Atmospheric Environment 138 (2016) 114–124

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Individual particles of cryoconite deposited on the mountain glaciers of the Tibetan Plateau: Insights into chemical composition and sources

Zhiwen Dong [a,*], Dahe Qin [a], Shichang Kang [a,b], Yajun Liu [a], Yang Li [c], Jie Huang [c], Xiang Qin [a]

[a] State Key Laboratory of Cryospheric Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China
[b] CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing 100101, China
[c] Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China

HIGHLIGHTS

- We present morphology and chemical composition of cryoconite in the Tibetan Plateau.
- Mineral dust particles was dominant (>50%) in the cryoconite at all locations.
- More BC and fly ash particles were found in YL (38%) and ZD (22%).
- A large amount of biological, NaCl and MCS particles were observed.

ARTICLE INFO

Article history:
Received 12 January 2016
Received in revised form
9 May 2016
Accepted 9 May 2016
Available online 10 May 2016

Keywords:
Cryoconite
TEM-EDX
Light absorbing impurities
Tibetan Plateau

ABSTRACT

Cryoconite deposited on mountain glacier surfaces is significant for understanding regional atmospheric environments, which could influence the albedo and energy balance of the glacier basins, and maintain the glacial microbiology system. Field observations were conducted on the glaciers of western China, including Laohugou Glacier No.12 (LHG), Tanggula Dongkemadi Glacier (TGL), Zhadang Glacier (ZD), and Baishui Glacier No.1 in the Yulong Mountains (YL), as well as Urumqi Glacier No.1 in the Tianshan Mountains (TS) for comparison with locations in the Tibetan Plateau, in addition to laboratory TEM-EDX analysis of the individual cryoconite particles filtered on lacey carbon (LC) and calcium-coated carbon (Ca-C) TEM grids. This work provided information on the morphology and chemical composition, as well as a unique record of the particle's physical state, of cryoconite deposition on the Tibetan Plateau. The result showed that there is a large difference in the cryoconite particle composition between various locations on the Tibetan Plateau. In total, mineral dust particles were dominant (>50%) in the cryoconite at all locations. However, more anthropogenic particles (e.g., black carbon (BC) and fly ash) were found in YL (38%) and ZD (22%) in the Ca-C grids in the southern locations. In TGL, many NaCl and MCS particles (>10%), as well as few BC and biological particles (<5%), were found in cryoconite in addition to mineral dust. In TS, the cryoconite is composed primarily of mineral dust, as well as BC (<5%). Compared with other sites, the LHG cryoconite shows a more complex composition of atmospheric deposition with sufficient NaCl, BC, fly ash and biological particles (6% in LC grid). The higher ratio of anthropogenic particles in the southern Tibetan Plateau is likely caused by atmospheric pollutant transport from the south Asia to the Tibetan Plateau. Cryoconite in the northern locations (e.g., TGL, LHG, and TS) with higher dust and salt particle ratio are influenced by large deserts in central Asia. Therefore, the transport and deposition of cryoconite is of great significance for understanding regional atmospheric environment and circulation. Large amounts of biological, NaCl and MCS particles were observed in the cryoconite, implying that in addition to dust and BC, many types of light absorbing impurities (LAI) together could influence the glacier albedo change and induce ice melting in the mountain glaciers of the Tibetan Plateau. Moreover, a high BC concentration in the south (e.g., YL and ZD) could significantly change the albedo

* Corresponding author.
E-mail address: dongzhiwen@lzb.ac.cn (Z. Dong).

http://dx.doi.org/10.1016/j.atmosenv.2016.05.020

of snow and ice, at a greater rate than dust, causing significant melting of the glaciers under global warming.

1. Introduction

Cryoconite deposited on the mountain glacier surfaces is significant for understanding regional atmospheric environments, which could influence the albedo and energy balance of the glacier regions and maintain the glacial microbiology system. Research has indicated that cryoconite originates from the atmospheric deposition of various light absorbing impurities (LAI) in the snowpack and ice surfaces on high mountains (Stibal et al., 2012). With increased glacier ablation, the impurities melted and subsequently accumulated on the glacier surface (Wharton et al., 1985). Cryoconite has a dark color and generally consists of mineral dust, black carbon (BC) and biological particles (Takeuchi and Li, 2008; Grzesiak et al., 2015), which reduces the energy balance of the glaciers and accelerates glacier melting (Fujita, 2002; Oerlemans et al., 2009; Wientjes et al., 2011; Naegeli et al., 2015). Each component of LAI has different radiative forcing in the atmosphere and cryoconite (IPCC AR5). Therefore, studying the cryoconite deposition under recent dramatic glacier change when water resources might be impacted is important.

Previous studies have characterized the biological composition of cryoconite and its climate effects in the Arctic and Asian regions (e.g. Takeuchi et al., 2001, 2003; Margesin et al., 2002; Anesio et al., 2009; Singh et al., 2015; Grzesiak et al., 2015). In addition, some studies have provided the mineralogical and geochemical information for cryoconite in central Asia (Nagatsuka et al., 2014), and biological processes that occur on the surface cryoconite of glaciers and ice sheets can affect the physical behavior of glaciers by changing surface reflectivity (Stibal et al., 2012). Moreover, transmission electron microscope (TEM) is a good method to learn the particle morphology and physicochemical composition (Semeniuk et al., 2014). For example, study based on observation and TEM analysis has found that dust and biological aerosols from the Sahara and Asia may influence precipitation in the Western U.S. (Creamean et al., 2013). However, few studies have been conducted on the morphology, chemical composition and the particle's physical state of cryoconite deposition on the alpine glaciers in the Tibetan Plateau and central Asia.

The Tibetan Plateau is called as "The Third Pole" of the earth, with a large number of glaciers existing in the high mountains. However, limited study of cryoconite on the glaciers in the Tibetan Plateau has been conducted, due to its high altitude and remote location. As a result, information on the physiochemical composition and sources of cryoconite is still lacking; e.g., BC, dust, and biological particles deposited on the glacier surface over the different locations of the Tibetan Plateau, which could provide regional atmospheric environment information at a large scale, as well as its transport route with atmospheric circulation. Therefore, field observations were conducted on the glaciers of western China, including Laohugou Glacier No.12 (LHG), Tanggula Dongkemadi Glacier (TGL), Zhadang Glacier (ZD), and Baishui Glacier No.1 in the Yulong Mountains (YL), as well as Urumqi Glacier No.1 in the Tianshan Mountains (TS) for comparison with locations in the Tibetan Plateau, in addition to laboratory TEM-EDX analysis of the individual cryoconite particles filtered on lacey carbon (LC) and calcium-coated carbon (Ca-C) TEM grids. This work provided information on the morphology and chemical composition, as well as a unique record of the particle's physical state of cryoconite deposition on the Tibetan Plateau, to determine its source and transport route under the influence of regional atmospheric circulation.

2. Data and methods

From July to September in 2014, we collected cryoconite samples on the glaciers at five different locations in the Tibetan Plateau, including Laohugou Glacier No.12 (LHG), Tanggula Dongkemadi Glacier (TGL), Zhadang Glacier (ZD), and Baishui Glacier No.1 in the Yulong Mountains (YL), as well as Urumqi Glacier No.1 (43°05′N, 86°48′E) in the Tianshan Mountains (TS) for comparison with locations in the Tibetan Plateau (Fig. 1). Among these glaciers, the LHG Glacier No.12 (39°20′N, 96°34′E) and HLG Shiyi Glacier (33°13′N, 99°53′E) are located in the northeast Tibetan Plateau on the northern slope of the Qilian Mountains with typical continental climatic conditions (Dong et al., 2014). Dongkemadi Glacier (33°04′N, 92°04′E) is located in the Tanggula Mountains of the central Tibetan Plateau. While Zhadang Glacier (30°28′N, 90°38′E) is located on the western Nyainqentanglha in the southern Tibetan Plateau, and Baishui Glacier No.1 (27°18′N, 100°08′E) in the Yulong Mountains is located in the southeast Tibetan Plateau, with typical Monsoon climatic conditions (Fig. 1). Therefore, these locations could represent the large scale deposition of cryoconite on the glaciers in the Tibetan Plateau. The information on sampling location, time period and snow depth are shown in Table 1. Cryoconite samples were collected at different elevations along the glacier surface of the study. Pre-cleaned low-density polyethylene (LDPE) bottles (Thermo scientific) were used for the sample collection. All samples were kept frozen until they were transported to the lab for analysis.

Analyses of the individual cryoconite particles were conducted using a JEM-2100F (JEOL) transmission electron microscope (TEM) operated at 200 kV. The analyses involved conventional and high-resolution imaging using bright field mode, electron diffraction (Zinatloo-Ajabshir et al., 2015, 2016; Salavati-Niasari, 2005), and energy-dispersive X-ray spectrometry (EDX). A qualitative survey of grids was undertaken to assess the size and compositional range of particles and to select areas for more detailed quantitative work that were representative of the entire sample. This selection ensured that despite the small percentage of particles analyzed quantitatively, our results were consistent with the qualitative survey of the larger particle population on each grid. Quantitative information on size, shape, composition, speciation, mixing state, and physical state was collected for a limited set of stable particles. Volatile particles, including nitrate, nitrite, and ammonium sulfate, are not stable under the electron beam and could not be measured accurately in this study, although they can often be detected on EDX at low beam intensity. All stable particles with sizes 20 nm to 35 μm were analyzed within representative grid mesh squares located near the center of the grid. Grid squares with moderate particle loadings were selected for study to preclude the possibility of overlap or aggregation of particles on the grid after sampling. In general, 100 particles were analyzed per grid, yielding totals of ~300 particles per sample (from the three grid fractions). The use of LC and Ca-C grids resulted in clear and unprecedented physical and