Insights into mercury in glacier snow and its incorporation into meltwater runoff based on observations in the southern Tibetan Plateau

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ABSTRACT

The Tibetan Plateau (TP) is recognized as “Water Tower of Asia”. Yet our understanding of mechanisms influencing incorporation of mercury (Hg) into freshwater in mountain glaciers on the TP remains quite limited. Extensive sampling of environmental matrices (e.g., snow/ice) were conducted on the East Rongbuk glacier on Mt. Everest and Zhadang glacier on Mt. Nyainqentanglha for Hg speciation analysis. Speciated Hg behaved quite different during snowmelt: a preferential early release of DHg (dissolved Hg) was observed at the onset of snowmelt, whereas PHg (particulate-bound Hg) and THg (total Hg) become relatively enriched in snow and released later. Small fraction of Hg in snow was lost during a snowmelt day (18.9%–34.7%) with a large proportion (58.1%–87.3%) contributed by PHg decrease, indicating that the deposited Hg is most likely retained in glacier snow/ice. Furthermore, THg were positively correlated with PHg and crustal major ions (e.g., Ca²⁺, Mg²⁺) during snowmelt, indicating that Hg is mainly migrated with particulates. The main pathway of Hg loss during snowmelt was most probably associated with release of PHg with meltwater, which was greatly influenced by ablation intensity of snow/ice. This should be paid particular concern as Hg preserved in mountain glaciers will mostly enter aquatic ecosystem as climate warms, impacting on downstream ecosystems adversely. Obvious decrease of THg during the downstream transport from glacier was observed with a large proportion contributed by PHg decrease. The main removal mechanism of Hg was associated with sedimentation of PHg during the transport process.

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Introduction

Mercury (Hg) is well-known as a globally hazardous pollutant because of its potential for long-range transport via the atmosphere, persistence and biomagnification through food chains (Selin, 2009). Mercury mainly exists in atmosphere in three forms: gaseous elemental Hg (Hg⁰), divalent reactive gaseous Hg (Hg(II)), and particulate-bound Hg (PHg). Reactive
gaseous Hg and PHg have relatively high dry deposition velocity and water solubility and are more readily to be scavenged from atmosphere via dry/wet deposition. Gaseous elemental Hg is the predominant form of Hg in atmosphere (>90%) and has a long atmospheric residence time of 0.5–2 years, which enables Hg to undergo a long-range transport before being oxidized to Hg(II) and being deposited to remote areas (Schroeder and Munthe, 1998).

With an average elevation above 4000 m above sea level (a.s.l.), the Tibetan Plateau (TP, including the Himalayas), or the “Third Pole”, is one of the most remote and pristine areas in the world and is the most glacier-concentrated region at low- and mid-latitudes (Yao et al., 2012). Pollutants originating from heavily-polluted areas surrounding it (e.g., central and southern Asia) could be transported a long distance and eventually deposited onto glaciers over the TP (Beal et al., 2015; Kang et al., 2016). The accumulated pollutants will be largely released as glacier snow/ice melting accelerates due to global warming, impacting on human health and ecosystems of downstream regions adversely (Sun et al., 2016; Zhang et al., 2017). This issue is of particular concern as TP serves as the source region of Asia’s major rivers (e.g., Yangtze River, Indus and Brahmaputra) (Yao et al., 2012), and glacier melt in the TP is an important contributor to river discharge of these rivers (e.g., 48% of annual river discharge for Indus river basin; Immerzeel et al., 2010). To date, some previous studies focused on spatiotemporal distribution and deposition of Hg in glacier snow on the TP have been conducted (Huang et al., 2012a, 2012b; Loewen et al., 2007; Zhang et al., 2012a). For instance, previous studies have revealed that concentration levels of Total Hg (THg) in glacier snow over western China (i.e., Tibetan Plateau and northwest China) were higher in northern region compared to those from southern region, and higher in non-monsoon season than in monsoon season. The spatiotemporal variability of THg concentrations in glacier snow was consistent with that of atmospheric particulate loadings, suggesting that deposition of atmospheric Hg over western China was primarily associated with particulate matter and dust storm activity might provide the largest source of Hg deposition on the TP. However, it is still unclear Hg is transported long distance with dust or partitioning onto particulates nearby the deposition sites (Loewen et al., 2007; Zhang et al., 2012a). For spatial distribution of Hg in snow of an individual glacier, a previous study reported an increase in THg with increasing altitude in surface snow of four high-altitude glaciers over the TP, and proposed a possible altitude magnification effect on Hg deposition in alpine snow (Huang et al., 2012).

However, a knowledge gap in this region was the lack of information on the fate of Hg following its deposition onto glacier snow/ice. For instance, a part of deposited Hg could probably be remitted into atmosphere via a sunlight-induced mechanism (Lalonde et al., 2003); Some part of Hg might be released with meltwater and contaminate aquatic ecosystem (Dommergue et al., 2003). To date, it’s still unclear what the main pathway of Hg loss and mechanisms influencing migration process of speciated Hg during snowmelt in glacier snow on the TP is. Three major loss mechanisms of Hg in snow have been proposed during post-depositional processes, included (1) percolation, (2) settling of PHg and 3) photo-induced reduction of Hg(II), which may then be emitted back to the atmosphere as Hg0 (Lalonde et al., 2002). Previous studies in the Arctic (Poulain et al., 2004; Dommergue et al., 2009) and some mid-latitude sites (Lalonde et al., 2002, 2003; Poulain et al., 2007) have revealed that a significant fraction of deposited Hg might probably not enter the aquatic/terrestrial environment due to the subsequent photoreduction of Hg(II) in snow, which could result in >40% loss of THg concentration in surface snow within 24 hr (Lalonde et al., 2003). However, deposition of Hg over the TP is driven primarily in the form of PHg (Loewen et al., 2007). The deposited PHg in glacier snow/ice over the TP could be far less reducible than deposited Hg(II) in redox reactions, and thus less influenced by the photoreduction process (Durnford and Dastoor, 2011; Loewen et al., 2007). This could be evidenced by most high THg concentration peaks corresponded to high particulate loads in snowpits, and significant correlations between insoluble particles and THg concentrations in snowpits and ice core of the TP (Zhang et al., 2012a; Kang et al., 2016). Consequently, post-depositional release of Hg via the photoreduction and reemission should be not significant in glacier snow of the TP. Instead, Hg stored in glacier snow of the TP would be most likely released with meltwater after its deposition due to snow/ice melt. Studies on post-depositional fate of Hg were required in order to understand the relationship between Hg deposition onto snow and its incorporation into snowmelt and freshwater, which is essential for assessing its potential downstream impact and biogeochemical cycles of Hg in high-elevation glacier basins on the TP.

In this study, concentrations of speciated Hg in various environmental matrices (i.e., glacier snow/ice, lake/stream water) are presented. Migration process of speciated Hg during snowmelt and downstream transport of Hg from glacier were discussed. This study is an attempt to provide insights for assessing post-depositional fate of Hg in snow and potential environmental risk of Hg release by accelerated glacier melt to glacial-fed downstream ecosystems on the TP as climate warms.

### 1. Material and methods

#### 1.1. Study area and sampling location

The Himalayas is the highest mountain ranges on Earth acts as a natural barrier between the TP and Indian subcontinent. The East Rongbuk (ER) glacier (28.02°N, 86.96°E) is located on the northeastern slope of Mt. Everest in the central Himalayas (Fig. 1), with a length of 14.0 km, a width of 0.8 km and a total area of 48.45 km². The altitude of glacial terminus is approximately 5540 m a.s.l. (Zhang et al., 2012b). The equilibrium line altitude (ELA) of ER glacier is estimated to be 6419 m a.s.l. (King et al., 2017). According to air temperature records at 6000 m a.s.l. of ER glacier, the annual mean temperature is ~5.4°C with the extreme high temperature of 18.6°C and extreme low temperature ~29.3°C. The daily mean temperature is above 0°C from June to August (Yang et al., 2011). The mass balance of ER glacier between 2000 and 2015 was −0.44 ± 0.19 m water equivalent (w.e.)/year with the mean surface lowering rates of −1.04 ± 0.18 m/year in glacier ablation zones (King et al., 2017). Landscape in the glacier basin consists of glaciers, rivers and lakes (Fig. 1). A proglacial lake formed at 5214 m a.s.l. and is approximately 3 km from the...
glacial terminus of ER glacier. Glacial meltwater is the main water supply for the proglacial lake through a stream formed between the glacial terminus and the proglacial lake. Moreover, there is an outflow stream formed beneath the proglacial lake.

The Zhadang (ZD) glacier is located on the northern slope of Nyainqentanglha Range and is approximately 380 km northeast of Mt. Everest. The ZD glacier is a valley-type glacier facing north-northwest and has a length of 2.2 km, an altitude range of 5515–6090 m a.s.l. and a total area of 2.0 km². The measured 3-year mean ELA of ZD glacier (2005–2008) is 5750 m a.s.l. (Yu et al., 2013). The annual mean air temperature near glacial terminus (5400 m a.s.l.) is −3.4°C, and the daily mean air temperature was >0°C from June to middle September. The glacier mass balance between 2011 and 2014 is −1.6 m w.e./year (Zhang et al., 2016).

The atmospheric circulation in our study region is mainly influenced by the Indian monsoon and westerly. The former prevails from June to September (i.e., Monsoon period) and induces moisture from Indian Ocean to the southern TP whereas westerly dominates the atmospheric circulation in other months (i.e., non-monsoon season; Tian et al., 2007).

1.2. Sample collection

Extensive sampling campaign of various environmental matrices (i.e., glacier snow/ice, lake/stream water) for Hg speciation analysis was conducted on ZD glacier (August/September, 2011) and ER glacier (April 2016; Fig. 1 and Table 1).

1.2.1. On the East Rongbuk (ER) glacier

To investigate altitudinal variation of Hg in glacier snow, surface snow samples (0–5 cm) were collected in the early morning before snow started to melt along altitude gradient on ER glacier (6300–6700 m a.s.l.; April 23th, 27th and 28th, 2016). Surface “old snow” samples (i.e., fine-grained snow) were collected, since no snowfall events occurred during the sampling period. Besides, a 140- cm-depth snowpit was dug at the col of ER glacier (6460 m a.s.l.), and snow samples from the snowpit were collected at a vertical resolution of 10 cm.

To investigate fate of speciated Hg during snowmelt, intensive samplings of snow (0–5 cm; Coarse-grained snow) on ER glacier were conducted on glacier surface (6280 m a.s.l.) at a time interval of 2 hr on a bright sunny day (April 28th; “intensive surface snow”, Table 1). To characterize the variation of Hg during snowmelt, intensive sampling of “aged snow” (i.e., Coarse-grained snow) started in the early morning (9:00 am) immediately after sunrise and before the surface snow started to melt due to the low temperature during the sampling season (April/May; Yang et al., 2011, 2015). For the “intensive snow” episode, snow samples were collected within a given sampling plot of 1 m × 1 m to reduce the possible effect of fine-scale spatial variability of Hg concentrations. The intensive snow sampling plot (1 m × 1 m) on ER glacier was located at the bottom of a slope. Three replicates of surface snow was collected randomly within the plot and mixed into a composite sample for each intensive snow sample. The composite sample was collected in duplicate at each time.
Surface ice samples (0–5 cm) on ER glacier were collected underneath the snow at altitudes ranging between 6250 and 6400 m a.s.l. The overlying snow was relatively thin at surface ice sampling sites with snow depth ranging between 8 and 20 cm according to the field measurement. "Aged ice" samples were collected from seracs at 6278 m and 5800 m a.s.l. and from an ice cave at 5715 m a.s.l. on ER glacier (Fig. 1 and Table 1).

Supraglacial lake/stream water, proglacial lakewater and glacial-fed river water samples were collected from downstream along the glacial-fed river (April 29th) to investigate the downstream transport of Hg from the glacier (Fig. 1). A small supraglacial lake was observed on the glacier surface (6278 m a.s.l.) near the intensive snow sampling site. There was also a small and shallow stream on the glacier surface during the sampling period. Supraglacial lake/stream water samples were collected at 18:00 when obvious snowmelt was observed and the frozen supraglacial lake surface has partially thawed. The proglacial lakewater samples were collected at 21:00. Glacial-fed riverwater samples were collected at the outflow of the proglacial lake at night (21:00), when the runoff are elevated compared to those observed in the daytime (8:00–20:00).

### Table 1 – Detailed information of sampling sites and THg concentrations in environmental matrices on East Rongbuk (ER) glacier and Zhadang (ZD) glacier. THg concentrations in sample types (i.e., surface snow/ice and snowpit, marked with different letters) differ significantly (ANOVA, Tukey post hoc test, p = 0.05).

<table>
<thead>
<tr>
<th>Sampling location</th>
<th>Sample type</th>
<th>Longitude/latitude</th>
<th>Altitude (m a.s.l.)</th>
<th>Hg speciation measurement</th>
<th>THg concentrations (ng/L)</th>
<th>Sample numbers</th>
<th>Sampling time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mean ± SD Range</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ER glacier</td>
<td>Surface snow (Fine-grained snow)</td>
<td>–</td>
<td>6300–6700</td>
<td>THg/DHg</td>
<td>19.1 ± 16.5c</td>
<td>9.6–69.8</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Snowpit</td>
<td>28°01.25′N, 86°57.54′E</td>
<td>6250–6400</td>
<td>THg/DHg</td>
<td>21.3 ± 30.0c</td>
<td>7.6–90.7</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Intensive surface snow (Coarse-grained snow)</td>
<td>28°02.12′N, 86°56.65′E</td>
<td>6280</td>
<td>THg/DHg</td>
<td>3.9 ± 1.2</td>
<td>2.6–6.4</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Serac</td>
<td>28°02.16′N, 86°56.67′E</td>
<td>6278</td>
<td>THg/DHg</td>
<td>12.6 ± 0.9</td>
<td>11.5–13.7</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Serac</td>
<td>28°05.05′N, 86°54.99′E</td>
<td>5800</td>
<td>THg/DHg</td>
<td>33.6 ± 1.9</td>
<td>31.4–36.0</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Ice cave</td>
<td>28°05.06′N, 86°54.92′E</td>
<td>5715</td>
<td>THg/DHg</td>
<td>56.1 ± 5.6</td>
<td>50.3–62.6</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Supraglacial lakewater</td>
<td>28°02.12′N, 86°56.65′E</td>
<td>6278</td>
<td>THg/DHg</td>
<td>6.8 ± 1.0</td>
<td>5.8–7.9</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Supraglacial streamwater</td>
<td>28°05.04′N, 86°54.98′E</td>
<td>5750</td>
<td>THg/DHg</td>
<td>4.6 ± 0.4</td>
<td>4.2–5.0</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Proglacial lakewater</td>
<td>28°06.98′N, 86°51.75′E</td>
<td>5214</td>
<td>THg/DHg</td>
<td>2.2 ± 0.2</td>
<td>1.9–2.4</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Glacial-fed riverwater</td>
<td>28°08.11′N, 86°51.10′E</td>
<td>5151</td>
<td>THg/DHg</td>
<td>1.9 ± 0.4</td>
<td>1.5–2.3</td>
<td>4</td>
</tr>
<tr>
<td>ZD glacier</td>
<td>Surface snow (fresh snow)</td>
<td>–</td>
<td>5550–5800</td>
<td>THg/RHg</td>
<td>0.7 ± 0.2a</td>
<td>0.4–1.4</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>Intensive surface snow (glacier surface)</td>
<td>30°28.52′N, 90°38.41′E</td>
<td>5565</td>
<td>THg/DHg</td>
<td>0.7 ± 0.2</td>
<td>0.4–1.2</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Intensive surface snow (grassland)</td>
<td>30°28.56′N, 90°38.40′E</td>
<td>5480</td>
<td>THg/DHg</td>
<td>0.9 ± 0.2</td>
<td>0.6–1.1</td>
<td>5</td>
</tr>
</tbody>
</table>

1.2.2. On the Zhadang (ZD) glacier

Three snowfall events occurred on August 18th, 22th and September 7th, 2011 on ZD glacier. Snow fell overnight and stopped in the early morning on August 18th and 22th. Snowfall event on September 7th occurs at night. Surface fresh snow samples (0–5 cm) on ZD glacier were collected along altitude gradient (5550–5800 m a.s.l.) in the early morning before the snow start to melt (August 18th, 22th and September 7th).

Intensive samplings of the fresh snow (0–5 cm) were conducted four times for ZD glacier after snowfall events (i.e., fresh snow), including three times on glacier ice surface near glacial terminus (5565 m a.s.l., August 18th, 22th and September 7th) and once on grassland (5480 m a.s.l., August 22th). The fresh snow depth on ice surface on August 18th, 22th and September 7th was 12 cm, 14 cm and 9 cm, respectively, according to field measurements at the intensive sampling sites on glacier surface. The intensive snow samplings on ZD glacier were conducted at a time interval of 1 hr immediately when snowfall stopped on August 18th (11:00 am) and 22th (10:30 am), and was conducted starting in the early morning (9:00 am) on September 7th. There was no underlying “old snow” beneath the fresh snow at the intensive sampling sites.
on glacier ice surface near glacier terminus. The meteorological parameters (e.g., air temperature) during intensive sampling days (August 18th, 22th and September 7th, 2011) were recorded at 5-min intervals using a portable automatic weather station (Davis Vantage Pro 2) near the intensive snow sampling site on glacier ice surface (5565 m a.s.l.). According to air temperature records during the intensive sampling days, the near surface air temperature (50 cm above the glacier surface) rose above 0°C at approximately 11:00 am (Fig. 2), indicating that snowmelt began at approximately 11:00 am. Intensive samplings of fresh snow (0–5 cm) were all conducted before/when the snow start to melt on ZD glacier. The weather was overcast on September 7th and was sunny on August 18th and 22th, 2011, during the collection of “intensive snow”. An averaged decrease of 3.0 ± 0.5 cm in fresh snow depth on ice surface of ZD glacier was observed at the sampling sites during each intensive snow sampling episode. For each “intensive snow” episode, snow samples were collected within a given sampling plot of 1 m × 1 m. The intensive snow sampling plots (1 m × 1 m) of ZD glacier located on the flat terrain. The sampling procedures for the intensive snow samples on ZD glacier were similar with that on ER glacier.

All samples (both on ER glacier and ZD glacier) were collected in duplicate strictly following “clean hands–dirty hands” Hg sampling protocols (Fitzgerald, 1999). Snow/ice samples were collected using an acid-rinsed (HNO3, 20 mL/100 mL) high density polystyrene scoop and stored in Whirl-Pak bags. These samples were melted in the dark at room temperature in a clean room in the field (e.g., field stations), thoroughly mixed by manual shaking, and then split into 50-mL polypropylene Falcon® centrifuge tube. Lake/river water samples were collected using 50-mL polypropylene Falcon® centrifuge tube and immediately doubly packed in Ziploc bags. Field blanks filled with ultrapure water were opened during sample collection and were handled as samples. Surface snow samples from ZD glacier were analyzed for THg and reactive Hg (R-Hg) (Table 1). Other snow/ice/water samples were analyzed for THg and dissolved Hg (DHg). All samples for THg analysis were spiked with 100–μL ultraclean HCl (BV-III grade from Beihua Chemical, China) in situ (for lake/streamwater samples) or in the field (e.g., field stations) within 24 hr after sampling (for snow/ice samples) where field conditions precluded the onsite spike. Samples for dissolved Hg (DHg) determination were filtered through a 0.45-μm membrane (Durapore, Millipore) first using a 500-mL borosilicate glass filtering apparatus and then acidified to 0.5% (V/V) with HCl for preservation. All samples were then kept frozen in a refrigerator in the field, during the transportation and were stored in a dark refrigerating chamber in the laboratory until analysis.

1.3. Analytical methodology

Total Hg (THg) and dissolved Hg (DHg) were quantified within 2 weeks after sampling using an Analytik-Jena Hg analyzer (Analytik-Jena Corporation Inc., Jena, Germany) following US EPA Method 1631 (version E; US EPA, 2002). Particulate-bound Hg (PHg) was calculated by the difference of THg and DHg (Zhang et al., 2012a). Briefly, BrCl (0.5 mL/100 mL sample) was firstly added to each sample for THg and DHg analysis to oxidize Hg species to Hg²⁺ followed by the addition of NH₄OH·HCl (0.2 mL/100 mL sample) for the removal of excess BrCl. SnCl₂ was then added to the sample to reduce Hg²⁺ to Hg⁰, which was quantified by fluorescence spectrophotometry. Reactive Hg (RHg) was determined following the similar procedure except that SnCl₂ was directly added to the sample without prior addition of BrCl or NH₄OH·HCl.

Each sample was measured in duplicate and the relative standard deviations (RSDs) for the replicate measurements were <5%. An Ongoing Precision and Recovery (OPR) standard of 5 ng/L and a method blank were interspersed in every 10 samples to check instrument operation. The recovery percentage for Hg in the OPR standard was between 95%–105%. The method detection limit (MDL), defined as 3 times the standard deviation of 10 replicate measurements of a blank solution, was less than 0.1 ng/L. THg concentrations of method/field blanks were always below MDL, indicating minimal contamination during sampling, transportation and treatment of samples.

Analysis of major cations (Ca²⁺, Mg²⁺, Na⁺, NH₄⁺ and K⁺) and major anions (Cl⁻, NO₃⁻, and SO₄²⁻) were carried out on a Dionex ISC 2000 and Dionex ISC 2500 ion chromatograph, respectively. The MDLs were 1 μg/L for all ions, and analytical precision was within 5%.

1.4. Statistical analysis

All of the data processing and statistical analysis were conducted using IBM SPSS Statistics 20. The correlations calculated using Pearson correlation analysis were considered statistically significant when significance level p < 0.05. Comparisons of THg concentrations in sample types (i.e., surface snow/ice and snowpit) were performed by one-way factorial analysis of variance (ANOVA) with sample type followed by Tukey post hoc test (Sun et al., 2017). Log-normality tests for THg concentrations in environmental matrices (i.e., surface snow/ice and snowpit) were conducted using Shapiro–Wilk (S–W) test. Data are Lognormally distributed when S–W p > 0.05. THg concentrations in surface snow/ice and snowpit samples all passed the S–W test and are Log-normally distributed (Table 2). Thus, the geometric mean THg concentrations were used for these environmental matrices. Also, the geometric mean Hg concentrations were used for water samples (n ≤ 6) for comparison of THg concentrations among environmental matrices.
2. Results and discussion

2.1. Hg in surface snow, snowpit and ice

2.1.1. Concentration levels of speciated Hg in surface snow and snowpit

The geometric mean THg concentration in surface snow of ZD glacier was 0.7 ± 0.2 ng/L (n = 31; Table 1), which was comparable to those determined in the Arctic in the absence of AMDEs (<1–5 ng/L; Atmospheric mercury depletion events; Ferrari et al., 2005; Steffen et al., 2008), at the low end of those determined in central and southern TP (<1–15 ng/L; Huang et al., 2012), and lower than those measured in snowpits in ZD glacier (mean: 4.3 ng/L; Huang, 2011). RHg concentrations in surface snow of ZD glacier were always below the MDL (0.1 ng/L). The mean THg concentration in surface snow of ER glacier was 19.1 ± 16.5 ng/L (range: 9.6–69.8 ng/L; n = 19, Fig. 3), which was comparable to those reported for the French Alps (13–130 ng/L; Ferrari et al., 2002). The concentration level of THg in surface snow of ER glacier was also comparable to those reported for the northern regions of western China, which were adjacent to major dust source regions (e.g., Taklimakan Desert) and had mean THg concentrations typically >10 ng/L (Zhang et al., 2012a). The majority of THg concentrations in surface snow samples were <30 ng/L (n = 15). PHg concentration in surface snow of ER glacier was 16.8 ± 16.5 ng/L and accounted for 87.8% ± 6.0% of THg.

THg concentration in snowpit of ER glacier was 2.8 ± 5.0 ng/L (n = 14, Table 1 and Fig. 4) which was comparable to those determined in western China (<1–43.6 ng/L; Zhang et al., 2012a). The highest THg concentration in the snowpit was observed in the surface layer of 0–10 cm (21.1 ng/L), which was comparable to those observed in surface snow (19.1 ± 16.5 ng/L; Table 1). PHg concentration was 2.2 ± 4.5 ng/L, and occupied 78.3% ± 10.3% of THg in snowpit of ER glacier.

Previous studies have suggested that particulate matter played an important role in atmospheric Hg transport and deposition over western China (Loewen et al., 2007). Significant positive correlation between THg and PHg were found in both surface snow/ice and snowpit samples on ER glacier (Fig. 5). Similar to what has been found in previous studies, our results confirmed that deposition of atmospheric Hg was mainly associated with particulate matter, and PHg was the dominant factor influencing distribution and concentration levels of Hg in glacier snow/ice on the TP.

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Table 2 - Results of the Shapiro-Wilk (S-W) test for Log-normality tests of THg concentrations in environmental matrices. Data are Log-normally distributed when S-W p > 0.05.

<table>
<thead>
<tr>
<th>Sample type</th>
<th>ER glacier</th>
<th>ZD glacier</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface snow</td>
<td>Surface ice</td>
</tr>
<tr>
<td>Skewness</td>
<td>0.979</td>
<td>0.595</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>−0.071</td>
<td>−1.171</td>
</tr>
<tr>
<td>S-W p</td>
<td>0.065</td>
<td>0.076</td>
</tr>
</tbody>
</table>

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Fig. 3 – Concentration levels of speciated Hg in various environmental matrices on East Rongbuk (ER) glacier. The error bars are the standard deviations (SDs).

Fig. 4 – Depth profiles of speciated Hg in the 140- cm-depth snowpit from East Rongbuk (ER) glacier. The error bars are the SDs for Hg concentrations.
resulting in several times higher in THg in snow during non-monsoon season than during monsoon season. Previous studies have identified that prevalent spring dust storms over the southern/central Asia (Kang et al., 2002; Xu et al., 2009) or Tibetan Plateau (Kang et al., 2004) were important sources of dust deposited on snow in the Mt. Everest region. Previous work on ER glacier has suggested that dust from arid regions in southern Asia (e.g., Northwestern India) was the main source of particulates in snow/ice at high altitudes of ER glacier (Xu et al., 2009). Thus, given the prevalent spring dust storms over southern/central Asia (Wake et al., 1994) or the TP (Wang et al., 2004) and consequent high atmospheric particulates loading onto the glacier snow, THg concentration in surface snow of ER glacier during the sampling season (April, 2016; Non-monsoon season) was significantly elevated compared to those observed in snowpits which would have characterized the entire snow season.

Previous work on Hg wet deposition in remote stations on the TP revealed that wet deposition of Hg was mainly in the form of PHg, and THg concentrations in precipitation (both snow and rain) were lower in monsoon season than in non-monsoon season (e.g., Nam Co station, 50 km northeast of ZD glacier), indicating that the low THg concentration in precipitation in monsoon season has been influenced by dilution effect of increased precipitation (i.e., the higher the precipitations, the lower the concentrations; Guo et al., 2015; Huang, 2011). Thus, low THg concentrations in surface fresh snow in this study (August/September, 2011; Monsoon season) compared to the snowpits (4.3 ng/L; Huang, 2011) on ZD glacier could be explained by the fact that the increased precipitation (i.e., snowfall and rainfall) during the sampling season (i.e., monsoon season) could effectively remove Hg (especially PHg) from the atmosphere, resulting in low concentrations of PHg in the atmosphere and consequent low Hg concentrations in fresh snow for each snowfall event (i.e., dilution effect of increased precipitation; Huang, 2011; Huang et al., 2012a).

2.1.2. Concentration levels of speciated Hg in ice on the East Rongbuk (ER) glacier

Proportion of PHg to THg (PHg/THg) ratios in all ice samples from ER glacier ranged between 83.2%–98.0%. THg concentration in aged ice of ice cave (n = 4) was 56.1 ± 6.0 ng/L. The glacier ice below approximately 5700 m a.s.l. of ER glacier was coved by debris (i.e., debris-covered area; Zhang et al., 2012b). The ice cave (5715 m a.s.l.) was located in the debris-covered area of ER glacier (the cave roof was coved by debris) and directly contacted the bedrock. As a result, ice samples of the ice cave were endowed with large amounts of visible particulates and consequent high THg concentrations, which could be possibly ascribed to influence of glacier erosion onto underlying bedrock and local input of wind-blown crustal dust from the debris-coved area (Loewen et al., 2007). THg concentration in ice of serac (n = 4) at 5800 m a.s.l. (Fig. 1) was 33.6 ± 6.9 ng/L, which is approximately 3 times higher than those determined in serac at 6278 m a.s.l. (12.6 ± 0.9 ng/L). This phenomenon could be possibly explained by local input of wind-blown crustal dust considering that the sampling site at 5800 m a.s.l. is near debris-covered area, and wind speed is high and daily maximum wind speed could be up to 20 m/sec during the sampling season (Ciren and Wang, 2009; Yang et al., 2015), which could move crustal dust short distances from the nearby debris-coved areas onto the ice (Kang et al., 2007; Zhang et al., 2008).

THg concentrations in surface ice of ER glacier fell in a broad range of 7.6–90.7 ng/L with a mean of 21.3 ± 30.0 ng/L (n = 11), which is obviously higher than those determined in the snowpit (2.8 ± 5.0 ng/L). Particulate-bound Hg in snow/ice may be settled and accumulated on glacier surface when snow/ice melt occurs, resulting in high THg concentrations in surface ice. Specifically, settling of PHg could result in removal of Hg from the upper snow layers, and transported PHg to the lower strata (e.g., ice layer). This phenomenon could be evidenced by the fact that at the surface ice sampling sites, slight visible dust was observed on ice surface underneath the snow (Huang et al., 2014; Zhang et al., 2012a); On the other hand, percolation columns form within snowpacks when snowmelt occurs and resulted in the downward movement of Hg-enriched (e.g., water-soluble Hg) meltwater, which will refreeze when temperature drops. The lower ice layers act as an effective barrier for depleted PHg and percolation of snowmelt from the upper snow layers, resulting in accumulation of Hg and consequent high THg concentrations in ice samples (Zhang et al., 2012a).

2.1.3. Variations of THg with elevation in surface snow/ice

Some previous studies have suggested a possible altitude magnification effect on Hg deposition onto alpine snow (i.e., increased Hg deposition onto glacier snow at high altitudes;
An increase in THg with altitude in surface “old snow” (i.e., Coarse-gained snow) was observed in four high-altitude glaciers over the TP, which was proposed to be attributed to the temperature-driven mechanism (i.e., low temperature at high altitudes may enhance deposition efficiency of atmospheric Hg [e.g., PHg] onto snow surface, resulting in increases in atmospheric Hg deposition onto snow surface with increase of altitude). However, no positive, even negative relationship were found between altitude and THg in surface “old snow” (i.e., coarse-grained snow) and fresh snow of ZD glacier (Fig. 6). Strong winds occurred during spring over the high-altitude regions of Mt. Everest and could significantly influence the altitudinal distribution of crustal dust/elements (Kang et al., 2007; Zhang et al., 2008) and pollutants (e.g., heavy metals, POPs; Wang et al., 2007; Yeo and Langleyturnbaugh, 2010) in glacier snow. Previous studies revealed that wind speed in the northern slope of Mt. Everest region (including the ER glacier) showed significant seasonal variation with high values in winter and spring (i.e., from November to May of the next year) and relatively low values in summer and autumn (i.e., from June to October; Guo et al., 2013; Yang et al., 2008, 2015). Indeed, our living tents (6300 m a.s.l.) could be even blown down occasionally due to high wind speed events during the field sampling period. Thus, the strong wind could significantly redistribute glacier snow and influence the vertical profiles of chemical species in the atmosphere (Kang et al., 2007; Zhang et al., 2008), resulting in the random trends of THg variation with altitude in snow of the ER glacier. The collected surface snow on ZD glacier were fresh snow which were collected in the early morning after snowfall events, and should be minimally influenced by the subsequent deposition of PHg from the atmosphere. Thus, the altitude magnification effect on atmospheric Hg deposition onto snow surface was not observed in fresh snow on ZD glacier. Instead, the no clear trends of THg variations with elevation in fresh snow from ZD glacier reflected the spatially heterogeneous wet deposition of Hg over the glacier in each snowfall event.

Significant positive relationship between THg and altitude was observed in surface ice of ER glacier (\(R^2 = 0.55, p = 0.03\); Fig. 6). More snow/ice melt is expected at low altitudes than that at high altitudes attributed to higher air temperature. Thus, the positive relationship between altitude and THg in surface ice samples was most likely attributed to the fact that the removal of Hg (especially PHg settled on the ice surface) by snow/ice melt was greater at low altitudes than that at high altitudes (Huang et al., 2014).

### 2.2. Fate of speciated Hg during snowmelt

To characterize Hg variation during snowmelt, diurnal observations on speciated Hg in snow were conducted on ER glacier (April, 2016) and ZD glacier (August/September, 2011). The RSDs for replicates of intensive snow samples were generally <5%, indicating minimal spatial heterogeneity of Hg concentrations in snow within the given sampling plot of 1 m × 1 m.

THg concentrations in snow on glacier ice surface decreased within 24 hr after deposition. An averaged 28.8% ± 8.7% loss of THg in snow on glacier surface of ZD glacier was observed (range: 18.9%–34.7%), 70.2% ± 11.0% of which was contributed by decrease of PHg (range: 58.1%–79.5%, Fig. 7). Similarly, THg concentrations in snow of ER glacier decreased by 24.1% after deposition, 87.3% of which was contributed by decrease of PHg. Field observation found that during snowmelt in a sub-Arctic site, more than 90% of Hg in surface snow was likely released with the meltwater during a snowmelt day.
(Dommergue et al., 2003). Relatively small loss of THg in glacier snow of the TP during snowmelt, indicated that the deposited Hg in mountain glaciers of the TP was less influenced by the postdepositional processes, and was most likely retained within glacier snow/ice after deposition.

In contrast to those observed on glacier ice surface, concentrations of speciated Hg in snow collected from grassland near glacial terminus of ZD glacier increased throughout the entire sampling period (Fig. 7e). An overall 34% increase of THg in surface snow on the grassland was observed throughout the entire sampling period (9:30–13:30), 66.0% of which was contributed by increase of DHg. This phenomenon could be possibly attributed to the vertical translocation of Hg from the underlying soil into snow (Jonasson, 1973; Nelson et al., 2008). For instance, an in-situ experiment using stable Hg isotope tracer (Hg\textsuperscript{202}) revealed a upward mobility of Hg from soil into overlying snow, which constitute up to 64% of THg in the snowpack (Nelson et al., 2008).

Numerous laboratory/field studies on the fate of chemicals (e.g., organic contaminants, heavy metals) during snowmelt revealed a preferential early elution of water-soluble substances (e.g., inorganic ions), whereas less soluble substances (e.g., chemicals bound to particulates) become relatively enriched in snow and released later during snowmelt (Colbeck, 1981; Dommergue et al., 2009). Similarly, an averaged 45.9% ± 9.1% of DHg decrease was observed in fresh snow of ZD glacier within 1 hr after snow started to melt (11:00 am; range: 33.2%–53.8%; Figs. 2 and 7). The rapid decreases of DHg in fresh snow of ZD

![Fig. 7](image-url) - Variation of speciated Hg in snow during snowmelt on East Rongbuk (ER) glacier and Zhadang (ZD) glacier. a represents snow samples collected on ice surface of ER glacier on April 28th, 2016. b, c and d represent snow samples collected on ice surface of ZD glacier on August 18th, 22th and September 7th, 2011, respectively. e represents snow samples collected on grassland near glacial terminus of ZD glacier on August 22nd, 2011. The error bars are the SDs for Hg concentrations. The air temperature at each sampling time were the hourly mean temperature between the sampling time and the earlier sampling time according to air temperature records at intensive sampling site on ice surface of ZD glacier (5565 m a.s.l.).

<table>
<thead>
<tr>
<th></th>
<th>THg</th>
<th>DHg</th>
<th>Cl\textsuperscript{−}</th>
<th>NO\textsubscript{3}\textsuperscript{−}</th>
<th>SO\textsubscript{4}\textsuperscript{2−}</th>
<th>Na\textsuperscript{+}</th>
<th>NH\textsubscript{4}\textsuperscript{+}</th>
<th>K\textsuperscript{+}</th>
<th>Mg\textsuperscript{2+}</th>
<th>Ca\textsuperscript{2+}</th>
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<tr>
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<td></td>
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<tr>
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<tr>
<td>NO\textsubscript{3}\textsuperscript{−}</td>
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<td>–0.26</td>
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<td>SO\textsubscript{4}\textsubscript{2−}</td>
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<td>0.54</td>
<td>0.12</td>
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<td>0.00</td>
<td>0.69**</td>
<td>0.05</td>
<td>0.20</td>
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<tr>
<td>NH\textsubscript{4}\textsuperscript{+}</td>
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<td>0.23</td>
<td>0.17</td>
<td>0.58**</td>
<td>0.72**</td>
<td>0.21</td>
<td>1</td>
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<td></td>
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<td>–0.22</td>
<td>0.59**</td>
<td>–0.06</td>
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<td>0.93**</td>
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<td>0.50*</td>
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<td>0.87**</td>
<td>0.44</td>
<td>0.53</td>
<td>0.11</td>
<td>0.49*</td>
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glacier (both collected on ice surface and grassland) observed at the onset of snowmelt reflected the sudden release of DHg from snow with the first meltwater fractions. Previous studies in the Arctic reported that Hg\(^{2+}\) is included in the ionic pulse, and a considerable fraction of oxidized Hg (e.g., Hg\(^{2+}\)) would be rapidly released from the snow to the earliest meltwater fractions (Dommergue et al., 2003). With the increase of thickness of quasi-liquid layer surrounding snow grains as the snow warms, ionic solutes (e.g., Hg\(^{2+}\)) are segregated toward the exterior quasi-liquid layer of snow grains during snow metamorphosis where they are available to enrich the downward percolating meltwater (Colbeck, 1981). Liquid water presents and percolation columns are commonly observed within the snowpack when snowmelt occurs, and channel the Hg-enriched meltwater downward or horizontally (Durnford and Dastoor, 2011), resulting in the rapid decrease of DHg in snow of ZD glacier. No significant relationship between DHg and most soluble major ions (e.g., Cl\(^{-}\), NO\(_3\)\(^{-}\), NH\(_4\)\(^{+}\)) were found during snowmelt of ZD glacier (Table 3), indicating that DHg did not migrate consistently with these ion species probably ascribed to different elution sequence from the snowpack (Cragin et al., 1996). However, no rapid decrease of DHg, even a gradual increase of DHg in snow was observed between 9:00–15:00 on ER glacier (Fig. 7a). Temperature is one of the key factors that would influence both snow metamorphosis and consequently determine the timing of release of Hg in snow (Lahoutifard and Lean, 2005). Previous measurements of air temperature at high altitudes (>6000 m a.s.l.) of ER glacier have shown that air temperature was low during the sampling season (April/May, spring) with monthly mean temperature a few degrees below 0°C and daily maximum air temperature near 0°C (Qin et al., 2013; Yang et al., 2011, 2015). According to air temperature records on ZD glacier (5565 m a.s.l.) during the intensive sampling days, the mean daily maximum air temperature (4.4 ± 0.5°C) was higher than freezing point on ZD glacier and daily mean air temperature were above 0°C on August 18th (0.8 ± 1.4°C) and 22th (0.8 ± 1.6°C) and near 0°C on September 7th (–0.3 ± 1.9°C) (Fig. 2). Thus, the delay of DHg release on ER glacier could be most likely attributed to slower snow metamorphosis than at ZD glacier due to its low temperature. Additionally, the proportion of PHg to THg decreased from 77.7% ± 3.3% to 63.8% ± 3.4% during the period (April/May, spring) with monthly mean temperature a few degrees below 0°C and daily maximum air temperature near 0°C (Qin et al., 2013; Yang et al., 2011, 2015). According to air temperature records on ZD glacier (5565 m a.s.l.) during the intensive sampling days, the mean daily maximum air temperature (4.4 ± 0.5°C) was higher than freezing point on ZD glacier and daily mean air temperature were above 0°C on August 18th (0.8 ± 1.4°C) and 22th (0.8 ± 1.6°C) and near 0°C on September 7th (–0.3 ± 1.9°C) (Fig. 2). Thus, the delay of DHg release on ER glacier could be most likely attributed to slower snow metamorphosis than at ZD glacier due to its low temperature. Additionally, the proportion of PHg to THg decreased from 77.7% ± 3.3% to 63.8% ± 1.7% from 9:00 to 15:00, indicating a relative increase in DHg compared to PHg at the earlier stage of snowmelt. Specifically, DHg concentrations increased from 1.0 ± 0.03 ng/L at 9:00 and reached its maximum of 1.9 ± 0.4 ng/L at 15:00 (Fig. 7a). PHg concentrations varied within a relatively small range of 2.8 ± 0.1 ng/L –3.4 ± 0.1 ng/L during the period (i.e., 9:00–15:00). The sampling plot (1 m × 1 m) on ER glacier was located at the bottom of a slope. Previous studies have revealed that DHg concentrations in the earlier meltwater fractions could be significantly higher than the average meltwater concentrations (Durnford and Dastoor, 2011; Kuhn, 2001). Thus, at the particular location on ER glacier, snow in the intensive sampling plot could probably received the earlier Hg-enriched meltwater fractions from the upper locations, resulting in the increase of DHg at the earlier stage of snow metamorphosis.

Both THg and PHg increased initially at the onset of snowmelt followed by obvious decreases. Notable positive relationship between THg and PHg were observed in each snowmelt episode (Fig. 8). Furthermore, variation of THg during snowmelt was mainly contributed by PHg, indicating that PHg was the dominant factor controlling variation and migration of Hg during snowmelt. Thus, the initial increase of THg was caused by the retention of PHg at the earlier stage of snowmelt due to the fact that PHg are less mobile than water-soluble Hg (e.g., Hg\(^{2+}\)) and could be remained in snow until actual massive melt occurs (Dommergue et al., 2009). This phenomenon is especially significant in glacier snow of ER glacier (Fig. 7a) and in glacier snow collected on the overcast day on ZD glacier (September 7th, 2011; Fig. 7d). Similar with that of DHg during snowmelt, the delay release of THg/PHg in snow of ER glacier in the afternoon compared to those observed on ZD glacier should be attributed to low air temperature and consequently slow snowmelt. Previous studies have revealed that air temperature was highest at approximately 17:00 pm at high altitudes (>6000 m a.s.l.) of ER glacier during the sampling season (April/May; Qin et al., 2013; Yang et al., 2011, 2015). Obvious snowmelt was observed on the bright sunny day (April 28th, 2016), even small meltwater flow formed on glacier surface near the sampling site between 17:00–19:00 according to field observation. As snowmelt accelerated, PHg once trapped within surface snow could be scavenged by and released into meltwater, and consequently removed from snow with meltwater, resulting in decrease of PHg in surface snow (Dommergue et al., 2009). Ca\(^{2+}\) was an ideal proxy for atmospheric particulate matter over the TP (Yao et al., 2004). Significant positive relationship were found between THg and crustal major ions (e.g., Ca\(^{2+}\), Mg\(^{2+}\); Table 3), whereas no significant relationships were found between THg and other ions (e.g., Na\(^{+}\), K\(^{+}\), Cl\(^{-}\), NO\(_3\)\(^{-}\)) during snowmelt in ZD glacier, indicating similar migration process of Hg and crustal major ions. This phenomenon further supported the previous studies that Hg was mainly migrated with terrigenous particulates, and loss of Hg from snow is due primarily to the release of PHg with meltwater during snowmelt.

### 2.3. Transport of Hg from glacier to its downstream

THg concentrations in supraglacial and proglacial lakewater of ER glacier were 6.8 ± 1.0 ng/L (n = 4) and 2.2 ± 0.2 ng/L (n = 6), respectively (Fig. 3), which was consistent with those determined in 38 lakes in the TP (<1–40.3 ng/L; Li et al., 2015), comparable to those reported for remote lakes in French Alps (0.1–4.34 ng/L; Maruszczak et al., 2011) and North America (0.1–14.7 ng/L; Vaidya et al., 2000), slightly higher than those measured in Antarctic natural lakes (0.4–1.9 ng/L; Watras et al., 1995), whereas significantly lower than those reported for polluted areas (e.g., 20.3–336.0 ng/L; Baihua Lake, China; Hou et al., 2004). THg concentrations were 4.6 ± 0.4 ng/L (n = 4) and 1.9 ± 0.4 ng/L (n = 4) in supraglacial and glacial-fed streamwater of ER glacier, respectively, which was comparable to those determined in uncontaminated freshwaters worldwide (<5 ng/L; Ullrich et al., 2001). The low concentration levels of THg in lake/stream water indicated that THg concentrations in fresh waters of ER glacier were minimally influenced by human activities and represented the background concentration levels of THg in natural freshwaters over the Tibetan Plateau. Particulate-bound Hg was the dominant Hg species in water samples on ER glacier (57.5%–83.4% of THg), except in glacial-fed river water, where PHg proportion was 41.1%.

A previous study in the Zhaghan Glacier Basin investigated the spatiotemporal distribution of Hg in meltwater runoff based on 24-hr sampling during the massive snow/ice melt period
(August), and revealed that both THg and PHg was relatively high in supraglacial streamwater compared with those in glacial-fed riverwater, whereas DHg concentration did not change obviously (Guo, 2012). Consistent with the previous study, THg and PHg concentrations varied synchronously during the transportation from supraglacial meltwater to the downstream and generally decreased as an order of supraglacial lake water (6278 m a.s.l.) > supraglacial streamwater (5750 m a.s.l.) > proglacial lake water (5214 m a.s.l.) > glacial-fed riverwater (5151 m a.s.l.) on ER glacier (Fig. 3), suggesting removal of Hg during the downstream transport of meltwater runoff. DHg concentration fell within a small range of 0.9 ± 0.2 – 1.1 ± 0.3 ng/L and did not vary obviously during the transportation process. Particulate-bound Hg was the dominant Hg species in various environmental matrices, indicating that PHg was the governing factor influencing transport and export of Hg from glacier to its downstream. Approximately 58.6% of THg loss in meltwater runoff was observed in ER glacier during the downstream transport process (i.e., from supraglacial meltwater to glacial-fed riverwater), of which 98.5% were contributed by decrease of PHg, indicating that the main removal mechanism of Hg was associated with sedimentation of PHg in meltwater runoff during the downstream transport process (Daye et al., 2015). This is supported by the fact that PHg/THg ratio fell obviously from an averaged 81.2% ± 3.1% in supraglacial lake/stream water to 57.5% ± 4.5% in proglacial lakewater, and further decreased to 41.1% ± 5.4% in glacial-fed river water. Thus, the overall decrease trend of THg and PHg concentration during the transportation process could be explained by increased sedimentation of PHg during the downstream transport, which could be ascribed to increase of meltwater-carrying distance, reduced topographic slope and slowdown of the meltwater runoff (Zhang et al., 2012b).

3. Conclusions

Results of Hg speciation analysis revealed that PHg was the dominant Hg species in glacier snow/ice, confirming that PHg was the dominant factor influencing distribution and concentration levels of Hg in glacier snow/ice over the TP. Inconsistent with previous study, no clear trends of THg in surface “old snow” with increasing altitude was found on ER glacier, which could be probably ascribed to snow redistribution by strong winds in spring (April, 2016).

Speciated Hg behaved quite different during snowmelt: rapid decreases of DHg in fresh snow were observed at the onset of snowmelt on ZD glacier, whereas PHg become enriched within the snow initially, and was released later during snowmelt. At a particular location at the bottom of a slope on ER glacier, an increase of DHg concentrations in surface snow at the early stage of snowmelt was observed, which could probably ascribed to the influence of earlier Hg-enriched meltwater fractions from the upper locations. Inconsistent with those observed in the sub-Arctic with a large fraction of Hg is likely released with meltwater during a snowmelt day (e.g., 90%; Dommergue et al., 2003), our results revealed a relatively small loss of Hg (18.9%–34.7%) during snowmelt in the two high-altitude mountain glaciers, indicating that the deposited Hg in mountain glaciers are most likely retained within the glacier snow/ice after deposition. Furthermore, Total Hg (THg) were positively correlated with PHg and crustal major ions (e.g., Ca²⁺, Mg²⁺) during snowmelt, indicating that Hg is mainly migrated with terrigenous particulates, and PHg release with meltwater was the main pathway of Hg loss during snowmelt, which was greatly influenced by ablation intensity of snow/ice. Mercury
preserved in glacier snow/ice on the TP could be mostly likely released with meltwater and enter the aquatic environments through glacial-fed ecosystems with the ongoing global warming. This should be paid particular attention as the melting mountain glaciers on the TP supplies potable water for people who inhabit downstream.

Obvious decreases of THg were observed during the downstream transport from glacier with a large proportion contributed by decrease of PHg. Sedimentation of PHg in meltwater runoff was believed to be an important mechanism for the removal of Hg during the downstream transport process (i.e., from supraglacial meltwater to glacial-fed riverwater).

Acknowledgments

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