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ORIGINAL PAPER

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Farthest north lake and fjord populations of calanoid copepods *Limnocalanus macrurus* and *Drepanopus bungei* in the Canadian high Arctic

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Abstract The zooplankton assemblages of Lake A and Disraeli Fjord, northern Ellesmere Island (83°N, 75°W), were surveyed in early summer 1999. In permanently ice-covered Lake A, two glacial relict calanoid copepod species (*Drepanopus bungei* and *Limnocalanus macrurus*) were found in the top 30 m. All developmental stages of the more abundant *D. bungei* were present, whereas only adults of *L. macrurus* were found. Analysis of gut contents showed that *L. macrurus* preyed upon the smaller species. A net tow sample of zooplankton from Disraeli Fjord was mainly composed of *D. bungei* and *L. macrurus*, along with two marine cyclopoid copepods (*Oncaea borealis* and *Oithona similis*). These two zooplankton communities occur within unusual environments that are strongly influenced by perennial ice and snow. They will be subject to major habitat disruption should the current warming trends continue in the north polar region.

Introduction

The distribution of copepods in the Arctic Ocean and arctic coastal waters is well documented (summarized in Mauchline 1998; Thibault et al. 1999); however, information concerning lake and fjord populations at extreme latitudes in the circumpolar Arctic is still limited. In the present study, we examined the zooplankton assemblages at the northern limit of these habitat types: perennial ice-covered Lake A and ice-dammed Disraeli Fjord. Both sites are located at latitude 83°N in the Canadian high Arctic.

Lake A was first investigated in 1969 (Hattersley-Smith et al. 1970), and there have been occasional visits since that time (Jeffries et al. 1984; Retelle 1986; Ludlam 1996). Little attention, however, has been given to the biological limnology of this lake. Nearby Disraeli Fjord has been sampled sporadically since 1967, and previous collections of zooplankton have revealed the presence of *Drepanopus bungei* (Bowman and Long 1968). Given their extreme location at the northern limit of North America, the species composition at these sites is of special interest for biogeographical analyses. In addition to the zooplankton collections, we also undertook a limnological analysis of these sites to provide background information on habitat characteristics.

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Materials and methods

Lake A (83°00′N, 75°30′W; Fig. 1), and Disraeli Fjord (82°50′N, 73°40′W; Fig. 1) are located on the northern coast of Ellesmere Island. Lake A is meromictic (permanently stratified) and has a maximum depth of >115 m, a surface area of 4.9 km^2, an apparently perennial ice cover up to 2 m in thickness, and a catchment area of 37 km^2 containing no glaciers. It was formed after the last ice age when isostatic uplift of northern Ellesmere Island trapped pockets of seawater in a pre-existing depression (Lyons and Mielke 1973). Disraeli Fjord is a stratified, 45-km-long fjord that is presently dammed by the Ward Hunt Ice Shelf. At time of sampling, the ice cover on the fjord was 2.4 m.

Water column measurements were made in Lake A during the first week of June 1999 and Disraeli Fjord was profiled on 9 June 1999. Temperature, salinity and dissolved oxygen were measured using a Hydrolab Surveyor 3 profiler. Estimates of phytoplankton biomass were made by measuring chlorophyll *a* (Chl *a*) concentration. Water was sampled at 1-m intervals in the oxic zone in Lake A and at 1- to 10-m intervals in Disraeli Fjord. Sampling was made with a 2-l Kemmerer bottle and 250-ml subsamples were filtered through GF/F glass fiber filters. Filters were kept frozen and pigments were extracted within less than a month, using boiling ethanol according to Nusch (1980). Fluorescence was measured with a Sequoia-Turner Model 450 fluorometer, with correction for phaeopigments using the equations of Jeffrey and Welschmeyer (1997).

Zooplankton was sampled from Lake A on 8 June 1999 and Disraeli Fjord on 9 June 1999. At Lake A, a hole was cut through the ice and was kept open for 3 days before zooplankton sampling. A 1-m-long conical plankton net (mesh size 100 μm; mouth diameter 20 cm) was used to sample the zooplankton. Duplicate net tows were made sequentially at the following depths: 2.5, 5,

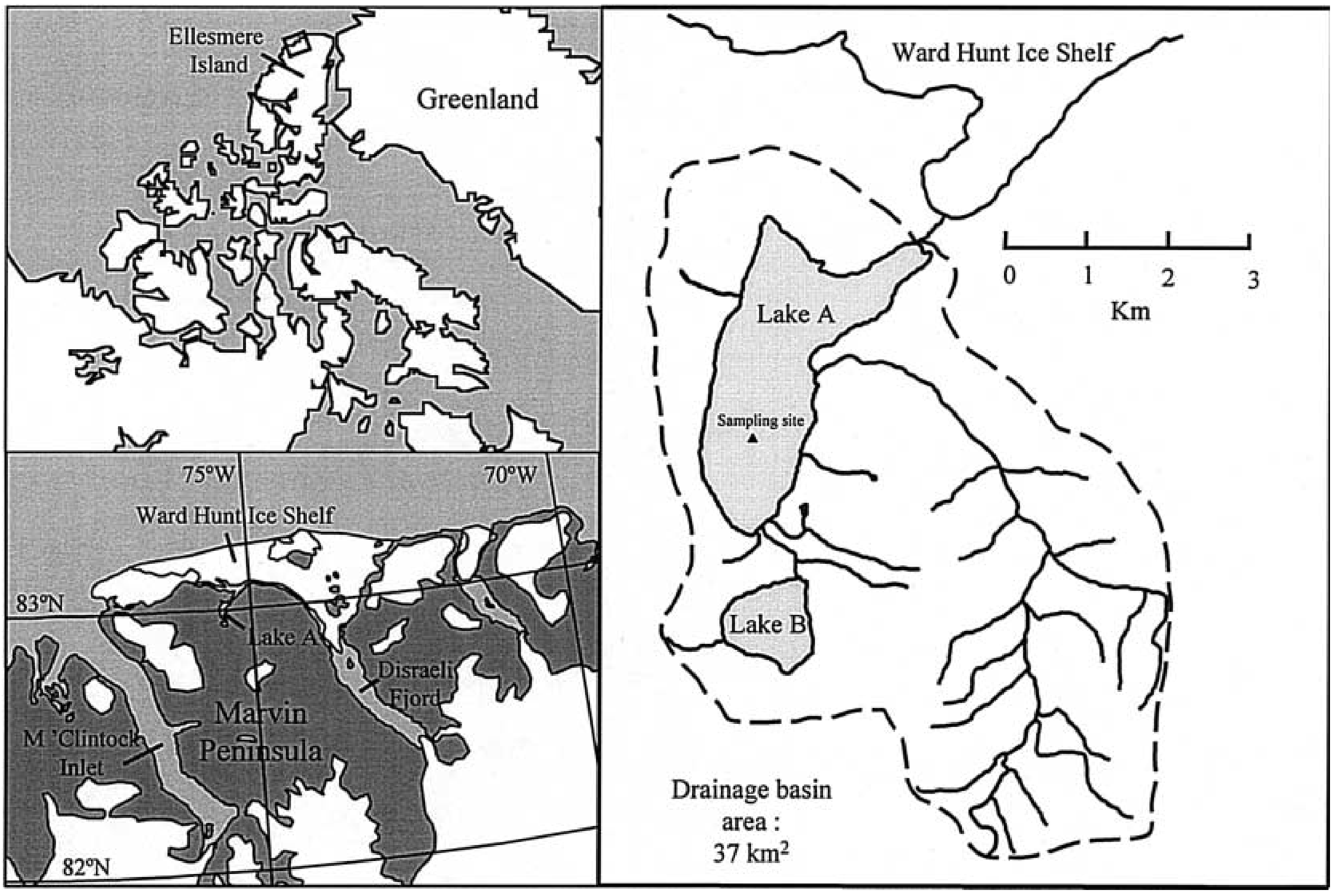

Fig. 1 Location of Lake A and Disraeli Fjord on northern Ellesmere Island, Canadian high Arctic

7.5, 10, 12.5, 15, 17.5, 20, 25, and 30 m. The net was towed by hand vertically at approximately 1 m/s from a given depth to the surface. In Disraeli Fjord, logistical constraints allowed us only a single tow from the brackish-water layer, from 30 m to the surface. All samples were preserved with final concentrations of 0.2% glutaraldehyde and 0.02% formaldehyde, a preservative used for phytoplankton studies but which gave very good preservation of zooplankton. The specimens were identified and enumerated using a binocular microscope (×32 magnification). For each species, copepodite stages were counted separately, but nauplii stages were pooled. The volume filtered by the plankton net was determined by multiplying the mouth area by the depth of sampling. To calculate zooplankton densities, a filtration efficiency of 100% was assumed (Tranter and Smith 1968), and the differences between numbers in each tow were used to calculate the stratum density. The stomach contents of several adults of *Limnocalanus macrurus* and *D. bungei* were determined by dissecting and mounting their intestines on a glass microscope slide and examining them at ×400 magnification.

Results and discussion

Disraeli Fjord and Lake A were both highly stratified (Figs. 2, 3). Lake A had temperature and salinity profiles similar to other polar meromictic lakes (cf. Gibson 1999), with a temperature maximum below the surface and a gradual halocline. The oxygenated zone was limited to a 13-m supersaturated low conductivity layer (0.26 mS/cm, 0.13‰) at the surface in which Chl *a* concentrations ranged from 0.2 to 0.5 μg Chl a l^{-1}. These

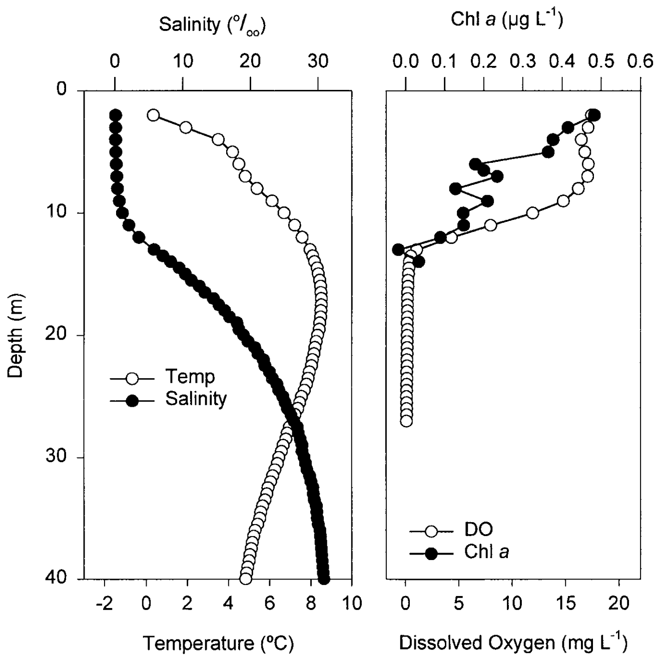

Fig. 2 Water column properties of Lake A (8 June 1999)

values for Chl *a* are similar to concentrations in other lakes in the high Arctic (Lake Char 0.46–0.78 μg l^{-1}, Lake Garrow 0.04–0.40 μg l^{-1}; Markager et al. 1999) and in oligotrophic lakes in the McMurdo Dry Valleys in Antarctica (Vincent 1987).

Disraeli Fjord had a sharp halocline at 32 m that likely reflected the depth of the nearby ice shelf at the mouth of the fjord (Vincent et al., in press). The surface waters were brackish (0.68 mS/cm, 0.67‰), while salinity and other conditions below 32 m were similar to the Arctic Ocean. The water column sampled was well oxygenated with temperatures close to 0 °C. Chl *a* concentrations were very low, reaching a maximum of 0.3 μg l^{-1}, comparable to the lower limit of the values measured in the Arctic Ocean (Wheeler et al. 1996).

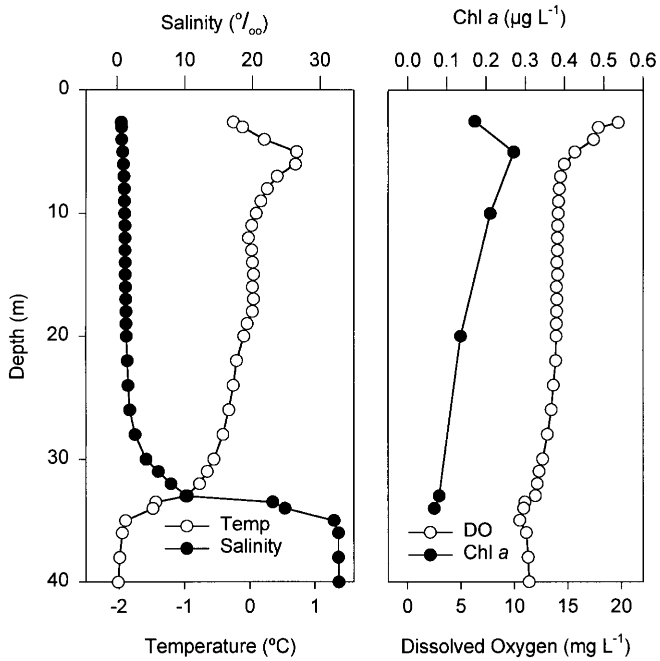

Fig. 3 Water column properties of Disraeli Fjord (9 June 1999)

Two species of calanoid copepod, *Limnocalanus macrurus* and *Drepanopus bungei*, were the only metazoans present in the samples collected from Lake A. They have a well-documented distribution over the Siberian arctic shelf, particularly in the brackish surface waters influenced by riverine input (Zenkevitch 1963; Holmquist 1970). These species have also been found in some marine localities in the Canadian Arctic Archipelago (Bowman and Long 1968; Holmquist 1970; Evans and Grainger 1980). Table 1 shows the abundance of each stage for both species, and the density for every 5-m layer is shown in Fig. 4. The two net tows made for each depth were not significantly different (paired *t*-test, $t=0.58$, $P=0.57$). Only the adult stages of *L. macrurus* were present in our collections, whereas *D. bungei* was represented by adults, copepodites, and nauplii. Of the copepodid stages, CIII was the most abundant.

Previous studies have shown that *L. macrurus* and *D. bungei* both have a 1-year life-cycle, and that the adults overwinter (Roff and Carter 1972; Evans and Grainger 1980). The absence of the earlier stages of *L. macrurus* in the present study suggests that the population was composed only of the overwintering adults. The developmental stages of *D. bungei* that were found in Lake A, along with the record of spermatophores attached to some females, indicate that the population of this species was in its reproductive phase. The large numbers of nauplii of this species are probably derived from reproduction by the overwintering adults.

The enumeration data show that a high proportion of the Lake A zooplankton population resided in the 5- to 10-m stratum, close to the oxic-anoxic interface, with a second density maximum in the 15- to 20-m stratum, well into the anoxic but non-sulfidic zone. This lower peak may indicate a deep population of food particles and an area of refuge from predation. The presence of fish has not been determined, but observations from other lakes

Table 1 Number of individuals of each species and life-cycle stage of zooplankton found in net tows in Lake A, and size for these stages. For the number of individuals per tow, each value is the mean of two net hauls (range *in parentheses*)

Depth of tow (m)	*Limnocalanus macrurus*		*Drepanopus bungei*						Both spp. Total
	Female Adults	Male Adults	Female Adults	Male Adults	Copepodites			Nauplii	
					C I–II	C III	C IV–V		
2.5	0.5 (0.5)	0 (0)	0 (0)	0 (0)	0.5 (0.5)	0 (0)	0 (0)	0.5 (0.5)	1.5 (0.5)
5	1.5 (0.5)	1 (0)	0.5 (0.5)	0 (0)	0 (0)	0 (0)	0 (0)	5 (0)	8 (1)
7.5	2.5 (0.5)	0.5 (0.5)	0 (0)	0 (0)	0 (0)	4 (2)	0 (0)	43.5 (5.5)	50.5 (8.5)
10	2.5 (0.5)	3 (2)	1 (1)	0 (0)	2 (1)	14 (5)	1.5 (1.5)	82 (10)	106 (21)
12.5	2.5 (0.5)	3 (3)	1.5 (1.5)	0.5 (0.5)	0.5 (0.5)	11.5 (3.5)	0 (0)	64.5 (1.5)	84 (1)
15	12 (1)	3.5 (3.5)	6 (4)	0 (0)	1.5 (0.5)	6.5 (2.5)	0.5 (0.5)	65.5 (12.5)	95.5 (18.5)
17.5	9 (4)	4 (3)	8.5 (0.5)	2 (1)	2 (0)	12 (2)	2 (1)	87 (6)	126.5 (17.5)
20	7.5 (3.5)	3 (0)	7.5 (1.5)	1.5 (0.5)	0.5 (0.5)	19 (1)	0 (0)	93.5 (9.5)	132.5 (13.5)
25	18 (1)	3.5 (1.5)	8 (2)	2 (2)	0.5 (0.5)	22.5 (7.5)	0.5 (0.5)	95 (10)	150 (25)
30	11.5 (3.5)	3.5 (0.5)	8 (3)	1.5 (0.5)	0 (0)	20 (4)	0.5 (0.5)	96.5 (14.5)	141.5 (13.5)
Size (mm)									
Mean	2.24	2.11	0.99	0.70		0.69		0.19	
SD	0.14	0.20	0.08	0.08		0.05		0.02	
n	76	24	40	6		87		79	

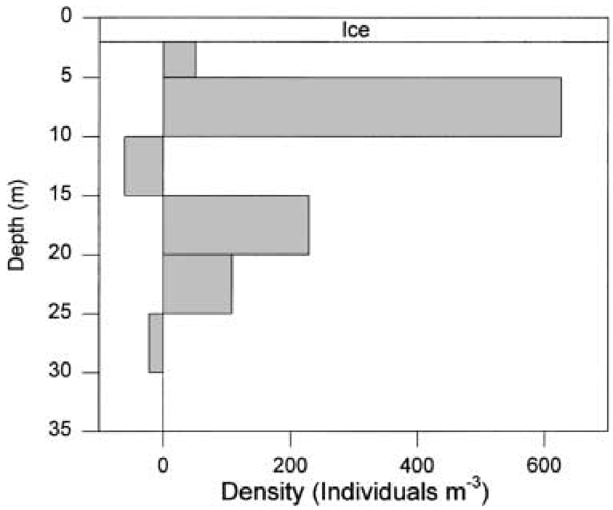

Fig. 4 Copepod densities in Lake A, northern Ellesmere Island. The values for each stratum were calculated from differences between concentrations in tows from adjacent depths

in the area (Lake C3, R.S. Bradley, personal communication; Lake Garrow, Dickman 1995) suggest that there may be a population in the lake. It is possible that the observed distribution of copepods was influenced by the sampling hole being open for 3 days before the sampling, in particular given the low irradiances that they normally experience beneath the snow and ice ($<1\%$ of surface incident irradiance, unpublished results).

The gut contents of six male and four female *L. macrurus* were examined from the Lake A samples. Fragments of crustacean legs were found in several of the guts, and one entire nauplius of *D. bungei* was present in the gut of an adult male. This is evidence of predadory behavior by *L. macrurus*, consistent with previous studies (Warren 1985) and suggests that *L. macrurus* could be a major controlling factor on the *Drepanopus* population. The gut contents of five female adult *D. bungei* were also examined but no recognizable matter was found.

The plankton samples collected from Disraeli Fjord were dominated by copepodites and adults of *D. bungei* (78%) (Table 2). Adult male and female *L. macrurus* were also present, but in very low numbers (1%). Other organisms present in the plankton tow included the early copepodite stages of two species of cyclopoid copepods, *Oithona similis* (3%) and *Oncaea borealis* (4%), and unidentified copepod nauplii (14%).

The zooplankton species of Lake A are not found in the coastal waters of northern Ellesmere, or elsewhere in the central Arctic Ocean (Grainger 1964). The marine copepod assemblage in nearby Nansen Sound (between Ellesmere and Axel Heiberg Islands) is dominated by *Calanus* spp. (Cairns 1967), which in general dominate zooplankton assemblages of the Arctic Ocean (Grainger 1964; Thibault et al. 1999) Although large-bodied zooplankton such as *Calanus* can be under-represented in net hauls of the type obtained here, their complete absence from all tows suggests that they did not occur in Lake A or in the surface waters of Disraeli Fjord. *Oncaea borealis* and *Oithona similis*, found in Disraeli Fjord, are common constituents of the Arctic Ocean zooplankton, reflecting the direct contact of Disraeli Fjord with the open sea. However, the presence of *L. macrurus* and *D. bungei* in Disraeli Fjord sets it apart from the Arctic Ocean, and provides an intermediate situation between Lake A and marine assemblages.

Table 2 Number of individuals of each species and life-cycle stages of zooplankton in Disraeli Fjord from a 20-m tow (0.63 m^3 filtered assuming 100% efficiency)

Species	Stage	Number
Limnocalanus macrurus	Female adult	2
Drepanopus bungei	Female adult	14
	Male adult	2
	Copepodite	61
	Nauplius	394
Oithona similis	All	20
Oncaea borealis	All	25
Unidentified	Nauplii	87

The environmental conditions of Lake A and Disraeli Fjord are highly dependent on the presence of ice, which limits the amount of light, wind-induced mixing and, in the case of Disraeli Fjord, acts as a dam that maintains the presence of a low-salinity surface layer. Climate change can greatly influence ice conditions and current monitoring data show that the Arctic is undergoing considerable warming and ice melt at present (Hartmann et al. 2000; Vincent et al., in press). If these trends continue, then the zooplankton assemblages recorded here will be subject to major disruption and loss of their unusual habitats.

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