Surface Water Stable Isotope Geochemistry in King George Island, Antarctica

Aurel Perșoiu[1,2], Carmen-Andreea Bădăluță[2], and Jeonghoon Lee[3]

[1]Emil Racoviță Institute of Speleology, Romanian Academy, Cluj-Napoca, Romania.

[2]Stable Isotope Laboratory, Ștefan cel Mare University, Suceava, Romania.

[3]Deptartment of Science Education, Ewha Womans University, Seoul, Republic of Korea.

Corresponding author: Aurel Perșoiu (aurel.persoiu@gmail.com, aurel.persoiu@usv.ro)

Key Points:

- Clear separation of water bodies in terms of stable isotope composition
- General tendency towards lower $\delta^{18}O$ and $\delta^{2}H$ values with increased distance from the Bellinghsausen Sea in the lake waters
- Possible step towards reconstructions of wind directions in the Southern Hemisphere westerly wind belt

Abstract

The region around the tip of the Antarctic Peninsula is one of the fastest warming regions of the world, a situation that will lead to widespread changes in permafrost state, local hydrological cycles and biological activity. Further, it is located in the path of the southern westerly winds, one of the poorest-understood components of the global climatic system. The sedimentary archives in the lakes from the ice-free regions on this region host a yet untapped wealth of information on the past changes and links between the regional climatic, hydrologic and biological systems. Especially important are the stable isotope compositions of these sediments, but to understand how they record these changes, an in-depth knowledge of their links to present-day conditions is required. We present here the first study of the stable isotope composition of the surface waters in the ice-free southern peninsulas of King George Island, Antarctica. Our results suggest that a clear separation of the various water bodies (permafrost, snow, meltwater, lakes) based on the stable isotope composition of the water is possible, allowing for future studies aiming to understand (changing) feeding behavior of terrestrial fauna. Further, water in lakes on a W-E transect have distinct stable isotope composition, leading to the possibility of studying the past changes in the strength and dynamics of the westerly winds in the region.

1 Introduction

Polar regions are experiencing rapid alterations of their hydrological cycles, linked to accelerated warming over the past decades (Pacahuri et al., 2014; Walvoord & Kurylik, 2016), alterations that are also affecting the structure, dynamics and functioning of local ecosystems (Hass et al., 2010; Amesburry et al., 2018; Aracena et al., 2018). General climate warming will result in complex changes of local climate components (e.g., Vaughan et al., 2003; Rückamp et al., 2011; Turner et al., 2016), with their impact on local ecohydrology being difficult to assess in the absence of baseline data (Gibson et al., 2015; Arnoux et al., 2017; Ala-aho et al., 2018) on climate-hydrology-ecosystems links.

The majority of studies of the hydrological cycle in polar areas have focused on the northern high-latitudes (Welp et al., 2005; Zacharavova et al., 2009; Delaveau et al., 2015; Tetzlaff et al., 2018); with only few (Noon et al., 2002; Wand et al., 2011; Falk & Sala, 2015; Gómez et al., 2017; Sziło & Bialik, 2017; Falk et al., 2018; Stowe et al., 2018) addressing related issues in the Antarctic region. The massive Antarctic Ice Sheet leaves little land exposed at the interface with the Southern Ocean. Such permanent ice-free areas are located on the edges of the Antarctic Peninsula and the surrounding islands, a region that has had a strongly amplified and complex response to the ongoing global warming. The region experienced one of the strongest (+0.32±0.2 °C/decade) warming rates globally at the end of the 20th century (Turner et al., 2005), followed by an even stronger (-0.47~0.25 °C/decade) cooling since about 1998 (Turner et al., 2016). At the northern tip of the Antarctic Peninsula, King George Island (KGI, Figure 1) has a series of ice-free peninsulas, hosting a complex network of linked lakes and rivers, fed by glaciers, snow and rain, and underlain by a thick permafrost (Headland, 1984; Vieira et al., 2010; Meredith et al., 2018). The seasonal melting of glaciers, snow cover and permafrost determines a specific hydrology, with ephemeral streams linking permanent and temporary lakes, creating an extensive network of wetlands. In permafrost areas, both short and long-term climatic changes are affecting the depth of the active layer, affecting the hydrological connectivity (Quinton et al., 2011), possibly leading to altered flow paths and increased discharge to inland lakes and the open ocean (e.g., Peterson et al., 2002). Further, relative contribution of the different water sources (precipitation, ice melt, snowmelt and groundwater) to surface flow changes on time scales ranging from hours to decades (e.g., Barnett et al., 2005; Yde et al., 2016) and understanding their dynamics on these time scales could led to improved predictive skills for hydrological models.

In studying the interactions between climate and the hydrological cycle, the stable isotopes of hydrogen and oxygen are particularly useful, as they can track the origin of precipitation, the variable contribution of various water sources (precipitation, snow, glacier and permafrost melt) and the fluxes between the various water bodies (e.g., Gibson, 2005; Bowen, 2010; Wassenaar et al., 2011). The covariance between the ratios of heavy to light oxygen and hydrogen isotopes in precipitation results in the possibility to construct Local Meteoric Water Lines (LMWL, Craig, 1961) that can be used as a benchmark against which the same isotopic ratios in lake, river, snow and permafrost water can be plotted and further analyzed in order to disentangle hydrological sources, processes and mechanisms (e.g., Wassenaar et al., 2011). Further, KGI is ideally located in the path of southern westerly winds, whose dynamics during the Holocene (and beyond) has been the focus of intense scrutiny (Noon et al., 2003). Lack of suitable paleorecords limits our understanding of the spatial and temporal dynamics of these wind systems, and stable isotopes in lake sediments are one of the best proxies of such changes. Studies in Maritime Antarctica (Noon et al., 2003) have shown that $\delta^{18}O$ values of lake carbonates reflect changes in $\delta^{18}O$ of lake waters, in turn affected by climatic factors. However, such studies are sparse in Maritime Antarctica, and a network of palaeoclimate reconstructions are needed to better understand the spatial variability of past climate changes. Further, calibration of climate proxies is needed and a first step in this approach is to understand the links between climate and the stable isotope composition of lake waters. Lakes in KGI have been shown to contain sediments rich in carbonates covering at least Holocene (Mäusbacher et al., 1989; Hernández et al., 2018) thus offering the possibility to reconstruct the dynamics of sedimentation and past climate variability, provided that we understand what the proxies in these sediments record in terms of climate elements.

Here we present a first study of the isotopic composition of surface waters in the southern peninsulas (Barton, Fildes, Weaver and Potter) of King George Island, Antarctica. The objectives of our study were to 1) investigate the spatial distribution of oxygen and hydrogen stable isotopes in lake waters, as a first step towards developing new proxies of past climate changes in the areas and 2) disentangle the various water sources and reservoirs implicated in the summer hydrological cycle.

2 Data and methods

2.1 Site description

King George Island is the largest landmass (1250 km^2) of the South Shetland Islands, lying about 120 km north of the West Antarctic peninsula (Figure 1a). A glacier cap covers 92 % of the island, with only a few peninsulas (mainly in the SW) being ice-free (Figure 1b and 1c). Two icefields (Arctowsky and Warszawa) form the northern boundary of the ice-free zones of the four largest peninsulas: Fildes, Weaver, Barton and Potter (Figure 1c). These are separated by several gulfs, between 5 and 9 km in width. The peninsulas have a roughed topography, peaking at elevations between 120 and 290 m asl. The island has a mild maritime climate, the mean annual temperature at the Bellingshausen Station (Fildes Peninsula) being -2.3 °C (1968-2009, Fernandoy et al., 2012). Precipitation is delivered to the island mainly from eastward moving cyclones within the southern westerlies wind belt (Braun & Hock, 2004). The moisture source is restricted to the Southern Pacific Ocean and the Amundsen and Bellingshausen seas, generally between 60 °S and 65 °S (Fernandoy et al., 2012), with a limited contribution from more northwesterly (including South America) sources. Consequently, a precipitation gradient is developed from the westernmost peninsula (Fildes) towards the farthest eastern one (Potter), across Weaver and Barton Peninsulas (Figure 1c). Precipitation falls as snow between April and November, and as rain and snow, between December and March. Positive temperatures, gradually melt the snow layer and permafrost beginning in December, the resulting water feeding streams, lakes and wet, marsh-like areas. Weather observations at King Sejong Station (Barton peninsula) since 2018 show a reduced amplitude of air temperature variations (between -20.2 °C and 9.7 °C) and annual precipitation of 363 mm (Kim et al., 2020). This value is low considering the position of the island, but it might reflect the rain-shadow effect, as Barton peninsula is shielded from the westerly and north-westerly winds by the Fildes and Weaver peninsulas and the KGI ice Cap (Figure 1), with important implications for the distribution of stable isotopes in water (see below).

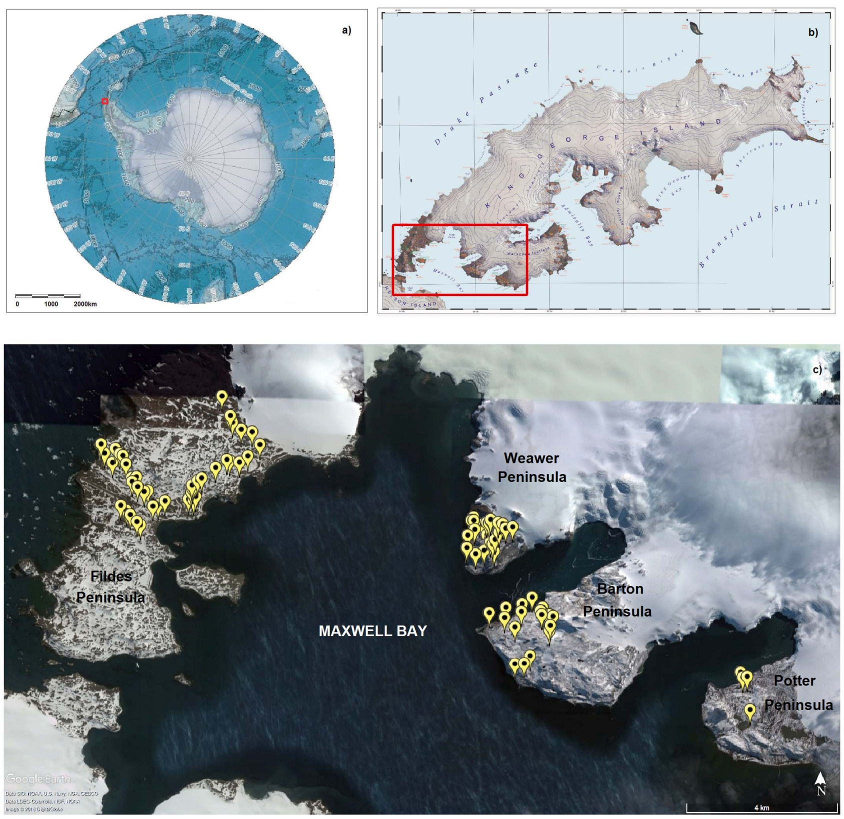

Figure 1. Location of the water sampling sites. A) Location of King George Island. B) Map of King George Island with the location of the investigated peninsulas. C) Sampling locations in Fildes, Weaver, Barton and Poter Peninsulas.

2.2 Sample collection and analysis

We have collected 97 samples of glacier ice, permafrost, snow from the previous winter, recently falling precipitation, snowmelt, lake, river and groundwater, on the Fildes, Weaver, Barton and Potter peninsulas (Figure 1c) at the end of melt season in late February 2016. Glacier ice was sampled from above the melting base of the Fourcade Glacier, in Potter Cove (between Barton and Potter peninsulas). Permafrost samples (Figure 2a) were collected around Baekje Hill on Barton Peninsula (200.2 m above sea level), by digging several pits down to the rock/ice interface and mixing together 12 distinctive samples from the permafrost layer. Precipitation samples were collected at King Sejong Station (Barton Peninsula) on February 20, 2016, following a snowstorm. Snow from the previous winter, snowmelt, ground, lake and river water was collected on all peninsulas (between 0 and 200 m above sea level), except Potter Peninsula, where only lake water was sampled (the collection campaign was scheduled after a heavy storm, when all surface waters were mixed with fresh snow). Lake and river water was sampled at 10-50 cm depth below the surface, from ice- and snow-free sectors of the water bodies (Figures 2b and 2c). On Fildes Peninsula, we have also collected lake water samples from three shallow (0.2 m) lakes (Figure 2d), during a period of warm, dry and windy weather. Snowmelt was sampled from below melting patches of snow (Figure 2e) and groundwater from water seeping out of ground (Figure 2f). In order to distinguish between permafrost melt and "pure" meltwater, pits were excavated in the rock/soil above the groundwater seepage points and only locations where no direct permafrost input was observed were sampled. Further, snow pits were excavated an the entire now column above the 2014-2015 and 2015-2106 transitional surface was recovered, melted at room temperature and subsequently a 22-ml aliquot was collected for stable isotope analyses. During our field campaign (end of summer), most of the ground was snow-free, and, with few exceptions in Barton and Potter Peninsulas, all lakes were ice-free. All samples were collected in Parafilm®-sealed 22 ml HDPE scintillation vials and stored at 4 °C before analyses (in fridge and cooling bags during transport).

Stable isotope analyses were performed using a Picarro L2130-*i* CRDS analyzer coupled to a High Precision Vaporizer Module at the Stable Isotope Laboratory, Ștefan cel Mare University (Suceava, Romania). Prior to analysis, samples were filtered using 0.45 µm nylon microfilters. To avoid memory effects, each sample was manually injected at least nine times, and when the standard deviation of the last four injections dropped below 0.03 for $\delta^{18}O$ and 0.3 for $\delta^{2}H$ respectively, the average of these injections was used as the δ value of the sample. The raw δ value were normalized on the SMOW-SLAP scale using two internal standards calibrated against the VSMOW2 and SLAP2 standards provided by the IAEA. A third standard was used to check the long-term stability of the analyzer. The stable isotope composition of oxygen and hydrogen are reported in the standard δ notation, with precision better than 0.16 ‰ for $\delta^{18}O$ and 0.7 ‰ for $\delta^{2}H$ (based on repeated measurements of an internal standard), respectively.
No precipitation sampling was active during the visits; as such, data for the stable isotope composition in precipitation was obtained from Fernandoy et al. (2012). The samples were collected at the Frei (Barton Peninsula, King George Island) and O'Higgins (Isabel Riquelme Islet, 140 km south of KGI) Chilean Stations between January 2008 and March 2009.

3 Results and discussions

The results of the analysis of water samples from the KGI are presented in Table 1, as average values for the different types of water sampled (lake, river, melt water, groundwater, snow, glacier ice and permafrost), separately for the four peninsulas. In order to better characterize the dataset, we have calculated the mean, maximum, minimum and the amplitude, for both $\delta^{18}O$ and $\delta^{2}H$. On a $\delta^{18}O$-$\delta^{2}H$ diagram (Figure 3), the values plot along the LMWL, defined by Fernandoy et al. (2012) for the O'Higgins station as $\delta^{2}H = 7.84*\delta^{18}O + 1.2$ (black dots in Figure 3).

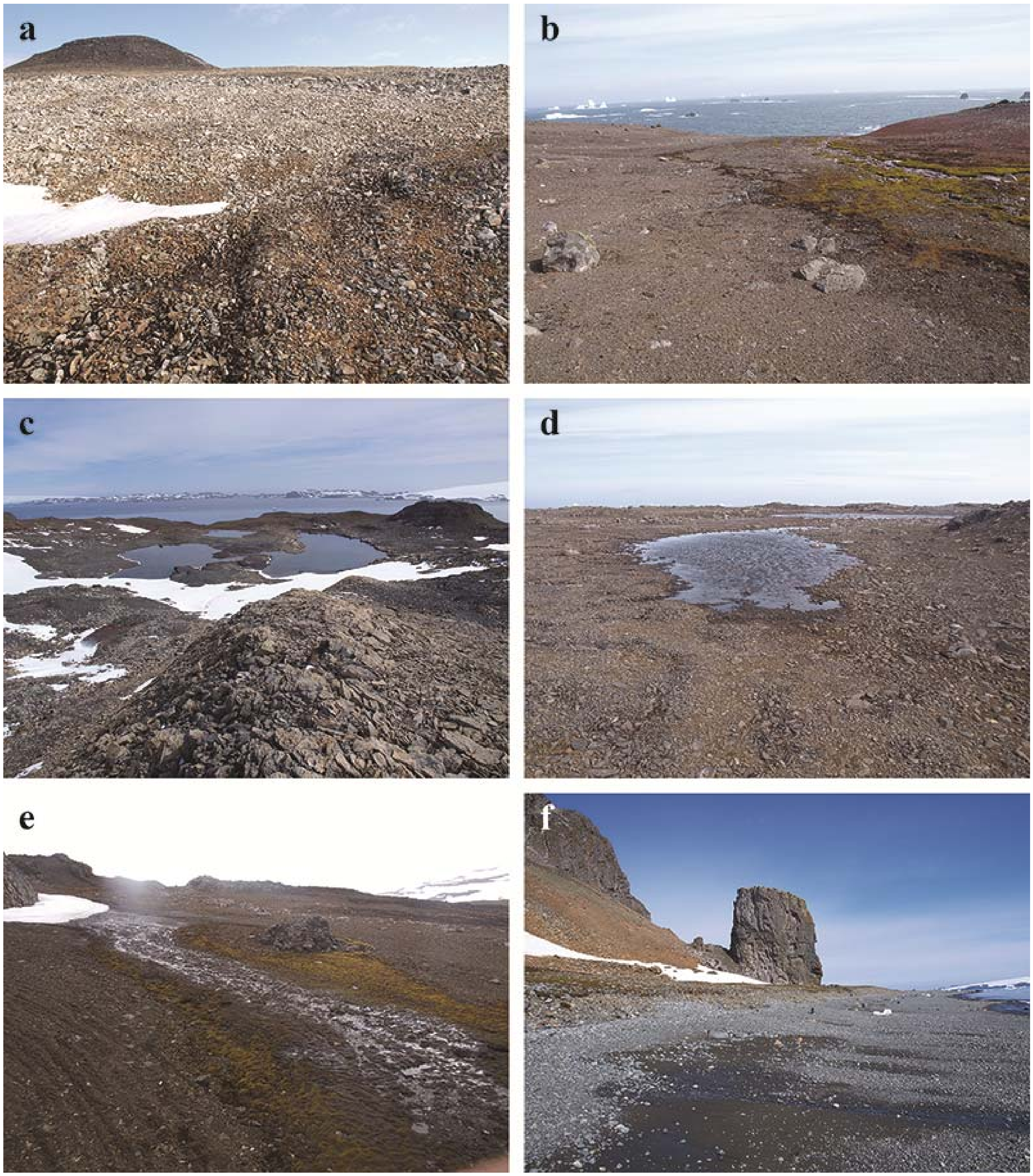

Figure 2. General overview of the types of sampling locations: a – site of permafrost sampling, Barton Peninsula, b – river on Fildes Peninsula, c – lakes in Weaver Peninsula, d – evaporatively enriched lake, Fildes Peninsula, e – snowmelt, Fildes Peninsula, f – groundwater seepage, Weaver Peninsula. All photos by Aurel Perșoiu.

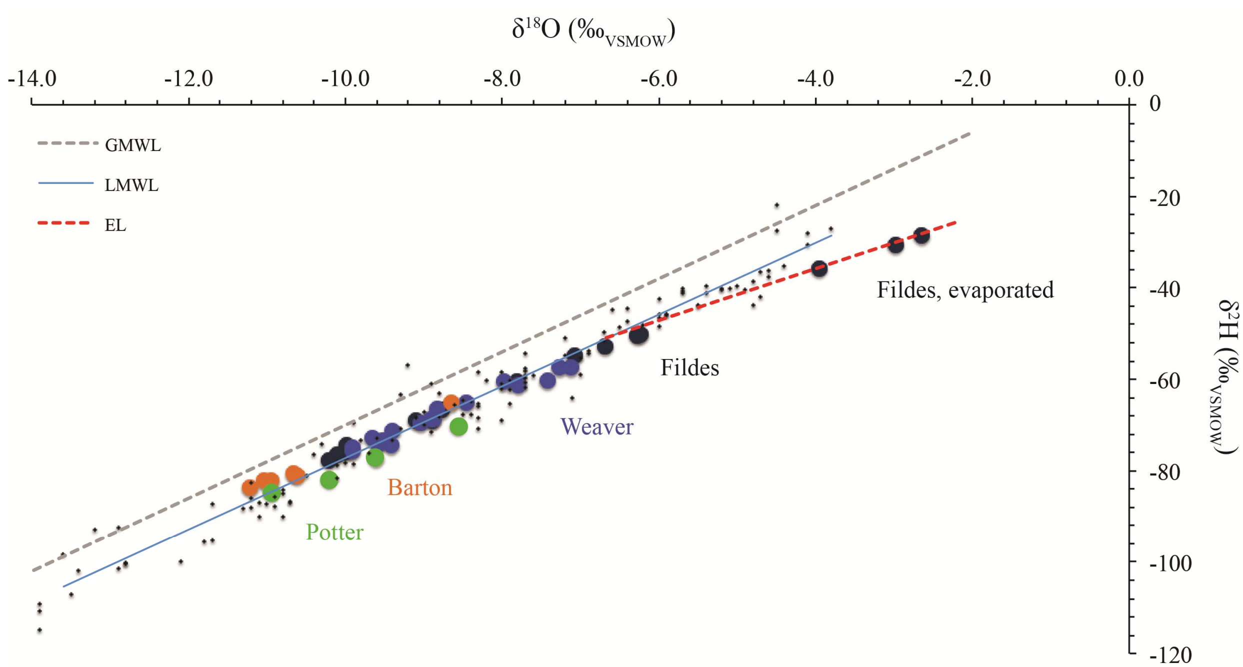

Figure 3. Stable isotope composition of lake waters in King George Island, shown against the Local (Fernandoy et al., 2012, black dots) and Global Meteoric Water Lines.

Samples from permafrost and groundwater have the highest δ values (Figure 4). The high values of the single permafrost sample might reflect its origin in the partial freezing of infiltration water. Freezing of water is accompanied by strong kinetic fractionation (Jouzel and Souchez, 1982; Perşoiu et al. 2011) and the resulting ice is enriched in heavy isotopes (^{18}O and ^{2}H) leading to higher than in water δ values. Interestingly, the δ values of groundwater from Barton Peninsula (average values of -7.7 ‰ for δ^{18}O and -58 ‰ for δ^{2}H, respectively) are higher than those found by Kim et al. (2020) for groundwater samples collected in January 2018 (average values of -11.5 ‰ for δ^{18}O and -87 ‰ for δ^{2}H, respectively). Similarly, average δ values of meltwater, snow and lake water in Barton Peninsula (Table 1) at the end of the melt season (February 2016) were higher than in either January 2014 (Lee et al., 2020) or January 2018 (Kim et al., 2020) during the early-to-mid melt season. These differences possibly suggest that during the melt season, fresh snow from the previous winter contributes a larger proportion of water to both lakes and groundwater, and as melting progresses, sources enriched in ^{18}O and ^{2}H become progressively important in the overall mass (and isotope) balance of surface waters. Several studies (Taylor et al., 2001; Lee et al., 2020 and references therein) have shown a continuous increase of δ^{18}O and δ^{2}H in a melting snowpack as a result of isotopic exchange and enrichment in heavy isotopic species as percolating water refreezes inside the snowpack. Thus, we suggest a potential shift in the δ values of surface waters in the region, shift that could be the result of 1) changes in the δ values of source waters (snowpack) and rainfall and/or 2) changes in the relative contribution of different reservoirs to the overall mass balance of surface waters, with meltwater from fresh snow dominating in the early months of summer and diagenetically modified snow and permafrost becoming dominant towards the end of the melt season.

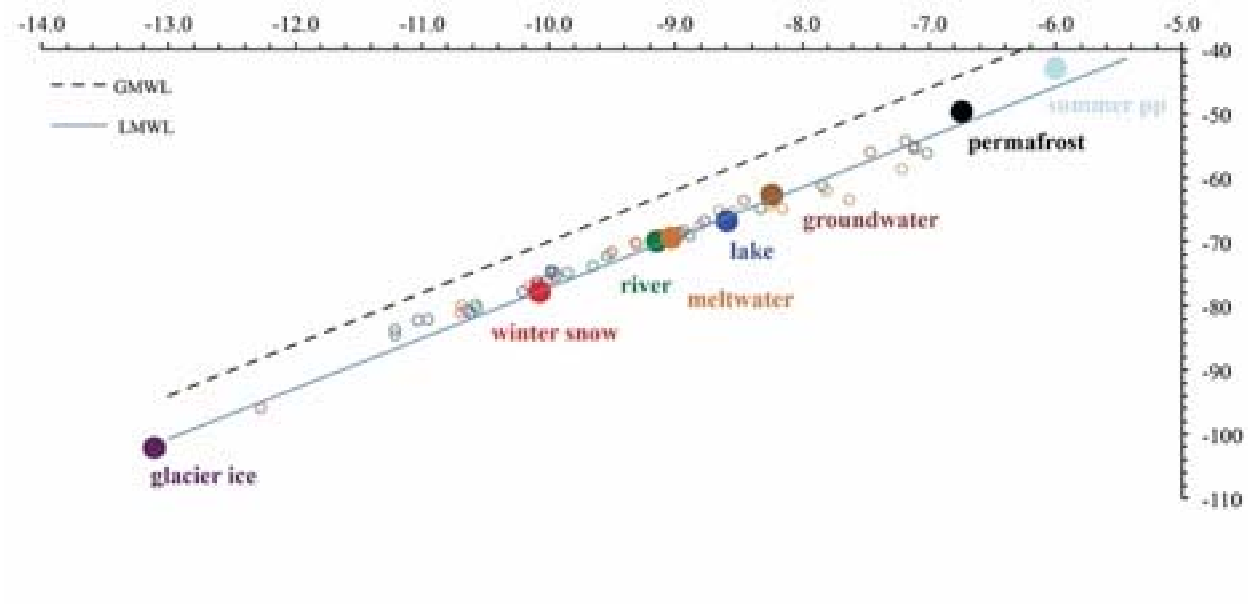

Figure 4. Average $\delta^{18}O$ and $\delta^{2}H$ values in the water bodies in King George Island.

Lake, river and melt water δ values have a clear decreasing tendency from west (Fildes) to east (Potter); seen in both mean and maximum values, as well as amplitude, but not so evident in the minimum values (Table 1). The maximum amplitude of the δ values is seen in lake waters (up to 4 ‰ for $\delta^{18}O$ and 23 ‰ for $\delta^{2}H$), with groundwaters being more uniform between the different peninsulas. The deuterium excess (d-excess, defined as $d = \delta^{2}H-8*\delta^{18}O$, Dansgaard, 1964) values of all water bodies are low (between -7.4 and 6.1 ‰), suggesting post-depositional processes are affecting all types of surface waters. The low d-excess values in surface liquid waters (lakes, rivers and snowmelt) are likely the result of kinetic fractionation of O and H stable isotopes during evaporation (Craig & Gordon, 1965; Gonfiantini et al., 2018). Strong winds also very likely resulted in the sublimation and kinetic fractionation of the snowpack, melting having a reduced effect on the stable isotope composition of snow, due to the very low diffusion coefficient (10-11 $cm^2\ s^{-1}$) of the water molecules in ice (Posey & Smith, 1957). However, isotopic exchange between ice and liquid water (from surface melt) as the later is percolating through the snowpack could lead to a lower slope of $\delta^{18}O$-$\delta^{2}H$ line (Zhou et al., 2008; Lee et al., 2010a, 2010b) and thus further influence the d-excess values of river and lake waters. The combination of evaporative loss, isotopic exchange between percolating water and snowpack and strong kinetic fractionation during partial freezing of water followed by melting of the resulting ice which has low d-excess could thus result in the overall low d-excess values recorded by the different water bodies in KGI.

The $\delta^{18}O$ and $\delta^{2}H$ values of lake waters in KGI were plotted on a $\delta^{2}H$-$\delta^{18}O$ diagram against the LMWL and GMWL (Figure 3), and their main characteristics (maximum, minimum, mean and amplitude values) are shown in Table 1. The three samples collected from shallow lakes (Figure 2d) have the highest δ values and the lowest d-excess values. They plot on an "evaporative line" (EL), defined by the equation $\delta^{2}H=5.44*\delta^{18}O-14.35$. Evaporation of surface waters (Gat, 1981; 2008; Gibson et al., 2005; 2016) results in the enrichment of the remaining water in the heavy isotopes of O and H, due to lower diffusion rate of the $H_2{}^{18}O$ and $^{2}H^{1}H^{16}O$ isotopologues, compared to $^{1}H_2{}^{16}O$. The enrichment is proportional to the evaporation rate, which in turn is controlled by relative humidity, temperature and salinity (Gonfiantini, 1986). The ensuing fractionation (a sum of equilibrium and kinetic fractionation, Craig & Gordon, 1965; Gonfiantini et al., 2018) results in a slope lower than the LMWL for the line defined by the samples from the residual water (the EL). These three samples whose stable isotope composition reflects evaporative processes (Figure 3), were collected during a period of strong winds that lead to the quick removal of the evaporated water molecules enriched in the light isotopes from the boundary layer and thus minimization of equilibrium and dominance of kinetic fractionation – resulting in the residual water being enriched in heavy isotopologues and alignment along the EL line shown in figure 3. Water from large lakes adjacent to the shallow ones plot at the intersection of the LMWL and the EL, this intersection points likely indicating the stable isotope composition of the shallow lakes' water before evaporation.

A clear west to east trend (with increasing distance from the Drake Passage) of δ values in lake waters is evident, with samples from Fildes Peninsula having the highest values, and those from Barton, the lowest. Samples from Potter do not fit in this trend, the δ values being slightly higher than those in Barton, although the peninsula is located further east. Possibly, this difference (although minor) is due to the higher elevation of the sampled lakes in Barton (between 5 and 270 m asl) compared to Potter (~20-60 m asl). Moisture delivered to KGI is originating in the Drake Passage (Fernandoy et al, 2012), west of Barton, so that this W-E trend of decreasing $^{18}O/^{16}O$ and $^{2}H/^{1}H$ ratios is consistent with Rayleigh fractionation processes (Dansgaard, 1964) along a rainout path from the Fildes through Weaver and Barton peninsulas (Figure 3). The W-E trend of lower δ values seen in the stable isotope composition of lake water is mirrored by values in surface (snowmelt and river) waters but not in groundwaters (Table 1), suggesting origin from the same parent source. However, the low number of river and snowmelt samples calls for caution in interpreting this trend in a way similar to that seen in lakes water.

We interpret the low d-excess values of surface waters as a result of evaporative (and sublimation in the case of snow) processes affecting all surface water after deposition, resulting in subsequent enrichment in the heavy isotopes of O and H (and associated decrease in d-excess – Table 1). Studies in the Alps (Moser & Stichler, 1975), Antarctica (Satake & Kavada, 1997) and the Andes (Stichler et al., 2001) have shown that sublimation results in enrichment in ^{18}O and ^{2}H in the remaining snow. Partial melting of this snow and subsequent alimentation of river and lake waters would thus result in the high $\delta^{18}O$ and $\delta^{2}H$ values in surface water samples in KGI.

Figure 4 shows the $\delta^{18}O$ and $\delta^{2}H$ values of the different water bodies, allowing for a clear separation of the various water bodies based on their stable isotope values. The stable isotope composition of water in lakes and streams is mainly controlled by that of winter precipitation. Melting of winter snow in summer is the principal source of water for rivers and lakes, with additional input from ^{18}O- (and ^{2}H-) depleted water (-7.7 through -9.8 ‰ for $\delta^{18}O$) from degrading permafrost (-6.7 ‰ for $\delta^{18}O$). Further, following melting of snow, all resulting waters are subjected to strong, wind-driven evaporation, as also indicated by the very low d-excess values (Table 1). Winds are a constant feature of KGI, blowing constantly from a W and SW direction, and thus the continuous evaporation of surface waters results in high $\delta^{18}O$ and $\delta^{2}H$ and low d-excess values.

No clear relationship between the stable isotope composition of lake water with altitude has been found, potentially due to the low (less than 300 m) maximum height of the "hills", thus potentially reducing the 'altitude-effect' of the stable isotope composition of precipitation. Nevertheless, the lowest values were found in Barton Peninsula, which has the highest topography of the four investigated areas. While altitude would have played a negligible role, we suggest that sheltering from wind of the lakes (due to the more rugged topography, compared to the other peninsulas) was likely the cause of the low δ values. High d-excess values in lakes from Barton compared with those in the Fildes, Weaver and Potter peninsulas, suggest a lower degree of evaporative fractionation, supporting our inference.

4 Conclusions

The results of stable isotope analyses in water from king George Island indicate 1) a clear separation of the various water bodies in terms of stable isotope composition, likely triggered by the variable contribution of different sources to the final mass (and stable isotope) budget and 2) a general tendency towards lower $\delta^{18}O$ (and $\delta^{2}H$) values with increased distance from the Bellingshausen Sea.

KGI is home to the largest concentration of research stations and a permanent settlement in Antarctica, as well as for a wide selection of animal and vegetation life. The results allow for the establishment of a baseline against which ongoing and future alterations of the hydrological cycle could be analyzed, and a better management of the water resources for human and natural usage. Further, our data offers a first step towards potential future studies aiming to quantify the link(s) between climatic conditions and stable isotopes in lake sediments, a necessary tool for future reconstructions of past climate conditions.

Acknowledgments

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		$\delta^{18}O$ (‰$_{VSMOW}$)				$\delta^{2}H$ (‰$_{VSMOW}$)				d-excess
		Mean	Min	Max	Amplitude	Mean	Min	Max	Amplitude	
Lakes	Fildes (14)	-8.7	-10.2	-6.2	4.0	-67	-78	-50	28	2.7
	Fildes, evaporated (3)	-4.3	-6.3	-2.6	3.7	-38	-51	-29	22	-4.0
	Weaver (17)	-8.8	-9.9	-7.1	2.8	-68	-76	-57	19	2.4
	Barton (5)	-10.9	-11.2	-10.6	0.6	-82	-84	-81	3	5.2
	Potter (4)	-9.8	-10.9	-8.6	2.3	-79	-85	-72	13	0.1
Rivers	Fildes (10)	-8.8	-10.1	-7.0	3.1	-68	-76	-55	21	2.4
	Weaver (3)	-9.0	-9.7	-8.3	1.4	-70	-74	-65	9	2.0
	Barton (3)	-10.8	-11.2	-10.6	0.6	-82	-85	-80	5	4.7
Meltwater	Fildes (14)	-8.5	-10.3	-7.2	3.1	-66	-77	-59	18	2
	Weaver (3)	-9.8	-10.1	-9.5	0.6	-76	-77	-75	2	2
	Barton (7)	-9.8	-10.7	-8.7	2.0	-74	-81	-65	16	4
Groundwater	Fildes (4)	-8.5	-9.5	-7.1	2.4	-65	-72	-55	17	3
	Weaver (1)	-9.0	-	-	-	-69	-	-	-	3
	Barton (3)	-7.7	-8.5	-7.2	1.3	-58	-64	-54	10	4
Snow (3)	Fildes/Weaver/Barton	-10.1	-12.3	-8.6	3.7	-78	-96	-67	29	2.8
Glacier (1)	Potter/Barton	-13.1	-	-	-	-102	-	-	-	3
Permafrost (1)	Barton	-6.7	-50	-	-	-	-	-	-	4
Precipitation (1)	Barton	-6.0	-	-	-	-43	-	-	-	5

Table 1. Main characteristics of the stable isotope composition of surface waters in King George Island, Antarctica.