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Isotopic characteristics of snow and its meltwater over the Barton Peninsula, Antarctica

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A B S T R A C T

The stable isotopic compositions of snow and meltwater are a very useful tool to investigate water provenances and to increase the accuracy of paleoclimate studies in glacial watershed systems. To better understand the factors that affect the isotopic compositions of snow and meltwater in the western Antarctic Peninsula, the isotopic compositions of snow/ice and meltwater from the Barton Peninsula in Antarctica were examined. The isotopic compositions of snow are more enriched than those of meltwater and the variability of the isotopic compositions decreases from snow to meltwater. The melting process changes the linear slope between two water isotopes, which is different from the meteoric water line. We observe that the isotopic compositions of snow are altered by tephra, which results in isotopically enriched snow that is covered by tephra. This tephra decreases the snow's albedo, and the increased energy that is absorbed by the snow surface increases the melting rate, which causes isotopic exchange between liquid water and ice. Hydrological processes, such as daily variations in the melting rate and contributions from groundwater/runoff to seawater, also affect the isotopic compositions of water over the Barton Peninsula. Our works imply that uncertainty caused by these variations should be considered when applying stable water isotopes in this area for water flowpath and paleoclimate study.

1. Introduction

Better understanding of the controls on water resources, flow paths, and water travel times in both polar regions, which are highly sensitive to climate change, is very important (Barnett et al., 2005; Lee et al., 2008a; Lee et al., 2008b; Piao et al., 2010). In glacier-fed watershed systems, the principal water sources to bulk run-off originate from ice melt, snowmelt, rainfall, and groundwater components (Yde et al., 2016). Investigating stable water isotopes is a very useful technique to infer the water origin, movement, and history in glacially fed watersheds. Laboratory, field, and numerical experiments proved that the isotopic compositions of meltwater vary over time throughout melting (Taylor et al., 2001; Dahlke and Lyon, 2013; Ham et al., 2019). This observation is crucial to the accuracy of 1) estimations of snow/ice contributions to stream-water alpine hydrology, 2) reconstructions of paleoclimate variables in ice-core studies, and 3) reconstructions of paleoenvironments in limnology (Jouzel et al., 1982; Wolfe and Edwards, 1997; Stenni et al., 2017).

Stable water isotopic measurements have been extensively used to study hydrological cycles, particularly processes that are related to water movement among different reservoirs (Lee et al., 2010a; Steen-Larsen et al., 2014). The isotopic compositions of snow/ice are a very useful tool to investigate the contributions from sub-surface water and meltwater to glacial river systems (Moore et al., 2005; Yde et al., 2016; Kim et al., 2017). Thus, the isotopic compositions can be used to determine the timing and origin of changes in water sources and flow paths because different water masses often have isotopically different isotopic compositions (Taylor et al., 2001). In ice-core studies, the isotopic compositions of snow/ice have been used to infer paleo-temperatures based on the linearity between precipitation stable isotopes and surface temperature. In limnology, lake sediments act as “memory cards” that record most climate changes over time. The oxygen-isotope records in sediments, thus, result from changes in precipitation vs. evaporation, variations in lake temperature, changes in hydrological pathways that provide water to the lake, and oscillations in the oxygen isotopes in precipitation or the temperature at the source of precipitation (Monien et al., 2011; Bush et al., 2017; Yang et al., 2017; Werner et al., 2018). In all cases, the isotopic compositions of snow/ice have been assumed constant or not modified by other physical processes over time.

The western Antarctic Peninsula is one of the most sensitive and dynamic areas on the Earth's surface, where the cryosphere systems respond rapidly to climate changes (Domack et al., 2001). One consequence of the local warming trend is a significant increase in the melting of the continent glaciers. Although chemical weathering is still negligible on continental Antarctica (Lee et al., 2004), enhanced melting may modify the isotopic compositions of snow/ice. To date, however, comprehensive isotopic investigations of snow and meltwater

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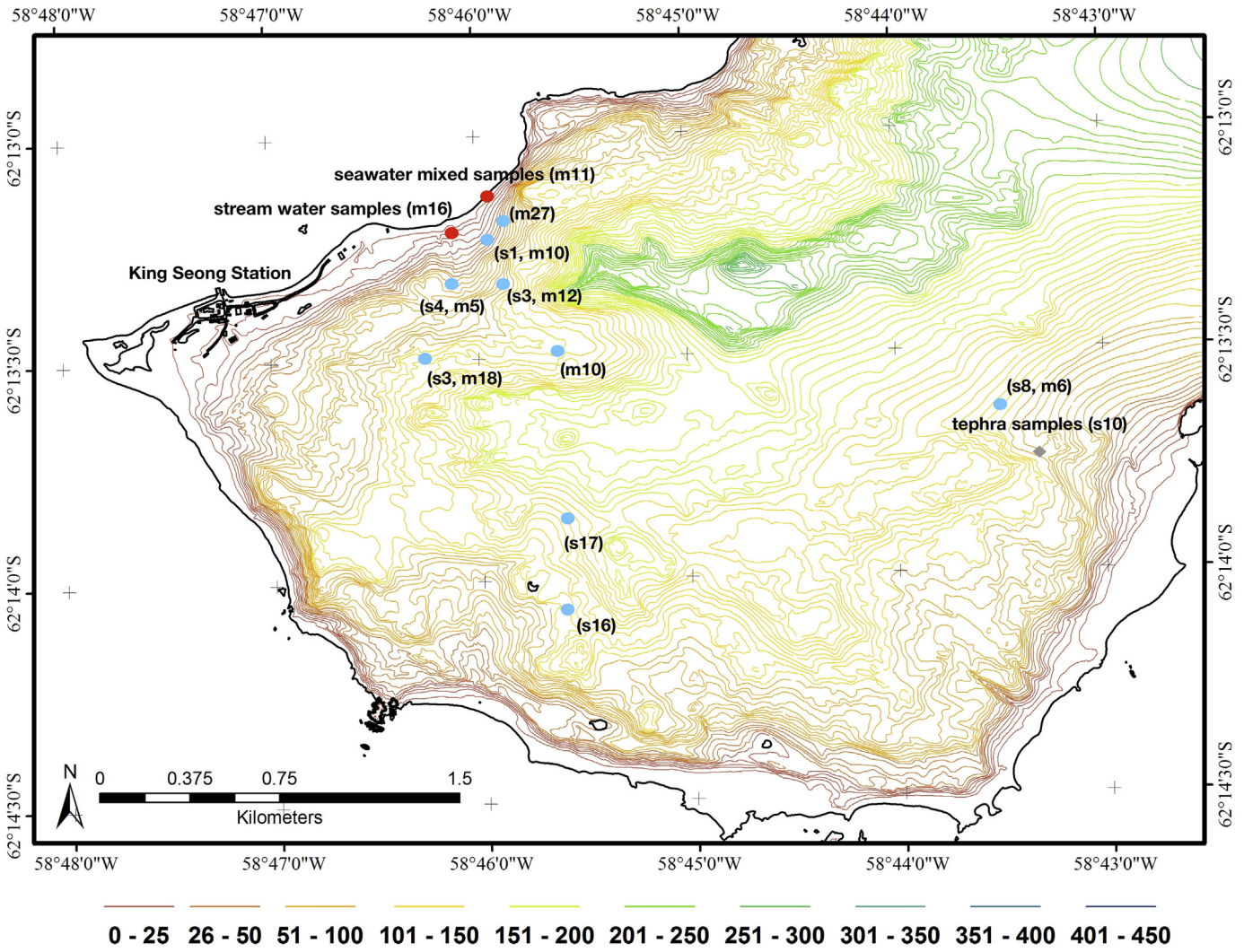

Fig. 1. Topography and sampling locations of the study area. In each parenthesis, s and m represent snow and meltwater, respectively. For example, s10 represents 10 snow samples.

in this area are nonexistent. In this study, the first comprehensive isotopic characterization of meltwater and snow/ice from the Barton Peninsula on King George Island is presented here. Our work is, thus, designed to increase our understanding of isotopic processes of melting in the glaciers by investigating stable water isotopes in snow/ice and meltwater from the Barton Peninsula for hydrology and limnology implications.

2. Study area and methods

2.1. Study area

King George Island is the largest of the South Shetland Islands archipelago, which is located at the northern tip of the Antarctic Peninsula (61°50′S to 62°15′S and 57°30′W to 59°01′W). King George Island is in the middle of the South Shetland Islands, with > 90% of its volcanic bedrock covered by snow and ice. The study area, the Barton Peninsula, is the southwestern region of King George Island (KGI, Fig. 1). The surface area of KGI is approximately 1310 km^2. Most of King George Island is covered with glaciers (approximately 92%), and ice-free areas are exposed only along the shorelines in restricted areas. The Barton Peninsula has a rugged topography with a wide and gentle slope in the central belt, having elevations of 90–180 m above sea level. Geologically, mafic to intermediate volcanic lavas are widely distributed in the peninsula, which makes constraining the eruption difficult (Lee et al., 2004). A granodiorite stock with minor fine-grained diorite occurs in the central northern peninsula, which was intruded during the Eocene. Several units of thick-bedded lapilli tuffs are intercalated with lava flows. Although the eruption ages are difficult to constrain, most of the lavas likely erupted from the Paleocene to Eocene (Lee et al., 2004)

King George Island has a cold oceanic climate. Weather data for the study area measured at the King Sejong Station during the study year (winter of 2013) showed an average annual temperature of −2.5 ± 4.6 °C (1σ), relative humidity of 87.1 ± 7.8%, precipitation of 598.2 mm, and wind speed of 8.1 ± 4.6 m/s, with the major directions being northwest and southwest. The depth of the snow cover is 2–73 cm (Lim et al., 2014), and snow mostly melts substantially in summer. This area is warmer and more humid than other Antarctic regions, with a relatively high availability of water in the summer. These features favor periglacial processes and the presence of a usually saturated active layer in summer. The depth of the active layer reaches 1 m, and permafrost is present below the active layer (Lee et al., 2004).

2.2. Sampling and analytical methods

Snow (n = 62) and meltwater (n = 116) samples for water-isotope analysis, totaling 178 samples for this study, were taken from 9 to 30

January 2014 to understand the isotopic variations in snow/ice and meltwater. Snow samples were collected at the surface. And meltwater samples were collected at the top, middle and bottom of a stream nearby the snow where we collected the snow samples. The locations of distinct samples are presented in Fig. 1. Snow/ice samples were sampled in plastic bags and melted at the King Sejong Station in polyethylene bottles, and meltwater samples were stored in polyethylene bottles in the field and kept frozen until analysis at the Korea Polar Institute (KOPRI). Snow samples that were covered by tephra and clean snow samples were collected to examine how impurities affect the isotopic compositions of snow. Five snow samples from the tephra area and four samples from clean snow were collected. The first sample was taken at a distance of 35 cm from a tephra hill, and subsequent samples were taken at intervals of 100 cm in the both directions. Mixed seawater samples were collected at the edge of the coast near the King Sejong Station.

The samples were analyzed for both δD and $\delta^{18}O$ on a wavelength-scanned cavity ring-down spectroscope (L-2120-I, Picarro), which is one type of isotope-ratio infrared spectroscope that is installed at the KOPRI. The D/H and $^{18}O/^{16}O$ ratios were expressed in δ notation as part-per-thousand differences relative to the Vienna Standard Mean Ocean Water. Memory effects were corrected as suggested by Penna et al. (2012), and the precisions of oxygen and hydrogen were 0.08‰ and 0.6‰, respectively (1σ).

3. Results and discussion

Our research objective was to study the variations in the isotopic compositions of snow/ice and meltwater from the King Sejong Station in the Barton Peninsula. In this section, we show the isotopic results of meltwater and snow/ice from the study area and discuss their patterns and the factors that influenced these isotopic variations.

3.1. Isotopic changes from melting

One widely used isotopic technique in isotope hydrology is to explore the slope of the $\delta^{18}O$ vs. δD regression line. Usually, soil- or lake-water evaporation produces a slope below eight, which is the slope of the local meteoric water line. The δD-$\delta^{18}O$ diagram from the study area is shown in Fig. 2. The slope of the $\delta^{18}O$-δD relationship for the whole samples (snow and meltwater) was 7.0, which indicates that the original snow experienced isotopic fractionation through significant melting.

Processes other than evaporation, such as an isotopic exchange between liquid water and ice/snow or between water vapor and ice/snow, may also affect the slope of the $\delta^{18}O$ vs. δD relationship (Lee et al., 2010a). Earman et al. (2006) explored the $\delta^{18}O$ vs. δD slope to identify processes (exchange between snow and water vapor) that are responsible for the alteration of snow isotopic compositions (88.2/11.4–7.7). Sublimation can be minor influence during the melting season when solar radiation causes relatively intensive melting at the snow surface. Vapor-ice exchange may be critical during the early accumulative phase of the snow when the temperature is low and melting is limited.

Zhou et al. (2008) observed that the $\delta^{18}O$ vs. δD slope of a glacier decreased with time and attributed this result to the thawing and refreezing of pore water that had a smaller $\delta^{18}O$–δD slope than ice. Lee et al. (2010a) attributed the slope decrease to isotopic exchange between liquid water and ice according to field observations and model calculations. Such a slope decrease can be obtained without incorporating sublimation or evaporation (Stichler et al., 2001; Earman et al., 2006).

The comparison between snow and meltwater throughout the study area is shown in Table 1 and Fig. 3. The mean values of $\delta^{18}O$ in snow were significantly greater than those in meltwater ($p < .0001$). The standard deviations decreased from snow to snowmelt, indicating that the variability of the isotopic compositions decreased from snow to snowmelt and implying that isotopic redistribution occurred because of snow metamorphism and melting at the surface. Similar observations were previously reported for isotopic variations in temperate regions (Taylor et al., 2001; Unnikrishna et al., 2002; Lee et al., 2010a).

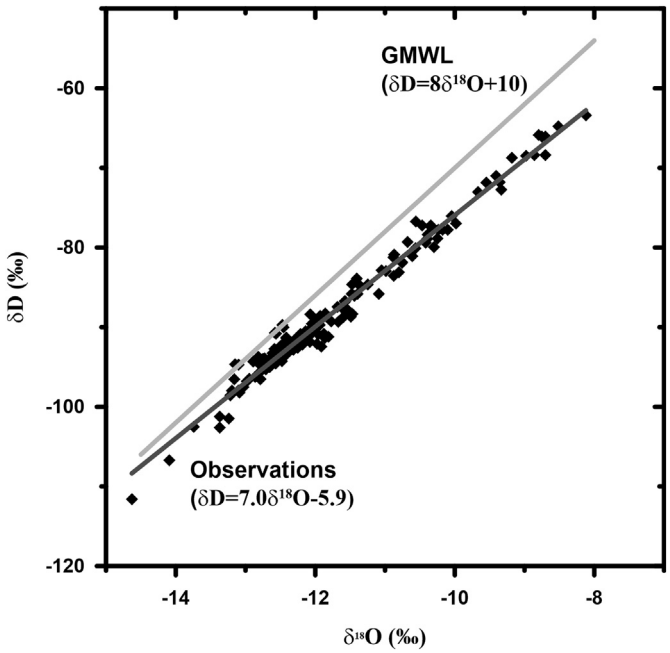

Fig. 2. Linear relationship between $\delta^{18}O$ and δD in snow and meltwater from the study area; the slope of snow and meltwater is smaller than that of the GMWL.

Generally, the meltwater became enriched in ^{18}O and D as the snow melted, particularly during the summer melting season. Laboratory data by Herrmann et al. (1981) and Taylor et al. (2001) presented that both meltwater and remaining snow in a column becomes increasingly enriched in ^{18}O as melting progresses. Many other field studies indicated that the mean $\delta^{18}O$ of snow increases throughout the winter, which reflects how isotopically light water is lost earlier in the season, causing the snow and meltwater to become progressively heavier (Taylor et al., 2001; Feng et al., 2002; Taylor et al., 2002; Lee et al., 2010a). When snow melts at the surface, little isotopic fractionation occurs because the entire snow layer is melted. As this meltwater infiltrates down the snow/ice, isotopic exchange between liquid water and ice occurs.

3.2. Isotopic redistribution from impurities at the snow surface

Snow albedo can be decreased if any impurities are present, such as black carbon and continental dust, on the snow/ice surface beyond the snow itself (Sterle et al., 2013). With a lower snow albedo, the absorption of solar radiation increases, thereby accelerating snowmelt, which is very crucial in climate change and hydrology in many areas of the world. Changes in melting rates at the snow surface are accompanied by changes in the percolation of liquid water in the snow and the contact time between liquid water and snow (Taylor et al., 2001). Lee (2014) numerically examined how isotopic exchange between liquid water and snow/ice with different melting rates influences isotopic variations in snow and showed how differences between the isotopic compositions of snow/ice and meltwater decrease as the melting rate increases.

We observed that the isotopic compositions of clean snow were more depleted than those of snow that was covered by weathered tephra in the study area (Fig. 4). The presence of tephra decreased the snow albedo, causing the snow to absorb more solar radiation. The

Table 1
Isotopic characteristics of snow and meltwater from the Barton peninsula.

	Snow	Meltwater
Mean value	$\delta^{18}O$: −10.94 ± 1.8 (1σ) δD: −83.05 ± 11.0 (1σ)	$\delta^{18}O$: −12.30 ± 0.5 (1σ) δD: −91.78 ± 3.65 (1σ)
Maximum	−8.12, −63.41 ($\delta^{18}O$, δD)	−10.24, −77.25 ($\delta^{18}O$, δD)
Minimum	−14.63, −111.61 ($\delta^{18}O$, δD)	−13.22, −98.58 ($\delta^{18}O$, δD)
Linear relationship between two isotopes	7.43 ± 0.12	6.69 ± 0.17

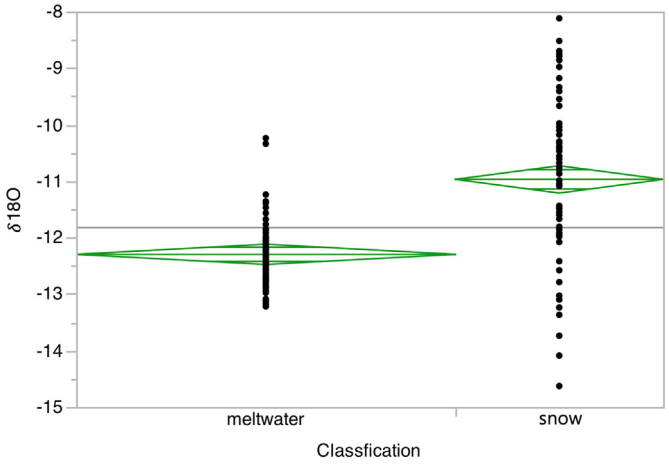

Fig. 3. Isotopic differences caused by melting.

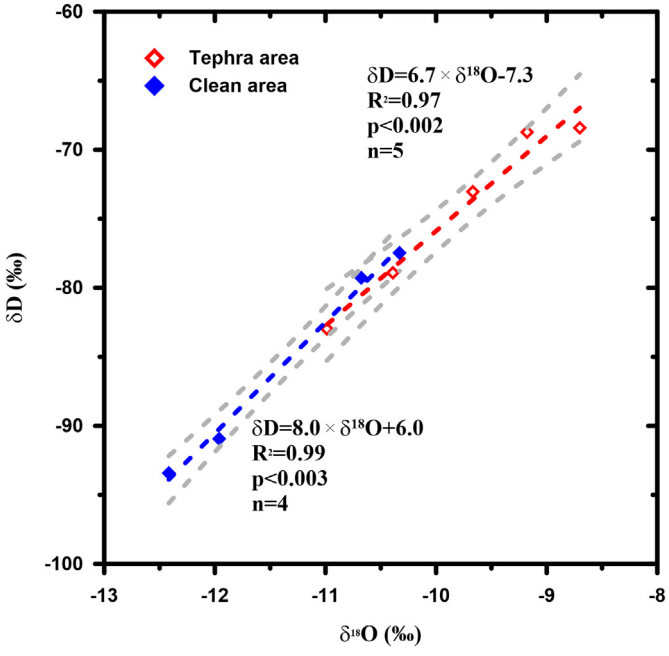

Fig. 4. Isotopic differences caused by the tephra layer.

isotopic compositions of snow that was covered by tephra and clean snow were − 9.8 ± 1.0‰ and − 11.3 ± 0.9‰, respectively. The increased energy that was absorbed by the surface snow increased the melting rate at the snow surface, which enhanced isotopic exchange between liquid water and snow (Lee, 2014). This result produced isotopically more enriched snow that was covered by tephra compared to the clean snow (*t-test*, $p < .02$).

Post-depositional processes, such as sublimation and isotopic exchange between liquid water and ice through melting, can cause isotopic redistribution and change the slope of the linear relationship between two stable water isotopes ($\delta^{18}O$ and δD). The slopes of clean snow and snow that was covered by tephra were 8.0 and 6.7, respectively. Fig. 4 illustrates the linear relationship between oxygen and hydrogen isotopes in the clean snow and snow that was covered by tephra. The linear slope of clean snow was close to that of the Global Meteoric Water Line (GMWL, 8.0). The isotopic fractionation between liquid water and ice is 3.1‰ for oxygen and 19.5‰ for hydrogen, and Lee et al. (2009) reported that the linear slope of two stable isotopes would be different from that of GMWL, which would be close to 19.5/3.1–6.3. Lee et al. (2010a) and Lee et al. (2010b) attributed the slope decrease from new snow to the snowpack to isotopic exchange between liquid water and snow/ice that was generated at the snow surface by melting and flow through the snowpack by percolation.

Isotopic variations from impurities may be linked to ice cores that are collected for paleoclimate studies (Steen-Larsen et al., 2014; Stenni et al., 2017; Werner et al., 2018). These studies assume that the isotopic compositions ($\delta^{18}O$ and δD) of precipitation indicate the surface temperature near the ocean, the isotopic compositions are preserved sequentially in a snow or ice profile, and isotopic modification from vapor and water is trivial. Not many studies reported how glacier snow and firn are changed isotopically by water or vapor flow (Earman et al., 2006; Lee et al., 2010b; Moran and Marshall, 2009; Moran et al., 2011; Ham et al., 2019). For instance, if the snow surface is contaminated by volcanic activity, the isotopic composition of the snow becomes enriched because depleted meltwater leaves the snow. Tephra layers in Greenland and Antarctic ice cores indicated albedo changes and, thus, isotopically enriched ice. Our work may help elucidate the possible results of these processes and assess the accuracy of the isotopic compositions of ice cores as a proxy for the surface temperature of nearby oceans.

3.3. Effect of hydrological processes on meltwater isotopic compositions

A comparison of the isotopic compositions between meltwater from the entire study area and surface seawater samples (seawater mixed samples) that were collected near the coast (see Fig. 1) is shown in Table 2, which may indicate the water sources near the coast. The oxygen isotopic composition of surface ocean water is close to zero (LeGrande and Schmidt, 2006). The average isotopic values of seawater mixed samples that was collected from the coastline were − 12.02‰ and − 89.25‰ for oxygen and hydrogen, respectively. The two mean $\delta^{18}O$ and δD values between mixed seawater and meltwater were significantly different when using a *t-test* ($p = .05$ and 0.02 for oxygen and hydrogen, respectively). Near the coast, water sources can be both (either) shallow groundwater through the active layer and/or meltwater runoff. If the active layer is relative thin in this region, the

Table 2
Isotopic differences between seawater mixed and meltwater in the study area.

	Seawater mixed	Meltwater
Mean value ($\delta^{18}O$, δD)	−12.02, −89.25	−12.33, −92.04
Standard error ($\delta^{18}O$, δD)	0.16, 1.08	0.05. 0.35
Confidence interval (lower and upper 95%, $\delta^{18}O$, δD)	−12.33, −11.70 −91.38, −87.12	−12.43, −12.23 −92.73, −91.35
Number of observations	11	105

isotopic compositions of both shallow groundwater and meltwater runoff were not different. Although these two isotopic means of meltwater and mixed seawater were statistically different, the differences for both oxygen and hydrogen isotopes were approximately ± 0.3‰ and ± 2.8‰ between them, respectively, implying that the contributions from meltwater in the form of groundwater and/or runoff to surface seawater near the coast were substantial.

Diel variations in the isotopic compositions of snowmelt were reported by Taylor et al. (2001) and Lee et al. (2010b). These authors ascribed these isotopic variations to changing hydrological conditions at the surface and their effects on the snowpack, which were caused by daily variations in the melting rate. When the melting rate is high, water flows through the snowpack with high velocity, which limits the contact time between liquid water and ice and produces melt that is isotopically close to the composition of the melting snow. Theakstone (2003) also observed diel variations in the isotopic composition of glacier river water during fine weather, but the diel fluctuations were interrupted by natural rain-on-snow.

We observed isotopic diel variations from a small stream around 1 km from the King Sejong Station. The small stream began to flow on 16 January and stopped flowing on 26 January. We could not obtain water samples because of bad weather on five days. The stream no longer flowed and the stream slope failed because of increases in the active layers. Despite this increase in the meltwater, the more deepening of active layers likely increased the groundwater flux. In Fig. 5, the isotopic compositions of stream water (‰) are plotted as a function of time. Distinct short-term diel variations existed in both oxygen and hydrogen isotopes in the stream water. The magnitude of diel variations of stream water isotopes diminished from 0.7‰ (the long arrow) to 0.3‰ (the short arrows) as the depth of active layer increased. If the active layer is thin, the isotopic diel variations within the snowpack can be observed in the stream water through runoff and/or shallow groundwater, but as the active layer gets thicker, the isotopic diel variations from the snowpack may disappear because the meltwater does penetrate into the soil as groundwater.

4. Summary and implications of this work

In this work, we investigated the isotopic compositions of snow/ice and meltwater from the Barton Peninsula to improve our understanding of the factors that affect the isotopic compositions of snow/ice and meltwater. Our works can imply that uncertainty caused by these variations should be considered when applying stable water isotopes in this area for inferring flowpath of water and reconstruction of paleoclimate study. The following results were found:

- In the study area, the mean isotopic compositions of snow were more enriched than those of meltwater, and the variability of the isotopic compositions decreased from snow to meltwater. The linear slope for two stable water isotopes in snow and meltwater (7.0), which differed from the meteoric water line, could be explained by isotopic fractionation from melting.
- The isotopic compositions of the snow were altered by tephra in the study area. The isotopic compositions of clean snow were more depleted than those of snow that was covered by tephra. This tephra decreased the snow albedo, so the increased energy that was absorbed by the snow surface increased the melting rate and enhanced isotopic exchange between liquid water and snow.
- Hydrological processes affected the meltwater isotopic compositions. The isotopic compositions of seawater from the coast were different from those of meltwater, but these differences were relatively small. This result indicates that the contribution from meltwater as groundwater to surface seawater near the coast was substantial. We observed diel variations in the isotopic compositions of stream water, which were caused by daily variations in the melting rate.

Author statement

Jeonghoon Lee was responsible for the implementation of the sample collection, processing and writing of the manuscript.

Soon Do Hur provided constructive comments and funding.

Hyoun Soo Lim and Hyejung Jung provided constructive comments for this manuscript.

Declaration of Competing Interest

All authors declare that they do not have any conflict of interest.

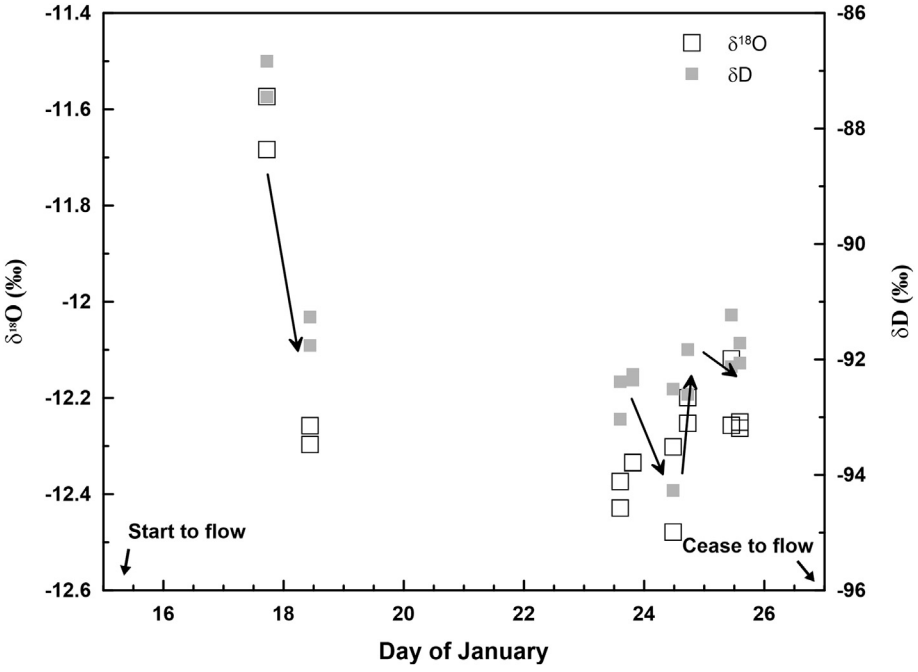

Fig. 5. Diel variations in the isotopic compositions of stream water near the King Sejong Station.

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