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Increasing dust fluxes on the northeastern Tibetan Plateau linked with the Little Ice Age and recent human activity since the 1950s

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ABSTRACT

Arid and semi-arid areas in inner Asia contribute lots of mineral dust in the northern hemisphere, but dust flux evolution in the past is poorly constrained. Based on particle sizes and elemental compositions of a sediment core from Lake Qinghai on the northeastern Tibetan Plateau, dust fluxes during ~1518–2011 A.D. were reconstructed based on 18–100 μm fractions of the lake sediment. The dust fluxes during the past ~500 years ranged between 100 and 300 g/m^2/yr, averaging 202 g/m^2/yr, experiencing four stages: Stage 1 (~1518–1590s), the flux was averaged 165 g/m^2/yr, much lower than that in the Stage 2 (1590s–1730s, 254 g/m^2/yr); similarly, an average flux of 169 g/m^2/yr in the Stage 3 (1730s–1950s) was followed by an increased flux of 259 g/m^2/yr in the Stage 4 (1950s–2011). During the first three stages the fluxes were dominated by natural dust activities in arid inner Asia, having a positive relation with wind intensity but a poor correlation with effective moisture (or precipitation) and temperature. The high dust flux in Stage 2 was due to relatively strong wind during the maximum Little Ice Age, whereas the remarkably high flux in 1950s–2011 was resulted from recent increasing human activities in northwestern China. The dust record not only documents past dust fluxes on the northeastern Tibetan Plateau but also reflects evolutions and mechanisms of dust activity/emission in inner Asia during the past ~500 years.

1. Introduction

Arid and semi-arid areas in inner Asia, where deserts, gobi, and dried clods are widely distributed and dust activity occurs frequently, have been widely recognized as one of the most important dust sources in the world (Zhang et al., 1997; Xuan and Sokolik, 2002; Shao et al., 2011). According to the estimation by Shao et al. (2011), about six hundred million tons of dust are released into the atmosphere from this region every year, accounting for nearly one third of the world annual amount of aeolian dust. Along with the northern hemispheric Westerlies in the upper troposphere, the emitted dust can be transported eastwardly to the East Asia (Mikami et al., 2006), the North Pacific (Duce et al., 1980; Blank et al., 1985; Kurtz et al., 2001), the North America (Zdanowicz et al., 2006), the Greenland (Bory et al., 2003), the French Alps (Grousset et al., 2003), and even for one full circuit around the globe (Uno et al., 2009). On the one hand, dust aerosols in the atmosphere can affect the climate through changing the earth's radiation budget (e.g. Andreae, 1996; Ramanathan et al., 2001; Mikami et al., 2006), influence precipitation distributions (e.g. Ramanathan et al., 2001), and damage air quality (e.g. Liu et al., 2009b; Mikami et al., 2006). On the other hand, after deposited into oceans, lakes or land surfaces, the mineral dust can influence biogeochemical cycles in various ecosystems, such as increasing marine primary productivity through Fe-fertilization and hence having feedbacks on the climate (e.g. Jickells et al., 2005; McTainsh and Strong, 2007; Maher et al., 2010; Mahowald, 2011; Shao et al., 2011), improving soil quality by inputting nutrients and trace elements (e.g. Kurtz et al., 2001; Reynolds et al., 2001; Mladenov et al., 2012), and so on. Therefore, understanding evolutions and changing mechanisms of the Asian dust is important for investigating biogeochemical cycles and environmental and climatic changes in the Asian-Pacific region and even in the entire northern hemisphere.

In previous studies, evolutions of the Asian dust at long timescales have been reconstructed by various geological records, such as by lake sediments in the inner Asia (e.g. Xue and Zhong, 2008;

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Mischke et al., 2010; An et al., 2011, 2012; Lu et al., 2012; Chen et al., 2013; Qiang et al., 2014; Liu et al., 2016), by ice-core sequences from the Tibetan Plateau (Wang et al., 2006; Yang et al., 2006), by loess deposits from the Loess Plateau (An and Xiao, 1990; Sun and An, 2005), by deep-sea sediment sequences from the North Pacific (e.g. Hovan et al., 1989; Rea et al., 1998; Pettke et al., 2000; Irino and Tada, 2003; Wan et al., 2012b), etc. Although these works have provided valuable understanding on evolutions of the Asian dust at centurial to orbital timescales, they revealed only relative intensity of past dust activity in inner Asia (e.g. Wang et al., 2006; Yang et al., 2006; Chen et al., 2013; Liu et al., 2016). To date, little is known about variations of dust flux in the past in this area.

On the other hand, owing to substantial expansion of agriculture and grazing livestock since the Industrial Revolution, it is reported that the dust flux has increased several folds during the last one or two centuries in many dust source areas and/or at their downwind areas over the globe (Mahowald et al., 2010), such as in the western America (Neff et al., 2008), in the northwestern Africa (Mulitza et al., 2010). In northwestern China human activities of agriculture and grazing livestock also have increased dramatically during the past several decades (Ta et al., 2006), but until now there is few study to reveal how the dust changed under such influence in this area. Therefore, it is necessary to find high-resolution geological records to quantitatively reconstruct past dust flux and to understand its variation mechanisms in the recent centuries, especially its changes under the influence of recent human activities in inner Asia.

Lake Qinghai is located on the northeastern Tibetan Plateau (LBCAS, 1994; An et al., 2012). In this area the westerly wind prevails during winter and spring. Owing to its location at the directly leeward area of dust sources (such as the Qaidam basin, the Taklimakan Deserts) in inner Asia (Fig. 1a), the lake receives substantial dust from these dust source areas every year (Jin et al., 2009; An et al., 2012; Wan et al., 2012a). According to dust observations by Wan et al. (2012a), the modern dust flux is averaged 266 ± 55 g/m^2/yr in the lake area, which contributes 56.6 ± 11.7% of the modern Lake Qinghai sediment. Therefore, the Lake Qinghai sediment sequences may faithfully document evolutions of the Asian dust in the past.

In this study a short sediment core was drilled in the central area of Lake Qinghai, dust proxy was defined in the sediment core, and high-resolution dust flux history was reconstructed during the past ~500 years. Then, variations of dust flux were related with climatic and anthropogenic factors in the past, which is significant for understanding the coupling relationship of the Asian dust, climate change, and human activity at the decadal/centurial timescale in inner Asia.

2. Site description

Lake Qinghai (36°32′–37°15′N, 99°36′–100°47′E), situated on the northeastern Tibetan Plateau, is the largest, hydrologically-closed drainage system on the plateau. It lies at the transitional area from the arid to the semi-arid zones and is sensitive to climate changes. The climate in this area is dominated by the Westerlies during winter and spring and the Asian and Indian monsoons during summer (LBCAS, 1994; Colman et al., 2007; An et al., 2012). Due to its unique geographical and geological settings, Lake Qinghai has attracted increasing attentions on understanding regional climatic and environmental changes, focusing on the evolution of the Asian monsoons and the Westerlies and their interplay in the past, using its high-resolution sediment sequences (Shen et al., 2001, 2005; Colman et al., 2007; Henderson and Holmes, 2009; An et al., 2012; Jin et al., 2015).

The Lake Qinghai catchment is characterized by a continental climate. Annual temperature in the lake area averaged 1.2 °C and exhibited remarkable seasonality, varying from about −11 °C in winter to about 12 °C in summer (Colman et al., 2007). Annual precipitation in Gangcha (GC) (Fig. 1b) varied from 270 mm to 510 mm between 1961 and 2008, with an annual average of 382 mm (Liu et al., 2009a). Whereas the annual potential evaporative capacity is as high as 800–1000 mm in the lake area (Li et al., 2007), about 2–3 times higher than the precipitation. Under the influence of the Westerlies, the annual strong wind days (⩾17 m/s) are averaged 47 days/yr, mainly in spring. Due to its location at the downwind area of several important dust sources in inner Asia (Fig. 1a), strong winds often lead to heavy dust events in dry seasons. According to the modern meteorological data from 1990 to 2003 A.D., the annual dust storm days were as many as 8–32 days/yr, averaging 18 days/yr (Wang et al., 2004; Jin et al., 2009; Wan et al., 2012a).

3. Materials and methods

3.1. Sample collection

In October 2011, a 49.0-cm-long sediment core (QHS11-02, 36°40′47.5″N, 100°07′19.5″E) was drilled in the central area (the water depth of 24.7 m) of Lake Qinghai using an UWITEC gravity corer (Fig. 1b). The uppermost 3 cm of sediment is yellow–grey clay, and the underlying 4–5 cm is grey–black clay, while sediment below 7 cm is black clay. The sediment core was sectioned sequentially in the field at 0.5 cm intervals.

Representative fluvial suspended particulate matter (SPM) samples were collected from the Buha River, which is the largest river in the catchment and provides about half of river water amount and more than 70% SPM to the lake (Colman et al., 2007; Li et al., 2007), at the Buha River hydrological station (BH) (Fig. 1b). For the SPM sampling, 2–4 L of river water was filtered through 0.45 μm filters using a pressure-adjustable time-accumulating, bottled or horizontal suspended load sampler and dried in an oven at 100–105 °C.

Dust deposition was collected every month for two years (from June 2009 to May 2011) at two sites (BH and GC) surrounding Lake Qinghai (Fig. 1b). Details of dust sampling method can be found in our previous study of Wan et al. (2012a).

3.2. Analysis

Due to dust deposition mainly (~50%) occurring during the springs (Fig. 2) and insufficient amount of dust samples collected in other seasons surrounding Lake Qinghai, only typical dust samples collected in spring were used for particle-size analysis.

Particle sizes of the samples were determined using a Malvern 2000 laser-diffraction analyzer at the Institute of Earth Environment, Chinese Academy of Sciences (IEECAS). Prior to particle size measurements, all samples were pretreated with 10% H_2O_2 and 30% HCl to remove organic matter and carbonates respectively, and then dispersed by ultrasonification with 10 ml 10% $(NaPO_3)_6$ solution. The particle-size measurement range of the analyzer is from 0.02 to 2000 μm, and replicate analyses indicate that the mean particle size has an analytical error of <2% (Sun et al., 2003; Wan et al., 2013).

Carbonate contents of the samples were measured using a carbon analyzer (CM150) at the IEECAS. The repetitive errors were less than 3%. Method of elemental analysis for all samples can be found in our previous studies of Wan et al. (2012a) and Jin et al. (2010).