



Hydrochemical characteristics of ground ice in permafrost regions of the Qinghai-Tibet Plateau



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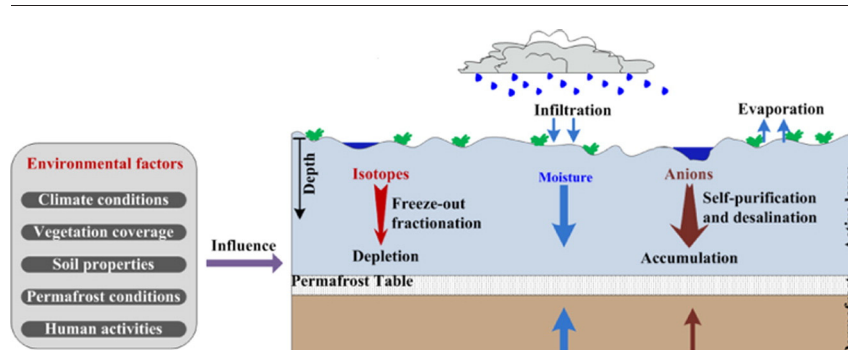
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HIGHLIGHTS

- The hydrochemical characteristics of ground ice of the QTP were examined.
- Well-developed hydrochemical depth gradients occurred within the soil profile.
- Freeze-out fractionation, self-purification, and desalination affect hydrochemistry.
- Soil moisture, air temperature, and active layer thickness have great impacts on the characteristics of ground ice hydrochemistry.

GRAPHICAL ABSTRACT



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ABSTRACT

Ground ice is a distinctive feature of permafrost terrain. The vertical distribution and factors controlling the hydrochemistry of ground ice are important for studying soil moisture and salt migration during the freeze–thaw process in soil. These factors are also important components of hydrological cycles in cold regions. The hydrochemical characteristics of ground ice on the Qinghai-Tibetan Plateau (QTP) are not well known. We examined the characteristics of ground ice hydrochemistry using data from 9 soil profiles in permafrost regions of the central QTP. The isotopes and anion concentrations of subsurface water on the QTP were higher than those in Arctic polygonal ground regions. The spatial distribution of anions was complex. Well-developed hydrochemical depth gradients occurred within the soil profile. Isotopes decreased and anions increased with depth, suggesting general vertical patterns of soil hydrochemistry across different permafrost regions. Cl^- and SO_4^{2-} concentrations in soil water increased with depth, while NO_3^- concentration did not change with depth. Freeze-out fractionation, self-purification, and desalination greatly impact soil hydrochemistry. The major factors controlling variation of soil water chemistry were soil moisture, air temperature, and active layer thickness. The results could provide a framework for understanding ground ice origins and the moisture and salt migration pathways in the context of permafrost changes. This information could be useful in developing process-based permafrost hydrologic models.

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1. Introduction

Soil hydrochemistry in permafrost regions is important in biogeochemical cycling (Newman et al., 2015), and may affect the freshwater resource utilization and ecological functioning of soils, lakes, and rivers (Lamhonwah et al., 2017; Song et al., 2017). Dissolved ion concentrations in soil water reflect redox states, nutrient cycling by plants, mineralogy, cation exchange capacities, and moisture migration pathways (Boucher and Carey, 2010; Newman et al., 2015), and their vertical distributions could provide insight into the sources and pathways of soil moisture and salt (Harris et al., 2007). Ground ice is a distinctive feature of permafrost terrain and is an important hydrological reservoir and a proxy index of past climates (Meyer et al., 2002), which were sensitive to climate change (Yang et al., 2017). Ground ice hydrochemistry reflects hydrological and geochemical cycling during the freeze–thaw process (Kokelj and Burn, 2003). Therefore, it is important to understand the characteristics of ground ice hydrochemistry under a warming climate.

The Qinghai-Tibet Plateau (QTP) is the largest low-latitude and high-altitude permafrost region on earth, and it occupies approximately 8% of the global permafrost area (Jin et al., 2007). This area is vulnerable to climate change (Wang et al., 2011). The total volume of ground ice on the QTP is about 9528 km³ (Zhao et al., 2010). The QTP has suffered permafrost degradation in recent decades due to climate warming (Cheng and Wu, 2007; Wu et al., 2015), thickening of the active layer, and thawing of ground ice, particularly near the permafrost table (Wu and Zhang, 2010). This has influenced hydrological and ecological processes, plant communities, biogeochemical cycling, and soil water chemistry (Frey and McClelland, 2009; Cheng and Jin, 2013; Throckmorton et al., 2016; Lamhonwah et al., 2017). Due to the harsh environment, limited hydrological monitoring network, and the lack of long-term field observations, the sources and pathways of soil water and solutes migration in permafrost regions remain poorly understood in the context of permafrost degradation (Lamhonwah et al., 2017). This has resulted in uncertainties when simulating and predicting the regional hydrological and biogeochemical cycling (Painter et al., 2013; Newman et al., 2015). Previous studies in permafrost regions mainly focused on the hydrochemistry of seeps (Harris et al., 2007) and soil pore water (Pokrovsky et al., 2006; Jessen et al., 2014; Raudina et al., 2017). Element migration has been analyzed and soil hydrochemical impacts of climate change on arctic polygonal ground has been studied (Newman et al., 2015; Lamhonwah et al., 2017). However, few studies have examined the hydrochemistry of ground ice in permafrost-affected regions, particularly in the active layer and the underlying permafrost layer (Petroni et al., 2006). Study of the spatial distributions and controlling factors of ground ice hydrochemistry on the QTP is necessary to understand the migration mechanism of soil moisture and salt.

Several mechanisms could shape the vertical patterns of ground ice chemistry. These include flushing (Lamhonwah et al., 2017), evapoconcentration (Zagana et al., 2007), leaching (Whitehead, 2000), cryoturbation (Ping et al., 2015), and self-purification and desalination (Wang et al., 1996). The subsurface water chemistry in arctic polygonal ground can be affected by microtopography, depth (Newman et al., 2015), rainfall, ground ice (Lamhonwah et al., 2017), active layer thickness (Frey et al., 2007), and permafrost thawing (Kokelj and Burn, 2003). In addition, vegetation types, soil texture, and soil moisture also play key roles in base ions in alpine grassland (Tian et al., 2017). Jobbágy and Jackson (2001) found that K⁺ decreased with depth, while Mg²⁺, Na⁺, Cl⁻, and SO₄²⁻ increased with depth. However, the generality of vertical patterns and controls of ground ice hydrochemistry has not been thoroughly examined in permafrost regions of the QTP.

We analyzed the spatial variations and controls of ground ice hydrochemistry in permafrost regions on the QTP using data from 9 soil profiles sampled from September 20 to October 9, 2015. The study objectives were to examine the spatial variation of ground ice

hydrochemistry on the QTP and to determine the influence of environmental factors on ground ice chemistry. The result would be expected to enhance our understanding of ground ice origins and the moisture and salt migration pathways under a warming climate.

2. Study area

The study area was in the continuous permafrost region of the central QTP. Water samples were collected from 9 sites along the Qinghai-Tibet Highway (QTH) (Fig. 1a). The 9 sampling sites from north to south were Xidatan1 (Q1), Xidatan2 (Q2), Konlunshan (Q3), Qingshuihe (Q4), Wudaoliang1 (Q5), Wudaoliang2 (Q6), Kekexili (Q7), Fenghuoshan (Q8) and Tanggula (Q9), respectively, and the elevation ranged from 4488 m to 4960 m. The slope in these locations was <5° (Fig. 1b, Table 1 in Supporting Information). This area is characterized by a sub-frigid semiarid climate (Li et al., 2012), with mean annual air temperature ranging from -5.3 to -2.2 °C and mean annual precipitation of 212 to 310 mm (data from the Chinese National Meteorological Centre, 2015). Precipitation in this region has a seasonal distribution, with 83% occurring from May to September (Zhao et al., 2008). The active layer thickness ranged from 1.4 to 3.1 m, and the mineral substrate is dominated by sandy loam and loam (Table 1 in Supporting Information; Fig. 1d). The vegetation types present include alpine desert, alpine steppe, and alpine meadow, with vegetation coverage ranging from 12% to 90% (Table 1 in Supporting Information, Fig. 1c).

3. Methodology

3.1. Field and laboratory methods

Fieldwork was conducted from September 20 to October 9, 2015, when the thaw depth of the active layer reached an annual maximum. Water samples included active layer water, ground ice near permafrost table, and permafrost water. These were collected from 9 sites in permafrost regions along the QTH by excavation of the soil profile (Fig. 1b). For each soil profile, active layer water samples were collected at the thawing layer. Ground ice samples were collected near the permafrost table and permafrost water samples were collected at a 0.5 m below the permafrost table. Precipitation samples were collected at the Tanggula meteorological station from September 20, 2015 to October 1, 2016. A total of 158 water samples were collected (38 precipitation, 66 active layer water, 27 ground ice near permafrost table, and 27 permafrost water). All samples were immediately sealed in 250 mL high-density polyethylene bottles using disposable PE gloves, wrapped with parafilm to avoid evaporation, and stored in coolers until they were returned to the laboratory.

The vegetation coverage at all sites was studied using a quadrat method. Within each 100 m × 100 m site, five 1 m × 1 m quadrats were uniformly established to measure the vegetation types and coverage (Zhao and Sheng, 2015). Soil bulk density and moisture content were determined while collecting soil water samples at each site. Bulk density was measured by the clod method using a bulk soil sampler with a stainless steel cutting ring (5 cm in diameter and high). Samples used for soil moisture content determination were stored in aluminum sampling boxes that were sealed to prevent changes of soil moisture. Soil gravimetric moisture content was determined by weighing and drying soil samples at 105 °C for 24 h and was expressed as the ratio of the mass of water over the dry weight of the soil sample. Soil temperature was measured using a 105 T Thermocouple Probe manufactured by Campbell Scientific Inc. with an analytical precision of ±0.1 °C according to depth increments at each site. The soil temperatures were continuously monitored by the Cryosphere Research Station on the Qinghai-Tibet Plateau, Chinese Academy of Sciences.

The stable isotope compositions and major ion concentrations in water were determined at the State Key Laboratory of Cryosphere Sciences, Northwest Institute of Eco-Environment and Resources, Chinese

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