Black carbon in seasonal snow across northern Xinjiang in northwestern China

Hao Ye¹, Rudong Zhang¹, Jinsen Shi¹, Jianping Huang¹, Stephen G Warren² and Qiang Fu¹,²

¹ Key Laboratory for Semi-Arid Climate Change of the Ministry of Education, College of Atmospheric Sciences, Lanzhou University, Lanzhou 730000, Gansu, People’s Republic of China
² Department of Atmospheric Sciences, University of Washington, Box 351640, Seattle, WA 98195, USA

E-mail: qfuatm@gmail.com

Received 26 June 2012
Accepted for publication 20 September 2012
Published 4 October 2012
Online at stacks.iop.org/ERL/7/044002

Abstract
Black carbon (BC) particles in snow can significantly reduce the snow albedo and enhance the absorption of solar radiation, with important impacts on climate and the hydrological cycle. A field campaign was carried out to measure the BC content in seasonal snow in Qinghai and Xinjiang provinces of western China, in January and February 2012. 284 snow samples were collected at 38 sites, 6 in Qinghai and 32 in Xinjiang. The observational results at the sites in Xinjiang, where the absorbing impurities in snow are dominated by BC particles, are reported in this work. The BC mass fractions in seasonal snow across northern Xinjiang have a median value of ∼70 ng g⁻¹, much lower than those in northeast China. The estimated concentration of BC at the cleanest site in Xinjiang is 20 ng g⁻¹, which is similar to that found along the coast of the Arctic Ocean. It is found that the BC content of snow decreases with altitude. Taking into account this altitude dependence, our measured BC contents in snow are consistent with a recent measurement of BC in winter snow on Tianshan glacier. The data from this field campaign should be useful for testing transport models and climate models for the simulated BC in snow.

Keywords: black carbon, seasonal snow, Northern Xinjiang, climate change

1. Introduction
Black carbon (BC) particles are products of incomplete combustion related to burning of fossil fuel and biomass (e.g., Bond et al 2004). When BC particles are emitted into the atmosphere, they can be transported long distances before being removed by wet deposition, such as rain and snow, or by dry deposition (e.g., Flanner et al 2007, Shindell et al 2008). The BC particles strongly absorb solar visible radiation and thus impose an important positive radiative forcing to the climate system (e.g., Jacobson 2001, Hansen et al 2005, IPCC 2007). Since snow is the most reflective natural surface on Earth, small amounts of absorptive impurities such as BC and dust particles deposited into snow can reduce the albedo of snow significantly (e.g., Warren and Wiscombe 1980, Warren 1982). The quantitative link between BC concentration and reduction of snow albedo has been established through both radiative transfer modeling and field and controlled experiments (e.g., Warren and Wiscombe 1980, Grenfell et al 1994, Brandt et al 2011, Hadley and Kirchstetter 2012). Recent modeling studies indicate that the radiative forcing caused by BC in snow has been an important anthropogenic forcing for climate change of the past century, producing warming both in the Arctic and across the Northern Hemisphere (e.g., Hansen and Nazarenko 2004, Jacobson 2004, Flanner et al 2007). Such model studies, however, need to be tested by, among other things, comparing simulations with observations of BC concentration in snow. Notably, BC
in snow and ice is one of the largest sources of uncertainty in the assessment of various radiative forcings for climate change (Hansen et al. 2005).

While BC has been measured in Arctic snow (Clarke and Noone 1985, Grenfell et al. 2002, Forsström et al. 2009, Doherty et al. 2010), it now appears that the larger effect may be in the midlatitudes, where the snow is closer to the sources of BC and also exposed to more sunlight. Radiative forcing due to BC in snow in middle latitudes may impact the timing and rate of snow melt (e.g., Qian et al. 2009, 2011). Thus, similarly comprehensive field campaigns need to be conducted across the Northern Hemisphere midlatitudes.

The first large-area survey of absorbing impurities in seasonal snow over northern China was conducted in the winter of 2010 (Huang et al. 2011). It covered six provinces including Qinghai, Gansu, Inner Mongolia, Heilongjiang, Jilin and Liaoning (figure 1). The absorbing impurities were principally dust and BC particles, respectively, in northwestern and northeastern China. The estimated concentration of BC was only \( \sim 40 \) ng g\(^{-1}\) in the far north of Heilongjiang province, but increased to several hundred ng g\(^{-1}\) in heavily-industrialized Liaoning, Jilin, and the southern part of Heilongjiang. The BC content of snow in northeastern China was comparable to values found in Europe (Huang et al. 2011). The further analyses of this survey were reported by Wang et al. (2012).

This work describes a field campaign carried out in the winter of 2012, following the campaign in 2010, to measure the absorptive impurities in seasonal snow in western China, covering the northern part of Xinjiang Uygur Autonomous Region (hereafter Xinjiang) and the southeast of Qinghai province (figure 1). The preliminary results of BC content of snow in northern Xinjiang are reported here (i.e., the sites from 53 to 84).

2. Field campaign

During a road trip in January–February 2012, seasonal snow was collected at 38 sites: 6 in Qinghai and 32 in Xinjiang. Snow samples were also obtained at two sites on the campus of Lanzhou University in early March 2012. The sampling site locations in both 2010 and 2012 campaigns are shown in figure 1, which are numbered chronologically. Between the clusters of sampling locations in figure 1 are some large blank areas (far-west Inner Mongolia, northwestern Gansu, northwestern Qinghai, eastern Xinjiang and central Xinjiang). These are desert regions with little snowfall; the ground was bare when we passed through these regions, so no snow was available for collection.

The sampling sites (except two sites on the campus of Lanzhou University) were chosen to be distant from roads and villages so as to avoid local pollution, so that the results can represent large areas. At each site, a snow pit was dug and snow samples were gathered in two vertical profiles separated by \( \sim 50 \) cm (‘left’ and ‘right’) to check for consistency. The snow was stored in plastic bags and kept frozen during the trip until we stopped to filter the samples. The influence of the plastic bags on the composition analysis is negligible (Doherty 2012). The vertical profiles of snow density were also measured for a depth of 5 cm of each layer downward while the temperatures were measured at the center of each layer. These data may be used, together with the concentrations, to quantify the deposition flux of BC and/or dust. Two pictures taken while collecting snow samples are shown in figure 2.

We normally collected the snow samples from adjacent vertical layers from the top to bottom with a depth of \( \sim 5 \) cm for each layer (figure 3), and the reported BC concentration is considered to represent the corresponding layer. In Qinghai and Xinjiang, some sites had very thin snow and strong wind, so that sampling was only possible in snow drifts. In Qinghai,
Figure 2. (a) Snow collection in a pasture in the Tianshan Mountains (Site 55), (b) snow collection in Altai Mountains (Site 68) and (c) filtering meltwater in a hotel room in Jinghe.

3. Analysis of preliminary results

3.1. Surface and depth-integrated BC concentration

We collected samples at 32 sites in Xinjiang, with freshly fallen snow at the surface layer at 12 sites. The surface and depth-integrated BC concentrations are shown in figure 4 and accomplished at 13 sites, one in Qinghai at Site 52 and the others in Xinjiang shown in figure 4.

284 snow samples were collected in Qinghai and Xinjiang, which were processed at four temporary laboratories en route, one in Qinghai and three in Xinjiang (figure 2(c)). The samples collected in Lanzhou were processed at Lanzhou University. The processing method is the filtering technique which was first used by Clarke and Noone (1985) and recently employed by Doherty et al (2010) and Huang et al (2011). Each snow sample was spooned into a large beaker which was then put into a microwave oven. The snow was melted rapidly to minimize adherence of BC particles to the wall of the beaker. A measured volume of meltwater was sucked into a syringe and immediately filtered through a 0.4 µm nuclepore filter, using a hand pump to maintain a partial vacuum. Small samples of meltwater, both before and after filtration, were saved in 60 ml bottles and refrozen for further chemical analysis to enable source attribution (Hegg et al 2009, 2010).

After drying, the filters were compared visually against a set of standard filters with known BC loading provided by Clarke, to obtain an estimate of equivalent BC loading of the samples. Together with measurement of the exposed area of each filter, and the volume of meltwater passed through the filter, BC mass fractions in snow can be derived. These values are ‘equivalent BC’, as defined by Grenfell et al (2011), meaning the amount of BC that would be needed to explain the total wavelength-integrated absorption by particulate impurities, if BC were the only absorber on the filter. In our follow-on study, the filters will be measured by an integrating-sandwich spectrophotometer (Grenfell et al 2011, Wang et al 2012), and our visual estimates will be compared with these measurements. Previous studies showed that the visual estimates of equivalent BC concentrations agree with those derived from the integrating-sandwich spectrophotometer within about a factor of 2 (e.g., Grenfell et al 2011, Wang et al 2012). The equivalent BC concentrations in snow reported here have been multiplied by 1.15 to account for the under-catch of the 0.4 µm filter, based on prior measurements indicating that approximately 15% of BC passes through the 0.4 µm filter (Clarke and Noone 1985, Doherty et al 2010).

The equivalent BC loading cannot be estimated accurately by visual inspection if the filter is heavily loaded with soil dust, because of the color difference between the sample filter and the calibration filters. Therefore, the results of the Qinghai sites, where the filters are yellow due to heavy loading of soil dust, are not reported here. On the other hand, the filters from all but two of the Xinjiang sites are gray in color, indicating that the impurities are dominated by BC particles. This work reports the visual estimate of filters for the equivalent BC content of snow in northern Xinjiang.
Figure 3. Examples of snow pits at sites 54, 77, and 84.

Figure 4. BC content of snow at the 32 sampling sites in Xinjiang. The numbers above red points are visual estimates of the BC-equivalent concentrations in the top layer at each site; the numbers below are depth-integrated values and the sites number is in red beside. The ‘D’ indicates that the snow samples were collected in snow drifts and the ‘F’ indicates that there was fresh snow at the surface layer at these sites. At the two sites with pink circles the filters were yellow, indicating that the light absorption was probably dominated by dust. The topography data is from NASA Shuttle Radar Topographic Mission (SRTM) V4 digital elevation models (DEM) data (http://srtm.csi.cgiar.org).

also in table 1, and the vertical profiles of BC concentrations are shown in figure 5. The surface BC concentrations are the values in the top layer, while the depth-integrated BC concentrations are average values of all the snow-sampled layers, weighted by the snow mass in each layer. The density of snow and temperature for each layer at each site are shown
concentrations were low, i.e., 20–30 ng g$^{-1}$; this value may represent the background BC content of snow in the region. Sites 55–62 are located on basins with farmland and pastures; their BC values are mostly between 30 and 200 ng g$^{-1}$; this value may have resulted from sublimation of snow (Liston and Sturm 2004) and dry deposition of BC between snowfall events. However, the high surface BC concentration observed at Site 84 in new snow (i.e., 70 ng g$^{-1}$) is undoubtedly the result of wet deposition of local pollution by snowfall.

As we moved north from the Tianshan to the hilly areas (Sites 63–67), most places were grassland (Wu et al. 2010). In this particular year, this area had experienced little snowfall, so the snow was thin and patchy there. The high surface BC concentration from sublimation of snow (Liston and Sturm 2004) and dry deposition of BC between snowfall events. However, the high surface BC concentration observed at Site 84 in new snow (i.e., 70 ng g$^{-1}$) is undoubtedly the result of wet deposition of local pollution by snowfall.
Table 2. The snow density (g cm\(^{-3}\)) and temperature (\(^\circ\)C) profiles at each sampling site, which were measured every 5 cm downward.

| Site | Layer depth from the surface downward (cm) | Snow density (g cm\(^{-3}\)) | Temperature (\(^\circ\)C) |
|------|------------------------------------------|-----------------------------|--------------------------|
|      | 0–5                                      | 0.43                        | -18.0                     |
|      | 5–10                                     | 0.41                        | -20.0                     |
|      | 10–15                                    | 0.39                        | -20.5                     |
|      | 15–20                                    | 0.27                        | -21.0                     |
|      | 20–25                                    | 0.27                        | -20.0                     |
|      | 25–30                                    | 0.285                       | -18.0                     |
|      | 30–35                                    | 0.14                        | -21.5                     |
|      | 35–40                                    | 0.19                        | -20.5                     |
|      | 40–45                                    | 0.16                        | -19.0                     |
|      | 45–50                                    | 0.1                         | -8.0                      |
|      | 50–55                                    | 0.12                        | -10.0                     |
|      | 55–60                                    | 0.17                        | -7.0                      |
|      | 60–65                                    | 0.19                        | -7.0                      |
|      | 65–70                                    | 0.1                         | -8.0                      |
|      | 70–75                                    | 0.21                        | -9.0                      |
|      | 75–80                                    | 0.23                        | -7.0                      |
|      | 80–85                                    | 0.2                         | -6.0                      |

Table 2. The snow density (g cm\(^{-3}\)) and temperature (\(^\circ\)C) profiles at each sampling site, which were measured every 5 cm downward.

result of sublimation as well as dry deposition. The low BC concentrations at other sites occurred in the snow layers that existed for less than half a month based on meteorological data of nearby weather stations from China Meteorological Data Sharing Service System.

The far north of Xinjiang is occupied by the Altai Mountains. The natural vegetation there is forest and grassland; part of this region is now farmed (Wu et al. 2010). The cleanest snow was found at our northernmost site, Site 70, near the borders of Russia, Kazakhstan and Mongolia. Its
Table 2. (Continued.)

| Site | Layer depth from the surface downward (cm) | Snow density (g cm$^{-3}$) | Temperature (°C) |
|------|------------------------------------------|-----------------------------|-------------------|
| 80   | 0–5                                      | 0.13                        | −10.0             |
| 81   | 5–10                                     | 0.17                        | −7.5              |
| 82   | 10–15                                    | 0.09                        | −11.5             |
| 83   | 15–20                                    | 0.13                        | −7.0              |
| 84   | 20–25                                    | 0.11                        | −6.5              |

Figure 5. Vertical profiles of visually-determined BC-equivalent concentrations at Sites 53–84 in Xinjiang. The depths and layers of snow are different from one site to another. At some sites the concentrations are discontinuous (as indicated by gaps in the color bars) because samples were not collected at these layers.

BC values were 20 ng g$^{-1}$, which are comparable to those of Canadian Arctic, Alaskan Arctic and Svalbard (Doherty et al 2010). The higher BC concentrations occurred near cities or large villages such as at Sites 69 and 72, with BC values of 230 ng g$^{-1}$ and 210 ng g$^{-1}$, respectively, at the top layers.

In the 2010 campaign in the northeast China, the estimated surface concentrations of BC in seasonal snow ranged from 40 to 1600 ng g$^{-1}$, with a median value of 500 ng g$^{-1}$ (Huang et al 2011). The BC contents of snow over northern Xinjiang, which have a median surface value of 70 ng g$^{-1}$ (figure 4), are thus much lower than those in northeast China.

3.2. BC distribution with altitude

A previous investigation by Ming et al (2009a) on the Tibetan Plateau and Tianshan Mountains found that BC concentrations showed a negative correlation with the altitudes of the sites, and suggested that altitude was the dominant factor influencing BC concentrations. We find that the BC content of seasonal snow in northern Xinjiang also shows similar behavior, decreasing with altitude (figure 6). In contrast to the studies of Ming et al (2009a, 2009b), whose sampling sites were all above 3700 m, our sampling sites in Xinjiang were at altitudes 240–3500 m, which were more likely to be influenced by local pollution transported within the atmospheric boundary layer. Note that the BC-equivalent concentrations at Site 53 were relatively high for both surface and layer-averaged values. This may be due not to BC, but rather to the natural limestone soil there, which was visually gray. Forthcoming chemical analysis of the meltwater may be able to distinguish these possibilities.

BC content has been reported for snow and ice core in numerous glaciers on the Tibetan Plateau and in the Tianshan Mountains, using the thermo-optical (controlled-combustion) method (Ming et al 2008, 2009a, 2009b, Xu et al 2006, 2009, 2012). The derived BC contents range from 4 to 141 ng g$^{-1}$ (Ming et al 2012). The values from Tianshan glaciers ranged from 87 to 141 ng g$^{-1}$ with an average of 112 ng g$^{-1}$ (Ming et al 2009a, 2009b, 2012). Note that these data refers to BC contents in summer snow where BC are largely enriched. A recent measurement by Xu et al (2012) showed that the winter BC contents in surface snow at altitude of 4100 m on Tianshan glacier are only 27–31 ng g$^{-1}$, which is consistent with our measurements by taking into account the altitude dependence of BC concentrations.

4. Discussion and conclusions

The snow depth in Xinjiang has increased over the past several decades, according to Qin et al (2006) and Peng et al (2010). Northern Xinjiang is an arid/semiarid region, so the main vegetation there is grass (the grasslands have largely turned into farms in the basin valley regions) (Wu et al 2010), and the snow is exposed to sunlight more than would be the case in forested regions. Therefore, the planetary albedo of northern Xinjiang in winter is dominated by snow, so it can be affected by absorptive impurities.

The absorptive impurities in snow in Xinjiang are dominated by BC particles. The BC content of snow in
Xinjiang is much lower than that in northeast China. Despite the farmland and pastures spreading over the basin regions, the sources of BC particles are still mainly residential fossil fuel burning in winter (Cao et al. 2006). But the smaller population in northern Xinjiang and relatively smaller cities lead to much less BC emission than in northeast China. At the cleanest site in the far north of Xinjiang, the estimated concentration of BC is about 20 ng g$^{-1}$, similar to that found at the coast of Arctic Ocean (Doherty et al. 2010). The BC content of snow is found to decrease with altitude. Taking into account this altitude dependence, our measured BC contents in snow are consistent with a recent measurement of BC in winter snow on Tianshan glacier (Xu et al. 2012).

The field campaigns conducted in 2010 and 2012 together provide a comprehensive survey of absorbing impurities in seasonal snow over northern China. The dataset will be useful to test models and to evaluate the effect of BC on snow albedo and thus the radiative forcing caused by BC in seasonal snow.

**Acknowledgments**

This work was supported by National Science Foundation of China under Grants 40725015 and 41175134, the Program for Changjiang Scholars and Innovative Research Team in University (IRT1018), and the Fundamental Research Funds for Changjiang Scholars and Innovative Research Team in China under Grants 40725015 and 41175134, the Program to Support Top-notch Young Professionals, and the Central Universities (lzujbky-2010-k06).

**References**

Bond T C, Streets D G, Yarber K F, Nelson S M, Woo J H and Klimont Z 2004 A technology-based global inventory of black and organic carbon emissions from combustion J. Geophys. Res. 109 D14203–27

Brandt R E, Warren S G and Clarke A D 2011 A controlled snowmaking experiment testing the relation between black carbon content and reduction of snow albedo J. Geophys. Res. 116 D08109

Cao G L, Zhang X Y and Zheng F C 2006 Inventory of black carbon and organic carbon emissions from China Atmos. Environ. 40 6516–27

Clarke A D and Noone K J 1985 Soot in the arctic snowpack—a case for perturbation in radiative-transfer Atmos. Environ. 19 2045–53

Doherty S J 2012 personal communication

Doherty S J, Warren S G, Grenfell T C, Clarke A D and Brandt R E 2010 Light-absorbing impurities in Arctic snow Atmos. Chem. Phys. 10 11647–80

Flanner M G, Zender C S, Randerson J T and Rasch P J 2007 Present-day climate forcing and response from black carbon in snow J. Geophys. Res. 112 D11202

Forström S, Ström J, Pedersen C, Isaksson E and Gerland S 2009 Elemental carbon distribution in Svalbard snow J. Geophys. Res. 114 D19112

Grenfell T C, Doherty S J, Clarke A D and Warren S G 2011 Light absorption from particulate impurities in snow and ice determined by spectrophotometric analysis of filters Appl. Opt. 50 2037–48

Grenfell T C, Light B and Sturm M 2002 Spatial distribution and radiative effects of soot in the snow and sea ice during the SHEBA experiment J. Geophys. Res. 107 8032

Grenfell T C, Warren S G and Mullenn P C 1994 Reflection of solar-radiation by the Antarctic snow surface at ultraviolet, visible, and near-infrared wavelengths J. Geophys. Res. 99 18669–84

Hadley O L and Kirchstetter T W 2012 Black-carbon reduction of snow albedo Nature Clim. Change 2 437–40

Hansen J and Nazarenko L 2004 Soot climate forcing via snow and ice albedos Proc. Natl Acad. Sci. USA 101 423–8

Hansen J et al 2005 Efficacy of climate forcings J. Geophys. Res. 110 D18104

Hegg D A, Warren S G, Grenfell T C, Doherty S J and Clarke A D 2010 Sources of light-absorbing aerosol in Arctic snow and their seasonal variation Atmos. Chem. Phys. 10 10923–38

Hegg D A, Warren S G, Grenfell T C, Doherty S J and Clarke A D 2009 Attribution of black carbon in Arctic snow Environ. Sci. Technol. 4311 4016–21

Huang J P, Fu Q, Zhang W, Wang X, Zhang R D, Ye H and Warren S G 2011 Dust and black carbon in carbon in seasonal snow across northern China Bull. Am. Meteorol. Soc. 92 175–81

IPCC (Intergovernmental Panel on Climate Change) 2007 Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change ed S Solomon, D Qin, M Manning, M Marquis, K Averitt, M Tignor, H L Miller and Z Chen (Cambridge: Cambridge University Press)

Jacobson M Z 2001 Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols Nature 409 695–7
Jacobson M Z 2004 Climate response of fossil fuel and biofuel soot, accounting for soot’s feedback to snow and sea ice albedo and emissivity J. Geophys. Res. 109 D21201
Liston G and Sturm M 2004 The role of winter sublimation in the Arctic moisture budget Nord. Hydrol. 35 325–34
Ming J, Cachier H, Xiao C, Qin D, Kang S, Hou S and Xu J 2008 Black carbon record based on a shallow Himalayan ice core and its climatic implications Atmos. Chem. Phys. 8 1343–52
Ming J, Xiao C D, Cachier H, Qin D H, Qin X, Li Z Q and Pu J C 2009a Black carbon (BC) in the snow of glaciers in west China and its potential effects on albedos Atmos. Res. 92 114–23
Ming J, Xiao C D, Du Z and Flanner M G 2009b Black carbon in snow/ice of west China and its radiative forcing Adv. Clim. Change Res. 5 328–35 (in Chinese with English abstract)
Ming J, Xiao C D, Du Z and Yang X G 2012 An overview of black carbon deposition in High Asia glaciers and its impacts on radiation balance Adv. Water Resour. at press ( doi:10.1016/j. advwatres.2012.05.015)
Peng S, Piao S, Ciais P, Fang J and Wang X 2010 Change in winter snow depth and its impacts on vegetation in China Glob. Change Biol. 16 3004–13
Qian Y, Flanner M, Leung L and Wang W 2011 Sensitivity studies on the impacts of Tibetan Plateau snowpack pollution on the Asian hydrological cycle and monsoon climate Atmos. Chem. Phys. 11 1929–48
Qian Y, Gustafson W J Jr, Leung L R and Ghan S J 2009 Effects of soot-induced snow albedo change on snowpack and hydrological cycle in western US based on WRF chemistry and regional climate simulations J. Geophys. Res. 114 D03108
Qin D H, Liu S Y and Li P J 2006 Snow cover distribution, variability, and response to climate change in western China J. Clim. 19 1820–33
Shindell D, Chin M, Dentener F, Doherty R, Faluvegi G, Fiore A, Hess P, Koch D, MacKenzie I and Sanderson M 2008 A multi-model assessment of pollution transport to the Arctic Atmos. Chem. Phys. 8 5353–72
Wang X, Doherty S J and Huang J P 2012 Black carbon and other light-absorbing impurities in snow across Northern China J. Geophys. Res. submitted
Warren S G 1982 Optical properties of snow Rev. Geophys. 20 67–89
Warren S G and Wiscombe W J 1980 A model for the spectral albedo of snow, 2. Snow containing atmospheric aerosols J. Atmos. Sci. 37 2734–45
Wu Z, Zhang H, Krause C M and Cobb N S 2010 Climate change and human activities: a case study in Xinjiang, China Clim. Change 99 457–72
Xu B Q, Cao J J, Joswiak D R, Liu X Q, Zhao H B and He J Q 2012 Post-depositional enrichment of black soot in snow-pack and accelerated melting of Tibetan glaciers Environ. Res. Lett. 7 014022
Xu B Q, Wang M, Joswiak D R, Cao J J, Yao T D, Wu G J, Yang W and Zhao H B 2009 Deposition of anthropogenic aerosols in a southeastern Tibetan glacier J. Geophys. Res. 114 D17209
Xu B Q, Yao T D, Liu X Q and Wang N L 2006 Elemental and organic carbon measurements with a two-step heating-gas chromatography system in snow samples from the Tibetan Plateau Ann. Glaciol. 43 257–62