prior to ~AD 1850, with a steady concentration in-



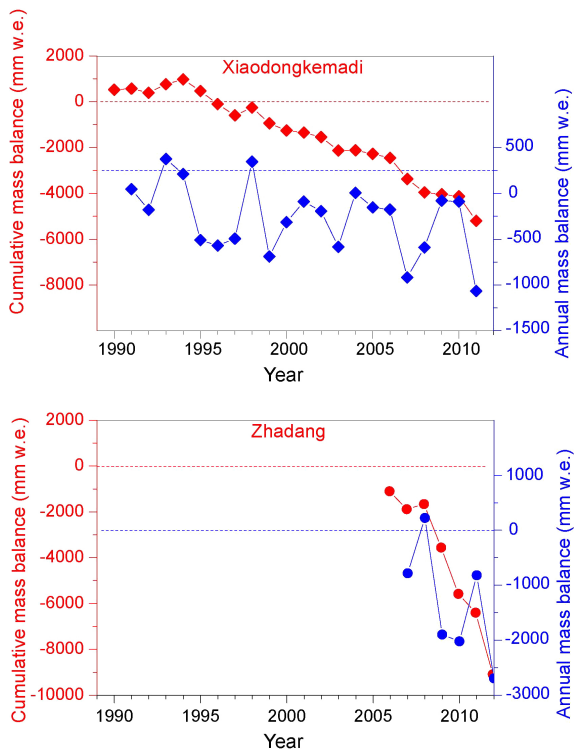
**Figure 5.** Comparisons of Hg records from the Geladaindong (GL) ice cores with those from Lake Nam Co sediments (Li, 2011), as well as with known history of regional (Asia and former USSR) and global Hg production (Hylander and Goodsite, 2006).

crease from the mid-20th century to the 1980s. Beyond the 1980s, the Nam Co sediment record shows a decline in Hg concentrations, which matches global and regional emission trends. Such declining trends are absent in the Geladaindong ice core, supporting that this site has not received net ice accumulation since the 1980s. There are some secondary timing differences of the Hg trend between the lake sediment and the ice core (e.g., during the 1970s), which might be attributed to the lower resolution of the lake sediment record (about 5 yrs) compared to that of the ice core record (1 yr).

The lack of recent deposition of mass (ice) at the Nyainqêntanglha and Geladaindong glaciers, as well as at the Naimona'nyi Glacier (Kehrwald et al., 2008), suggests that the melting and/or loss of the accumulation area of glacier occurred in at least these three ice coring regions of the Tibetan Plateau. Although there is a consensus that glaciers in the Tibetan Plateau are largely retreating (Yao et al., 2004, 2012; Bolch et al., 2012; Neckel et al., 2014),  $^3\text{H}$  and Hg records reported herein provide direct evidence of dramatic thinning occurring at the upper regions of glaciers (probably up to about 5800 m a.s.l.) that had traditionally been considered as net accumulation areas (Zhang, 1981; Shi et al., 2005).

### 3.2 Observed and modeled mass balance

Due to a lack of precipitation data at the coring sites, we cannot directly quantify the annual ice loss in these high-altitude glaciers. The annual precipitation data from local lower elevation meteorological stations are 444 mm at Damxung (50 km southeast of Nyainqêntanglha but at an elevation of 4300 m a.s.l.) and 467 mm at Amdo (120 km south of Geladaindong but at an elevation of 4800 m a.s.l.) (Fig. 1). These data suggest that the glaciers have experienced a net loss of at least several hundred millimeters each



**Figure 6.** In situ observed annual and cumulative mass balance for the Xiaodongkemadi glacier in the Tanggula Mts. (Yao et al., 2012) and the Zhadang glacier in the Nyainqêntanglha Mts. (Qu et al., 2014).

year ( $\text{mm w.e. yr}^{-1}$ ). The estimate is considered as the lower limit, as glacier areas in high mountainous regions generally receive more precipitation (accumulation) than at lower elevation stations (Shen and Liang, 2004; Wang et al., 2009; Liu et al., 2011). Although no observational data are available for the central Tibetan Plateau region, precipitation has been shown to increase 0.87 to 11 mm with every 100 m increase in elevation in the neighboring Qilian and Tianshan Mts. (Liu et al., 2011).

In situ observational data using mass balance stakes close to our coring sites have only been available for a short time period in the recent past (Kang et al., 2009; Yao et al., 2012; Qu et al., 2014). Mass balance measurements of Xiaodongkemadi glacier (80 km south of Mt. Geladaindong, Fig. 1), started in 1989, showed slightly positive mass accumulation until the mid-1990s, then changed to a net mass loss over time (Yao et al., 2012) (Fig. 6). During the period AD 1995–2010, the cumulative mass loss reached 5000 mm with an annual mass loss rate of about 300 mm w.e. A much higher mass loss rate was observed in situ at Zhadang glacier (5 km east of the Mt. Nyainqêntanglha, Fig. 1) in the southern Tibetan Plateau; over the period AD 2005–2011 mass loss rate at this glacier averaged at approximately 1200 mm w.e.  $\text{yr}^{-1}$  (Qu et al., 2014). More recently, Neckel et al. (2014) reported the glacier mass changes

during AD 2003–2009 for the eight sub-regions in the Tibetan Plateau using ICESat laser altimetry measurements. These authors estimated that a regional average mass balance of  $-580 \pm 310 \text{ mm w.e. yr}^{-1}$  was observed in the central Tibetan Plateau sub-region covering the Geladaindong coring site. The mass balance of glaciers varies due to different measurements and time periods. Over the entire Tibetan Plateau, in situ observed glacier mass balances ranged from  $-400$  to  $-1100 \text{ mm w.e. yr}^{-1}$  during the last decade, with an exception of slight mass gain in the northwest of the Tibetan Plateau (e.g., western Kunlun Mts. and Karakoram regions) (Yao et al., 2012; Bolch et al., 2012; Gardelle et al., 2012; Neckel et al., 2014). The clear deficit mass balances of Zhadang and Xiaodongkemadi glaciers are consistent with our findings from the two ice core records.

In order to further assess whether intensive melting could happen at high elevations of the coring sites, a degree-day model (DDMs) was applied to estimate glacier melt at the two ice core sites. DDMs can determine the daily quantity of snow/ice melt ( $m_t$ , mm w.e.) as a function of the mean daily air temperature ( $T_t$ ,  $^{\circ}\text{C}$ ) using a factor of proportionality referred to as the degree-day factor (DDF,  $\text{mm } ^{\circ}\text{C}^{-1} \text{d}^{-1}$ ) (Gardner and Sharp, 2009):

$$\begin{aligned} m_t &= \text{DDF} \times T_t, & T_t &\geq 0 \\ m_t &= 0, & T_t &< 0. \end{aligned}$$

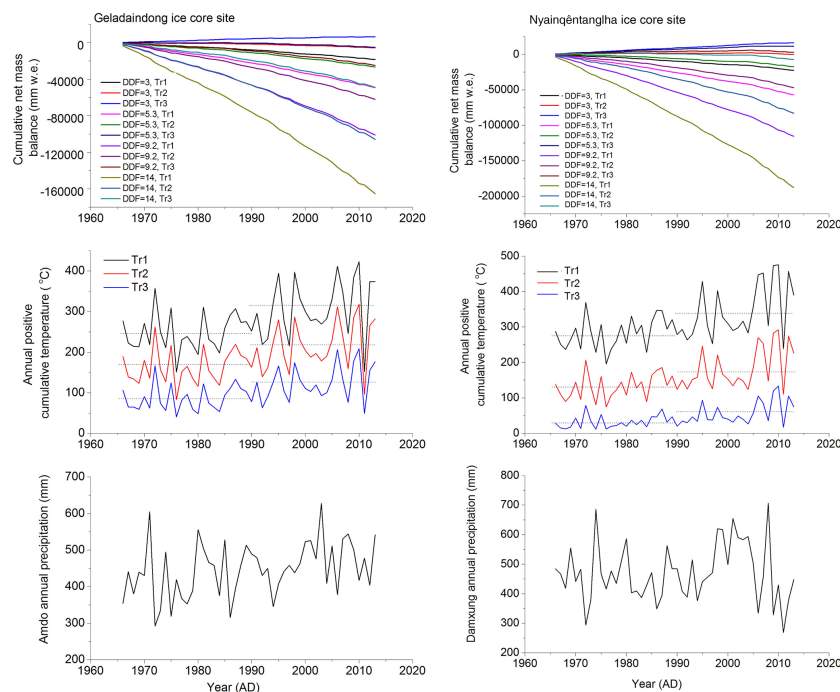
To detect the net mass balance at the Nyainqêntanglha and Geladaindong coring sites by DDMs, we selected daily temperature and precipitation data from the two meteorological stations, Damxung and Amdo, which are the nearest stations to the Nyainqêntanglha and Geladaindong sites (Fig. 1), respectively. Daily temperature and positive cumulative temperature at the two sites were calculated based on the minimum ( $0.5^{\circ}\text{C}/100 \text{ m}$ ) and maximum ( $0.72^{\circ}\text{C}/100 \text{ m}$ ) temperature lapse rate reported by Li and Xie (2006) and Yang et al. (2011), respectively, for the Tibetan Plateau (Tables 1 and 2, Fig. 7). The medium value was set as the global average of  $0.6^{\circ}\text{C}/100 \text{ m}$ . The accumulation rate at each coring site was considered the same as the precipitation amount at the stations nearby, although more precipitation is likely to occur at the higher elevations, as discussed before. Due to the differences in the surface energy balance characteristics of snow and ice (including albedo, shortwave penetration, thermal conductivity, and surface roughness), reported DDFs vary greatly among regions and times. Based on previous work in the southern and central Tibetan Plateau (Wu et al., 2010; Zhang et al., 2006), we selected DDF values of 3.0 (minimum for snow), 5.3 (medium for snow), 9.2 (medium for ice) and 14 (maximum for ice)  $\text{mm } ^{\circ}\text{C}^{-1} \text{d}^{-1}$  (Tables 1 and 2).

As shown in Fig. 7, there is a statistically significant ( $p < 0.01$ ) increase trend in annual positive cumulative temperatures at the Geladaindong ( $r = 0.5$ ) and Nyainqêntanglha ( $r = 0.6$ ) coring sites during AD 1966–2013, but not in pre-

**Table 1.** Calculated annual net mass balance (mm w.e. yr<sup>-1</sup>) during AD 1966–2013 based on various degree-day factor (DDF) values (mm °C<sup>-1</sup> d<sup>-1</sup>) and temperature lapse rates (°C 100 m<sup>-1</sup>) at the Geladaindong ice core site. Negative values represent deficit mass balances.

DDF <sup>a,b</sup>	Minimum 3.0 (snow)	Medium 5.3 (snow) 9.2 (ice)	Maximum 14.0 (ice)
Temperature lapse rate			
Minimum (Tr1) <sup>c</sup> 0.5	-386 ± 220	-1025 ± 369 -2108 ± 625	-3441 ± 944
Medium (Tr2) 0.6	-121 ± 192	-925 ± 576	-2203 ± 811
Maximum (Tr3) <sup>d</sup> 0.72	132 ± 157	-109 ± 247 -518 ± 408	-1021 ± 610

<sup>a</sup> Wu et al. (2010); <sup>b</sup> Zhang et al. (2006); <sup>c</sup> Li and Xie (2006); <sup>d</sup> Yang et al. (2011).

**Figure 7.** Variations in annual positive cumulative temperature at the Nyainqêntanglha and Geladaindong ice core sites, annual precipitation amount at Damxung and Amdo station, and the estimated cumulative net mass balance based on a degree-day model (DDM) at the two ice core sites during AD 1966–2013. (Tr1, Tr2, and Tr3 as listed in Tables 1 and 2; dashed lines represent the average of the annual positive cumulative temperature before and after AD 1990).

precipitation. DDM modeling shows clear decrease trends in the cumulative net mass balance at both sites under most of the scenarios, except when the maximum of temperature lapse rate and the minimum DDF were applied (Fig. 7). The calculated averaged annual net mass balance (medium) during AD 1966–2013 was  $-925 \pm 576$  mm w.e. yr<sup>-1</sup> (range from  $132 \pm 157$  to  $-3441 \pm 944$  mm w.e. yr<sup>-1</sup>) at the Geladaindong coring site (Table 1) and  $-671 \pm 538$  mm w.e. yr<sup>-1</sup>

(range from  $336 \pm 150$  to  $-3912 \pm 992$  mm w.e. yr<sup>-1</sup>) at the Nyainqêntanglha site (Table 2). Since there is likely more precipitation (Shen and Liang, 2004) in the glacier regions, the actual mass loss rates at the two sites might be slightly less than these estimated values. Nevertheless, the mostly deficit mass balances suggest that mass loss has most likely occurred at both coring sites during the last decades, which is consistent with the two ice core records. Furthermore, in situ-

**Table 2.** Calculated annual net mass balance (mm w.e. yr<sup>-1</sup>) during 1966–2013 AD based on various degree-day factor (DDF) values (mm °C<sup>-1</sup> d<sup>-1</sup>) and temperature lapse rates (°C 100 m<sup>-1</sup>) at the Nyainqêntanglha ice core site. Negative values represent deficit mass balances.

DDF <sup>a,b</sup>	Minimum 3.0 (snow)	Medium 5.3 (snow) 9.2 (ice)	Maximum 14.0 (ice)
Temperature lapse rate			
Minimum (Tr1) <sup>c</sup> 0.5	-469 ± 249	-1189 ± 400 -2410 ± 663	-3912 ± 992
Medium (Tr2) 0.6	-2.57 ± 212	-671 ± 538	-1733 ± 791
Maximum (Tr3) <sup>d</sup> 0.72	336 ± 150	234 ± 207 60.4 ± 313	-153 ± 450

<sup>a</sup> Wu et al. (2010); <sup>b</sup> Zhang et al. (2006); <sup>c</sup> Li and Xie (2006); <sup>d</sup> Yang et al. (2011).

observed mass balance of the central Tibetan Plateau (e.g., the Xiaodongkemadi glacier) has shown a continuous deficit mass balance (or cumulative negative mass balance) since the 1990s (Fig. 6) (Yao et al., 2012), which agrees with a dramatic warming as shown in Fig. 7 (positive cumulative temperature) in the same period.

#### 4 Conclusions

Meteorological data suggest dramatic warming has occurred in the Tibetan Plateau since the late 1980s and that the magnitude of warming is much greater than that in the low-elevation regions (Kang et al., 2010). This warming has resulted in a continuous negative mass balance (or mass loss) of glaciers during the last decade, ranging from the Himalayas to the north of the Tibetan Plateau except for the north-western Tibetan Plateau (e.g., Yao et al., 2012; Bolch et al., 2012; Gardelle et al., 2012; Neckel et al., 2014). In recent years, the altitude of the equilibrium line for some of the observed glaciers has risen beyond the highest elevations of the glaciers; that is, there is no more net accumulation area and subsequently the entire glacier is becoming an ablation area (Yao et al., 2012). Although glacier mass balance varies depending on climate change and geographical conditions as shown on the Tibetan Plateau (e.g., Yao et al., 2012; Bolch et al., 2012), our <sup>3</sup>H and Hg ice core records confirm that the upper glacier areas (e.g., about 5750–6000 m a.s.l.) have rapidly been transforming into ablation areas in recent decades. In particular, extensive ablation has caused substantial mass loss of the Nyainqêntanglha and Geladaindong glaciers since at least the 1950s in the southern part and the 1980s in the central part of the Tibetan Plateau, respectively.

We suggest that the glaciers on the southern to the central Tibetan Plateau might be melting faster than previous data have shown (Liu et al., 2006; Jacob et al., 2012; Gardner et al., 2013). Ice losses on such a large scale and at such

a fast rate could have substantial impacts on regional hydrology and water availability (Immerzeel et al., 2010), as well as causing possible floods due to glacier lake outbursts (Richardson and Reynolds, 2000; Zhang et al., 2009). Furthermore, the loss of glacier accumulation area warns us that recent climatic and environmental information archived in the ice cores is threatened and rapidly disappearing in the mid and low latitudes. As such, there is an urgent need to collect and study these valuable ice core records before they are gone forever.

*Author contributions.* S. Kang was the lead scientist of the entire project and F. Wang was the principal investigator of the mercury sub-project. S. Kang and F. Wang wrote the first draft of the manuscript, with inputs from all other co-authors. U. Morgenstern did the tritium measurement and interpretation. M. Schwikowski did the <sup>210</sup>Pb measurement and interpretation. Y. Zhang, B. Grigholm, S. Kaspari, and S. Kang did the major ions, elements, and stable oxygen isotope measurements and analyzed the data. J. Ren, T. Yao, D. Qin, and P. A. Mayewski conceived and designed the experiments.

*Acknowledgements.* This work was funded by the Global Change Research Program of China (2013CBA01801), the National Natural Science Foundation of China (41121001, 41225002, and 41190081), the US National Science Foundation (ATM 0754644), and the Natural Science and Engineering Council (NSERC) of Canada. We thank all members of the 2003 Nyainqêntanglha and 2005 Geladaindong expeditions.

Edited by: A. Klein

#### References

- Bolch, T., Kulkarni, A., Kääb, A., Hugge, C., Paul, F., Cogley, J. G., Frey, H., Kargel, J. S., Fujita, K., Scheel, M., Bajracharya, S., and Stoffel, M.: The state and fate of Himalayan glaciers, *Science*, 336, 310–314, 2012.
- Bryson, R.: Airstream climatology of Asia, in *Proceedings of International Symposium on the Qinghai-Xizang Plateau and Mountain Meteorology*, American Meteorological Society, Boston, 604–617, 1986.
- Cao, B., Pan, B., Gao, H., Jiang, S., Wen, Y., and Shangguan, D.: Glacier variation in the Lenglongling Range of eastern Qilian Mountains from 1972 to 2007, *J. Glaciol. Geocryol.*, 32, 242–248, 2010.
- Clark, I. D. and Fritz, P.: *Environmental Isotopes in Hydrogeology*, Lewis, New York, 1997.
- Eichler, A., Schwikowski, M., and Gäggeler, H.: Meltwater-induced relocation of chemical species in Alpine firn, *Tellus B*, 53, 192–203, doi:10.1034/j.1600-0889.2001.d01-15.x, 2001.
- Faïn, X., Ferrari, C. P., Dommergue, A., Albert, M., Battle, M., Arnaud, L., Barnola, J.-M., Cairns, W., Barbante, C., and Boutron,



- C.: Mercury in the snow and firn at Summit Station, Central Greenland, and implications for the study of past atmospheric mercury levels, *Atmos. Chem. Phys.*, 8, 3441–3457, doi:10.5194/acp-8-3441-2008, 2008.
- Fujita, K. and Nuimura, T.: Spatially heterogeneous wastage of Himalayan glaciers, *Proc. Natl. Acad. Sci. USA*, 108, 14011–14014, 2011.
- Gäggeler, H., von Gunten, H. R., Rossler, E., Oeschger, H., and Schotterer, U.:  $^{210}\text{Pb}$ -dating of cold Alpine firn/ice cores from Colle Gnifetti, Switzerland, *J. Glaciol.*, 29, 165–177, 1983.
- Gardelle, J., Berthier, E., and Arnaud, Y.: Slight mass gain of Karakoram glaciers in the early twenty-first century, *Nat. Geosci.*, 5, 322–325, 2012.
- Gardner, A. S., Moholdt, G., Cogley, J. G., Wouters, B., Arendt, A. A., Wahr, J., Berthier, E., Hock, R., Pfeffer, W. T., Kaser, G., Ligtenberg, S. R. M., Bolch, T., Sharp, M. J., Hagen, J. O., van den Broeke, M. R., and Paul, F.: A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009, *Science*, 340, 852–857, 2013.
- Gardner, A. S. and Sharp, M.: Sensitivity of net mass-balance estimates to near-surface temperature lapse rates when employing the degree-day method to estimate glacier melt, *Ann. Glaciol.*, 50, 80–86, 2009.
- Grinsted, A.: An estimate of global glacier volume, *The Cryosphere*, 7, 141–151, doi:10.5194/tc-7-141-2013, 2013.
- Holmes, C. D., Jacob, D. J., Corbitt, E. S., Mao, J., Yang, X., Talbot, R., and Slemr, F.: Global atmospheric model for mercury including oxidation by bromine atoms, *Atmos. Chem. Phys.*, 10, 12037–12057, doi:10.5194/acp-10-12037-2010, 2010.
- Hylander, L. D. and Goodsite, M. E.: Environmental costs of mercury pollution, *Sci. Total. Environ.*, 368, 352–370, 2006.
- Immerzeel, W. W., van Beek, L. P. H., and Bierkens, M. F. P.: Climate change will affect the Asian water towers, *Science*, 328, 1382–1385, 2010.
- Jacob, T., Wahr, J., Pfeffer, W. T., and Swenson, S.: Recent contributions of glaciers and ice caps to sea level rise, *Nature*, 336, 310–314, 2012.
- Kääb, A., Berthier, E., Nuth, C., Gardelle, J., and Arnaud, Y.: Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas, *Nature*, 488, 495–498, 2012.
- Kang, S., Chen, F., Gao, T., Zhang, Y., Yang, W., Yu, W., and Yao, T.: Early onset of rainy season suppresses glacier melt: A case study on the Zhadang Glacier, Tibetan Plateau, *J. Glaciol.*, 192, 755–758, 2009.
- Kang, S., Xu, Y., You, Q., Flügel, W., Pepin, N., and Yao, T.: Review of climate and cryospheric change in the Tibetan Plateau, *Environ. Res. Lett.*, 5, 015101, doi:10.1088/1748-9326/5/1/015101, 2010.
- Kaspari, S., Mayewski, P. A., Handley, M., Osterberg, E., Kang, S., Sneed, S., Hou, S., and Qin, D.: Recent increases in atmospheric concentrations of Bi, U, Cs, S and Ca from a 350-year Mount Everest ice core record, *J. Geophys. Res.*, 114, D04302, doi:10.1029/2008JD011088, 2009.
- Kehrwald, N. M., Thompson, L. G., Yao, T., Mosley-Thompson, E., Schotterer, U., Alfimov, V., Beer, J., Eikenberg, J., and Davis, M. E.: Mass loss on Himalayan glacier endangers water resources, *Geophys. Res. Lett.*, 35, L22503, doi:10.1029/2008GL035556, 2008.
- Kotzer, T. G., Kudo, A., Zheng, J., and Workman, W.: Natural and anthropogenic levels of tritium in a Canadian Arctic ice core, Agassiz Ice Cap, Ellesmere Island, and comparison with other radionuclides, *J. Glaciol.*, 46, 35–40, 2000.
- Li, Q.: Environmental changes retrieved from lake sediments across the Himalayas, Post-Doc. Report, Institute of Tibetan Research, Chinese Academy of Science, Beijing, 2011.
- Li, Q. and Xie, Z.: Analyses on the characteristics of the vertical lapse rates of temperature- taking Tibetan Plateau and its adjacent area as an example, *J. Shihezi University (Natural Sci.)*, 24, 719–723, 2006.
- Liu, S., Ding, Y., Li, J., Shangguan, D., and Zhang, Y.: Glaciers in response to recent climate warming in western China, *Quaternary Sci.*, 26, 762–771, 2006.
- Liu, J., Chen, R., Qin, W., and Yang, Y.: Study on the vertical distribution of precipitation in mountainous regions using TRMM data, *Adv. Water Sci.*, 22, 447–454, 2011.
- Loewen, M., Kang, S., Armstrong, D., Zhang, Q., Tomy, G., and Wang, F.: Atmospheric transport of mercury to the Tibetan Plateau, *Environ. Sci. Technol.*, 41, 7632–7638, 2007.
- Morgenstern, U. and Taylor, C. B.: Ultra low-level tritium measurement using electrolytic enrichment and LSC, *Isotopes Environ. Health Studies*, 45, 96–117, 2009.
- Nakazawa, F. and Fujita, K.: Use of ice cores from glaciers with melting for reconstructing mean summer temperature variations, *Ann. Glaciol.*, 43, 167–171, 2006.
- Neckel, N., Kropacek, J., Bolch, T., and Hochschild, V.: Glacier mass changes on the Tibetan Plateau 2003–2009 derived from ICESat laser altimetry measurements, *Environ. Res. Lett.*, 9, 014009, doi:10.1088/1748-9326/9/1/014009, 2014.
- Olivier, S., Blaser, C., Brutsch, S., Frolova, N., Gäggeler, H. W., Henderson, K. A., Palmer, A. S., Papina, T., and Schwikowski, M.: Temporal variations of mineral dust, biogenic tracers, and anthropogenic species during the past two centuries from Belukha ice core, Siberian Altai, *J. Geophys. Res.*, 111, D05309, doi:10.1029/2005JD005830, 2006.
- Pan, B. T., Zhang, G. L., Wang, J., Cao, B., Geng, H. P., Wang, J., Zhang, C., and Ji, Y. P.: Glacier changes from 1966–2009 in the Gongga Mountains, on the south-eastern margin of the Qinghai-Tibetan Plateau and their climatic forcing, *The Cryosphere*, 6, 1087–1101, doi:10.5194/tc-6-1087-2012, 2012.
- Pinglot, J. F., Vaikmae, R. A., Kamiyama, K., Igarashi, M., Fritzsche, D., Wilhelms, F., Koerner, R., Henderson, L., Isaksson, E., Winther, J.-G., Van de Wal, R. S. W., Fournier, M., Bouisset, P., and Meijer, H. A. J.: Ice cores from Arctic sub-polar glaciers: chronology and post-depositional processes deduced from radioactivity measurements, *J. Glaciol.*, 49, 149–158, 2003.
- Qu, B., Ming, J., Kang, S.-C., Zhang, G.-S., Li, Y.-W., Li, C.-D., Zhao, S.-Y., Ji, Z.-M., and Cao, J.-J.: The decreasing albedo of the Zhadang glacier on western Nyainqentanglha and the role of light-absorbing impurities, *Atmos. Chem. Phys.*, 14, 11117–11128, doi:10.5194/acp-14-11117-2014, 2014.
- Richardson, S. D. and Reynolds, J. M.: An overview of glacial hazards in the Himalayas, *Quaternary Int.*, 65, 31–47, 2000.
- Schuster, P. F., Krabbenhoft, D. P., Naftz, D. L., Cecil, L. D., Olson, M. L., Dewild, J. F., Susong, D. D., Green, J. R., and Abbott, M. L.: Atmospheric mercury deposition during the last 270 years: a glacial ice core record of natural and anthropogenic sources, *Environ. Sci. Technol.*, 36, 2303–2310, 2002.

- Shen, Y. and Liang, H.: High precipitation in glacial region of high mountains in High Asia: Possible cause, *J. Glaciol. Geocryol.*, 26, 806–809, 2004.
- Shi, Y., Liu, C., and Wang, Z.: *Brief Glacier Inventory in China*, Shanghai Popular Science Press, Shanghai, 2005.
- Tang, M.: Formation, evolution and variability characteristics of Qinghai-Tibetan Plateau Monsoon, in *Contemporary climatic variations over Qinghai-Tibetan Plateau and their influences on environments*, edited by: Tang, M., Chen, G., and Lin, Z., 161–182, Guangdong Sciences and Technology Press, Guangzhou, 1998.
- Van Der Wel, L. G., Streurman, H. J., Isaksson, E., Helsen, M. M., Van De Wal, R. S. W., Martma, T., Pohjola, V. A., Moore, J. C., and Meijer, H. A. J.: Using high-resolution tritium profiles to quantify the effects of melt on two Spitsbergen ice cores, *J. Glaciol.*, 57, 1087–1097, 2011.
- Wang, N., He, J., Jiang, X., Song, G., Pu, J., Wu, X., and Chen, L.: Study on the zone of maximum precipitation in the north slopes of the central Qilian mountains, *J. Glaciol. Geocryol.*, 31, 395–403, 2009.
- Wu, Q., Kang, S., Gao, T., and Zhang, Y.: The characteristics of the positive degree-day factors of the Zhadang Glacier on the Nyainqêngtanglha Range of Tibetan Plateau, and its application, *J. Glaciol. Geocryol.*, 32, 891–897, 2010 (in Chinese with English abstract).
- Yang, X., Zhang, T., Qin, D., Kang, S., and Qin, X.: Characteristics and changes in Air Temperature and Glacier's Response on the North Slope of Mt. Qomolangma (Mt. Everest), *Arct. Antarct. Alpine Res.*, 43, 147–160, 2011.
- Yao, T., Thompson, L. G., Yang, W., Yu, W., Gao, Y., Guo, X., Yang, X., Duan, K., Zhao, H., Xu, B., Pu, J., Lu, A., Xiang, Y., Kattel, D., and Joswiak, D.: Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings, *Nat. Clim. Change*, 2, 663–667, 2012.
- Yao, T., Wang, Y., Liu, S., Pu, J., Shen, Y., and Lu, A.: Recent glacial retreat in High Asia in China and its impact on water resource in Northwest China, *Sci. China Ser. D*, 47, 1065–1075, 2004.
- Ye, Q., Kang, S., Chen, F., and Wang, J.: Monitoring glacier variations on Geladandong mountain, central Tibetan Plateau, from 1969 to 2002 using remote-sensing and GIS technologies, *J. Glaciol.*, 52, 537–545, 2006.
- Zhang, D., Xiao, C., and Qin, D.: Himalayan glaciers fluctuation over the latest decades and its impact on water resources, *J. Glaciol. Geocryol.*, 31, 885–895, 2009.
- Zhang, G., Li, Z., Wang, W., and Wang W.: Rapid decrease of observed mass balance in the Urumqi glacier No.1 Tianshan Mountains, central Asia, *Quaternary Int.*, 349, 135–141, 2014.
- Zhang, L.: Glaciers at the source region of Tuotuo River in the upper reaches of the Changjiang (Tangtze River) and their evolution, *J. Glaciol. Geocryol.*, 3, 1–9, 1981.
- Zhang, Q., Huang, J., Wang, F., Mark, L., Xu, J., Armstrong, D., Li, C., Zhang, Y., and Kang, S.: Mercury distribution and deposition in glacier snow over Western China, *Environ. Sci. Technol.*, 46, 5404–5413, 2012.
- Zhang, Y., Liu, S., and Ding, Y.: Spatial variation of degree-day factors on the observed glaciers in western China, *Acta Geogr. Sinica*, 61, 89–98, 2006.
- Zhang, Y., Kang, S., Zhang, Q., Cong, Z., and Zhang, Y.: Snow/ice records on Mt. Geladandong in the central Tibetan Plateau, *J. Glaciol. Geocryol.*, 29, 685–693, 2007 (in Chinese with English abstract).