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Tracing the Provenance of Long-Range Transported Dust Deposition in Cryospheric Basins of the Northeast Tibetan Plateau: REEs and Trace Element Evidences

Ting Wei [1,2], Zhiwen Dong [1,3,*], Shichang Kang [1,4,*] and Sven Ulbrich [3]

1 State Key Laboratory of Cryosphere Sciences, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China; weiting@lzb.ac.cn
2 University of Chinese Academy of Sciences, Beijing 100049, China
3 Institute for Geophysics and Meteorology, University of Cologne, D-50923 Cologne, Germany; sulbrich@meteo.uni-koeln.de
4 CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing 100101, China
* Correspondence: dongzhiwen@lzb.ac.cn (Z.D.); shichang.kang@lzb.ac.cn (S.K.)

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Abstract: Based on cryoconite and snow dust samples collected from various glaciers and snowpacks in northeast Tibetan Plateau (NETP) margin and surrounding areas, this study investigated the rare earth element (REE) and trace element composition of long-range transported (LRT) dust in glacier surfaces at the NETP locations, in order to trace its source areas and the transport over the region. Results showed that the deposited dust in NETP mainly originated from the adjacent Qaidam Basin, Badain Jaran and Taklimakan Deserts based on the similarity in $(La/Sm)_N$, Th/Yb_N and Nb/Yb_N ratios. However, most samples collected at Miaoergou Glacier (MG) located in the Tianshan Mountains showed very different rare earth elements (REEs) ratios from the above locations attributed to the dominant contribution of LRT dust emitted by the southern Gobi Deserts. We found that large central Asian deserts rarely contributed LRT dust to Yuzhufeng (YG) in the hinterland Tibetan Plateau (TP). Taking the region as a whole, it was found that most of the glacier and snowpacks showed mixed dust sources and inputs from different parts of surrounding central Asian deserts that are characterized by different mineralogical settings. Geochemical data indicated that the NETP region acts as an important channel for aeolian transport from large Asian deserts into Loess Plateau and eastern regions, with atmospheric circulations bringing plenty of dust particles deposition to the high-altitude glacier surface in NETP margin. This work is of great importance in providing a new complete view of LRT aeolian emission and transport over the NETP region.

Keywords: northeast Tibetan plateau margin; long-range transported aeolian dust; glacier snowpack; asian dust transport channel; REE and trace element geochemistry

1. Introduction

The northeast Tibetan Plateau (NETP) and south Gobi Deserts in Mongolia, known as the active dust areas, are the primary contributors to the adjacent sand deserts and the Loess Plateau [1,2]. Previous studies showed that the aeolian deposited in the Badain Jaran Desert and Loess Plateau are predominantly derived from the Qilian Mountains and NETP margin initially via fluvial processes and wind erosion and/or deflation by westerly winds [2–5]. Meanwhile, the south Gobi, one of the major Asian dust emission sources, was identified as the dominant dust source for Loess Plateau and Ordos Plateau [6,7]. Geochemical composition of dust materials deposited in high mountain glaciers

can be used to improve understanding in transport routes and atmospheric cycle of aeolian dust in modern and ancient times [4]. Previous studies have revealed dust transport from the NETP and south Gobi Deserts into Loess Plateau during the historical processes [4,5,8,9]. However, the current regional aeolian cycle and transport routes of long-range transported (LRT) dust in high elevation from the surrounding Asian deserts to the NETP region remains unclear. Very limited research focused on understanding LRT dust in high latitudes from the Asian deserts to the NETP region owing to its remote and the lack of large range field investigation, which is of great importance as the high elevation transport of LRT dust could provide clear atmospheric environment and dust routes information on a large scale.

Due to glaciers existing on high mountain regions, glacier snowpack in the NETP can thus receive aeolian transported in the middle and upper troposphere through atmospheric circulation [9–12]. Thus, mountain glaciers in NETP region could represent a valuable area to trace the aeolian transport route from the central Asian deserts and also Tibetan Plateau (TP) surface crust [13–17]. Moreover, rare earth element (REE) and trace elements are demonstrated to be powerful tools for tracing the dust origin based on their obvious differences in regional distribution of desert sands [18]. Due to their low solubility of particulate forms, REEs are generally in the particulate phase during atmospheric transport [19]. These properties make REE fractionation with very little change during weathering and diagenesis.

In this study, large range fieldwork sampling were launched at the various glacier locations in the NETP region, including the Lenglongling Glacier (LG), Qiyi Glacier (QG), Dabanshan Snowpack (DS), Jingyangling Snowpack (JS) and Ober Ridge Snowpack (OS) in the Qilian Mountains, and Yuzhufeng Glacier (YG) in the Kunlun Mountains, and also the Miaoergou glacier (MG) in adjacent eastern Tianshan Mountains, which together are called as a pan-NETP region (Figure 1). The objective of this study is to investigate the REE and trace element compositions on cryoconite and snow dust deposited on the glaciers and further to trace the provenance of LRT Asian dust disposition on the NETP glaciers, providing a better understanding on dust transport process over the region. Moderate Resolution Imaging Spectroradiometer Aerosol Optical Depth (MODIS AOD) (http://giovanni.sci.gsfc.nasa.gov) [20] and wind vector data in the region were also used to demonstrate the potential dust transport source and routes.

2. Materials and Methods

2.1. Sampling

A total of 36 cryoconite and snow dust samples were collected at different elevations along the high mountain glaciers and snowpacks in June and August 2017. Among those glaciers and snowpacks, DS, LG, QG, JS, and OS are located in the Qilian Mountains. YG is located in the Kunlun Mountains (inner TP) and is adjacent to the Qaidam Desert. MG is located in the eastern Tianshan Mountains and is close to the south Gobi Deserts in Mongolia, one of the largest dust emission sources in the world (Figure 1). We also collected samples in MG for comparison with dust samples from the NETP region. In addition, 7 local surface crust samples were collected at nearby regions including Golmud, Hami, and the glacier basins to find out local dust contribution to those glaciers and snowpacks. The detailed information of sampling locations was listed in Table 1.

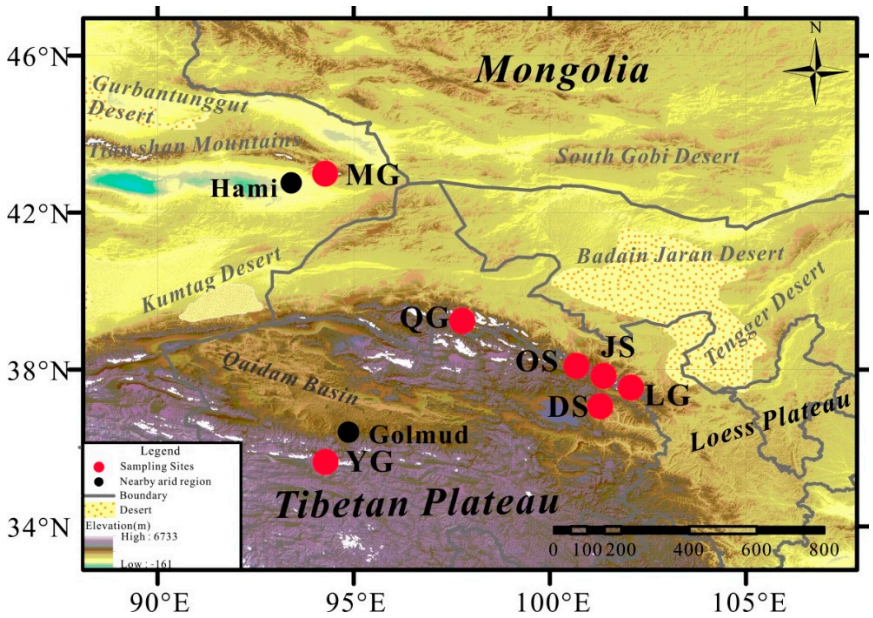

Figure 1. Location map showing the location of study area and sampling sites. MG, QG, YG, OS, JS, DS, and LG refer to Miaoergou Glacier, Qiyi Glacier, Yuzhufeng Glacier, Ober Ridge Snowpack, Jingyangling Snowpack, Dabanshan Snowpack and Lenglongling Glacier, respectively.

Table 1. Description for cryoconite and surface snow dust sampled from the glacier and snowpacks in the NETP and eastern Tianshan Mountains.

Location	Mountains	Latitude (N)	Longitude (E)	Altitude m a.s.l	Sample Number	Type
Dabanshan Snowpack (DS)	Qilian Mountains	37°21′	101°24	2556–3625	4 1	Snow dust Surface crust
Lenglongling Glacier (LG)	Qilian Mountains	37°30′	101°53′	3232–3992	8 1	Snow dust Cryoconite Surface crust
Qiyi Glacier (QG)	Qilian Mountains	39°14′	97°45′	3883–4750	9 1	Snow dust Cryoconite Surface crust
Miaoergou Glacier (MG)	Tianshan Mountains	42°59′	94°16′	3100–3320	5	Snow dust Cryoconite
Yuzhufeng Glacier (YG)	Kunlun Mountains	35°41′	94°16′	4342–4720	8	Snow dust Cryoconite
Ober Ridge (OS)	Qilian Mountains	37°59′	100°55′	3685	1 1	Snow dust Surface crust
Jingyangling Snowpack (JS)	Qilian Mountains	37°48′	101°09′	3469	2	Snow dust
Golmud	Kunlun Mountains	36°19	95°13′	2963	1	Surface crust
Hami	Tianshan Mountains	42°78′	93°44′	2692	1	Surface crust

Before sampling, all containers and collecting tools were cleaned following the successive nitric acid immersion with four different concentrations [21]. Then, we wore clean polypropylene suits and gloves during sampling to avoid contamination and ensure the accuracy of the laboratory measurement, and used the precleaned stainless-steel shovels to collect the snow and cryoconite samples. After that, all samples were stored in clean 30 mL polyethylene bottles and acidified with ultra-pure nitric acid (0.5% v/v) to dissolve the trace elements together with atmospheric particles and to prevent the elements adhering onto the walls of the bottles. Ultimately, the collected samples were kept frozen until the analysis at the Analytical Laboratory of Beijing Research Institute of Uranium Geology. During the experimental analysis process, protective clothing and footwear had to be used.

2.2. Rees and Trace Elements Analyzed

REEs are a group of 14 elements including La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu. The selected trace elements in this study included Nb, Zr, Th, Y, Sc. Aiming to break down the silicates and other salts, all samples were digested with ultra-pure HNO_3–HF in poly tetra fluoroethylene (PTFE) screw–top bombs at 100 °C for 24 h on a hotplate until no residue was detected. Then the totally dissolved samples were transferred to clean capped PTFE bottles using a Finnpipette to mark the volume, and were diluted with 5% HNO_3 (3 mL) for inductively coupled plasma-mass spectrometry (ICP–MS, Thermo Scientific Element/XR, Waltham, USA) analysis.

2.3. Tem-Edx Measurement

Analyses of the snowpack/cryoconite individual particles were conducted using a JEM–2100F (JEOL, Tokyo, Japan) transmission electron microscope (TEM) operated at 200 kV. The analyses involved conventional and high-resolution imaging using bright field mode, electron diffraction, and energy-dispersive X–ray spectrometry (EDX) [22,23]. Laboratory TEM–EDX analysis was performed on the individual cryoconite particles filtered on calcium-coated carbon (Ca–C) TEM grids. The TEM instrument had the advantages of high-resolution (up to 20 nm), and the "transmission" feature for individual particle analysis, when combined with EDX analysis for the particle elemental composition (Figure 2).

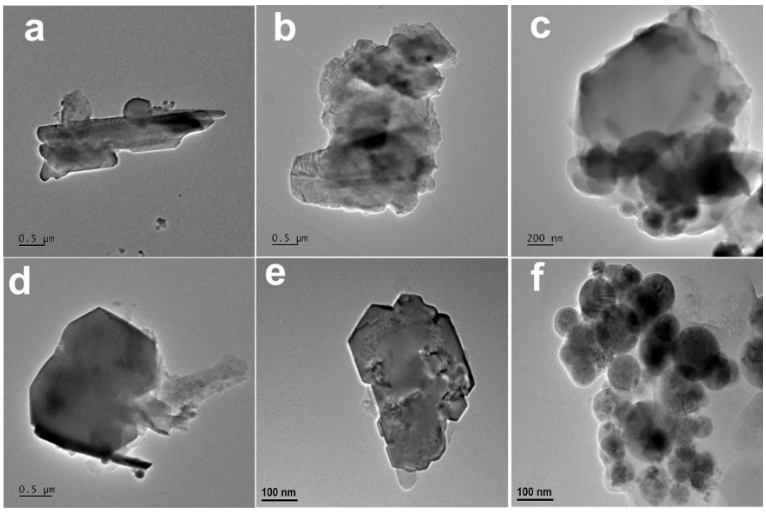

Figure 2. TEM–EDX measurement of individual particles in the glacier snowpack and cryoconite dust in northeast TP, (**a**) aggregated clay mineral and black carbon (BC) particles in LG, (**b**) $CaSO_4$ mineral aggregated particles in DS, (**c**) Mixed organic matter and aluminosilicate particles in QG; (**d**) Silicate and fly ash aggraded particles in MG; (**e**) Aluminate mineral particles in YG; (**f**) Soot and Fe-rich mineral aggregates in YG. The mixture of mineral and organic and BC also showed LRT source of glacier surface dust.

2.4. Quality Control of Chemical Analysis

The blank samples from both the laboratory and field work were also measured using the same procedure. Result of the blank analyses showed that there was negligible contamination (<5%), during the sampling, storage, and transportation. Elemental concentrations were quantified using external calibration standards. For analytical precision, the corresponding RSD(relative standard deviation) values of all element concentrations measured in the reference material were found to be less than 5%.

2.5. Data Analysis and Geochemical Parameters

The REE and trace element compositions in those locations of the NETP glacier and snowpack were measured. REE abundance in chondrites, the most primitive substance from solar system, was used to eliminate the odd-even effect and standardize the element compositions [24]. In detail, $(La/Yb)_N$ ratio can reflect the different degree between Light Rare Earth Element (LREE) and Heavy Rare Earth Element (HREE). The $(La/Sm)_N$ ratio can represent the difference of LREE, with a positive correlation between the ratio and the differential degree. Moreover, $(Gd/Yb)_N$ may indicate the differential degree of the HREE and it is negatively correlated with the differential degree. Also, Eu/Eu* = $(Eu_N/(Sm_N * Gd_N)^{1/2})$, could indicate not only the sedimentary environment but also the parent rock characteristics of dust materials. La-Th-Sc composition is generally used to discriminate the sediment sources [25,26]. Th/Yb_N and Nb/Yb_N ratios are useful tools for the discrimination of tectonic settings [27–29]. Y/Zr and Nb/Zr ratios represent differential degree in different minerals due to different mineral-liquid distribution coefficients [27].

3. Results and Discussion

3.1. Geochemical Compositions of Aeolian Materials in Different Locations Of the NETP Glaciers and Snowpacks

Several REE characteristic-parameters are used here to find out the provenance of dust deposition onto the glaciers and snowpacks. In general, all samples from MG are uniformly described as lower $(La/Sm)_N$ (averaging 2.65), lower Th/Yb_N and Nb/Yb_N (averaging 0.26 and 0.39, respectively), and a weak negative even positive Eu anomaly (averaging 0.98), suggesting a large discrepancy from other study locations in NETP region (Figure 3). The elemental ratios exhibit similar REE characteristics in the NETP locations (QG, OS, DS, JS, LG), implying an identical dust source in this region. However, the ratios of several samples from YG display lower $(La/Sm)_N$, higher Eu/Eu*, but similar Nb/Yb_N to the NETP locations, indicating the mixture LRT dust sources in the region. Moreover, DS shows lower Y/Zr and higher $(La/Sm)_N$ compared to the other NETP locations, showing the obvious difference existed between those NETP locations, which is probably caused by mixed source and routes of LRT dust under the regional atmospheric circulations of fine dust particles originated from different areas with different geochemical settings.

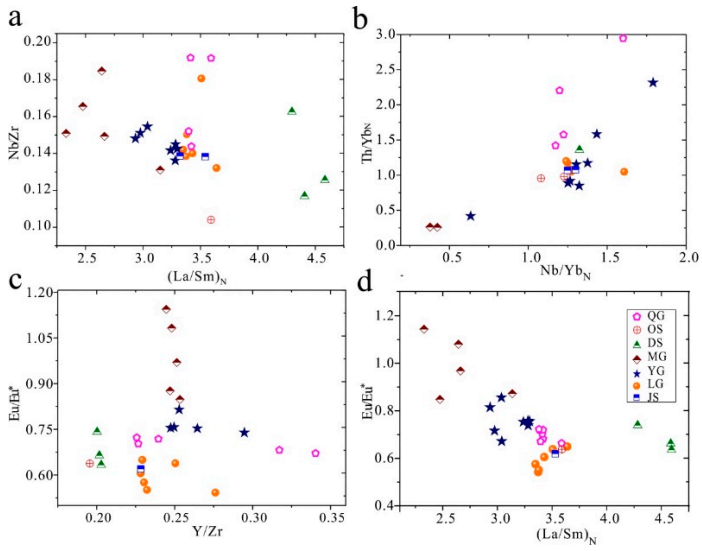

Figure 3. Bivariate plots and spatial distributions of geochemical compositions of snow dust and cryoconite samples from the glaciers and snowpacks in the Tianshan Mountains and northeast Tibetan Plateau. (**a**) $(La/Sm)_N$ versus Nb/Zr; (**b**) Nb/Yb_N versus Th/Yb_N; (**c**) Y/Zr versus Eu/Eu*; (**d**) $(La/Sm)_N$ versus Eu/Eu*.

In total, there is large spatial difference existed in trace elements and REE composition among MG, YG, and the other Qilian Mountains sites (QG, LG, DS, JS, OS). The climatic conditions (atmospheric circulation, prevailing wind, etc.) and surrounding deserts environment are the main reasons for the large difference of dust provenance among these locations. In specific, the climatic conditions of MG situated in the eastern Tianshan Mountains, is with westerlies prevailing around all the year. YG is different from MG with more precipitation (maximum precipitation in summer) and is controlled by westerlies and also the summer/winter monsoon over the plateau surface. Another factor is the topography of the area. MG is surrounded by the Gobi Deserts in central Asia, and to the south lies the Taklimakan Desert, which contributes with a large dust flux to the northern Hemisphere [30], and the LRT dust may have even been transported to the Loess Plateau through the eastern Tianshan and the NETP region. Southern and Northern Gobi Deserts in Mongolia and in also north China are both adjacent to the glaciers in the Tianshan Mountains, which will certainly influence the central Asia dust transport route to the MG basin. The YG, located in the downwind of the Qaidam Basin and the Kumtag Desert, is also likely to be affected by the arid deserts of the TP surface crust because of the expanded desert on the northern plateau during recent years [15].

The glaciers in the Qilian Mountains (e.g., QG, LG, DS, OS, and JS) are geographically close to the Badain Jaran and Tengger Deserts, which also have plenty of dust emission and then transport to the Loess Plateau and more eastern regions [3]. Regional climate background and dust source distribution may have together caused the complicated dust transport routes in the pan-NETP region. Therefore, various arid deserts source to the glaciers lead to the different geochemical element compositions of LRT dust deposited on the glaciers and snowpacks.

3.2. LRT Dust in NETP Region and Its Relationship with Large Scale Regional Atmospheric Circulation

The Bivariate diagrams of $(La/Sm)_N$, $(La/Yb)_N$, Eu/Eu* and $(Gd/Yb)_N$ ratios of samples from the glaciers and snowpacks for comparing of the sampling locations with potential dust sources are shown in Figure 4. The different locations of the Qilian Mountains (QG, LG, DS, and OS) show very similar dust geochemistry with the large deserts, such as Qaidam Basin, Badain Jaran and Taklimakan deserts. Moreover, many samples of the above locations show the similar REE and trace element geochemistry to the NETP surface crust (Figure 4), which is largely different from the western TP (such as higher $(La/Sm)_N$ and $(La/Yb)_N$). It is probable that the Badain Jaran and Tengger Deserts are the major sources for dust inputs of LG, QG, JS, and OS, as the similarity of $(La/Sm)_N$, $(La/Yb)_N$, Eu/Eu* and $(Gd/Yb)_N$ ratios between them, which is also demonstrated by La-Th-Sc and TiO_2–Zr–Al_2O_3 diagram (see Figure 5). Besides, REE data of NETP glacier is mainly close to that of the east of the TP surface crust dust. Therefore, the Qaidam Basin, Badain Jaran and Taklimakan deserts and NETP surface crust dust are the possible LRT dust source over the Qilian Mountains in addition to the local dust source in the glacier basin.

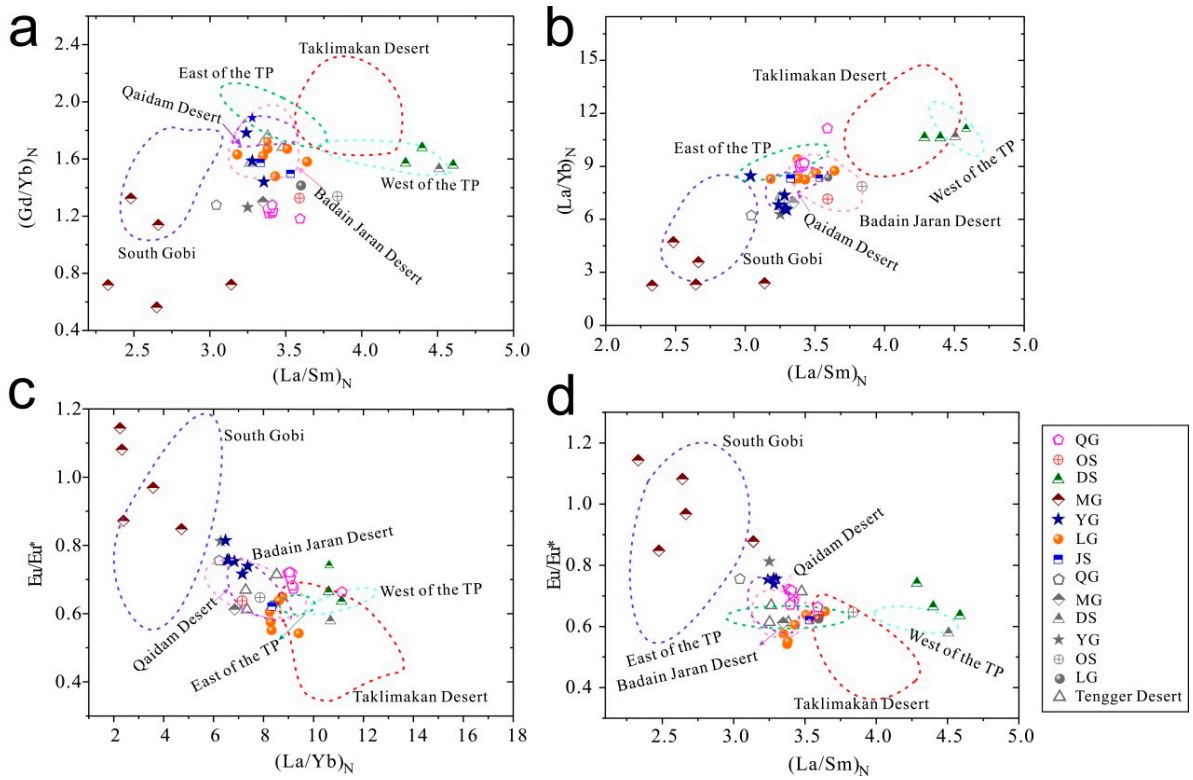

Figure 4. Bivariate diagrams of $(La/Sm)_N$, $(La/Yb)_N$, Eu/Eu* and $(Gd/Yb)_N$ ratios of samples from the glaciers and snowpacks, and the comparison with that of central Asian deserts sands, including South Gobi from References [31,32]; Taklimakan Desert finer fraction from [33,34]; Badain Jaran Desert finer fraction from [3,34]; Qaidam Basin and Tengger Desert from [34]; Eastern and western TP from [34,35]. Color icons and gray icons refer to snow dust/cryoconite samples and local dust samples, respectively.(**a**) $(La/Sm_{)N}$ versus $(Gd/Yb)_N$; (**b**) $(La/Sm)_N$ versus $(La/Yb)_N$; (**c**) $(La/Yb)_N$ versus Eu/Eu*; (**d**) $(La/Sm)_N$ versus Eu/Eu*.

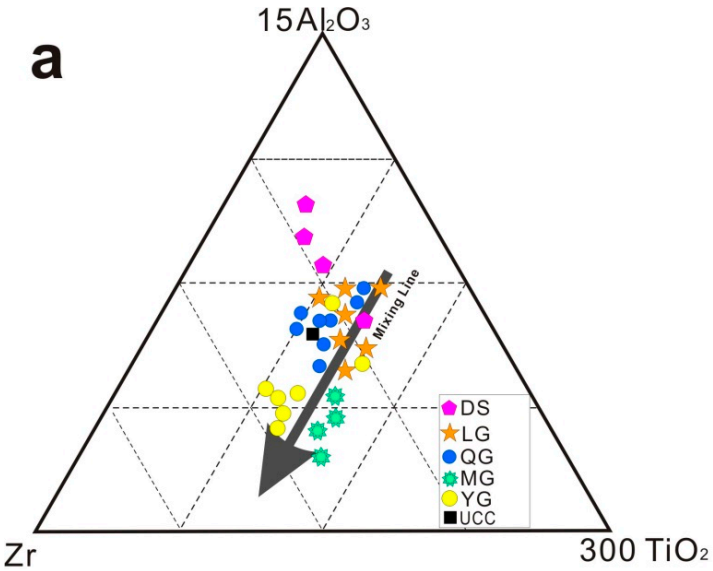

Figure 5. *Cont.*

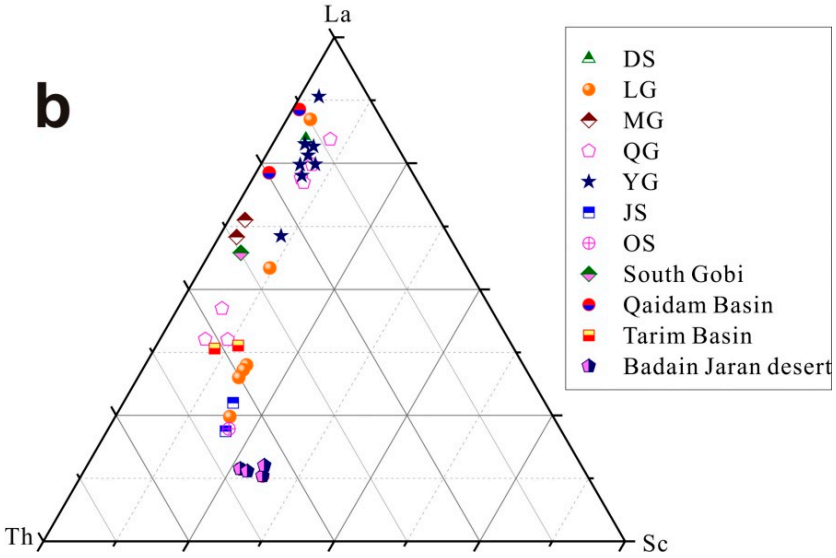

Figure 5. TiO_2–Zr–Al_2O_3 and La–Th–Sc diagrams ternary of cryoconite and snow dust collected in the various glaciers and snowpacks. Literature data of intrusive rocks from potential dust source areas in the Tarim Basin [36], the South Gobi [32], the Qaidam Basin [37] and the Badain Jaran desert [38] are also included for comparison. (**a**) TiO_2–Zr–Al_2O_3 of cryoconite and snow dust compositions; (**b**) La–Th–Sc of cryoconite and snow dust compositions by comparison with those of potential dust sources.

Compared with the Qilian Mountain locations (e.g., QG, LG, DS, and OS), samples from YG in the Kunlun mountains have lower $(La/Yb)_N$ ratio and higher Eu/Eu* (Figure 4b–d) but similar $(Gd/Yb)_N$ values. This suggests mixed sources for LRT dust deposited onto the NETP glaciers from the Qaidam and Badain Jaran Deserts, together with mineral particles from the Taklimakan Deserts. Furthermore, the distinct similarity is shown in the ternary diagrams of La-Th-Sc and TiO_2–Zr–Al_2O_3 (Figure 5), indicating a like composition between Qaidam Basin and YG. Moreover, the surface crust (e.g., Golmud crust dust) is also another source for dust input into YG snowpack, due to their similar geochemical compositions (Figure 4).

Compared to the above study sites, MG cryoconite in the eastern Tianshan Mountains indicates relatively lower $(La/Sm)_N$, $(Gd/Yb)_N$ and $(La/Yb)_N$ ratios, but shows less negative and even positive Eu anomaly (Figure 4), suggesting very different LRT dust sources for the MG basin. Moreover, the MG geochemistry data is very close to southern Gobi Deserts, as showing similar $(La/Sm)_N$, $(La/Yb)_N$, Eu/Eu* and $(Gd/Yb)_N$ ratios. This might indicate that the southern Gobi Deserts could represent an important potential source for regional LRT dust emission from north to NETP. Moreover, the REE ratios derived from MG local crust show higher $(La/Sm)_N$, $(La/Yb)_N$ and $(Gd/Yb)_N$, and lower Eu/Eu*, implying its small contribution to the glacier basin. From these results, we can find that mineral dust deposition on the investigated glaciers is dominated by LRT aeolian dust from central Asian deserts, besides small contribution from local dust in the glacier basin. Also, as shown in Figure 2, the LRT dust probably originated from different arid desert areas combined with various pollutant particles, such as black carbon (BC) and organic carbon (OC), in the glaciers and snowpacks.

The southern Gobi Desert is confirmed to be the dominant arid area exchanging crustal materials with the surrounding areas. It has been recognized that the southern Gobi (including the Gobi Deserts in western China) is a major dust emission source due to rare precipitation (<50 mm yr^{-1}) [39], low vegetation cover (10% even zero)], extremely dry climate conditions, as well as stronger surface wind speed in springtime (24–30 m/s). Dust emission from the Gobi Deserts are lifted up to more than >3 kilometers by cold front passage from northwest direction, and then are entrained toward southeast direction over the eastern Tianshan Mountains [39]. Therefore, not only is south Gobi identified as one of the major sources for the Chinese Loess Plateau [4,6], but is also a major contributor for materials transport to the NETP glaciers, suggesting the possible LRT dust transport route from the southern

Gobi Desert in a large range scale, which could also be demonstrated by analyzing aerosol particles properties and meteorological data (Figures 6 and 7).

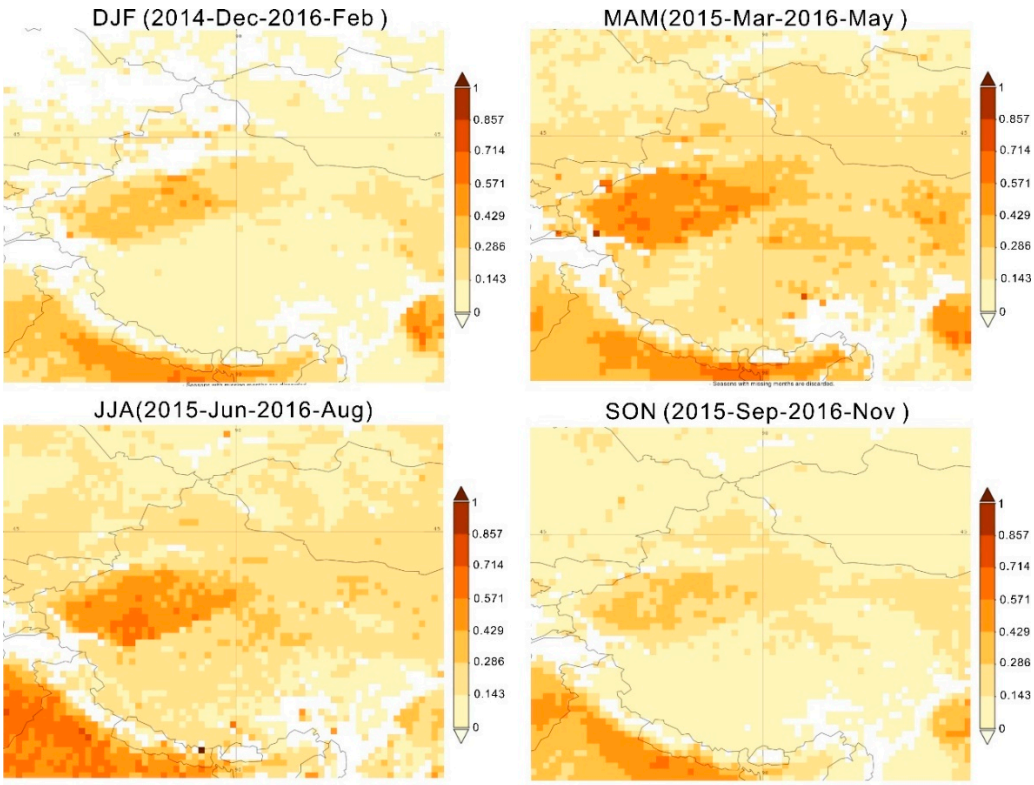

Figure 6. MODIS Aerosol Optical Depth at 0.55 microns for land Mean of daily Mean monthly (http://giovanni.sci.gsfc.nasa.gov) during each season in 2015–2017 in the Tibetan Plateau and surrounding areas.

Figure 6 shows the MODIS Aerosol Optical Depth (AOD) in the TP and its surrounding areas, reflecting the potential dust sources in the NETP and the adjacent arid regions. AOD in the Taklimakan Desert and Gobi-deserts in the northern China are much larger than the TP and Qaidam Basin during each season from 2014–2016, indicating more strong dust storms in the both arid regions. Thus, dust from the Taklimakan and Badain Jaran deserts might be transported to the high mountain glaciers (e.g., LG, OS, QG, JS, and DS) through atmospheric circulation. Because of the low AOD found in Qaidam Basin and the obstruction of the Qilian Mountains, it is very likely that the basin has a major contribution to glaciers (YG) in the hinterland TP, whereas very less contribution to the glaciers in NETP. Moreover, the large AOD in south Mongolian Gobi probably means large amounts of LRT dust transported to its downwind glacier areas, such as MG, by the East Asian Winter Monsoon.

Figure 7 indicates the wind vector data of near surface wind (850 mb) in study areas during each season (winter (December–January–February), spring (March–April–May), summer (Jun–July–August), and autumn (September–October–November)), indicating the potential LRT dust source and the transport routes in NETP margin and central Asia. Besides, the surface crust from the TP is ascertained as another dust source attributed to active aeolian process and desertification of the TP surface [14,15]. Moreover, the inner regions of the TP show very limited dust materials exchange with other arid deserts, such as the Gobi, Badain Jaran, and Tengger Deserts around the NETP.

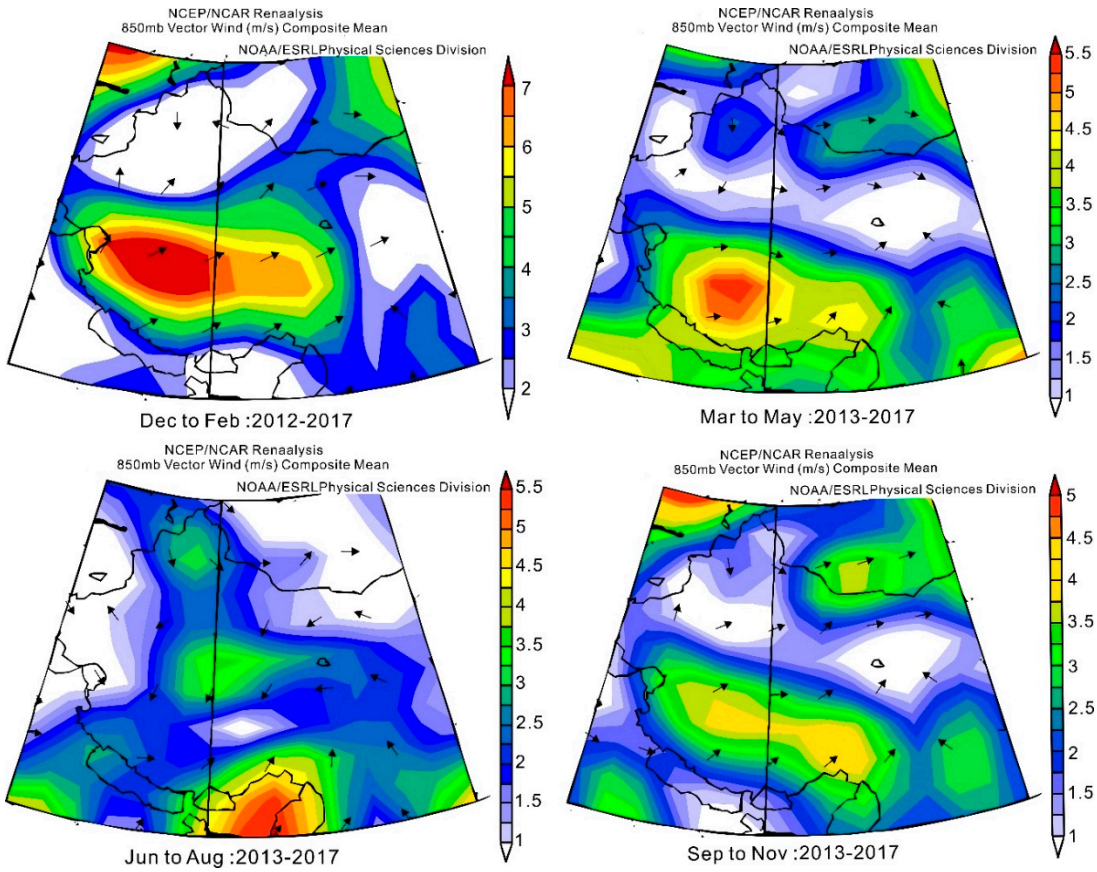

Figure 7. The mean wind vector data of 850mb wind in the study area during each season from 2012 to 2017, based on NCEP/NCAR (National Centers for Environmental Prediction/ National Center for Atmospheric Research) reanalysis data (https://www.esrl.noaa.gov/), reflecting the potential dust transport routes in northeast Tibetan Plateau and central Asia.

Taking the region as a whole, the mineral dust source deposited in the high mountain glaciers and snowpack is very complicated, as most of the glacier snowpack show mixed LRT dust sources input from its surrounding deserts. Demonstrated from meteorological data of AOD and wind vector data in the region, our results show that the NETP region acts as an important Channel for aeolian dust transport from central Asian deserts (e.g., the Qaidam, Taklimakan, and Gobi Deserts) into the Loess Plateau and surrounding areas, bringing plenty of dust particles deposition to the high-altitude glacier surface in northeast margin of the TP.

4. Conclusions

This study investigates REE and trace elements compositions of cryoconite and snow dust collected from the various glaciers in the northeast Tibetan Plateau and eastern Tianshan Mountains to determine LRT dust sources and regional atmospheric circulation in the NETP. Most samples from glaciers (LG, OS, QG, JS and DS) in the NETP margin display the similar $(La/Sm)_N$, Th/Yb_N and Nb/Yb_N ratios, while largely differe from those of MG and YG. Based on the similarity in geochemical ($(La/Sm)_N$, Th/Yb_N, Nb/Yb_N and La-Th-Sc) and mineralogical composition, we find that the major dust sources to NETP margin were mainly derived from Qaidam Basin, Badain Jaran and Taklimakan Deserts. However, most samples from the Miaoergou Glacier show the high similarity in $(La/Sm)_N$, Th/Yb_N, Nb/Yb_N and Eu/Eu* to the South Mongolian Gobi, implying the major contribution of the South Gobi. By comparison of the REEs, trace elements, and mineralogy (TiO_2–Zr–Al_2O_3, La–Sc–Th ternary diagrams) in cryoconite and snow dust with the central Asian deserts, the Qaidam Basin is identified as a source for dust deposition onto YG in the inner TP, while large central Asian deserts

rarely contributed with LRT dust to the glacier. We find that most of the glacier snowpack samples showed mixed dust sources from different parts of surrounding central Asian deserts. The LRT dust provenance in the NETP glacier is also supported from the AOD data and wind field in the region.

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Conflicts of Interest: The authors declare no conflict of interest.

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