Electrical Conductivity during the Ablation Process of the Glacier No. 1 at the Headwaters of the Urumqi River in the Tianshan Mountains

Authors: Han, Tianding, Li, Xiangying, Gao, Mingjie, Sillanpää, Mika, Pu, Hongzheng, et al.

Source: Arctic, Antarctic, and Alpine Research, 47(2) : 327-334

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/AAAR00C-13-138

Arctic, Antarctic, and Alpine Research, Vol. 47, No. 2, 2015, pp. 327–334

Electrical conductivity during the ablation process of the Glacier No. 1 at the headwaters of the Urumqi River in the Tianshan Mountains

Tianding Han[1]
Xiangying Li[1,2,6]
Mingjie Gao[3]
Mika Sillanpää[4]
Hongzheng Pu[1] *and*
Chengyang Lu[5]

[1]State Key Laboratory of Cryospheric Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China
[2]State Key Laboratory of Hydrology-Water Resources *and* Hydraulic Engineering/College of Hydrology and Water Resources, Hohai University, Nanjing 210098, China
[3]Shenzhen Environmental Engineering Science and Technology Center Co., Shenzhen 518000, China
[4]Laboratory of Green Chemistry, Lappeenranta University of Technology, Sammonkatu 12, 50130 Mikkeli, Finland
[5]Upstream of Hydrology and Water Resources Bureau in the Yellow River Conservancy Commission, Lanzhou 730030, China
[6]Corresponding author: shaanxilxy@163.com

Abstract

Electrical conductivity (EC) in aerosols, snow, and meltwater were evaluated at the headwater of the Urumqi River during the ablation seasons of 2003–2008. The results show that EC in meltwater can indicate the intensity of glacier ablation, which negatively correlated with air temperature and discharge. During the early ablation period, EC presents a fluctuation trend and runoff may be primarily from snow, frozen soil, and groundwater. EC decreases to the lowest level during the peak-flow period and runoff flows rapidly through a hydrological system predominantly in ice-walled conduits. EC increases to the highest level during the late ablation period, and runoff transports slowly through a distributed hydrological system at the ice-rock interface. EC in meltwater is far greater than in aerosols, surface snow, and precipitation, which are closely related to atmospheric circulation and dust loading. EC in snow pits denote the spatial variation of snow melting, the enrichment and loss of dissolved ions, and are affected by air temperature. The key ions to determine EC in meltwater are HCO_3^-, Ca^{2+} and SO_4^{2-}, and its dominant control might be biogeochemical pyrite oxidation coupled with calcite and/or dolomite dissolution.

DOI: http://dx.doi.org/10.1657/AAAR00C-13-138

Introduction

Electrical conductivity (EC) is closely associated with the concentration of total dissolved ions and is frequently used to estimate the mixing ratio of different water sources in hydrological systems (Hayashi et al., 2012). The EC in snow and ice varies with the loading of insoluble impurities in the atmosphere and subsequently glaciers, and can be used as an alternative indicator of atmospheric environment (Moore et al., 1992). Additionally, the EC in snow/ice provide valuable information about the source region of insoluble impurities and its transmission path (Hammer et al., 1985) and changes of a particular ion (Collins, 1981), and can be used as an indicator to track solute sources in glacier meltwater (Fenn, 1987). On a macroscopic scale, the EC in snow/ice over the Tibetan Plateau indicates the fluctuation of dust loading in the atmosphere, and positively correlates with Ca^{2+} in snow/ice from the continental source, suggesting that it is a good indicator of climate fluctuation in the arid and semiarid regions (Xiao et al., 2001). As a result, variations of the EC in snow/ice and glacier meltwater reflect the wet-dry deposition and the ablation intensity and process. In the wet (dry) years, less (more) dust is transported by the strong wind to the atmosphere above the glacier surface and then deposited in snow/ice through the wet/dry deposition processes, leading to a low (high) EC (Dong et al., 2008). The glacier ablation intensity also has a great influence on the EC in glacier meltwater due to the dilution of meltwater. Yet there are few studies available on the temporal and spatial variations of the EC during the ablation process of an alpine glacier.

Previous research showed that the EC in aerosols, snow pits, and meltwater at the headwater of the Urumqi River is affected by various factors including glaciation, permafrost conditions, moraine composition, and the interactions between water, rock, and atmospheric environment (Sheng and Yao, 1996). The EC in snow/ice of Glacier No.1 (GN1) has obvious seasonal variations, which are mainly affected by dust in central Asia (Li et al., 2007). Dong et al. (2009) indicated that the EC in snow pits corresponds well to the concentration of dust. Dust activity that reflects the cold dry climate leads to high EC values, whereas a warm wet climate leads to low EC values. Liu et al. (2005) analyzed the physical and chemical characteristics of sediment at the GN1 basin and indicated that the subglacial debris undergoes hydrolysis or carbonation, which leads to chemical element migration and enrichment releasing Ca^{2+}, K^+, Na^+, and silica sol. These processes directly cause spatial heterogeneity, periodic changes in chemistry, and variations in meltwater EC. This study, based on the EC in meltwater runoff from the GN1 at the headwater of the Urumqi River during the ab-

1523-0430/10 $7.00

lation period over 2003–2008, evaluates the temporal-spatial variations of the EC in meltwater and its controlling factors. Various methods of parameter comparison and statistical analysis are used. By comparing the variation of EC in atmosphere aerosols, snow pits, and precipitation, the differences in temporal-spatial variation of hydrochemistry, the characteristics of climate change, and their environmental significance are discussed.

Study Area and Methods

The GN1 (43°06′N, 86°49′E) is located at the headwater of the Urumqi River, eastern Tianshan Mountains (Fig. 1), and snow and ice meltwater from the GN1 is a major water source of the Urumqi River. The GN1 has an area of 1.65 km^2 and its drainage area is 3.34 km^2 (Liu et al., 2008). The GN1 gauging station is located at an elevation of 3659 m, about 300 m downstream of the GN1 (Liu et al., 2011), where meltwater discharge was monitored. In addition, the lithology of moraine at the headwater of the Urumqi River is primarily siliceous crystalline schist, with liberal amounts of granodiorite, gabbro, gneiss, quartzite, and granite, and occasional deposits of limestone. The dominant minerals are biotite, breadalbaneite, quartz, and dolomite, with small amounts of gypsum, carbonate, and pyrite (Wang and Zhang, 1981; Liu et al., 1999).

Meltwater was sampled at the GN1 gauging station (Fig. 1) at 14:00 daily during the periods 26 June to 30 August 2003, 21 May to 30 August 2004, and 8 May to 2 September 2008, and at 9:00 and 17:00 daily corresponding to the diurnal lowest and highest water stages during 1 June to 30 September 2013 in which a diurnal cycle was sampled once every two hours each month. Precipitation was sampled during the periods 19 June to 27 August 2003 and 5 May to 30 August 2004 at the Daxigou weather station at 3539 m a.s.l. (belonging to the China Meteorological Administration)

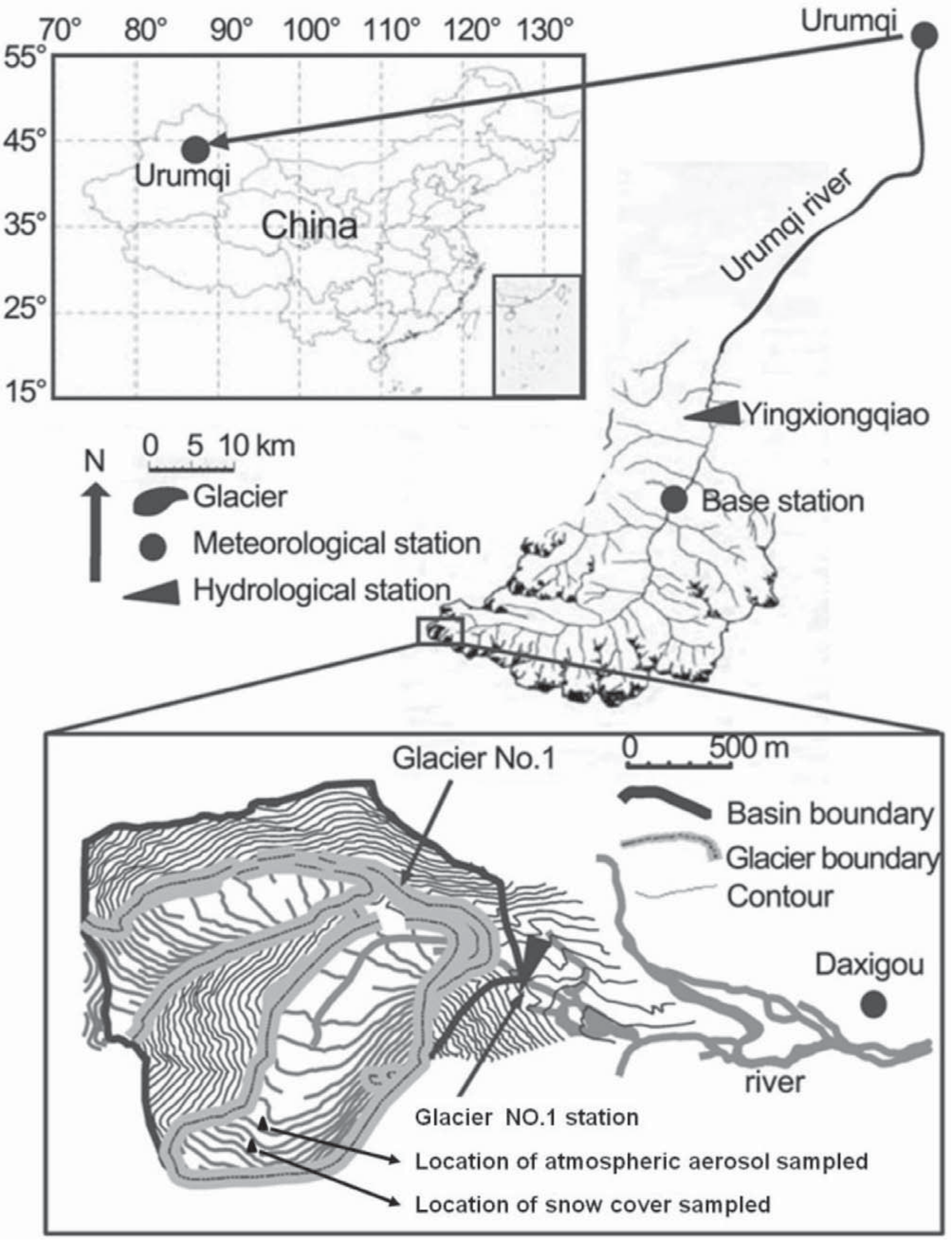

FIGURE 1. Sketch map showing the sampling sites, the GN1 gauging station, and the Daxigou weather station.

where meteorological data have been available from 1958. Both meltwater and precipitation samples were stored in the low-density polyethylene (LDPE) plastic bottles purified with deionized water beforehand. Snow/ice was sampled at an elevation of 4130 m in the accumulation area at the east branch of the GN1 during the periods 26 June to 30 August 2003, 21 May to 30 August 2004, and 13 July 2006 (Fig. 1). Snow samples were collected with a sampling frequency of once a week, and surface snow samples were taken from the top 5 cm of snow pits. Each snow/ice sample was carefully placed in a widemouthed LDPE plastic bottle in a frozen state to avoid evaporation and diffusion. Atmospheric aerosols were sampled at an elevation of about 4030 m at the east branch of the GN1 with a sampling frequency of once a week during 26 June to 30 August 2003 and 21 May to 30 August 2004. Aerosol samples were collected using a solar-powered 12 V DC pump. The sampling membrane was a Zeflour Teflon membrane with a pore size of 2 µm and a diameter of 47 mm. The volume of samples was measured using a volume flow meter. Atmospheric pressure and air temperature were measured every hour and used to calculate the standard volume of the air flowing through the membrane. Aerosol mass loadings were determined gravimetrically using a Sartorius MC5 electronic microbalance with a sensitivity of 1 µg. To extract the water-soluble species from the filters, each filter was wetted with 50 µL ultrapure ethanol, and the soluble components were then extracted with 10 mL Milli-Q water, followed by sonication in a water bath for 60 min. The samples were shaken twice on a mechanical shaker for 1 h each to completely extract the ionic compounds. The extracts were filtered with a 0.45 µm pore size microporous membrane, and the filtrates were stored at 4 °C in a clean tube before analysis.

The EC in meltwater was determined using an Orion-125A conductivity meter (with ±0.5% accuracy) in the field in order to reduce potential errors due to CO_2 and H^+ (Fenn, 1987). The EC in aerosol, snow/ice, and precipitation were determined using a DDSJ-308A conductivity meter (with ±0.1% accuracy) in the State Key Laboratory of Cryospheric Sciences (SKLCS), Chinese Academy of Sciences (CAS). Major cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}) in meltwater were analyzed by a Dionex 600 ion chromatograph using an IonPac CS12A column, 20 mM MSA eluent, and CSRS-ULTRA-II suppressor. Major anions (Cl^- and SO_4^{2-}) in meltwater were analyzed by a Dionex 2500 ion chromatograph using an IonPac AS11 column, 25 mM KOH eluent, and ASRS-ULTRA-II suppressor. The detection limits for all measured ions were below 0.1 µg L^{-1}.

Results and Discussion

SPATIAL AND TEMPORAL VARIATIONS

Interannual Variation

Table 1 shows the interannual variations of the EC in meltwater from the GN1 at the headwater of the Urumqi River over the period 1982–2008. Although the number of samples and the sampling time are not entirely consistent, the results reflect the interannual changes of the EC in meltwater relative to the changes in discharge, air temperature, and precipitation. Obviously, the EC in meltwater ranges from 27 (in 2007) to 537 µS cm^{-1} (in 2006), and its higher (lower) values appear over the period 2004 to 2006 (2007 to 2008), which corresponds to the relatively lower (higher) air temperature and precipitation during the ablation seasons (Table 1). This suggests that the interannual variation of the EC in meltwater may be associated with the variations of meteorological factors and may reflect the interannual differences in the glacier ablation intensity and associated water-rock interaction process in the subglacial/periglacial hydrological systems.

TABLE 1

Variations of mean, maximum (*Max*), and minimum (*Min*) values of the EC (µScm^{-1}) in meltwater from the GN1 over the period May to August of 1982–2008. T_m, P_t, and Q_d indicate the corresponding mean air temperature (°C) and total precipitation (mm) at the Daxigou weather station and mean discharge depth (mm) at the GN1 gauging station, respectively.

	1982*	2003	2004	2005	2006	2007	2008
n	105	62	40	83	94	36	109
Mean	86	102	243	168	182	72	85
Max	245	223	438	364	537	137	179
Min	30	46	95	62	60	27	34
T_m	2.7	2.9	3.6	3.5	3.8	4.2	4.5
P_t	384	375	343	402	383	448	386
Q_d	430	779	739	751	1020	659	755

n: Number in sample.

*From the Tianshan Glaciological Station (1982).

Seasonal Variations

The variations of EC in meltwater are closely associated with the bedrock mineralogy, the solution geochemistry (e.g., pH, mineral saturation states, and sediment concentrations), and the evolution of the subglacial hydrological system (Brown, 2002; Mitchell et al., 2004). Obviously, the EC in meltwater shows a clearly seasonal variation and a close association with meltwater discharge, air temperature, and precipitation during the ablation season (Fig. 2). During the period 8 May to 25 June (P_1), the EC ranging from 51.4 to 161 µS cm^{-1} (average value 91.1 µS cm^{-1}) presents a fluctuation trend. In detail, the EC shows lower values over 8 to 14 May and 28 May to 17 June and higher values over 15 to 27 May and 18 to 25 June, indicating a negative correlation with meltwater discharge ranging from 0.03 to 0.38 m^{3}s^{-1} (average value 0.16 m^3 s^{-1}). Correspondingly, air temperature ranging from –1.3 to 9.1 °C (average value 4.2 °C) presents an inverse fluctuation trend and a negative correlation with the EC in meltwater. Precipitation ranging from 0.2 to 14.3 mm (average value 3.8 mm) tends to present a relatively low fluctuation trend and an irrelevant association with the EC in meltwater. This suggests that lower (higher) temperature leads to weaker (stronger) ablation and less (more) meltwater during the early ablation period, in which meltwater may be primarily derived from snow cover, seasonally frozen soil, and groundwater. The melting of snow cover usually leads to an "ion pulse" phenomenon (Liu et al., 1997), suggesting that the retreat of snow cover may enhance variation of the EC in meltwater during the early ablation period, which is supported by the comparison between the EC in surface snow and meltwater (Fig. 3).

During the period 26 June to 13 August (P_2), the EC ranging from 33.5 to 126.7 µS cm^{-1} abruptly decreases to the lowest level and its average value (62.3 µS cm^{-1}) decreases by one-third relative to the period P_1 (Fig. 2). Correspondingly, meltwater discharge and air temperature present a sudden increasing trend, and their average values (0.4 m^3 s^{-1} and 6.2 °C) increase by almost double and

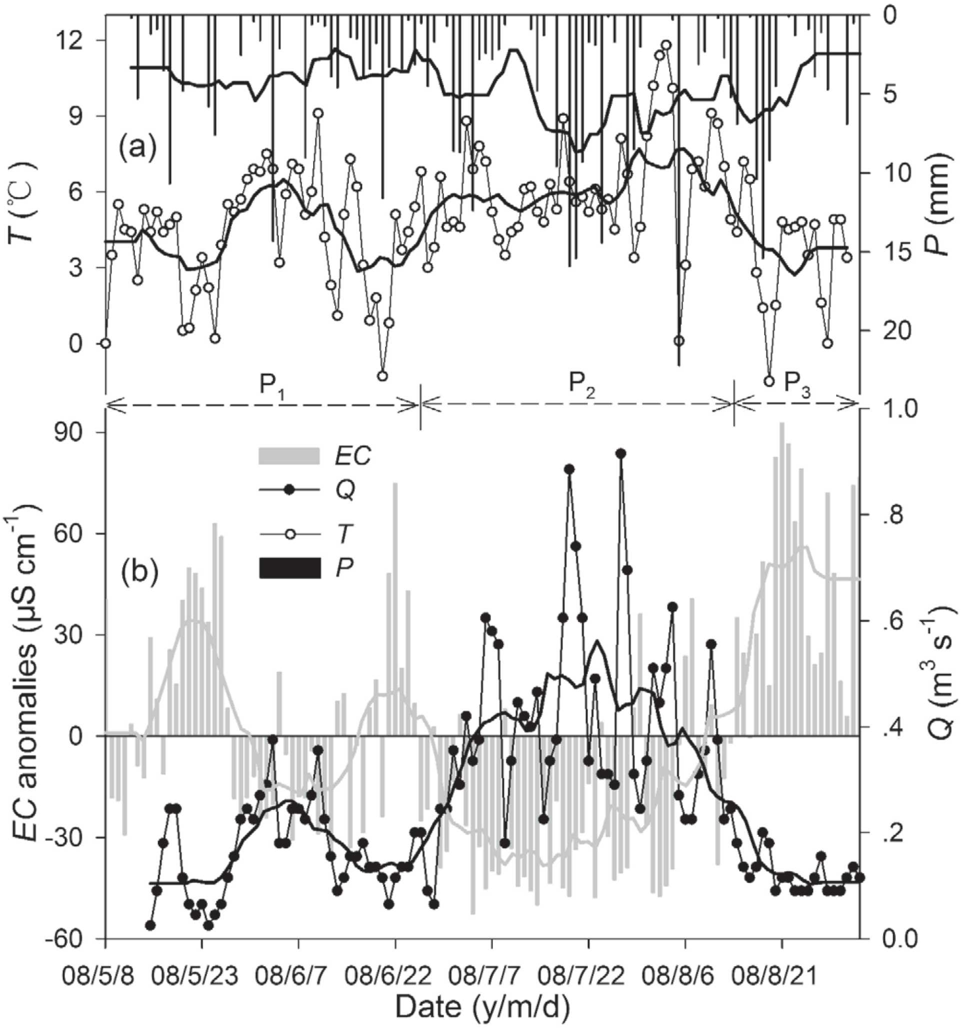

FIGURE 2. (a) Variations of air temperature and precipitation at the Daxigou weather station, and (b) the electrical conductivity (EC) in meltwater and meltwater discharge (Q) at the GN1 gauging station over the period 8 May to 2 September 2008.

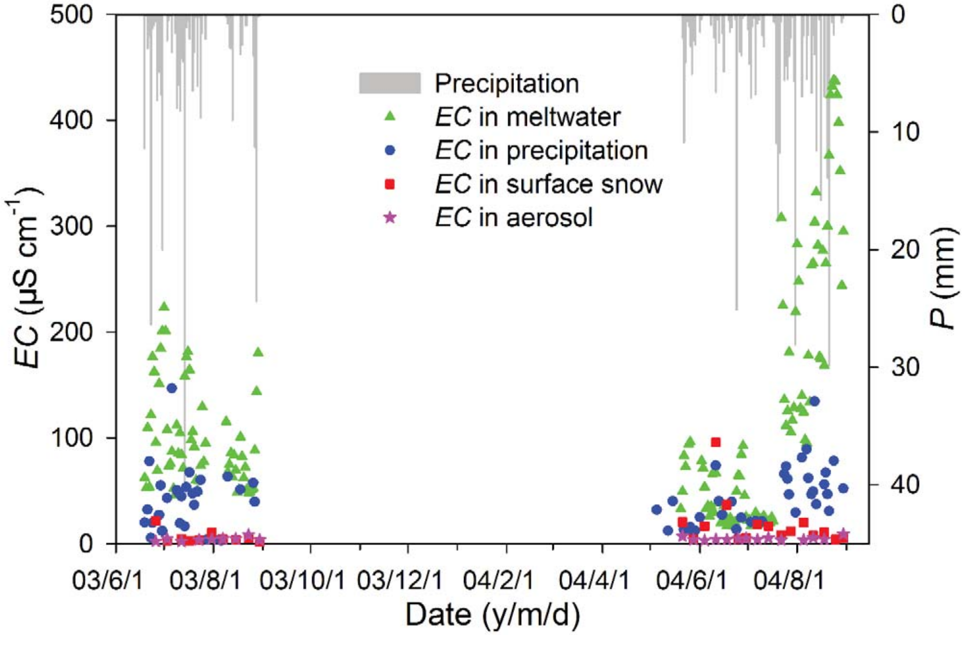

FIGURE 3. Variations of the EC in aerosols, surface snow, precipitation, and meltwater at the headwater of the Urumqi River over the ablation season of 2003 to 2004.

one-half, respectively, during the period P_2. Moreover, precipitation presents an obvious increasing trend and its average value (5.4 mm) increases by one-half relative to the period P_1 (Fig. 2), suggesting that precipitation may reduce the loading of total dissolved ions in meltwater due to the dilution process (Fig. 3). A sudden heavy rainfall may enhance the EC in meltwater, however, due to the dissolution of more surface materials from the erosion of slope soil, which may be supported by high values of the EC in meltwater relating to high precipitation events during the rainy seasons (Fig. 2). This suggests that meltwater discharge is mainly composed of precipitation and glacier ice meltwater during the peak-flow period, in which meltwater discharge flows rapidly through a hydrological system predominantly in ice-walled conduits, limiting the potential for solute acquisition, leading to the lowest loadings of total dissolved ions and the lowest values of EC in meltwater. During the period 14 August to 2 September (P_3), the EC, ranging from 85.8 to 178.8 $m^3 s^{-1}$, reaches the highest level and its average value (132.6 μS cm^{-1}) increases by one-half relative to the period P_1 (Fig. 2), suggesting that the glacier ablation decreases during the late ablation period. Correspondingly, meltwater discharge and air temperature decrease to a lower level similar to those during the period P_1 and their average values (0.12 $m^3 s^{-1}$ and 3.5 °C) range from 0.09 to 0.20 $m^3 s^{-1}$ and –1.5 to 7.2 °C, respectively. Precipitation ranging from 0.1 to 15.4 mm (average value 4.4 mm) presents a decreasing trend. This suggests that meltwater runoff transports slowly through a distributed hydrological system at the ice-rock interface, encouraging the potential for solute acquisition, resulting in higher loading of total dissolved ions and a higher value of the EC in meltwater.

The conceptual hydrological model shows that total meltwater runoff consists of quick-flow and delayed-flow components at the glacier basins (Brown, 2002; Tranter et al., 1993). At the minimum discharge, discharge is composed mainly of "delayed-flow" water from an inefficient distributed system, and then passes into a channelized system owing to high and low pressures in the distributed and channelized system, respectively (Hubbard et al., 1995). This promotes protracted and intimate contact with subglacial sediments, allowing more concentrated meltwater runoff to evolve (Brown et al., 1994, 1996). Conversely, as discharge increases, meltwater runoff is increasingly routed directly through a channelized system (Nienow et al., 1996), and solute is generated from the interaction of the supraglacial meltwater runoff and subglacial sediments (Brown et al., 1994, 1996). As more dilute water is routed into the subglacial environment, the dilution of delayed-flow water and duration of water-sediment interaction declines and thus reduces solute acquisition, resulting in lower concentrations of dissolved ions and then lower EC.

COMPARISONS AMONG AEROSOLS, PRECIPITATION, SURFACE SNOW, AND MELTWATER

The dissolved species adsorbed by the dust are usually carried by the wind to the atmosphere above glaciers and then accumulate onto the glacier surface through dry/wet deposition processes. The dust storms usually occur in spring at the headwater of the Urumqi River, which enhances the enrichment of dissolved ions in aerosols and precipitation and then the deposition in surface snow (Sheng and Yao, 1996). Thus, the EC in aerosols, precipitation, and surface snow are closely related to the atmospheric circulation and associated dust loading in the atmosphere. Additionally, most of the dissolved ions in snow cover and meltwater will be more or less washed away and will finally enter meltwater runoff during the ablation seasons, suggesting that the EC in snow cover is mainly affected by air temperature (not precipitation) during the elution process of dissolved ions (Li et al., 2006).

TABLE 2

Mean, maximum (*Max*), and minimum (*Min*) values of the EC (μS cm^{-1}) in aerosols, surface snow, precipitation, and meltwater at the headwater of the Urumqi River over the periods from June to August 2003 and May to August 2004.

	Aerosols	Surface snow	Precipitation	Meltwater
n	26	26	64	152
Mean	4.3	13.4	42.4	116.0
Max	9.0	95.5	146.6	438.0
Min	2.0	2.1	2.8	16.4
Max/Min	4.5	45.5	52.4	26.7

The data from aerosols, precipitation, surface snow, and meltwater during two summer ablation seasons are used here to systematically analyze the spatial change in the EC. The average value of the EC in meltwater is far greater than that in aerosols, surface snow, and precipitation, but its variation amplitude (*Max/Min*) is lower than that in surface snow and precipitation and higher than that in aerosols (Table 2; Fig. 3), suggesting that the EC in meltwater is determined by different factors from that in aerosols, surface snow, and precipitation. The EC in surface snow is lower than that in precipitation and higher than that in aerosols particularly for the ablation season of 2004 (Fig. 3), indicating that the EC in surface snow is closely related to the dry/wet deposition and elution processes. Moreover, the dissolved ions in surface snow are more or less washed away along with snow meltwater during the ablation seasons, resulting in lower EC values for surface snow than in precipitation. Thus, the EC provides a simple, convenient, and effective method of estimating the concentration and distribution of dissolved ions in different media (Smart, 1992). The variations of EC in meltwater reflect the characteristics of glaciations and the underlying surface, which are influenced by air temperature and precipitation. The EC in meltwater negatively correlates well with meltwater discharge and temperature, and meltwater discharge positively correlates well with air temperature, suggesting that the variations of EC in meltwater reflect the ablation intensity of glaciers due to changes in air temperature. Meltwater runoff and precipitation yield a poor correlation, indicating that the influence of precipitation on the dissolved ions is not as great as that of air temperature.

In addition, peak EC values for snow pits appear at the upper layers of snow pits at different altitudes on the GN1, and the EC decreases with the depth of snow pits (Fig. 4), suggesting the influence of the elution process on the EC in snow pits during the ablation season (Li et al., 2007). The profiles of the EC in snow pits change with their altitude (Fig. 4), denoting the spatial variation of snow melting and the enrichment and loss of dust-related dissolved ions in the process of glacier accumulation and ablation. This results in an increase in meltwater and a decrease in the EC in snow pits due to an increase in air temperature. Most of the high EC values for snow pits appear around the equilibrium line altitude (about 4068 m in 2006; Tianshan Glaciological Station, 2006), suggesting that the dissolved ions in snow pits are apt to gather in this area where snow pits are relatively stable and glacier accumulation equals glacier ablation.

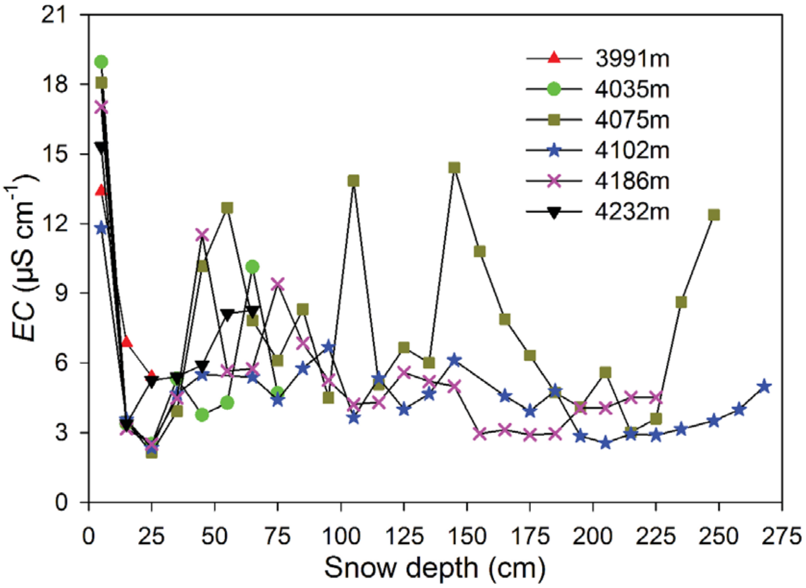

FIGURE 4. Variations of the EC in snow pits at different altitudes on the GN1 with the increase of snow depth during the ablation season (13 July 2006).

FACTORS TO DETERMINE THE EC

Studies indicated that the dust loading and related dissolved ions in surface snow are closely related to that in aerosols at the headwater of the Urumqi River (You and Dong, 2011). The dissolved ions to determine the EC in surface snow and precipitation are Ca^{2+}, Mg^{2+}, Na^+, and SO_4^{2-} (Li et al., 2007; Zhao et al., 2008). Significantly, the key ion to determine the EC is Ca^{2+} which derives from a local-plus-regional source and a long-distance source. Potential sources include local mineral aerosols entrained in the atmosphere by the strong winds that prevail during spring along with a more regional Asian dust flux (Li et al., 2006). Previous studies indicate that local bare rock and glacial sediments are available sources for Ca^{2+} (Williams et al., 1992; Sun et al., 1998; Hou and Qin, 2002), which is enhanced by the fact that calcification is the major soil formation process in semiarid and arid regions where abundant calcites are produced (Zhang et al., 2002).

The dissolved ions in meltwater are principally derived from atmospheric deposition and water-rock interaction, which mostly take place in subglacial and ice-marginal environments (Brown et al., 1994; Yde and Knudsen, 2004; Yde et al., 2005). Acid hydrolysis dominates chemical weathering, and carbonation draws CO_2 out of the atmosphere since it is a combination of relatively slow diffusion of gaseous CO_2 into solution and acid hydrolysis of minerals (Hasnain and Thayyen, 1999). Pyrite is the most common sulfide mineral at the glacial basins, and other sulphide minerals, metallic sulfides and silicate minerals may be additional sources of sulfate (Plummer et al., 1983). Table 3 shows correlation coefficients between the EC and dissolved ions in meltwater. The ions whose EC correlation coefficients exceed 0.45 ($p < 0.00001$) are HCO_3^-, Na^+, K^+, Ca^{2+}, Mg^{2+}, and SO_4^{2-}, indicating that these are the dominant ions to determine the EC in meltwater. In particular, the key ions dominating the EC in meltwater are HCO_3^-, Ca^{2+}, and SO_4^{2-} which account for 58.3%, 20.0%, and 15.4% of total ionic loading, respectively, followed by Mg^{2+} (2.0%), K^+ (1.9%), Na^+ (1.6%), and Cl^- (0.7%). Based on high loading of HCO_3^-, Ca^{2+}, and SO_4^{2-}, significant correlations for Ca^{2+} vs. Mg^{2+} and HCO_3^- ($r > 0.90$), and SO_4^{2-} vs. Ca^{2+} and Mg^{2+} ($r \geq 0.70$) (Table 3), it is suggested that the dominant control of chemical species might be biogeochemical pyrite (FeS_2) oxidation coupled with calcite ($CaCO_3$) and/or dolomite ($CaMg[CO_3]_2$) dissolution under oxidizing conditions. Feng et al. (2012) showed that the weathering of carbonate, pyrite, and feldspar dominates the solute acquisition at the headwater of the Urumqi River. This can be supported by the fact that glacier meltwater tends to carry relatively high calcium loading (Anderson et al., 1997), that the carbonate dissolution and sulfide oxidation dominate the solute fluxes (Anderson et al., 2000; Tranter et al., 2002), and that the fluxes of solutes produced by silicate weathering are relatively low at the glacial basins (Anderson, 2005). H_2CO_3-driven calcite dissolution requires a CO_2 source at the bed probably in the form of microbial respiration, and its extent reflects the water's residence time in a subglacial system, which modulates the accumulation of CO_2 (Anderson et al., 2003).

TABLE 3

Correlation coefficients between the EC and major dissolved ions in meltwater at the GN1 gauging station from June to September 2013. Italic numbers indicate the significant level at *p* < .00001 (*n* = 248).

	Na^+	K^+	Mg^{2+}	Ca^{2+}	Cl^-	SO_4^{2-}	HCO_3^-
EC	*0.49*	*0.54*	*0.54*	*0.58*	0.27	*0.55*	*0.47*
Na^+		*0.86*	*0.85*	*0.85*	*0.68*	*0.48*	*0.87*
K^+			*0.79*	*0.78*	*0.39*	*0.45*	*0.82*
Mg^{2+}				*0.95*	*0.39*	*0.70*	*0.90*
Ca^{2+}					*0.45*	*0.71*	*0.93*
Cl^-						*0.34*	*0.38*
SO_4^{2-}							*0.41*

Conclusions

EC in aerosols, snow, and meltwater were evaluated at the headwater of the Urumqi River during the ablation seasons of 2003–2008. EC in meltwater reflects the intensity of glacier ablation and negatively correlates with air temperature and discharge. EC presents a fluctuation trend and a negative correlation with discharge and air temperature during the early ablation period (P_1) in which runoff may be primarily from snow, frozen soil, and groundwater. EC abruptly decreases to the lowest level during the peak-flow period (P_2), in which discharge, air temperature, and precipitation increase, and runoff is mainly composed of precipitation and ice meltwater, which flows rapidly through a hydrological system predominantly in ice-walled conduits. EC reaches the highest level during the late ablation period (P_3), in which discharge and air temperature decrease to a lower level, precipitation presents a decreasing trend, and runoff transports slowly through a distributed hydrological system at the ice-rock interface. In addition, EC is far higher in meltwater than in aerosols, surface snow, and precipitation, and the factors to determine EC are different in each of these. EC in surface snow is lower than in precipitation and higher than in aerosols, and is closely related to the dry/wet deposition and elution process. EC in snow pits changes with the altitude, denoting the spatial variation of snow melting as well as the enrichment and leaching out of dissolved ions during accumulation and ablation. Dissolved ions in snow pits are apt to gather in the equilibrium line altitude area where snow pits are relatively stable and accumulation equals ablation. The key ions to determine EC in meltwater are HCO_3^-, Ca^{2+}, and SO_4^{2-}, which account for 58.3%, 20.0%, and 15.4% of total loading, respectively, and the dominant control of chemical species might be the biogeochemical pyrite oxidation coupled with calcite and/or dolomite dissolution.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (41271035, 41201060), Chinese Academy of Sciences (CAS) (KJZD-EW-G03-04), National Science and Technology Support Program (2013BAB05B03), Academy of Finland (Decision numbers 268170), Open Foundation of State Key Laboratory of Frozen Soil Engineering (SKLFSE201411), Open Foundation of State Key Laboratory of Cryospheric Science (SKLCS-OP-2014-06), West Light Program for Talent Cultivation of CAS, Fundamental Research Funds for the Central Universities (2014B16914), and Special Fund of State Key Laboratory of Hydrology–Water Resources and Hydraulic Engineering (20145027312). The authors thank their colleagues who worked in the Tianshan Glaciological Station.

References Cited

Anderson, S. P., 2005: Glaciers show direct linkage between erosion rate and chemical weathering fluxes. *Geomorphology,* 67: 147–157.

Anderson, S. P., Drever, J. I., Frost, C. D., and Holden, P., 2000: Chemical weathering in the foreland of a retreating glacier. *Geochimica et Cosmochimica Acta,* 64: 1173–1189.

Anderson, S. P., Drever, J. I., and Humphrey, N. F., 1997: Chemical weathering in glacial environments. *Geology,* 25: 399–402.

Anderson, S. P., Longacre, S. A., and Kraal, E. R., 2003: Patterns of water chemistry and discharge in the glacier-fed Kennicott River, Alaska: evidence for subglacial water storage cycles. *Chemical Geology,* 202: 297–312.

Brown, G. H., 2002: Glacier meltwater hydrochemistry. *Applied Geochemistry,* 17: 855–883.

Brown, G. H., Sharp, M., Tranter, M., Gurnell, A. M., and Nienow, P. W., 1994: Impact of post-mixing chemical reactions on the major ion chemistry of bulk meltwaters draining the Haut Glacier d'Arolla, Valais, Switzerland. *Hydrological Processes,* 8: 465–480.

Brown, G. H., Tranter, M., and Sharp, M., 1996: Experimental investigations of the weathering of suspended sediment by alpine glacial meltwater runoff. *Hydrological Processes,* 10: 579–597.

Collins, D. N., 1981: Seasonal variation of solute concentration in meltwater runoffs draining from an alpine glacier. *Annals of Glaciology,* 2: 11–16.

Dong, Z., Li, Z., Wang, F., et al., 2009: Characteristics of atmospheric dust deposition in snow on the glaciers of the eastern Tien Shan, China. *Journal of Glaciology,* 55(193): 797–804.

Dong, Z., Zhang, M., Li, Z., Wang, F., and Wang, W., 2008: The pH value and electrical conductivity of atmospheric environment from ice cores in the Tianshan Mountains. *Journal of Geography Science,* 19: 416–426.

Feng, F., Li, Z., Jin, S., Dong, Z., and Wang, F., 2012: Hydrochemical characteristics and solute dynamics of meltwater runoff of Urumqi Glacier No. 1, eastern Tianshan, northwest China. *Journal of Mountain Science,* 9: 472–482.

Fenn, C. R., 1987: Electrical conductivity. *In* Gurnell, A. M., and Clark, M. J. (eds.), *Glaciofluvial Sediment Transfer: An Alpine Perspective.* Chichester, UK: John Wiley and Sons, 377–414.

Giles, H. B., 2002: Glacier meltwater hydrochemistry. *Applied Geochemistry,* 17: 855–883.

Hammer, C. U., Clausen, H. B., and Langway Jr., C. C., 1985: The Byrd ice core: continuous acidity measurements and solid electrical conductivity measurements. *Annals of Glaciology,* 7: 214.

Hasnain, S. I., and Thayyen, R. J., 1999: Controls on the major-ion chemistry of the Dokriani glacier meltwaters, Ganga basin, Garhwal Himalaya, India. *Journal of Glaciology*, 45: 87–92.

Hayashi, M., Vogt, T., Machler, L., and Schirmer, M., 2012: Diurnal fluctuations of electrical conductivity in a pre-alpine river: effects of photosynthesis and groundwater exchange. *Journal of Hydrology,* 450–451: 93–104.

Hou, S., and Qin, D., 2002: The effect of postdepositional process on the chemical profiles of snow pits in the percolation zone. *Cold Regions Science and Technology,* 34: 111–116.

Hubbard, B. P., Sharp, M. J., Willis, I. C., Nielsen, M. K., and Smart, C. C., 1995: Borehole water-level variations and the structure of the subglacial hydrological system of Haut Glacier d'Arolla, Valais, Switzerland. *Journal of Glaciology,* 41: 572–583.

Li, X., Li, Z., Ding, Y., Liu, S., Zhao, Z., Luo, L., Pang, H., Li, C., Li, H., You, X., and Wang, F., 2007: Seasonal variations of pH and electrical conductivity in a snow-firn pack on Glacier No. 1, eastern Tianshan, China. *Cold Regions Science and Technology,* 48: 55–63.

Li, Z., Ross, E., Mosley-Thompson, E., Wang, F., Dong, Z., You, X., Li, H., Li, C., and Zhu, Y., 2006: Seasonal variabilities of ionic concentration in surface snow and elution process in snow-firn packs at PGPI Site on Glacier No. 1 in Eastern Tianshan, China. *Annals of Glaciology,* 43: 250–256.

Liu, F., Williams, M., and Yang, D., 1997: Preliminary investigation on the "ionic pulse" of snowmelt runoff at the Headwater of Urumqi River, TianShan. *Chinese Science Bulletin,* 42: 417–419.

Liu, F., Williams, M., Sun, J., Zhu, S. S., Hood, E., and Cheng, G. D., 1999: Hydrochemical processes and hydrological separation at the headwaters of Urumqi River, Tianshan Mountains, China. *Journal of Glaciology and Geocryology,* 21(4): 362–370.

Liu, G., Luo, R., Cao, J., and Cui, Z., 2005: Processes and environmental significance of the subglacial chemical deposits in Tianshan Mountains. *Science in China (D),* 48: 1470–1478.

Liu, Y., Metivier, F., Gaillardet, J., Ye, B., Meunier, P., Narteau, C., Lajeunesse, E., Han, T., and Malverti, L., 2011: Erosion rates deduced from seasonal mass balance along the upper Urumqi River in Tianshan. *Solid Earth,* 2: 283–301.

Liu, Y., Metivier, F., Lajeunesse, E., Lancien, P., Narteau, C., Ye, B., and Meunier, P., 2008: Measuring bed load in gravel-bed mountain rivers: averaging methods and sampling strategies. *Geodinamica Acta,* 21: 81–92.

Mitchell, A., Brown, G. H., and Fuge, R., 2004: Minor and trace element export from a glacierised alpine headwater basin (Haut Glacier d'Arolla, Switzerland). *Hydrological Processes,* 15: 3499–3524.

Moore, J. C., Wolff, E. W., Clausen, H. B., and Hammer, C. U., 1992: The chemical basis for the electrical stratigraphy of ice. *Journal of Geophysical Research,* 97: 1887–1896.

Nienow, P., Sharp, M., and Willis, I., 1996: Velocity-discharge relationships derived from dye-tracer experiments in glacial meltwater runoffs: implications for subglacial flow conditions. *Hydrological Processes,* 10: 1411–1426.

Plummer, L. N., Parkhurst, D. L., and Thorstenson, D. C., 1983: Development of reaction models for ground water systems. *Geochimica et Cosmochimica Acta,* 47: 665–685.

Sheng, W., and Yao, T., 1996: Acidity variation in the Guliya Ice Cap region approached by pH and electrical conductivity in ice core[A]. *In* Proceedings, Fifth Chinese Conference on Glaciology and Geocryology, Volume 1[C]. Lanzhou: Gansu Culture Press, 219–226.

Smart, C. C., 1992: Temperature compensation of electrical conductivity in glacial meltwater runoffs. *Journal of Glaciology,* 38: 9–12.

Sun, J., Qin, D., Mayewski, P. A., Dibb, J. E., Whitlow, S., Li, Z., and Yang, Q., 1998:, Soluble species in aerosol and snow and their relationship at Glacier 1, Tien Shan, China. *Journal of Geophysical Research,* 103(D21): 28022–28027.

Tianshan Glaciological Station. 1980~2006: *Annual Report of Tianshan Glaciological Station, Chinese Academy of Sciences,* Volumes 1–18. Lanzhou: Cold and Arid Regions Environmental and Engineering Research Institute.

Tranter, M., Brown, G. H., Raiswell, R., Sharp, M., and Gurnell, A., 1993: A conceptual model of solute acquisition by Alpine glacial meltwater runoffs. *Journal of Glaciology,* 39: 573–581.

Tranter, M., Huybrechts, P., Munhoven, G., Sharp, M. J., Brown, G. H., Jones, I. W., Hodson, A. J., Hodgkins, R., and Wadham, J. L., 2002: Direct effect of ice sheets on terrestrial bicarbonate, sulphate and base cation fluxes during the last glacial cycle: minimal impact on atmospheric CO_2 concentrations. *Chemical Geology,* 190: 33–44.

Wang, J., and Zhang, Z., 1981: Glacial sediments at headwater basins of Urumqi River, Tian Shan. *Journal of Glaciology and Geocryology,* 3 (Suppl.): 49–56.

Williams, M. W., Tonnessen, K. A., Melack, J. M., and Yang, D., 1992: Sources and spatial variation of the chemical composition of snow in the Tianshan, China. *Annals of Glaciology,* 16: 25–32.

Xiao, C., Yao, T., Qin, D., et al., 2001, The relations of snow-ice conductivity and precipitation alkalinity and atmospheric dust load change in Qinghai-Tibet Plain. *Science in China (D),* 34: 362–371.

Yde, J. C., and Knudsen, N. T., 2004: The importance of oxygen isotope provenance in relation to solute content of bulk meltwaters at Imersuaq Glacier, West Greenland. *Hydrological Processes,* 18: 125–139.

Yde, J. C., Knudsen, N. T., and Nielsen, O. B., 2005: Glacier hydrochemistry, solute provenance, and chemical denudation at a surge-type glacier in Kuannersuit Kuussuat, Disko Island, West Greenland. *Journal of Hydrology,* 300: 172–187.

You, X., and Dong, Z., 2011: Deposition process of dust microparticles from aerosol to snow-firn pack on Glacier No. 1 in eastern Tianshan Mountains, China. *Journal of Earth Science,* 22: 460–469.

Zhang, D., Peart, M. R., Jim, C. Y., et al., 2002: Alkaline rains on the Tibetan Plateau and their implication for the original pH of natural rainfall. *Journal of Geophysical Research,* 107(D14): 9-1–9-6, http://dx.doi.org/10.1029/2001JD001332.

Zhao, Z., Tian, L., Fischer, E., Li, Z., and Jiao, K., 2008: Study of chemical composition of precipitation at an alpine site and a rural site in the Urumqi River Valley, Eastern Tien Shan, China. *Atmospheric Environment,* 42: 8934–8942.

MS accepted January 2015