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Potential climate change impacts on the ecology of lakes in two contrasting Antarctic regions.

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Abstract:

Climate change is a topic prevalent throughout literature in a range of disciplines, particularly those relating to Antarctica because of the amplified impact climate change is predicted to have on the continent. The present study aims to assess the potential ecological impacts on a range on Antarctic lakes in the context of climate change progression by the year 2100. Rate of temperature increase is predicted for two contrasting Antarctic regions; maritime (Signy Island) and continental (Vestfold Hills). These predicted climate changes are translated into local changes relating to the study lakes including, but not limited to, changes to catchment area, lake depth and salinity. The impacts such changes will have on the ecology of each lake is discussed. This study adds to a wealth of multidisciplinary literature that aims to demonstrate the potential effects of climate change in the hope that knowledge and understanding will bring about important societal changes needed to reduce human impact on the environment.

Contents

INTRODUCTION

The issues of climate change and its potentially devastating consequences are prominent in literature of a range of disciplines. In Antarctic literature, it is a prevalent theme because climate change models generally predict amplified warming in polar regions. Although Antarctica is remote, its climate has huge influence on the global environment (IPCC, 2007; Turner *et al.*, 2014). Changes there could have considerable global impacts including on weather patterns and sea level rise (IPCC, 2007).

Decadal-scale temperature change differs amongst Antarctic regions. Since the early 1950s, surface temperatures have warmed across the Antarctic Peninsula and, to a lesser degree, throughout West Antarctica (Turner *et al.*, 2005). The most significant rates of warming have been recorded throughout maritime Antarctica, which includes the western regions of the Antarctic Peninsula and offshore islands (Turner *et al.*, 2014). Faraday/Vernadsky Station is situated on Galindez Island at 64.5^{o} South and has had an average temperature increase of 0.53^{o}C per decade from 1951 – 2006 (Franzke, 2013; Turner *et al.*, 2014). Information from satellite data and automated weather stations reveal an average warming of approximately 0.1^{o}C per decade throughout West Antarctica since 1957 (Steig *et al.*, 2009). While West Antarctica shows warming trends, the East Antarctic region demonstrated a net cooling between 1966 and 2000 (Doran et al., 2002; Turner *et al.,* 2014). In particular, the McMurdo Dry Valleys have cooled by 0.7^{o}C per decade from 1986 to 2000. The Amundsen-Scott Station at the South Pole has exhibited cooling of approximately -0.1^{o}C per decade since the 1950's (Turner *et al.*, 2014). Climate change, whether manifested by warming or cooling, is expected to result in the increased occurrence and severity of extreme climate events (Hoffman & Parsons, 1997; IPCC, 2007). Such events include heatwaves, which are defined as periods of at least five consecutive days during which average daily temperatures exceed the expected daily average temperatures by at least 5^{o}C (Tebaldi *et al.*, 2005).

Regardless of whether the changes in climate are of an increasing or decreasing nature, polar lakes are widely regarded as early indicators of environmental change (Laybourn-Parry & Wadham, 2014b; Quayle *et al.*, 2002). With direct human impacts on most Antarctic lakes systems non-existent (disregarding freshwater systems subject to anthropogenic impact through research station water supply, for which impacts are palpable and immediate), it is accepted that local and global climatic events and trends are the primary drivers of both physical and chemical changes within Antarctic lake systems (Laybourn-Parry & Wadham, 2014b). Antarctica boasts the highest diversity of lake types on Earth and most are very sensitive systems, exhibiting rapid, measurable responses to environmental change (Laybourn-Parry & Wadham, 2014b). It has been shown that polar lakes with high surface area to volume ratios respond rapidly to fluctuations in the precipitation-evaporation balance, making them prone to salinization and desiccation through changes to depth and thus changes in the concentration of dissolved salts (Roberts & McMinn, 1999; Smol & Douglas, 2007). Any changes to climate will also potentially alter snow and ice cover of Antarctic lakes which would have various measurable consequences on many physical, chemical and ecological variables (Quayle *et al.*, 2002; Roberts & McMinn, 1999). Changes to physical and chemical parameters within sensitive Antarctic lakes are expected to have palpable effects on the structure of biological communities as well as the ecological processes that take place within the lakes (Laybourn-Parry & Wadham, 2014b; Verleyen *et al.*, 2012). The potential extent of climate change impacts on Antarctic lake systems are of interest because Antarctic lakes are hotspots for biological production and biodiversity in an otherwise arid and relatively unproductive environment (Laybourn-Parry & Pearce, 2007; Laybourn-Parry & Wadham, 2014b). With predicted climate change trends varying throughout the Antarctic region, it is expected that the degree to which Antarctic lakes and ponds are impacted will also vary greatly.

The present study aims to explore the potential impacts climate change will have on lakes in two contrasting Antarctic regions; maritime and continental. Each study lake is different in its physical, chemical and biological characteristics. Recent climate data will be utilized to model climate change trends up until 2100 in both regions. The changing direction key physical and chemical parameters will take will be predicted for each study lake. The possible impacts these changes may have on the ecology of each lake will then be assessed.

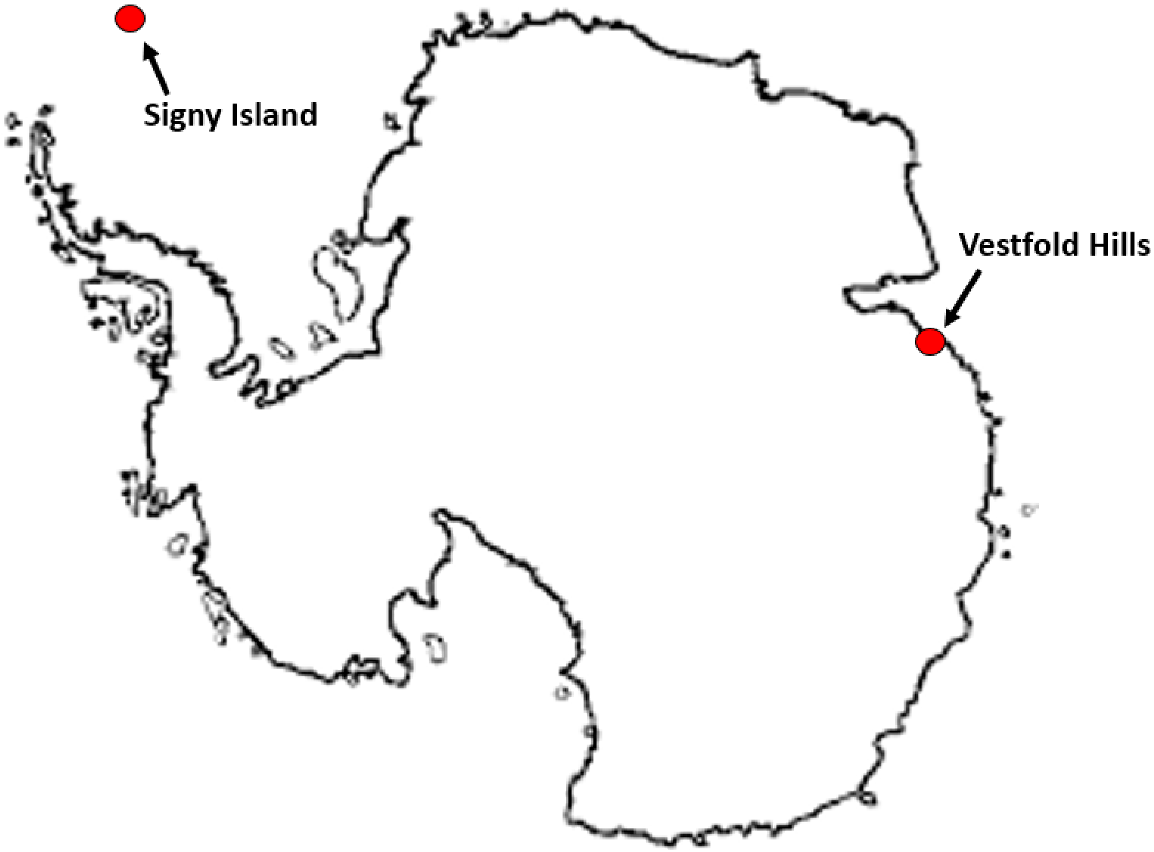

Figure 1. Map of the Antarctic continent displaying the approximate locations of Vestfold Hills and Signy Island

STUDY SITES

SIGNY ISLAND

With an area of 20km^2 and lying around 700km NW of the Antarctic Peninsula at 60°43'S, 45°38'W, Signy Island is part of the South Orkney Islands group within the maritime Antarctica region (Figure 1) (Heywood, 1967; Vincent & Laybourn-Parry, 2008). With a current average annual temperature of -3°C and annual precipitation ranging from 350 – 770mm, the maritime Antarctic climate of Signy Island is much milder and wetter than the typical continental Antarctic climate (Heywood, 1967; Jones *et al.*, 2000; Vincent & Laybourn-Parry, 2008). It is believed that the island was completely covered by an ice cap during the last glacial maximum (LGM) however it has since retreated, with approximately 32% of the island presently covered (Appleby *et al.*, 1995). Rate of glacial and snowfield melt has rapidly increased due to a rapid increase in air temperature of at least 2°C since 1903 (Jones *et al.*, 2000). For example, there was a 35% coverage reduction in ice areas from 1949 to 1989 during which some ice margins receded by over 100m and glacial thickness was reduced by 7-8m on some areas of the island (Jones *et al.*, 2000; Smith, 1990). The ice caps sensitivity to climate fluctuations can be attributed to the low altitude and isolated oceanic setting of the island (Smith, 1990).

Subject to this rapid environmental change are the 16 lakes and ponds. All lakes are glacial in origin, relatively shallow (typically <10m deep) and are capped with ice 8-12 months, annually (Heywood, 1967; Heywood *et al.*, 1980). All of them are considered 'freshwater' however some vary in salinity, explained by their location respective to the sea and the prominent wind direction (Heywood, 1967). A range of trophic status' are represented by the Signy Island lakes which range from clear and oligotrophic to turbid and eutrophic (Heywood *et al.*, 1980; Quayle & Convey, 2006).

Moss Lake and Heywood Lake are physically contrasting lakes and will be used as case studies to demonstrate potential climate change impacts on the ecology of contrasting lake systems by 2100.

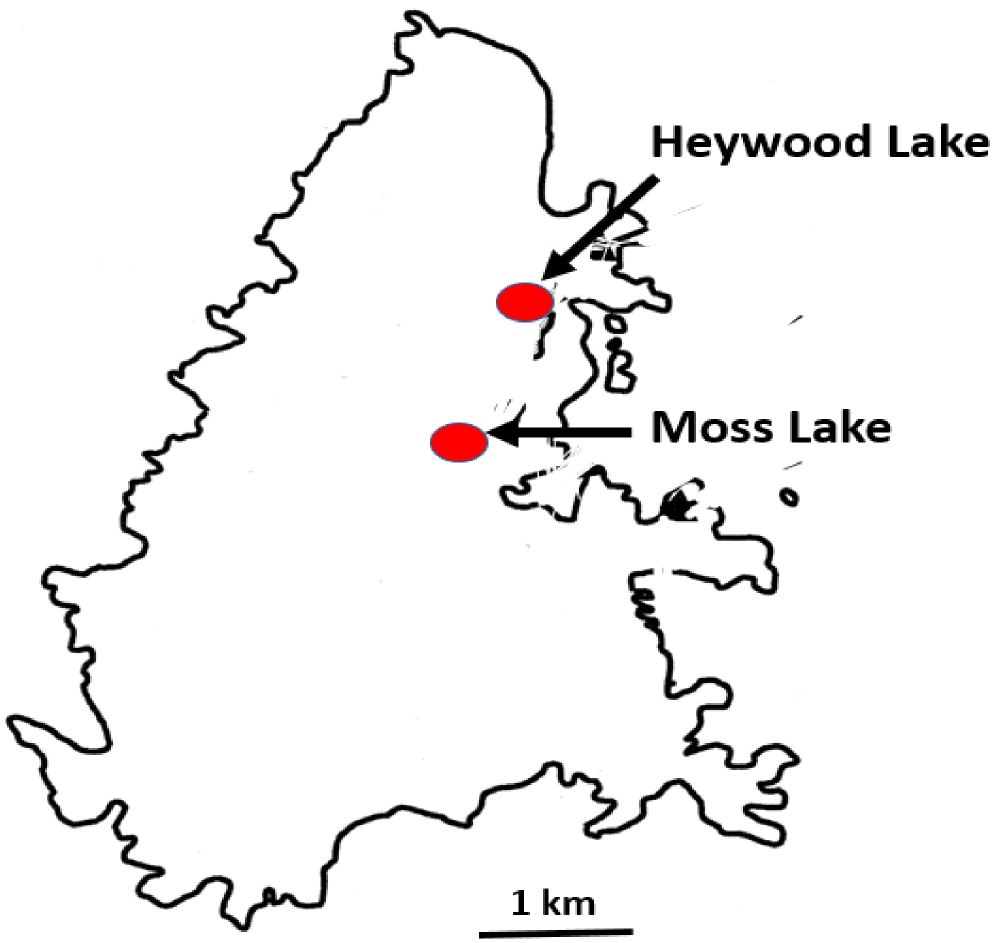

Figure 2. Map of Signy Island displaying the approximate locations of Moss Lake and Heywood Lake.

MOSS LAKE

Moss Lake is located on the east side of Signy Island, around 50m above sea level at the head of Paternoster Valley (Figure 2) (Priddle & Dartnall, 1978). It has a maximum depth of 10.4m and surface area of $0.015km^2$ (Laybourn-Parry & Wadham, 2014a; Priddle & Dartnall, 1978). During the summer, winds keep the waters well mixed while oxygen concentrations approach saturation and surface temperatures get as high as 6^oC (Priddle & Dartnall, 1978). The lakes ice cap, which begins forming in March, remains at maximum thickness (~1m) from September to October (Priddle & Dartnall, 1978). During periods of ice-cover, the lake becomes slightly stratified with oxygen concentrations lowering to about 10% saturation in the deepest areas (Priddle & Dartnall, 1978). Even though inflow and outflow streams are frozen during winter, lake levels drop during this season when about 75% of the total lake volume is lost due to subterranean drainage (Priddle & Dartnall, 1978). Volume is restored during the summer months by inflows of meltwater (Priddle & Dartnall, 1978).

The low water column chlorophyll values in Moss Lake are a reflection of very low nutrient concentrations; the lake is thus considered oligotrophic (Priddle & Dartnall, 1978). Despite lacking in nutrients, Moss Lake boasts the richest biological community of any Signy Island lake (Heywood *et al.*, 1980; Priddle & Dartnall, 1978). It is largely dominated by epiphytic organisms supported by the abundance of thick mats of moss of which the lake is characterised by (Priddle & Dartnall, 1978). The moss itself (*Calliergon sarmentosum* and a *Drepanocladus* species) is supported by a felt of blue-green algae and benthic diatom species upon which it grows (Priddle & Dartnall, 1978). Some moss stems have been found to be 40cm long, which is thought to represent 20-50 years of growth (Priddle & Dartnall, 1978).

Algae species dominate the epiphytic community, with 38 of the 49 species closely associated to the moss mats (Priddle & Dartnall, 1978). The epiphytic algae community, which reaches maximum development at around 10m depth, adds crucial productive value to the system, contributing up to half of the annual production (Priddle & Dartnall, 1978).

The faunal community is largely moss-dwelling, benthic organisms from the groups: Protozoa, Nematoda, Turbellaria, Annelida, Rotifera, Crustacea, Tardigrada and Gastrotricha (Priddle & Dartnall, 1978). Most appear to be non-specific, opportunistic grazers of the epiphytic algae while a few, such as free-swimming rotifers and large Protozoa, are predatory, making for a relatively complex food web compared to other Antarctic systems (Priddle & Dartnall, 1978).

HEYWOOD LAKE

Heywood Lake is the largest lake on Signy Island at 0.045km^2 and is situated in an ice-free catchment in Three Lakes Valley approximately 200m from the sea (Figure 2) (Jones *et al.*, 2000; Laybourn-Parry & Wadham, 2014a). The lake has an average depth of 2m, maximum depth of 6.4m and is ice-covered for around 8 months annually, to a depth of 1m (Butler, 1999; Pearce *et al.*, 2005). While Heywood Lake was previously described as mesotrophic, it has recently undergone eutrophication due to the rapid influx of Antarctic fur seal populations into the lakes catchment starting in 1974 (Butler, 1999). Presently there are often several hundred Antarctic fur seals within the catchment at a time. The mammal population leaves the catchment muddy while trampling and eroding the lake sediments (Butler, 1999; Jones *et al.*, 2000). Such erosion, along with nutrient input (seal excrement and moult) from land runoff and swimming activity has made the lake highly turbid and eutrophic, with nutrient levels having increased several-fold over the last three decades (Butler, 1999; Jones *et al.*, 2000). This has resulted in large spring phytoplankton blooms which rapidly deplete all nutrients in the lake, leaving minimal nitrogen available for crucial primary production during the summer period (Butler, 1999). Additionally, eutrophication has resulted in extensive anoxia in the water column during winter ice-cover periods brought on by the decomposition of organic carbon (Butler, 1999).

A simple planktonic food web exists in Heywood Lake. Phytoplankton consist of mainly flagellated cells, with only small populations of micotrophs surviving the dark, anoxic conditions of winter (Butler, 1999). Biodiversity increases in the spring, featuring chlorophytes, chrysophytes and dinoflagellates, before decreasing again in the peak of summer when many become outcompeted by dominant cryptophytes (Butler, 1999). Many flagellate taxa dominating Heywood Lake, such as *Euglena* and *Chlorella,* are typical of polluted waters, while previously abundant species, such as the sensitive algae *Ankistrodesmus falcatus*, are rarely seen (Butler, 1999). The abundance of protozooplankton, such as ciliates, fluctuated seasonally with numbers peaking in spring and summer, as did the abundance of microcrustaceans, a predator of phytoplankton (Butler, 1999).

VESTFOLD HILLS

The Vestfold Hills is a mostly ice-free area of approximately 400km^2 lying to the eastern edge of Prydz Bay on the Ingrid Christensen Coast, Princess Elizabeth Land, East Antarctica (68^{o}25' – 68^{o}40'S, 77^{o}50' – 78^{o}35'E) (Figure 1). This is the third largest ice-free region in Antarctica and is characterised by fjords, low-lying hills and lengthy peninsulas as well as the many freshwater and saline lakes (Mazumder *et al.*, 2013). There are approximately 300 lakes and ponds which vary greatly in salinity, depth, ice cover, age and history (Laybourn-Parry & Bell, 2014; Roberts & McMinn, 1999). It is widely accepted that most lakes formed as a result of isostatic rebound following the end of the LGM (Adamson & Pickard, 1986). As the ice sheet retreated and the land rose, pockets of sea and melt water were left trapped in pre-existing hollows to form present-day lakes (Adamson & Pickard, 1986; Roberts & McMinn, 1999). It is considered that those with little inflow and outflow remained saline systems while those consistently flushed by snow and glacial melt developed into freshwater systems (Laybourn-Parry *et al.*, 2002). Many contemporary lakes are meromictic, meaning the water column is partially mixed (Gibson, 1999). Many are also stratified either permanently or for large portions of the year, exhibiting significant physical and chemical gradients (Gibson, 1999). For example, salinity increases with depth in such lakes.

The climate is typical of a periglacial location being cold, dry and subject to frequent freeze-thaw cycles (Mazumder *et al.*, 2013). However, with an annual mean temperature of -10.2°C, the

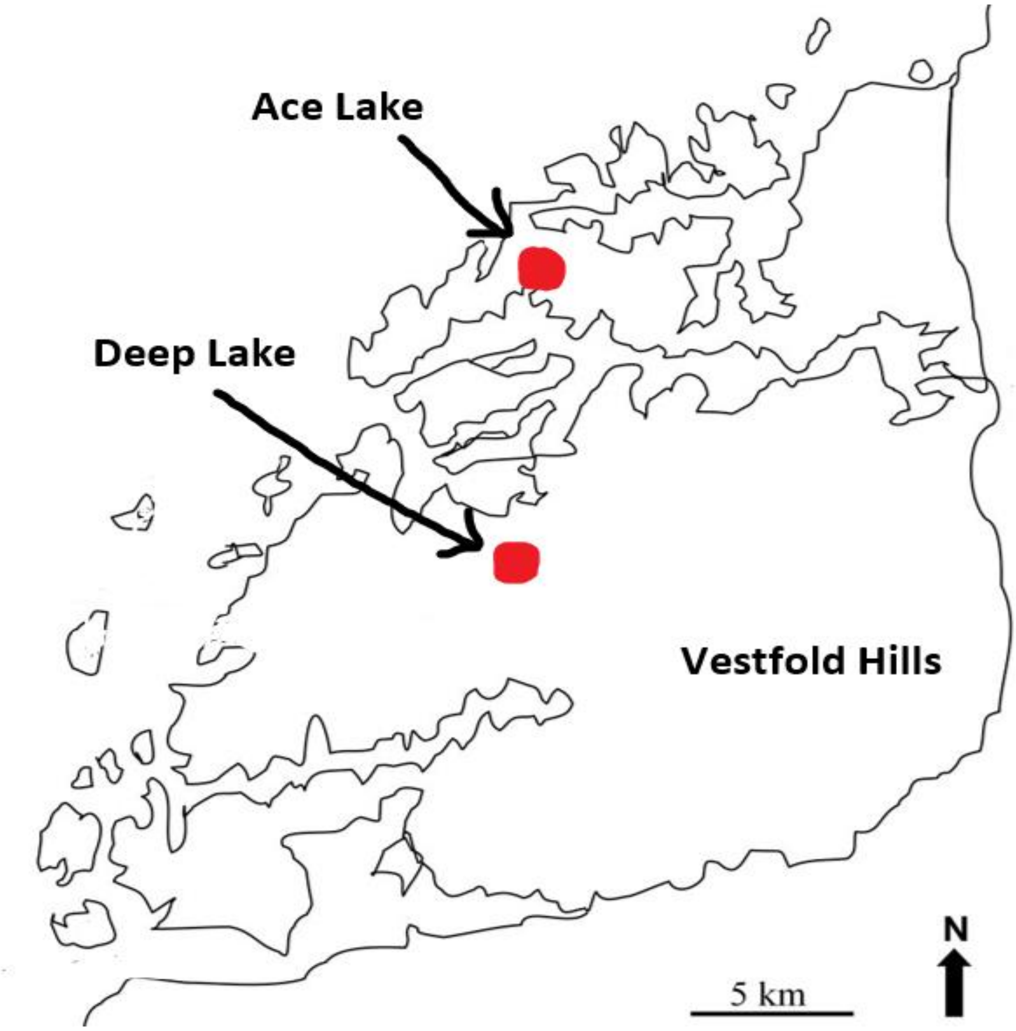

Figure 3. Map of Vestfold Hills displaying the approximate locations of Deep Lake and Ace Lake.

region is warmer than most other coastal continental Antarctic regions at about the same latitude (Mazumder *et al.*, 2013; Mergelov, 2014). There is no reliable precipitation data but rain and snow fall is a relatively rare occurrence with annual precipitation of less than 250mm (Mazumder et al., 2013). Snow and ice melt is limited to the summer period of December to February.

Deep Lake and Ace Lake are the two physically contrasting lakes that will be used as case studies to demonstrate potential climate change impacts on the unique biota of these systems by 2100.

DEEP LAKE

Located within the Vestfold Hills at 68°22'S and 78°11'E (Figure 3), Deep Lake is one of the most saline lakes in Antarctica (Setty *et al.*, 1980; Vincent & Laybourn-Parry, 2008). With a salinity of around 380 parts per thousand (ppt), Deep Lake, which presently lies around 50.4m below sea level, is approximately ten times the salinity of sea water (Ferris & Burton, 1988; Laybourn-Parry & Wadham, 2014a). Consequently, the water remains in an entirely unfrozen, liquid state year round, even while reaching minimum water temperatures of -18°C to -20°C (Ferris & Burton, 1988; Vincent & Laybourn-Parry, 2008). With a surface area of 0.064km^2 and a maximum depth of 36m, Deep Lake is considered to be relatively large, especially for a saline, ice free water body (Ferris & Burton, 1988; Vincent & Laybourn-Parry, 2008). Deep Lake lacks algal blooms and mats as well as any great extent of organic input, therefore the water is relatively clear and with little turbidity (Tschitschkoa *et al.*, 2016). Lack of an ice cover results in deep mixing of the lake during winter, while during the summer, Deep Lake has a significant vertical thermal gradient with a range of around 21 – 26°C (Ferris & Burton, 1988). During this time, surface waters can reach maximums of 7 – 11°C while bottom waters rarely rise above -14°C. The thermal cycle is monomictic (Ferris & Burton, 1988), undergoing one period of complete mixing from top to bottom during each year.

Given the extreme salinity of Deep Lake, it is considered to be an extreme environment, biologically, hosting limited abundances of only the most specially adapted species (Ferris & Burton, 1988). For example, microinvertebrates are completely absent (Ferris & Burton, 1988). Green algae species *Dunaliella,* populates the surface waters of Deep lake (Ferris & Burton, 1988). Although it exists in small abundances, *Dunaliella* is the main primary producer in the system (Tschitschkoa *et al.*, 2016). Two strains of *Halobacterium* have been identified in Deep Lake as well as four *Haloarchaea* species, three of which dominate the system by making up approximately 72% of the community (DeMaere *et al.*, 2013; Tschitschkoa *et al.*, 2016). *Halohasta litchfieldiae*, strain tADL, is the most abundant species overall in Deep Lake, making up approximately 44% of the community (Tschitschkoa *et al.*, 2016). All four species of *Haloarchaea*, three of which belong to the same family (*Halobacteriaceae*), have demonstrated significant horizontal gene flow (DeMaere *et al.*, 2013). Such gene exchange could potentially homogenise the populations, however, thus far, distinct genera appear to be maintained with distinguishing niche adaptations (DeMaere *et al.*, 2013).

The simple biological community is all but homogenous throughout the lake (when assessed at 5, 13, 24 and 36m during the summer) which is a reflection of the characteristic monomictic limnology of Deep Lake (DeMaere *et al.*, 2013).

ACE LAKE

Since the 1970's, Ace Lake has received much scientific attention, such that it is regarded as one of the most heavily researched lakes in Antarctica (Laybourn-Parry & Bell, 2014). It is situated on Long Peninsula in the Vestfold Hills region at 68°28'S, 78°11'E, a position that lies 150m from the sea, 10km from the ice cap and 8.73m above sea level (Figure 3) (Roberts & McMinn, 1999). Little snow accumulates in the Ace Lake catchment as it is removed by the prevalent strong north-easterly winds (Roberts & McMinn, 1999). Unlike Deep Lake, Ace Lake is covered by an (up to) 2m thick ice sheet for, on average, 11 months of the year (Roberts & McMinn, 1999). Also unlike Deep Lake, Ace Lake is a meromictic, permanently stratified lake (Laybourn-Parry & Bell, 2014). Permanent stratification occurs whereby the deep layer of saline water merging with the upper, weakly saline layer through strong physical and chemical gradients (Laybourn-Parry & Bell, 2014). A lake bottom salinity of 43ppt is often quoted in literature (Laybourn-Parry & Bell, 2014; Laybourn-Parry & Wadham, 2014a).

In terms of biology, Ace Lake is much more complex than Deep Lake, supporting four distinct communities which fluctuate in biomass throughout the seasons (Laybourn-Parry & Bell, 2014). The Ace Lakes mixolimnion, the uppermost euphotic stratum of water directly beneath the ice-cover, supports a distinct planktonic community dominated by microorganisms (Laybourn-Parry & Bell, 2014). Rotifers (*Encentrum* and *Notholca* species) are occasionally found within plankton samples from the mixolimnion, as is a single crustacean species, the marine copepod *Paralabidocera antarctica* (Bell & Laybourn-Parry, 1999).

The second distinct biological community is in the littoral zone (benthic zone down to 10m depth, in the case of Ace Lake, where light penetration is sufficient to support benthic photosynthetic activity), and is dominated by algal mats (Hand & Burton, 1981; Laybourn-Parry & Bell, 2014). Several cyanobacteria strains form the algal mats including, but not limited to: *Leptolyngbya antarctica, Leptolyngbya frigida, Phormidium murrayi, Phormidium priestleyi, Oscillatoria subproboscidea* and *Nostoc* species (Taton *et al.*, 2006). In comparison with algal mats in other Antarctic lakes, such as the mature pinnacle mats characteristic of lakes in the McMurdo Dry Valleys, the cyanobacterial mats within Ace Lake are relatively under developed (Laybourn-Parry & Bell, 2014).

Even so, they provide a habitat for an array of organisms including a rich community of diatoms, heterotrophic microorganisms and invertebrates, both protozoan and metazoan (Rankin *et al.*, 1999).

Another distinct biological community can be found within the anoxic, highly saline waters of the monimolimnion. Here exists a simple community dominated by anaerobic prokaryotes, namely photosynthetic green sulphur bacteria along with lesser abundances of purple sulphur photosynthetic bacteria (Laybourn-Parry & Bell, 2014; Rankin *et al.*, 1999). The fourth biological community within Ace Lake exists in sulphide rich, anoxic sediments well below the chemocline (Laybourn-Parry & Bell, 2014). There is very little published data relating to this community, however limited molecular studies have revealed surprisingly high levels of biodiversity with most inhabitants thought to be strains of sulphur-reducing bacteria (Laybourn-Parry & Bell, 2014).

CLIMATE CHANGE 2100

Linear climate change trends for Signy Island and Vestfold Hills are presented (Figure 5, Figure 6). The rates of change presented in this study have been derived from changes occurring over the 20th Century as quoted in literature (Signy Island – Jones *et al.* 2000; Quayle *et al.* 2002) as well as NASA thermal infrared information spanning 2 decades (Figure 4). The presented climate trends predict that the annual average temperature in Signy Island will be around -1.3^{o}C by the year 2100, a 1.8^{o}C increase on current average annual temperatures (Figure 5). Average annual temperature in Vestfold Hills are predicted to be around -9.4^{o}C by the year 2100, a 0.8^{o}C increase on the current average (Figure 6). Key physical and chemical parameters are described in terms of their current approximate values and the direction changes are likely to take given the predicted 2100 climatic conditions (Table 1, Table 2).

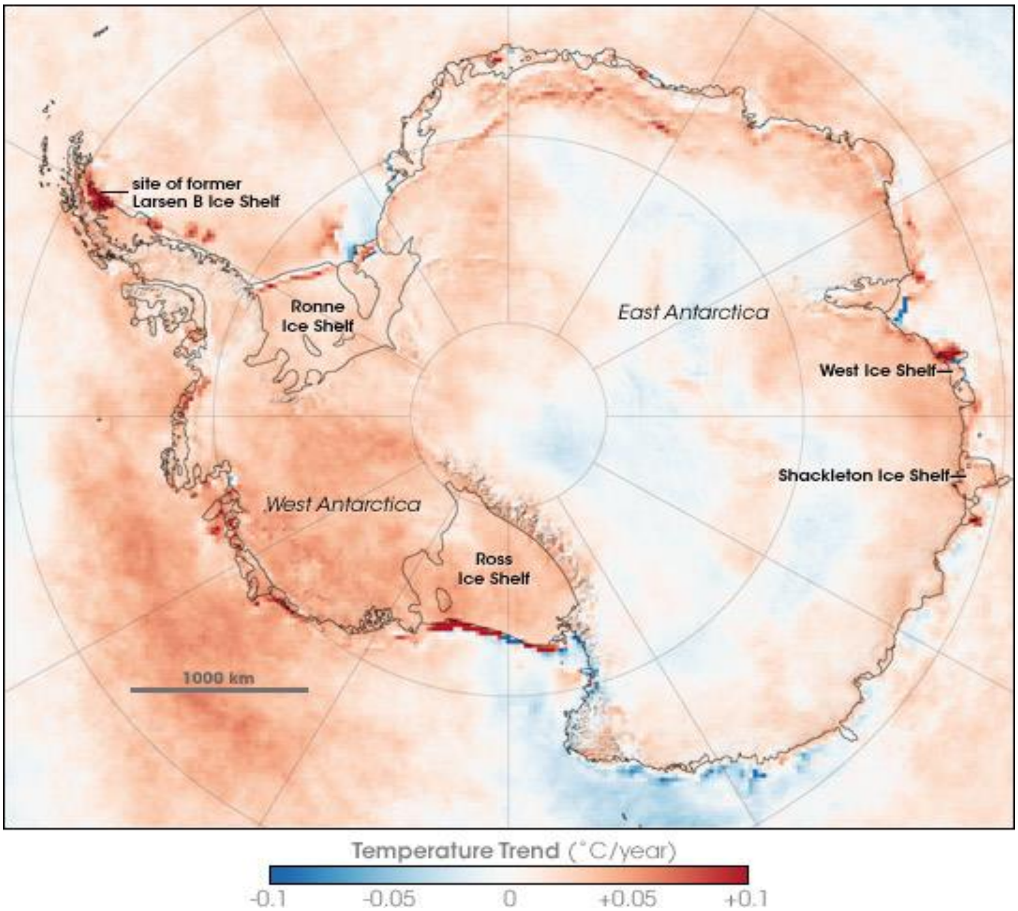

Figure 4. Image shows rate of temperature change (°C per year) over Antarctica from 1981-2007 using thermal infrared observations made by a series of NOAA satellite sensors. Image supplied by NASA (2007).

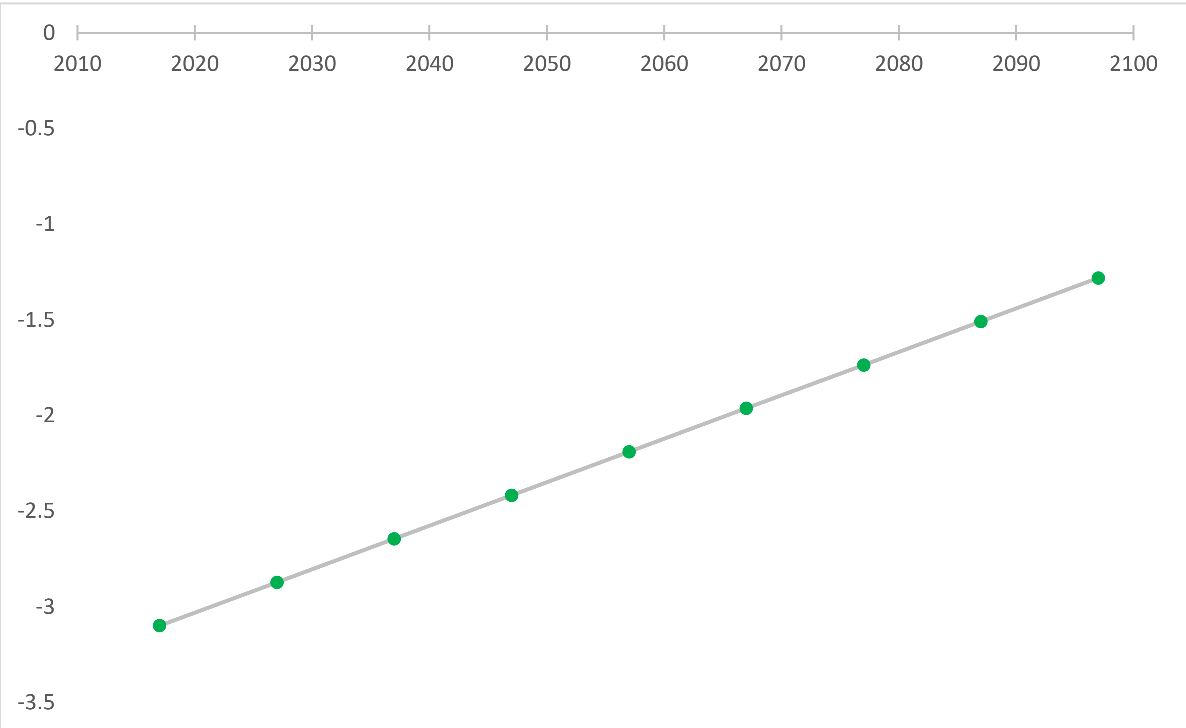

Figure 5. Time series graph showing theoretical climate change on Signy Island. Decadal increase of 0.2°C is based on a current ~2°C temperature increase since 1903 (Jones *et al.*, 2000; Quayle *et al.*, 2002).

Table 1. Physical and chemical parameters for two lakes on Signy Island. Present day values are presented as well as how these values may potentially change due to climate change by 2100.

Physical / Chemical Parameters	Moss Lake		Heywood Lake	
	Present	2100	Present	2100
Area (km^2)	0.015	>0.015	0.045	>0.045
Max depth (m)	10.4	>10.4	6.4	>6.4
Salinity (ppt)	N/A	N/A	N/A	N/A
Max summer surface temp (°C)	4.5	>4.5	5.3	>5.3
Max Ice-cover thickness (m)	~1	<1	~1	<1
Open days per annum	60	>60	~90	>90

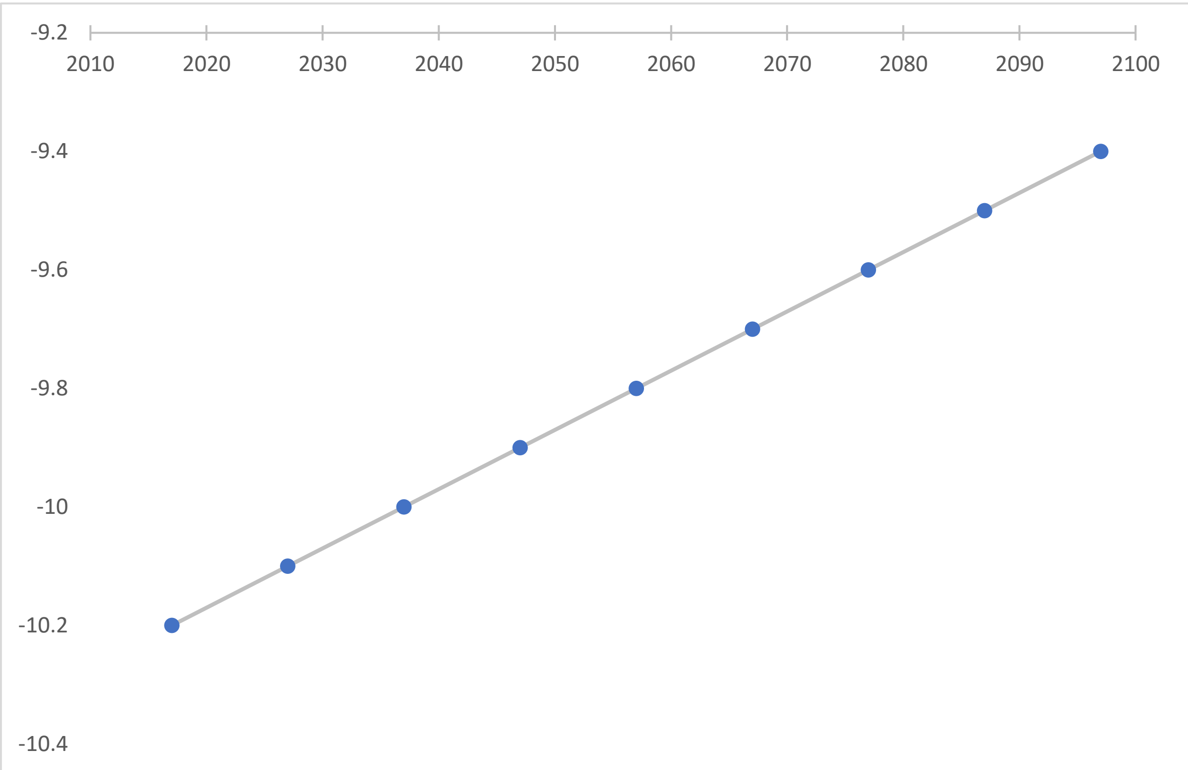

Figure 6. Time series graph showing theoretical climate change trend in the Vestfold Hills, Antarctica. Rate of climate change is based on a decadal increase of 0.1°C as derived from NASAs thermal infrared measurements taken from 1981 to 2007 (Figure 4.) (+~0.01°C annually).

Table 2. Physical and chemical parameters for two lakes in the Vestfold Hills. Present day values are presented as well as how these values may potentially change due to climate change by 2100.

Physical / Chemical Parameters	Deep Lake		Ace Lake	
	Present	**2100**	**Present**	**2100**
Area (km^2)	0.064	>0.064	0.18	>0.18
Max depth (m)	36	>36	25	>25
Salinity (ppt)	380	~380	43	~43
Max summer surface temp (°C)	11	>11	2 to 3	>3
Max Ice-cover thickness (m)	0	0	~2	<2
Open days per annum	N/A	N/A	~30	>30

ECOLOGICAL IMPACTS ON CONTRASTING LAKES

As indicated in Tables 1 & 2, the four Antarctic lakes, although contrasting in their locations and limnological properties, will all likely undergo some changes by the year 2100 if current climate change trends continue. The ecological characteristics of each lake system will therefore be impacted as well.

On Signy Island, where climate change is occurring quicker than in continental Antarctica, there would be further retreat of the ice cap by 2100. Melt water running across the newly exposed earth could potentially increase sediment content within Moss and Heywood Lakes with an associated increase in mineral presence. Introduction of more sediment into the lakes will also likely be brought on by rising lake levels due to increased melt water from the retreating ice cap. This could be particularly true for Heywood Lake where the banks are already eroding. When the lake levels raise, Heywood Lake will engulf substrate which is high in nutrients and biological waste from the Antarctic fur seal colony. Increased occurrence of sediment and the associated nutrients will increase turbidity within both Moss Lake and Heywood Lake. Turbidity influences how light travels within the water column, thus impacting primary productivity. Lake Heywood already experiences turbidity to an extent due to recent disturbance from the seal colony, however Moss Lake, with its oligotrophic status, currently exhibits minimal turbidity. Presently, the moss and epiphytic algae community, which dominate primary production, reach maximum density and efficiency at 10m depth (Priddle &

Dartnall, 1978). Turbidity would decrease light clarity at this depth, therefore by the year 2100, primary production efficiency within Moss Lake may be under impact. This would result in significant flow-on effects on the invertebrate and microbial communities which primary production supports. Such impacts may include decreased population abundances due to less energy in the system, and decreased species richness as more resilient species outcompete others. This could ultimately result in the loss of unique endemic species.

Longer periods of open water days due to increased average temperatures by the year 2100 is likely to effect Heywood Lake more than Moss Lake. This is because the slight rise in water temperature resulting from more open water days that Moss lake may experience, would not be as damaging as the further increased nutrient leaching potentially experienced by Heywood Lake by the same cause. Antarctic fur seals are known to swim in Heywood Lake during ice-free periods. If the ice-free period increases, the seals will be spending more time in and around the water, increasing the annual period of direct biological contamination. In turn, this will increase anoxia of the water column during winter, thus potentially further decreasing the range of species able to survive in the lake over the season.

Come 2100, continental saline lakes, Deep Lake and Ace Lake, will be largely influenced by climate driven changes to the precipitation and desiccation balance. The temperature changes predicted in this study will increase desiccation, causing both Deep Lake and Ace Lake to increase in salinity. However, this will be balanced out by precipitation events, which may increase due to the predicted increase in extreme and unusual weather event. Desiccation will also be balanced out by increased meltwater inflow resulting from the ongoing retreat of ice and snow reservoirs within individual catchments. This uncertainty in what will happen to salinity levels in a climate change context is depicted in Table 2, with future values quoted as being around the same as present levels. If there is a change in salinity, this may change the community composition of unique halophyte organisms residing in Deep Lake. Otherwise effecting the biological community of Deep Lake could be the potential increase of mixing in the water column brought on by increased rate of melt inflow and extreme weather events (such as usually string winds). Increased mixing of the already well mixed water column may further lesson the distinction between ecological niches. In this instance, water column mixing may drive further horizontal gene transfer in the four unique haloarchaea species found within Deep Lake. The eventual result could be as dramatic as the complete homogenisation of *Haloarchaea* species within Deep Lake. This would be an unfortunate loss to the characteristic biodiversity of the region.

Similar of the Signy Island lakes, increased melt inflow could increase the depths of the two study lakes in the Vestfold Hills by the year 2100. In Deep Lake, the main primary producer, *Dunaliella,* resides atop surface waters so will not be effected by an increase in depth. However, in Ace Lake, where there are reasonably extensive algal mats down to 10m deep, a climate change induced depth increase may mean that light strength is lessened in some areas or newly absent in others. The consequence of this is that primary production will not be carried out to the same efficiency, thus reducing the total energy available to the system. Like Heywood Lake, this theoretical change in light regime and energy input has potentially destructive flow-on consequences in terms of maintaining the unique biodiversity of the system.

UNCERTAINTIES IN CLIMATE MODELLING

There are several uncertainties associated with the climate models produced in this study. Firstly, are the uncertainties around the underlying data. Up to date climate data from direct sources such as British Antarctic Survey (Signy Island) and Australian Antarctic Program (Davis Station, Vestfold Hills) need permission to be accessed, therefore second-hand information had to be utilized for the purposes of this study. While climate data for Signy Island was reasonably accessible throughout the literature, there is a profound lack of climate data readily available for the Vestfold Hills, or any other nearby coastal Antarctic locations. The most regularly quoted climate data was taken from an extensive literature search to produce the trends presented in this report.

Other uncertainties in the climate models presented in this report are uncontrollable and include the ongoing and ever changing effects of both atmospheric CO_2 levels and ozone depletion and regeneration. It is unknown exactly how these factors will drive temperature changes around the world throughout the remainder of the 21st century, much less how they will drive local climate changes in two isolation regions of Antarctica. For this reason, rising CO_2 levels and ozone activity was not included in the models. They will however, both play a profound role in the rate of climate change over the coming century.

CONCLUSION

If climate warming remains at the current rate, the ecology of Antarctic lakes, in both maritime and continental locations, will be continually impacted, with biological communities racing to adapt to the changing parameters. The lakes investigated will likely all be impacted by increased inflow from nearby areas of ice melt. In the freshwater lakes of Signy Island, increased inflow will likely result in turbidity, and ecological impacts will likely be associated to changes in light clarity. Increased depth will be experienced by all four study lakes. This could have detrimental effects for Heywood Lake thanks to the potential to take on more sediment and biological waste, thus increasing winter anoxia. Lake depth will impact Moss Lake and Ace Lake by changing light availability and clarity at depths which support organisms crucial to primary productivity, ultimately reducing energy availability in each system. Disturbance caused by increased rates of inflow may mix the water column in Deep Lake such that ecological niches become less defined, potentially resulting in further horizontal gene transfer of *Haloarchaea*. As previously discussed, climate change by 2100 would provide various opportunities in each lake system for biological communities to alter in a way that is irreversible. Some unique species or community functions in Antarctic lakes may be lost for good.

This study adds to the multidisciplinary range of literature dedicated to describing the potential environmental changes and ecological impacts climate change will have in the future. Such studies, like the present report, are often produced in the hope that are range of knowledge and awareness will inspire societal shifts, reducing the anthropogenic impact on Earths varied and sensitive systems.

GLOSSARY

Oligotrophic	Water body low in nutrient concentration, high in oxygen saturation.
Eutrophic	Water body rich in nutrients, the decomposition of which kills aerobic life forms by creating an anoxic environment.
Mixotrophs	An organism that utilizes a range of different sources of energy and carbon.
Chlorophytes	Green algae species
Chrysophytes	Brown / golden algae species
Cryptophytes	Single-celled, often photosynthetic, organisms of the phylum Cryptophyta
Flagellate	organism with one or more whip-like organelles called flagella, often used as a means of motion.
Ciliates	Protozoans characterized by the presence of hair-like organelles called cilia.
Meromictic	Permanently stratified lake with strong physical and chemical vertical gradients.
Monomictic	Stratified lakes which experience one annual period of mixing.
Limnology	The ecological, chemical, and physical features of lakes and other freshwater bodies.
Mixolimnion	The uppermost, wind mixed stratum of a meromictic lake.
Euphotic Zone	Region of the water column which receives light adequate for photosynthetic activity.
Littoral Zone	Lake region near the shore in which sunlight penetrates all the way to the sediment allowing organisms to photosynthesise. Light levels of 1% or less of surface light values generally define this zone.

Heterotrophic	An organism unable to independently fix carbon. Obtains energy by consuming organic substances.
Monimolimnion	The deepest, densest and often most saline stratum within a meromictic lake.
Chemocline	Strong vertical gradient of chemical parameters.

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