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Salmonid fish and warming of shallow Lake Elliðavatn in Southwest Iceland

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Introduction

Fish are ectotherms, and hence their biological performance is dependent on the ambient water temperature. Because of climatically induced increases in water temperature, stenothermic, coldwater fish species are expected to be subject to various negative problems, including reduced growth, survival, and distributional range (Reist et al. 2006a, 2006b, Cushing 1997). Few empirical studies have demonstrated how coldwater fish respond to recent climate change and warming, with some exceptions (e.g., Kristensen et al. 2006), partly due to the complexity of Arctic ecosystems and biological variability of organisms, along with paucity of long-term, integrated hydro-ecological monitoring data (Wrona et al. 2006).

Lake Elliðavatn, Southwest Iceland, is inhabited by Arctic charr (*Salvelinus alpinus*) and brown trout (*Salmo trutta*), both coldwater fish species of the salmonid family (Reist et al. 2006a). Catch statistics and biology of these fishes have been monitored by the Institute of Freshwater Fisheries for the past 2 decades (Antonsson & Guðbergsson 2000, Antonsson et al. 2005). Recent studies on physico-chemical variables in the lake showing high values of temperature, alkalinity, and aluminium concentrations have raised concerns for negative impacts on the Arctic charr. The population has been declining for the past 20 years and is currently very small (Antonsson & Guðbergsson 2000, Gíslason & Eikríksdóttir 2001, Malmquist et al. 2004).

Recently, long-term data on lake temperature became available, with hourly recordings dating back to August 1988. The newly available temperature data provided us with an excellent opportunity to examine development of the lake temperature over the past 2 decades, and how population development and biology of the salmonids in the lake relate to temperature.

Key words: climate change, Iceland, Salmonidae, *Salvelinus alpinus*, warming

Study site

Elliðavatn (2.02 km^2) is a shallow lake, mean depth 1.03 m, max depth 2.3 m (Harðardóttir et al. 2002), situated at 75 m a.s.l. within the metropolitan area of Kópavogur and the capital city Reykjavík, Southwest Iceland.

The lake and accompanying in- and outlet rivers have been subjected to various impacts following urbanization in the catchment area that began early last century (Antonsson & Guðbergsson 2000, Malmquist et al. 2004). In 1924–1925 the outlet river Elliðaár was dammed for hydroelectric production, whereby water level rose by ~1 m, increasing the lake area by ~45 % to its present size. Water levels have been regulated to range about ~0.4 m, but for the last 6–7 years the lake has been regulated only during October–April, with a daily amplitude of <10 cm (Reykjavík Energy, log books).

Before damming, the only surface tributary to the lake was the spring-fed River Suðurá. Since damming, River Bugða, largely of direct run-off origin, also contributes to the lake. Currently, half of the inlet water is by River Bugða (~2.3 m^3/sec), whereas the rest is cold spring-fed water (3–6 °C), entering the lake by River Suðurá (~0.4 m^3/sec) and subsurface springs (~2.4 m^3/sec; Birgisson et al. 1999). The spring-fed groundwater has a high natural pH, usually pH 8.0–9.0, due to neo-volcanic bedrock origin in the catchment area (Hjartarson 1994). The lake itself is quite alkaline, with pH $\geq$7.5 all year around and with pH 9.0–10.0 for several weeks in July–August (Malmquist et al. 2004).

Arctic charr and brown trout are dominant fish species in the lake and are effectively resident to it and its tributaries. Arctic charr spawn primarily within the lake, whereas brown trout spawn mainly in the tributaries Suðurá and Bugða (Antonsson & Guðbergsson 2000). Three-spined stickleback (*Gasterosteus aculeatus*) are also abundant in the lake, but European eel (*Anguilla anguilla*) is less common. Considerably large populations of anadromous Atlantic salmon (*Salmo salar*) and brown trout are present in the outlet river Elliðaár below the dam (Antonsson et al. 2005). Atlantic salmon are able to migrate through the outlet at the dam, and some salmon spawn in river Bugða and Suðurá.

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Materials and methods

Information on fish in Elliðavatn is from 1974–2006. With the exception of the study by Björnsson (2001, 2003) in 1974–1976, all fish data were obtained from annual reports published by the Institute of Freshwater Fisheries, which started monitoring salmonids in 1984, with annual sampling since 1987 (Antonsson & Guðbergsson 2000, Antonsson et al. 2005). Fish were caught every year in late September/early October with 2 gillnet series, each series made of 10 nets of different mesh sizes; 16.5, 18.5, 21.5, 24.0, 30.0, 35.0, 39.0, 46.0, 50.0, and 60.0 mm, knot to knot. Beginning 1993, a net of 12.0 mm mesh size was added to the net series. Each net series was laid overnight in one of two main basins of the lake for ~12 hr. Additional catch data obtained between 1981–1994 was provided by the Elliðavatn Fisheries Society, based on annual catch effort conducted after mid-September, by use of 10 nets with a single mesh size of 35 mm (Antonsson & Guðbergsson 2000). For these additional data, and that by Björnsson (2001, 2003) who used nets with 22 mm mesh size only, information on total number of fish caught of each fish species was available, but not for calculating catch per unit effort (CPUE) because duration of netting effort was uncertain.

In the monitoring programme, all fish caught in each mesh size were identified to species and counted. As an indicator of relative population size, we used CPUE, calculated as the average number of individuals within fish species caught in the 2 net series. Fork length (± 0.5 cm) and wet weight (± 2.0 g) were measured on all fish and used in calculating Fulton's condition factor, weight/length^3 * 100 (Bagenal & Tesch 1978), indicating somatic well being of the fish.

Lake temperature was measured at the dam outlet by a digital data logger (± 0.05 °C), with first recording 23 August 1988 and then with 1–4 records/h until end of August 2006 (Hydrological Service 2007). We calculated daily mean temperature for all whole-month data and used regression analysis to test for significant variation in water temperature within months over the study period. To test for association between air and lake temperature we used data provided by the Icelandic Meteorological Office on monthly mean air temperature in Reykjavík (station 1) during January 1931–October 2006. The weather station is ~10 km northwest of Lake Elliðavatn.

Results

The Arctic charr population, but not that of brown trout, has declined profoundly over the past 15–20 years in Elliðavatn, as demonstrated by decreased catch per unit effort during 1987–2006 (Fig. 1a), and decreased proportion in total catch during 1974–2006 (Fig. 1b). Apparently, the decline began in the mid-1990s. For the past ten years or so, catch statistics of Arctic charr have been only ~30 % of those from 15–20 years ago. Similarly, the proportion of Arctic charr in total catch has decreased from 55–85 % during 1974–1984, to 3–23 % for 1996–2006.

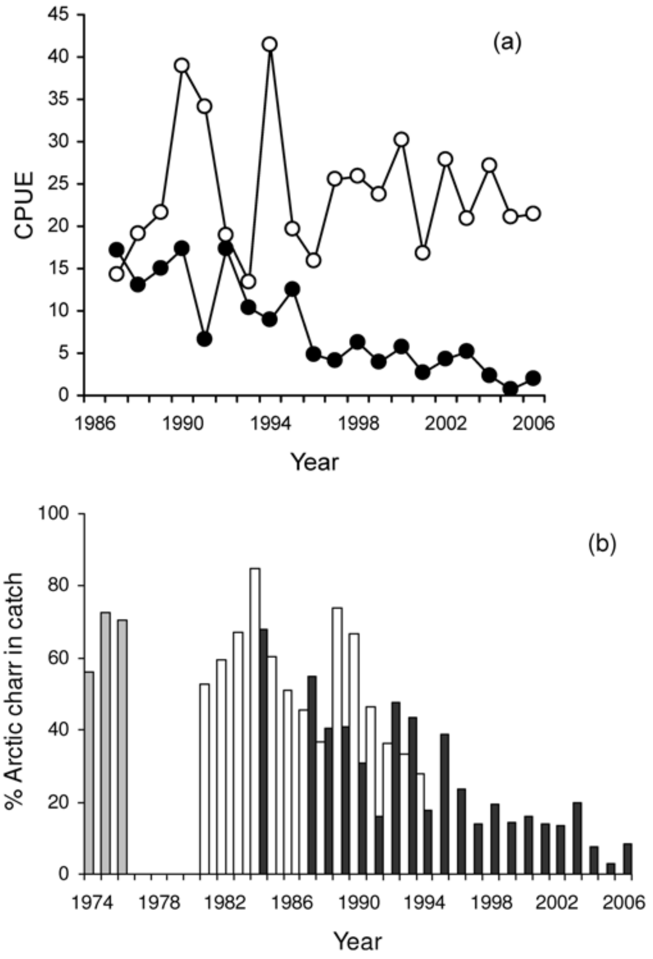

Fig. 1. (a) Catch per unit effort (CPUE) of Arctic charr (black dots) and brown trout (white dots) during 1987–2006 in Elliðavatn. Based on monitoring data by the Institute of Freshwater Fisheries. Arctic charr, Pearson's correlation, $R = -0.87$, $P < 0.01$; brown trout, $R = -0.01$, $P > 0.05$). (b) Proportion (%) of Arctic charr of total catch in Elliðavatn during 1974–1976 (grey columns), 1981–1994 (white columns, $R = -0.59$, $P < 0.05$) and 1984–2006 (black columns, $R = -0.86$, $P < 0.01$).

Condition factor of both fish species was in general high (>1.10), indicating somatic well being, and did not vary significantly over time for either Arctic charr (Pearson's correlation, $R = -0.06$, $n = 19$, $P > 0.05$) or brown trout ($R = 0.20$, $n = 19$, $P > 0.05$).

Water temperature in Lake Elliðavatn increased significantly over the study period in all months except October–January (Table 1). The most profound rise in temperature occurred in late winter–early spring (February–April) and summer (July–August; Fig. 2), with a rise in monthly mean temperature of 2.3 °C in March, 2.7 °C

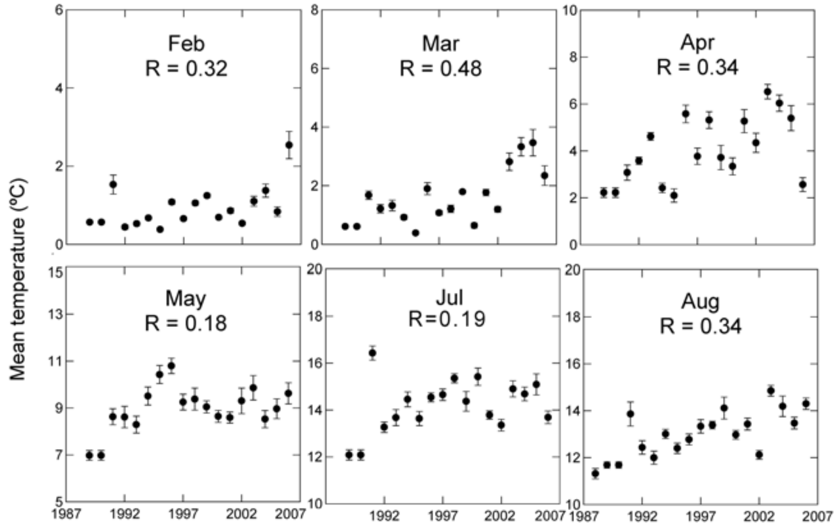

Fig. 2. Daily mean water temperature (± SE) in Elliðavatn in selected months with the most profound warming over the period September 1988–August 2006. R is Pearson's correlation coefficient (see Table 1).

in April, and 2.3 °C in August (Table 1). July was usually the warmest month, with a maximum record of 21.1 °C in 2003. Temperature ≥12 °C extended continuously over 1–2 months (late June–early August) in several years, especially after the late 1990s. Temperatures of 14–20 °C extended for 1–3 consecutive weeks (e.g. in 1999, 2000, 2003, and 2004), and records between 18–21 °C remained for several days, as in July 2003.

Air temperature decreased over 1931–1982, with a clear low around the early 1990s, and from 1983 and onward the temperature has increased significantly (Fig. 3). For all months but February, May, and October–December, the monthly mean air temperature increased significantly over 1983–2006 (Table 2). Furthermore, monthly mean air temperature during 1988–2006 (Table 2) was positively associated (Pearson's correlation, R = 0.64, n = 19, P < 0.05) with the corresponding mean monthly temperature in the lake (Table 1).

Table 1. Regression analysis on daily mean water temperature for each month in Elliðavatn over September 1988–October 2006. n.s. = not significant; * = P < 0.05; ** = P < 0.01; *** = P < 0.001. n = number of observations (daily means). The last column (°C) denotes increase in monthly mean temperature over the 19-yr study period, based on the correspondent regression equation.

	a	b	R	*P*	n	°C
Jan	–13.092	0.007	0.045	n.s.	558	0.1
Feb	–97.617	0.049	0.318	***	491	0.9
Mar	–253.254	0.128	0.478	***	510	2.3
Apr	–294.570	0.149	0.339	***	535	2.7
May	–152.091	0.081	0.176	***	546	1.5
Jun	–72.244	0.042	0.104	*	534	0.8
Jul	–129.960	0.072	0.191	***	558	1.3
Aug	–236.020	0.125	0.343	***	577	2.3
Sep	–101.545	0.055	0.120	**	530	1.0
Oct	–30.438	0.017	0.039	n.s.	518	0.3
Nov	–11.581	0.007	0.029	n.s.	507	0.1
Dec	–16.702	0.009	0.037	n.s.	527	0.2

Discussion

This study demonstrates that Lake Elliðavatn has been warming for the past 20 years due to rising air temperature. This occurred despite the contribution of a cold, spring-fed component in the lake water budget, amounting to ~50 % of the inlet water. The close connection between air and water temperature is to be expected, considering the shallow depth of Lake Elliðavatn, with thorough mixing and lack of thermocline, and thus easy transfer of heat energy, between air and the whole water mass.

The decline in catchable/adult Arctic charr population was closely accompanied with decline of Arctic charr juveniles in the lake and its tributaries (Antonsson 2002). This, along with the results on the condition factor, showing no significant changes over the study period, and the same applying to age- and length-composition of the fish (Antonsson & Guðbergsson 2000, Antonsson et al. 2005), strongly indicates that the cause for the population decline is affecting mainly early life history stages of the fish. Contrary to Arctic charr, brown trout juveniles seem to have been doing well in the catchment area during the study period (Antonsson

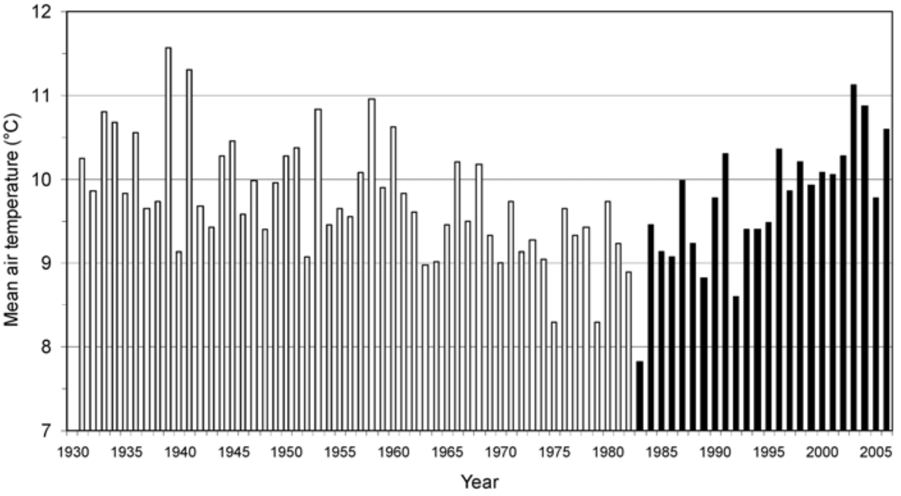

Fig. 3. Mean air temperature (°C) in Reykjavík based on monthly means averaged over June–September for the period 1931–1982. Air temperature decreased over 1931–1982 (Pearson's correlation, R = –0.56, n = 52, P < 0.01), but increased from 1983 and onwards (R = 0.73, n = 24, P < 0.01).

2002), being relatively stable in numbers in the tributaries just as older fish are in the lake.

The condition factor of Arctic charr was in general high and did not change significantly over the study period, suggesting that surviving fish were well off and did not suffer stress from shortage of food. Congruent with this, results on stomach analysis of the fish do not indicate any food shortage or consistent changes in dietary composition (Antonsson & Guðbergsson 2000, Antonsson et al. 2005). Further, despite sparse data on food resources, the available data on macroinvertebrates does not indicate any decline/changes in the resource base (Haraldsson 2004, Malmquist et al. 2004).

The warm thermal environment in Elliðavatn over the past decade, with ≥12 °C extending over 1–2 months and 14–20 °C for a week or two, may have caused the decline in the Arctic charr population. At such high temperatures, even with 18–21 °C for several calm sunny days, Arctic charr may experience various biological problems. The upper thermal optimum for growth of adult Arctic charr has been reported ~12.0 °C, with negative effects at 14.0 °C (Jobling 1983, Lyytikanen et al. 2002). Because of non-linear response in metabolic rate in fish to increased temperature, increase in energy demand may be expected to greatly exceed possible food supply, as has been suggested to apply to Arctic charr (Kristensen et al. 2006) and brown trout (McDonald et al. 1996). Arctic charr may also have difficulties with ovulation when water temperature exceeds 8 °C (Gillet 1991). Moreover, egg quality may be reduced by maintaining Arctic charr above 5 °C for several weeks (Jungwirth & Winkler 1984, Steiner 1984). For brown trout, thermal optima for growth of adult fish is considerably higher than for Arctic charr, with upper limits at 17.0°C, and still higher for Atlantic salmon, ~20 °C (Elliott 1994). Species-specific requirements of thermal habitat, as discussed earlier, have been used to clarify the wide distribution of brown trout, but near absence of Arctic charr in Faroese lakes (Malmquist et al. 2002). Temperatures in Faroese lakes are in general higher compared to Icelandic lakes, and resemble those observed lately in Lake Elliðavatn.

Table 2. Pearson's correlation coefficients (R) in tests for association between monthly mean air temperature and years over, respectively, 1983–2006 (n = 24) and 1988–2006 (n = 19). n.s. = not significant; * = P < 0.05; ** = P < 0.01.

	1983–2006		1988–2006	
	R	P	R	P
Jan	0.41	*	0.38	n.s.
Feb	0.03	n.s.	0.39	n.s.
Mar	0.40	*	0.50	*
Apr	0.51	*	0.64	**
May	0.21	n.s.	0.07	n.s.
Jun	0.53	**	0.60	*
Jul	0.42	*	0.21	n.s.
Aug	0.61	**	0.51	*
Sep	0.59	**	0.52	**
Oct	0.22	n.s.	0.00	n.s.
Nov	0.09	n.s.	–0.05	n.s.
Dec	0.33	n.s.	0.43	*

Negative effects of water regulation on Arctic charr (e.g., on spawning grounds and/or food supplies) seem to have been unimportant for the past 2 decades. During this time, the water level has fluctuated much less than 40 cm. Overfishing from either gillnetting or rod-fishing can also be omitted as likely cause for the decline of Arctic charr. Gillnetting effort has been more or less the same for 2 or more decades, and if it existed at all, it should have affected the brown trout and Arctic charr alike. The latter applies as well to fishing pressure from rod-fishing (Antonsson & Guðbergsson 2000, Antonsson et al. 2005).

Causes other than lake warming for the decline of Arctic charr cannot be ruled out, and synergetic and/or cumulative effects of stress factors must be considered. Concerns have been raised about the alkaline nature of the lake, with pH 9.0–10.0 for extended periods (Malmquist et al. 2004), which might cause problems for salmonids like Arctic charr (Poléo & Hytterød 2003). Concerns have also been raised due to high aluminium concentrations in the lake outlet (Gíslason & Eiríksdóttir 2001, Malmquist et al. 2004), but few measurements exist to assess importance of toxicity to the fish. In forthcoming years, assessment of physico-chemical factors, including aluminium, are important and would strengthen the ongoing salmonid monitoring in the lake.

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