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Water chemistry and pigment composition of 13 lakes and ponds in Maritime Antarctica

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Abstract: The Antarctic Peninsula has been rapidly warming, resulting in changes to the abundance and surface cover of terrestrial aquatic ecosystems, as well as their ecosystem structure and function. Therefore, comparative studies of aquatic ecosystems across large latitudinal gradients can be useful in better understanding these changes and making more reliable predictions regarding the consequences of climate change. During Turkish Antarctic Expeditions in 2018 and 2019, samples were collected from 10 lakes and 3 ponds across Maritime Antarctica (north-western coasts of the Antarctic Peninsula). These lakes and ponds were located on Ardley, Robert, Livingstone, Galindez, and Horseshoe islands, covering a latitudinal gradient of over 800 km.
Snapshot samplings were conducted of the water chemistry, including nutrient, major ion, and trace metal concentrations, as well as pigment compositions representing the primary productivity and plankton community composition. These lakes and ponds had large variations in nutrient concentrations (0.8–771 μg/L PO_4 and 30–886 μg/L total dissolved inorganic N) and conductivity (30–735 μS), representing a trophic status ranging from ultra-oligotrophic to a few eutrophic sites (for example a pond near penguin colonies). The total productivity, measured as the chlorophyll-a (Chl-a) level, was generally low (0.02–3.2 μg/L) in the lakes, reflecting their oligotrophic characteristics. However, the composition of pigments in the water column showed significant variation across the lakes. Both the patterns in the total Chl-a concentrations and pigment compositions reflected the patterns in conductivity and nutrient gradients across the lakes.
Overall, the observed patterns suggested a predominant role of nutrient transport from the sea in driving the chemical composition and primary productivity of Antarctic lakes, mediated by the distance to the sea, as well as the activities of seals and penguin colonies.

Key words: Phytoplankton, Antarctic lakes, high latitude ecosystems, land-sea interaction

1. Introduction

Antarctica hosts some of the most extreme environments on Earth, with unique ecosystems that have evolved in response to the continent's harsh conditions. These ecosystems are of global significance, playing a vital role in regulating the Earth's climate (Keeling and Stephens, 2001), providing important ecosystem services (Pertierra et al., 2021), and supporting a range of iconic species, such as penguins, seals, and whales in the marine ecosystem and mosses, lichens, plankton, and invertebrates in the terrestrial and inland aquatic ecosystems (Chown et al., 2015).

However, these ecosystems are facing unprecedented threats from climate change, which is causing rapid and dramatic changes in Antarctic Sea ice, ocean temperatures, terrestrial habitats, as well as coastal and inland lake ecosystems (Turner et al., 2014). One of the regions most affected by these changes is the Antarctic Peninsula, which is experiencing some of the most rapid warming on the planet, resulting in record-size sea ice breaks (Vaughan et al., 2003). The effects of climate change on marine ecosystems (Clarke et al., 2007) are evident in the shifts in species distribution and abundance, and alterations in the food web dynamics (Montes Hugo et al., 2009). Climate warming also causes widespread melting of ice shelves and glaciers (Schannwell et al., 2018), leading to changes in the distribution of terrestrial biota and altering the habitat suitability for certain species (Obryk et al., 2016). Alteration of the terrestrial ecosystems does not only affect terrestrial organisms but also marine food webs, as several marine birds and mammals are strongly coupled to the terrestrial habitats for their breeding and resting activity (Convey, 2006).

Despite the importance of Antarctic terrestrial and lake ecosystems, our understanding of these environments is limited due to the logistical challenges of conducting research in such a remote and harsh environment. Field research in Antarctica requires specialized equipment, experienced personnel, and careful planning, all of which are subject to the constraints of weather and transport availability.

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As a result, the number of studies on Antarctic terrestrial and lake ecosystems is relatively small compared to marine ecosystems, and our understanding of these ecosystems is limited by the scarcity of data (Convey, 2006; Chown et al., 2015). To address these limitations, there is a need for more systematic and targeted observations of terrestrial and lake ecosystems in Antarctica, using a combination of remote sensing, automated monitoring, and field survey methods. These efforts will be critical for improving our understanding of the ecological processes that occur in these environments and for developing effective conservation strategies to protect them (Chown et al., 2015).

While there are some areas of Antarctica that have been relatively well-studied (Roman et al., 2019), additional data are required for even these places in order to understand the effects of climate change on Antarctic terrestrial and lake ecosystems. In particular, repeated or long-term monitoring data are needed to track changes in key environmental parameters such as physical and chemical characteristics of aquatic ecosystems as well as population size and composition of organisms, which are essential to understand the impacts of these changes on ecological processes. Even small changes in these parameters may have significant effects on the distribution and abundance of plant and animal species, and on the structure and function of entire ecosystems. In addition, data from new areas and ecosystems are needed to fill in the gaps in our understanding of Antarctic biodiversity and ecosystem functioning. By collecting additional data with high temporal resolution from both new and established study areas, it will be possible to gain a more comprehensive understanding of the effects of climate change on Antarctic ecosystems and develop more effective conservation strategies to protect these unique and fragile environment (Chown et al., 2015).

Logistic constraints largely limit the availability of high-resolution spatial and temporal data in Antarctic ecosystems; however, snapshot sampling may still provide important insights, especially if it can be repeated over time. Snapshot sampling, which involves taking a single sample at a specific point in time, is a commonly used technique in lake research (Mantzouki et al., 2018). By collecting samples at multiple locations and time points, researchers may gain insights into how physical and biological parameters vary across space and time, and how these variations affect the structure and function of lake ecosystems. Snapshot sampling is particularly useful for detecting short-term changes in lake conditions, such as changes in the nutrient concentrations or the presence of harmful algal blooms. It is also an effective way to assess the impact of human activities on lake ecosystems, such as the discharge of pollutants or the introduction of nonnative species. However, snapshot sampling may have some limitations, such as the potential for missing key events that occur between the sampling periods. Nevertheless, it remains a valuable tool in lake research and can provide important information for understanding and managing these important ecosystems. Snapshot sampling has also been used in several studies to investigate the lake ecosystems of Antarctica (Roman et al., 2019) as well as the distribution and dynamics of microbial communities (Gooseff et al., 2003), invertebrate communities (Hughes and Worland, 2010), and phytoplankton communities (Izaguirre et al., 2016) in Antarctic lakes.

Herein, the lake water physical and chemical characteristics, as well as pigment compositions, in 13 lakes and ponds across the Antarctic Peninsula were presented and the main patterns and the driving factors were analyzed. These lakes were sampled during the second and third Turkish Antarctic Expeditions (TAE-II and TAE-III) in 2019 and 2020, across a latitudinal gradient larger than 800 km. It is our hope that these data will contribute to further research and a better understanding of the effects of ongoing climate change in the structure and functioning of the fragile ecosystems of the Antarctic Peninsula.

2. Materials and methods

During TAE-II and TAE-III in 2018 and 2019, surveys were conducted of 10 lakes and 3 ponds (hereafter lakes) along the northwestern coasts of the Antarctic Peninsula in Maritime Antarctica. The lakes were located on 5 different islands along a latitudinal distance of approximately 800 km (Figure 1). They were mostly located along the coastal rocky shores, free from glaciers. The coordinates and altitudes were recorded during the surveys, and lake morphometric characteristics were measured using Google Earth Engine (Gorelick et al., 2017). Any vertebrate mammal activity around the lakes was visually observed and recorded as on 4-point scale (low, medium, high, and very high).

The lakes were sampled using the snapshot sampling protocol (Jeppesen et al., 2017). As it was not logistically possible to use a boat during the surveys, the surveyor sampled the lake surface water (0–0.5 m) on the shore (at a depth of approximately 1.5 m) using a sampling bucket, with proper care to not resuspend any lake sediment into the surface water. Replication of the samples was not possible during the fieldwork due to logistic constraints.

To determine the water chemistry, 500 mL of lake water was placed into acid-washed PE bottles and kept frozen until the analysis were conducted. For the pigment analyses, lake water was filtered through Whatman GF\C glass fiber filters (pore size of 1.2 μm) on-site until visible color was observed on the filter paper (filter volume of 200–1000 mL). The filter papers were kept frozen in the dark until the pigment analysis was conducted. Pigment

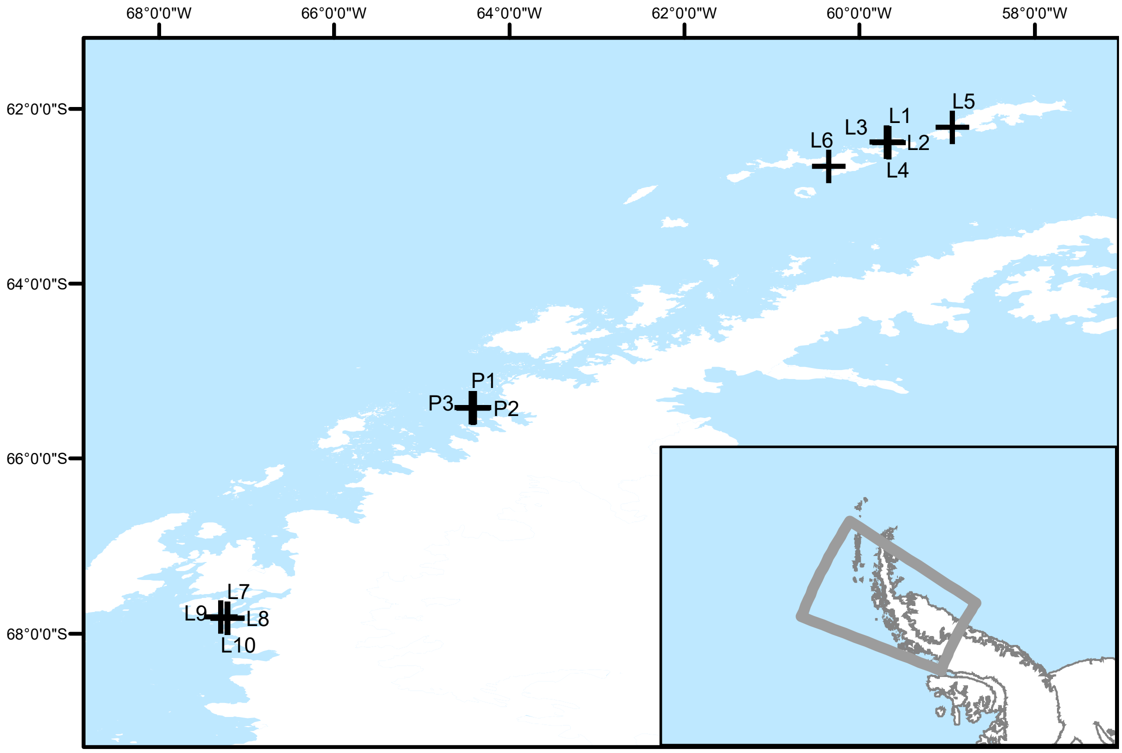

Figure 1. Map of the sampling locations in Maritime Antarctica along the northwestern coasts of the Antarctic Peninsula. The inset in the lower right corner depicts the map extent over the Antarctic Peninsula.

samples could not be collected from the ponds due to logistic constraints.

Dissolved inorganic nutrient analyses (nitrate + nitrite, NO_3 + NO_2; ammonium, NH_4; phosphate, PO_4; silicate, SiO_2) were carried out via automated methods using a Bran + Luebbe four-channel autoanalyzer (Grasshoff et al., 1983). The concentration of major ions was measured using a Dionex ICS-5000 ion chromatography instrument equipped with an electrochemical detector. Anions were detected with an AS11-HC separation column using KOH (30 mM) as an eluent, coupled with an AERS-500 (4 mm) suppressor; and cations were detected using a CS12-A separation column with MSA (20 mM) as an eluent, and coupled with a CSRS-300 (4 mm) suppressor, as described in Product Manual for Dionex IonPac AS11-HC-4m and IonPac CS12A. The calibrations for the analyses were conducted using Dionex 7 anion standard (Thermo Fisher Scientific Inc., Waltham, MA, USA; Product number: 056933) and Dionex 6 cation II standard (Product number: 046070). More details on the analytical methods are available in Nehir and Koçak (2018).

Chlorophyll-a (Chl-a) and other pigment concentrations were determined using high-performance liquid chromatography (HPLC) with an Agilent 1100 analyzer (Agilent Technologies, Santa Clara, CA, USA) with variable wavelength detector (flow cell of 14 µL and wave length of 440 nm) using the method described in Barlow et al. (1997). Sample extraction was performed by 1-min ultrasonication in 3 mL of acetate-water mix (90:10%), followed by filtration in a Millipore filter with a pore size of 0.2 µm and storage in dark bottles until the analyses. The analyses were conducted using Thermo Fisher Scientific C8 Hypersil MOS-2 analytical columns (particle size of 3 µm and pore size of 120 Å). Pigment separation was sustained with a 1 mL/min mobile phase flow rate, 0–20 min: 50:50 acetone:methanol, 20–25 min: 30:70 acetone:methanol, 25–35 min: 0:100 acetone:methanol, 35–39 min: 75:25 acetone:methanol mobile phase composition with 300 bar of pressure and a 100-µL loop. The pigment calibrations were performed using pigment standards acquired from DHI (https://c14.dhigroup.com).

Inductively coupled plasma mass spectrometry (IPC-MS) analyses for trace elements were conducted using a Nexions 350X ICP-MS analyzer (PerkinElmer Inc., Waltham, MA, USA) with a radiofrequency power of 1400 and nebulizer gas flow rate of 1 mL/min. The calibrations were performed using PerkinElmer multielement calibration solution (30 elements in 5% HNO_3, part number: N9300233) and internal standard mix (7 elements in 5%–10% HNO_3, part number: N9303832). All of the chemistry analyses were performed at the laboratories of the Institute of Marine Sciences, Middle East Technical University.

The pigment composition and its relationship with the lake chemical characteristics were analyzed using redundancy analyses (RDA; Legendre and Legendre, 2012). Data handling and statistical analyses were conducted using the vegan package (Oksanen, 2013) in R environment (R team, 2013).

3. Results and discussion

The sampled lakes were small (<12,000 m^2) and shallow (<2 m, Table 1). They were located near to the coast (<640 m), but without permanent connection to the sea, and up to the altitude of 83 m above sea level, as expected, due to the permanent glaciers covering the central regions of the islands.

Significant mammal and bird activity was observed in some of the lakes, reflecting the ecological importance of terrestrial aquatic systems in the breeding ecology of Antarctic fauna (Table 1). Elevated bird and mammal activity was observed in Lakes 3 and 4 on Robert Island for southern elephant seals (*Mirounga leonina*) and Antarctic fur seals (*Arctocephalus gazella*), and in Lake 10 on Horseshoe Island for skuas (south polar skua, *Stercorarius maccormicki* and/or brown skua, *Stercorarius antarcticus*, as definite identification was not possible in the field). Whereas extremely high faunal activity was observed in Pond 1 (P1) in Galindez Island, which was located in a large gentoo penguin (*Pygoscelis papua*) breeding colony.

The lakes were mostly freshwater (<100 µS/cm); only the lakes located in close vicinity to the coast had conductivities up to c. 700 µS/cm, reflecting the potential role of salinity influx via sea-spray (Table 1). The lakes generally had an oligotrophic character, with higher concentrations of N and P in the more coastal lakes (Table 2). Very high nutrient concentrations were only observed in P1, which was located within a penguin breeding colony.

Major ion concentrations largely reflected the patterns in the change in the conductivities, and major ions such as SO_4^{2-}, Na^{1+}, and Cl^{1-} were higher in the lakes located along the coasts, thus reflecting stronger sea influence (Table 3). Trace metal concentrations also exhibited a similar pattern (Table 4). Concentrations of elements like Fe and Mn were more elevated in the coastal lakes with stronger sea influence. Heavy metals that may have an anthropogenic influence and/or be a pollutant such as Cd or Cr showed very low concentration levels in all of the sampled lakes and ponds (Table 4), reflecting the isolated nature of Antarctic ecosystems from major pollutant sources. Elevated heavy metal concentrations have previously been detected, especially in the vicinity of large research bases (Claridge et al., 1995); however, no permanent human activity was present in close vicinity of the sampled lakes.

Table 1. Sampled lakes and ponds with their locations and morphological characteristics.

Sampling site	Latitude	Longitude	Altitude (m)	Max depth (m)	Area (m^2)	Circumference (m)	Distance to sea (m)
L1, Robert Island	62°23'05.6"	59°40'04.4"	38	1.5	11,961	481	638
L2, Robert Island	62°22'38.6"	59°41'12.8"	3	0.3	8,431	434	70
L3, Robert Island	62°22'49.5"	59°41'40.5"	1	0.8	6,379	489	10
L4, Robert Island	62°22'43.5"	59°41'35.3"	2	1.1	11,578	624	26
L5, Ardley Island	62°12'42.8"	58°56'40.0"	18	2	3,127	234	215
L6, Livingstone Island	62°39'31.3"	60°21'27.7"	40	2	12, 131	410	50
L7, Horseshoe Island	67°49'40.2"	67°13'29.7"	75	2	8,962	468	480
L8, Horseshoe Island	67°49'31.1"	67°13'35.4"	79	2	7,319	352	429
L9, Horseshoe Island	67°49'30.0"	67°13'23.0"	80	1.5	13,151	741	610
L10, Horseshoe Island	67°48'43.2"	67°18'11.9"	83	1.5	21,837	681	167
P1, Galindez Island	65°24'54.0"	64°25'77.0"	5	0.5	< 100	<50	5
P2, Galindez Island	65°24'76.0"	64°24'19.0	12	0.5	< 100	<50	10
P3, Galindez Island	65°24'81.0"	64°24'62.0	28	0.5	< 100	<50	17

Table 2. Dissolved inorganic nutrient concentrations in the water columns of the sampled lakes and ponds as well as the observed vertebrate animal activity in and around the sampling sites.

Site	Conductivity (µS/cm)	PO_4 (µg/L)	NO_3+NO_2 (µg/L)	NH_4 (µg/L)	TIN (µg/L)	SiO_4 (µg/L)	Animal activity*
L1	115	0.84	39.62	7.84	47.46	73.22	Low
L2	238	8.12	112.00	14.56	126.56	83.02	Low
L3	447	12.46	350.84	66.64	417.48	137.62	High (SES, AFS)
L4	735	18.62	553.70	81.76	635.46	148.26	High (SES, AFS)
L5	109	43.26	7.70	35.56	43.26	2.38	Low
L6	30	4.20	7.56	34.30	41.86	14.28	Low
L7	134	2.24	2.94	35.14	38.08	0.42	Low
L8	22.6	0.84	1.54	28.84	30.38	1.26	Low
L9	294	0.70	7.42	39.62	47.04	2.38	Low
L10	102	10.08	5.04	67.76	72.8	0.84	High (S)
P1	33	771.26	154.14	732.62	886.76	13.30	Very High (GP)
P2	18	81.20	63.84	257.46	321.3	0.28	Low
P3	43	35.28	141.40	87.92	229.32	2.66	Low

*SES, Southern elephant seal; AFS, Antarctic fur seal; S, skuas (south polar skua and/or brown skua); GP, gentoo penguin TIN, total inorganic nitrogen.

Table 3. Major ion concentrations in the water columns of sampled lakes and ponds.

Site	F^{1-} (µg/L)	Cl^{1-} (µg/L)	SO_4^{2-} (µg/L)	Br^{1-} (µg/L)	Li^{1+} (µg/L)	Na^{1+} (µg/L)	K^{1+} (µg/L)	Mg^{2+} (µg/L)	Ca^{2+} (µg/L)
L1	1.57	42214	5841	91	0.3	22354	561	2777	2644
L2	3.70	72289	10578	117	0.3	34932	967	3923	3201
L3	3.87	179295	33275	210	0.8	68122	3013	7254	3010
L4	5.07	343950	48805	444	1.5	114227	4501	12804	4071
L5	5.80	28507	5066	55	0.2	15236	629	1973	2361
L6	1.01	4595	1346	-	0.1	3686	190	427	1059
L7	4.36	38163	5057	70	0.5	20080	846	2242	1460
L8	2.74	64752	7192	126	0.5	29395	980	3145	2040
L9	1.73	108763	12749	188	0.7	48477	1874	5755	3066
L10	1.04	27434	5841	31	0.2	16414	674	1671	1286
P1	-	27755	11992	137	0.3	13881	7185	2739	3832
P2	1.79	6646	2044	-	0.2	3853	190	444	669
P3	1.34	8469	4439	-	0.2	5602	250	666	1213

The lake water PO_4 and NO_3 concentrations tended to increase with increasing lake water conductivity, whereas they decreased with increasing latitude, altitude, and distance to the sea (Figures 2 and 3). Intercorrelation between the total inorganic nitrogen (TIN), SiO_4 and conductivity in the RDA ordination also suggested a significant association between these parameters in the sampled lakes. The low sample size in the present study prevented a statistical test for significance or partial coefficient analyses from being conducted. However, the correlations all suggested a driving role of nutrient transport from the sea in the form of sea-spray (Abollino et al., 2004) and sea intrusion, as well as animal movements. A previous survey over the lake ecosystems on James Ross

Table 4. Trace metal concentrations in the water columns of the sampled lakes and ponds.

Site	Fe (µg/L)	Mn (µg/L)	Cd (µg/L)	Co (µg/L)	Cr (µg/L)	Cu (µg/L)	Pb (µg/L)	Zn (µg/L)
L1	97.94	6.80	0.01	0.09	0.27	1.30	0.18	1.76
L2	33.40	4.38	0.01	0.05	0.26	1.50	0.18	1.95
L3	207.72	10.07	0.02	0.18	0.37	1.80	0.21	2.26
L4	683.92	15.87	0.02	0.66	0.84	3.44	0.77	3.75
L5	51.10	1.12	0.01	0.16	0.04	1.24	0.00	0.57
L6	6.27	0.30	0.01	0.11	0.10	0.25	0.13	2.37
L7	49.35	2.60	0.02	0.13	0.14	0.74	0.05	1.03
L8	25.47	0.56	0.01	0.11	0.04	0.25	0.00	1.05
L9	22.22	0.57	0.01	0.08	0.05	0.81	0.03	2.39
L10	48.19	0.68	0.01	0.10	0.04	0.73	0.00	0.61
P1	258.11	5.52	0.16	0.20	0.33	8.90	0.26	9.08
P2	84.16	5.19	0.01	0.16	0.08	0.32	0.01	3.05
P3	180.65	13.73	0.01	0.18	0.10	0.99	0.68	3.31

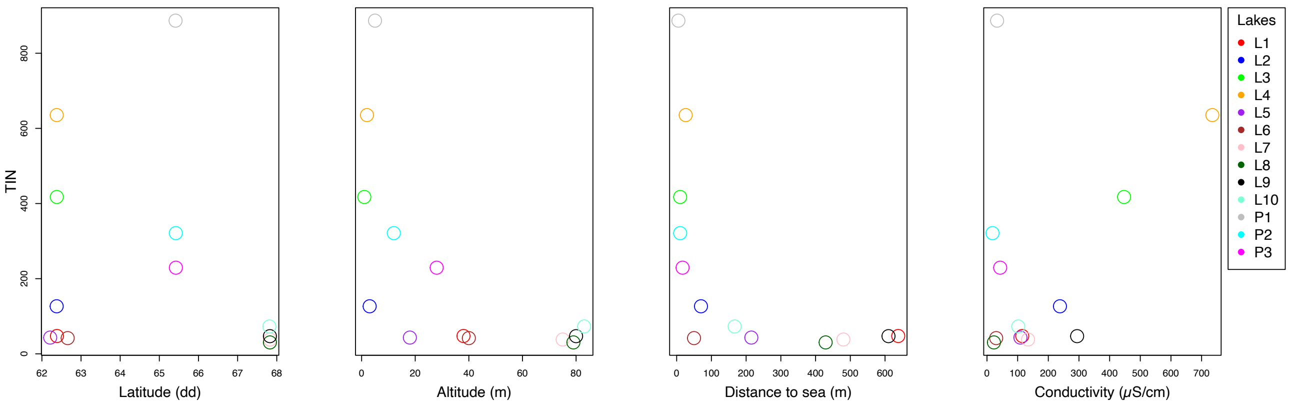

Figure 2. Lake water TIN concentrations vs. latitudes, altitudes, distances to the sea, and lake water conductivities for the sampled lakes and ponds.

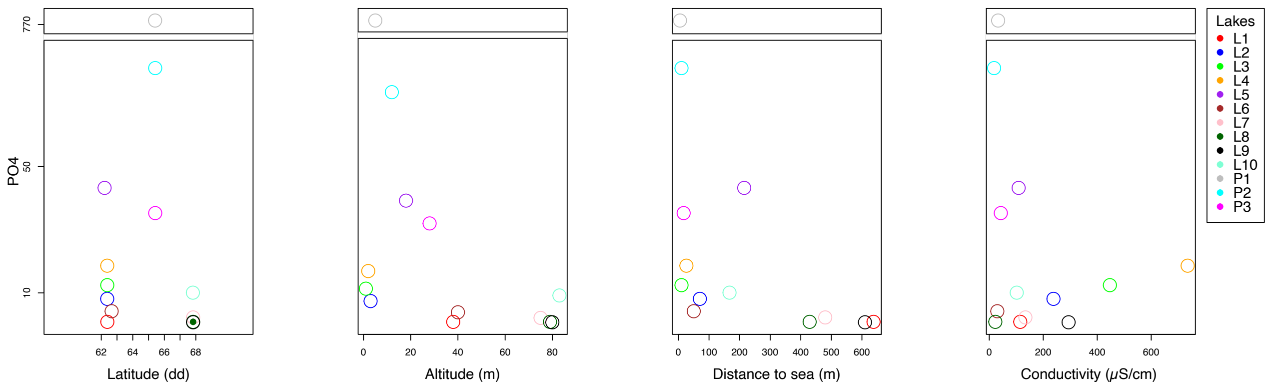

Figure 3. Lake water PO_4 concentrations vs. latitudes, altitudes, distances to the sea, and lake water conductivities for the sampled lakes. Note the broken Y-axis due to very high PO_4 concentrations in Pond 1.

Island in the Antarctic Peninsula also demonstrated the driving role of distance to the sea in the lake chemical characteristics (Roman et al., 2019). Furthermore, Hansson and Håkansson (1992) and Izaguirre et al. (2016) also documented that the trophic status and productivity of the Antarctic lakes was correlated with the intensity of faunal activity.

Chl-a was the pigment that had the highest concentration in all of the lakes (Figure 4, Table 5), followed by Chl-b, both representing the overall abundance of the major primary production groups (Figure 5; Jeffrey, 1974; Fietz and Nicklisch, 2004). Fucoxanthin, representing mostly diatom species (Jeffrey, 1974), reached high concentrations, especially in lakes with higher nutrient concentrations. Chl-c2, as an indicator of marine phytoplankton groups (Stauber and Jeffrey, 1988), attained higher concentrations in the more coastal lakes with higher conductivity, further evidencing the close coupling between coastal lakes and the sea.

Overall, the pigment concentrations were closely coupled with the patterns in the nutrient concentrations and conductivity levels, as revealed by the significant RDA ordination (Figure 5; $p = 0.001$) being higher in the lakes with higher nutrient concentrations and conductivity values. The majority of the pigments were significantly associated with increasing TIN, SiO_4, and conductivity values, all representing the nutrients transported from the sea potentially via sea-spray and faunal activity. Alloxanthin, which may indicate cryptomonads and cryomonads (Pennington et al., 1985), were not associated with any of the measured parameters. However, the abundance of both 19-hexanoloxyfucoxanthin and 19-butanoloxyfucoxanthin may indicate chrysophytes, prymnesiophytes, and some dinophlagellates (Vesk and Jeffrey, 1987; Bjørnland et al., 1989), and was more strongly associated by the change in the PO_4 concentrations.

4. Conclusion

Herein, the major physicochemical characteristics of 10 lakes and 3 ponds, as well as the pigment abundance and composition in their water columns in Maritime Antarctica (coastal Antarctic Peninsula), sampled during

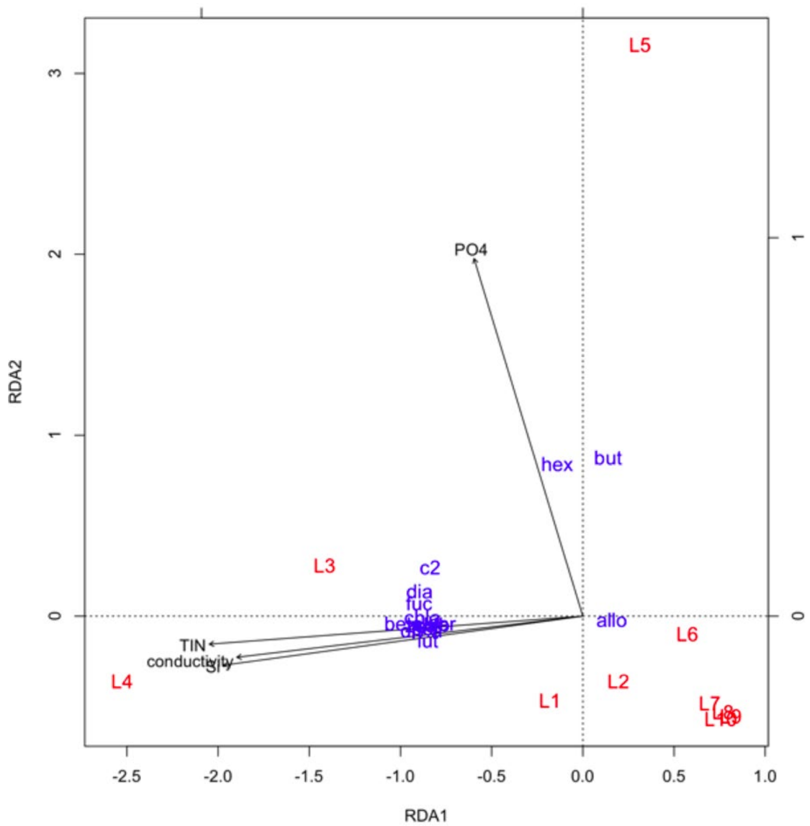

Figure 4. Multivariate ordinations of the lake water pigment compositions and a relationship with the lake water nutrients revealed by the RDA analyses. chl-a: chlorophyll-a, chl-b: chlorophyll-b, c2: chlorophyll-c2, per: peridinin, but: 19-butanoloxyfucoxanthin, fuc: fucoxanthin, hex: 19-hexanoloxyfucoxanthin, dia: diadinoxanthin, allo: alloxanthin, zea: zeaxanthin, lute: lutein, div-a: divinyl chlorophyll-a; beta: beta-carotene.

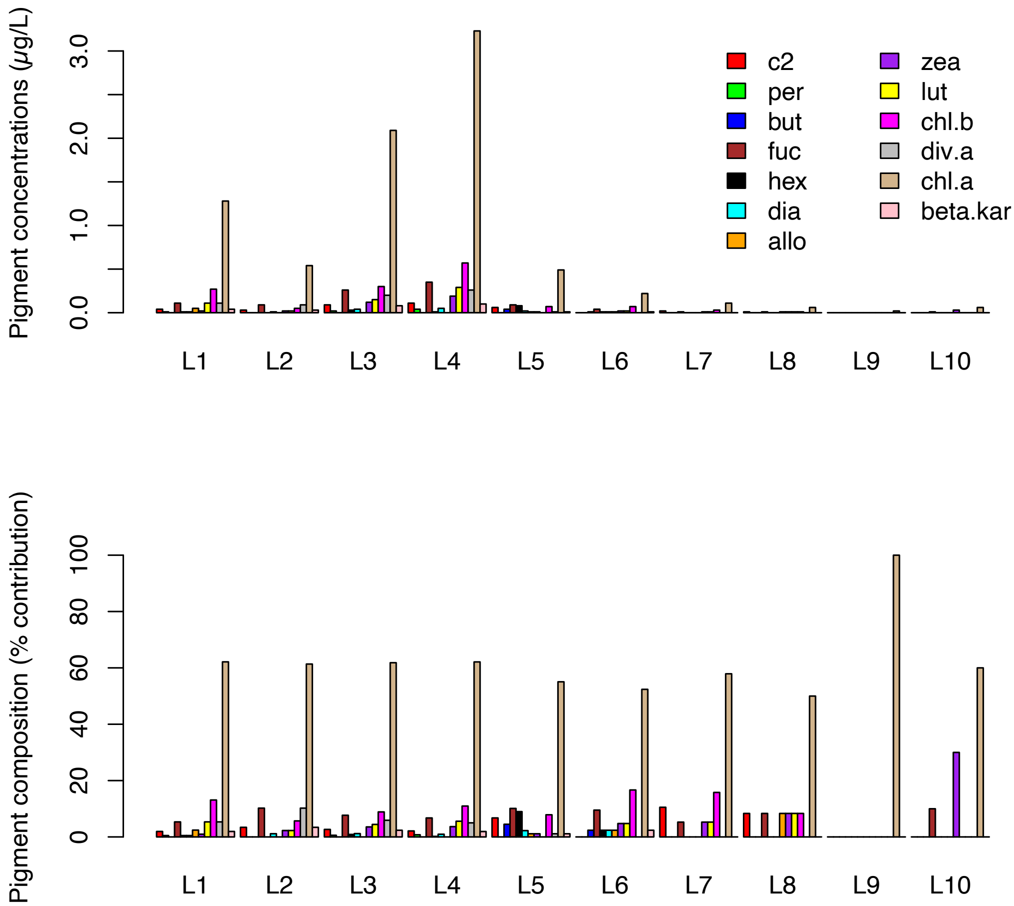

Figure 5. Pigment concentrations (top) and composition as the percent contribution (bottom) in the water columns of the sampled lakes.

Table 5. Pigment concentrations in the water columns of the sampled lakes (μg/L).

Site	chl-a	chl-b	c2	per	but	fuc	hex	dia	allo	zea	lut	div-a	beta
L1	1.28	0.27	0.04	0.01	-	0.11	0.01	0.01	0.05	0.02	0.11	0.11	0.04
L2	0.54	0.05	0.03	-	-	0.09	-	0.01	-	0.02	0.02	0.09	0.03
L3	2.09	0.30	0.09	0.02	-	0.26	0.03	0.04	-	0.12	0.15	0.20	0.08
L4	3.23	0.57	0.11	0.04	-	0.35	0.01	0.05	-	0.19	0.29	0.26	0.10
L5	0.49	0.07	0.06	-	0.04	0.09	0.08	0.02	0.01	0.01	-	0.01	0.01
L6	0.22	0.07	-	-	0.01	0.04	0.01	0.01	0.01	0.02	0.02	-	0.01
L7	0.11	0.03	0.02	-	-	0.01	-	-	-	0.01	0.01	-	-
L8	0.06	0.01	0.01	-	-	0.01	-	-	0.01	0.01	0.01	-	-
L9	0.02	-	-	-	-	-	-	-	-	-	-	-	-
L10	0.06	-	-	-	-	0.01	-	-	-	0.03	-	-	-

* chl-a: Chlorophyll a, chl-b: chlorophyll b, c2: chlorophyll c2, per: peridinin, but: 19-butanoloxyfucoxanthin, fuc: Fucoxanthin, hex: 19-hexanoloxyfucoxanthin, dia: diadinoxanthin, allo: alloxanthin, zea: zeaxanthin, lute: lutein, div-a: divinyl chlorophyll a; beta: beta-carotene. - represents below the detection limit.

TAE-II and TAE-III, were documented. The lakes generally had low nutrient concentrations and limited pollution from anthropogenic sources. The increase in the nutrient levels, and thus higher primary production, were mostly associated with the intensity of sea influence and being located at lower latitudes, as well as the potential effect of nutrient transport via faunal activity. However, the limited sample size in the present study precluded conclusive hypothesis testing and further research with larger sample sizes is needed to better quantify the relative roles of the drivers of the ecosystem structure and function of Antarctic Lakes. It should also be noted that replication of the field samplings and also of the laboratory analyses was not possible, and thus, the reported chemical concentrations should be used with caution.

The potential role of land–sea interaction in driving the structure and functioning of the sampled lakes in the present study suggests that any direct and indirect effects of climate change may induce significant changes in these ecosystems. Especially the change in the spatial patterns and population sizes of the breeding sea mammals and birds may have cascading effects in the coastal lake ecosystems. Although the present findings represent a snapshot survey of a limited number of ecosystems, they could be instrumental for future research to better understand the impact of climate change on the fragile ecosystems of Antarctica.

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