

## Climate warming experiments: Design of a mesocosm heating system

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### Abstract

Research into the impacts of climate change on lakes requires novel experimental methods that enable realistic tests of the effects of increased water temperatures on communities. This article describes the design of a heating system that has been used in situ to study the effects of an increase in lake surface temperatures on littoral communities. Water within four 700-L enclosures was heated using a propane-fuelled heat exchange system. Hot water was circulated through a network of heat exchange pipes nested in the bottom of enclosures and temperature within the enclosures was controlled electronically by regulating water flow through a series of valves. The system performed well, with temperatures within warmed enclosures paralleling diurnal fluctuations within control enclosures. The average temperature difference between warm and control enclosures of 4.5°C was close to our target temperature difference of 5°C. Strengths of the experimental system are discussed and potential improvements, including improved heat retention and a design adjustment to facilitate repair in the event of lightning damage are noted. The system is adaptable to larger and smaller volumes, different temperature regimes, and can be adapted for use in pelagic systems.

Most effects of climate change on lake ecosystems have been deduced from models (Byron and Goldman 1990; Regier et al. 1990), long-term monitoring (Schindler et al. 1990; George and Taylor 1995; Güss et al. 2000; Scheffer et al. 2001), or paleo-ecological research (Leavitt et al. 1997; Vinebrooke et al. 1998; Finney et al. 2000). Studies of thermal effluents also have advanced our understanding of the potential effects of climate change, but many are confounded by changes in the physical environment, the presence of introduced species or large increases in water temperatures that are

inconsistent with current climate change models (Patalas 1970; Klarer and Hickman 1975; Oden 1979; Konopacka and Jesionowska 1995). A limited amount of experimental work also has addressed climate-warming effects, but most projects have been performed in the laboratory (Beisner et al. 1997), hence conditions and communities vary from those of natural systems. A method allowing controlled increases in stream water temperatures has already been developed (Hogg and Williams 1996).

Given current predictions of a 1.4–5.8°C increase in global surface temperatures between 1990 and 2100 (Intergovernmental Panel on Climate Change 2001) and associated increases in lake surface temperatures (Hostetler and Small 1999), further experimental work to assess the effects of increased water temperature is required. The design of this mesocosm-scale experimental technique allows in situ experimental manipulation with replication, and will help further our understanding of climate-change effects on freshwater ecosystems.

The apparatus was successfully tested from August 3 until September 27, 2000, in a study of the effects of an increase in epilimnetic temperature on littoral communities (Baulch 2002). This article describes the design of the heating system and its performance, limitations and possible improvements.

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## Materials and procedures

*General design of apparatus*—We constructed eight 700-L enclosures within the littoral zone of Lake 239 at the Experimental Lakes Area in northwestern Ontario (49°40'N, 93°44'W) to study the ecological effects of increased epilimnetic temperature in a boreal forest lake. Lake 239 is a clear, oligotrophic lake, 56 ha in area. We warmed four enclosures using a closed-circulation heat exchange system and maintained four enclosures as controls. Hot water was pumped through insulated pipes to the warmed enclosures where approximately 10 m of heat exchange pipe (Kitec®) were coiled around the enclosure bottom. A mean temperature difference of 4.5°C was maintained over the course of the eight-week experiment. This was slightly lower than our target temperature difference of 5°C, but well within the warming range of 2°C to more than 7°C predicted by Hostetler and Small (1999) for the surface temperatures of North American lakes, following a doubling of atmospheric carbon dioxide concentrations. We used AC power from diesel generators (used to provide power to facilities at the Experimental Lakes Area) to fulfill relatively low power demand for pumps and electronics, and used propane hot water heaters to generate the necessary heat. The electrical system was ground-fault protected at our study site.

*Enclosure design*—Enclosures were made of woven white translucent polyethylene attached to an external wooden frame. All enclosures were 1.4 m × 1.4 m, and the average volume at the end of the experiment was 700 L. Enclosures had a sloping bottom that approximately paralleled the lake bottom. Enclosure height was 0.5–0.6 m on the shallow side and 0.7 m on the deeper side. The mean depth of water within the enclosures over the course of the experiment was 0.5 m. Enclosures were open to the lake bottom and secured by placing sandbags on a 0.7-m wide skirt. The sandbags did not completely seal the enclosures from the lake; instead, water exchange occurred. The average water residence time, measured at the end of the experiment, was 5.6 d (estimated by measuring sodium loss after addition of sodium chloride). Porosity of the enclosure material or leakage at the seams also may have contributed to water exchange.

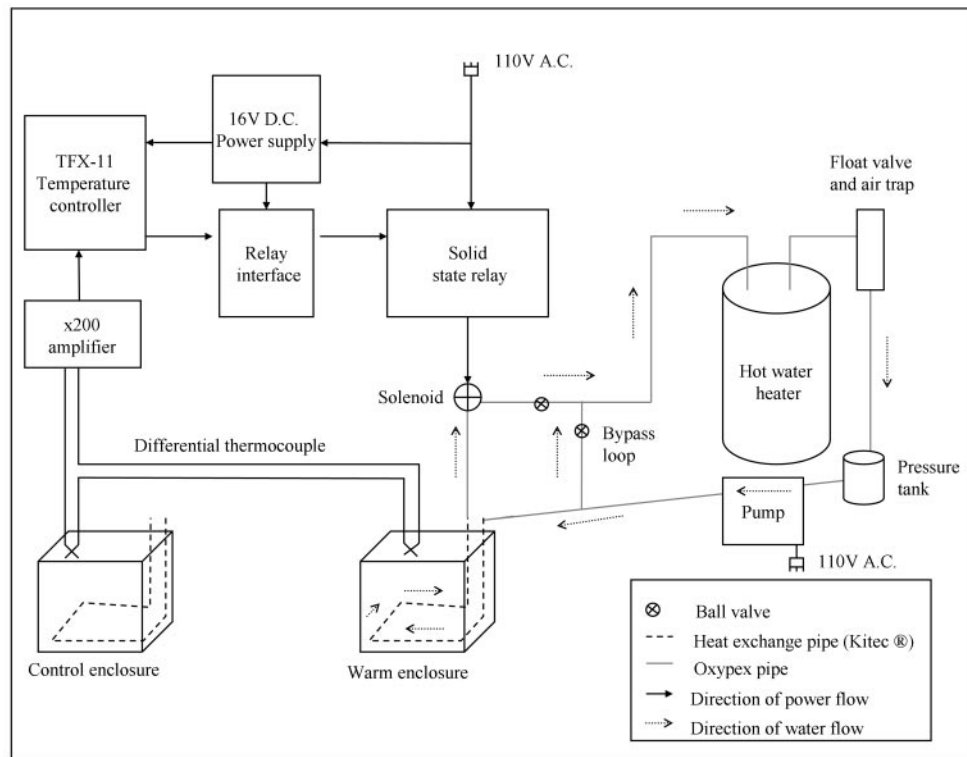
Enclosures were insulated on the exterior using a translucent closed-cell foam packaging material (Shippers Supply Inc.) attached to the wooden frames. Three layers of 0.3-cm (1/8-inch) thick insulation were wrapped around the enclosures. Strong waves periodically tore the insulation away from the enclosures leading to rapid heat loss. In the future, the insulation should be protected, perhaps by using a thick plastic sheet. However, finding alternative means of insulating enclosures would be advantageous. The foam insulation also was problematic because it increased the buoyancy of the enclosures, and a large amount of weight was required to counteract this buoyancy. Unfortunately, preliminary tests of other insulation materials (bubble wrap, water jackets, etc.) showed poor heat retention in water.

*Electronic temperature control*—Warmed and control enclosures were physically paired, and a differential thermocouple (Teflon-coated type-J thermocouple wire) was used to measure the temperature difference between both enclosures. Each pair of enclosures monitored by a single differential thermocouple was designated as a block, and a randomized block experimental design was used to minimize the effects of spatial heterogeneity along the shoreline. Thermocouple junctions were installed near the bottom of all enclosures. Temperature within the enclosures was monitored at the same locations using temperature loggers (HoboTemp, Onset; maximum error  $\pm 0.7^\circ\text{C}$  at 20°C, calibrated at the start of the experiment) set to record water temperature at 15-min intervals. Thermocouples were attached to a TFX-11 controller (Onset), and the controller was programmed using TFBasic to monitor the temperature difference between warmed and control enclosures every second, and produce a signal when the temperature difference was less than 5°C (diagram is shown in Fig. 1). This 5 V logic signal was amplified to a 16 V DC signal for a relay that opened a solenoid valve (Asco electric), allowing hot water to flow into the heat exchange pipe. When the temperature difference exceeded 5°C, the controller stopped producing an output signal, and the solenoid valve closed (Fig. 1).

The TFX-11 controller has a 10-channel capacity, hence it could be used to control temperature in ten warmed enclosures at one time. It may also be used to monitor temperatures, although the requirement of frequent (daily) downloading of data precluded its use for this task in this experiment. Most importantly, temperature control was unaffected by fluctuations in air temperature. This was a shortcoming of two other controllers that we tested (Chromalox Model 1601; Maxthermo MC-4501) which we found to be inadequate when used with differential thermocouples under field conditions.

The initial software program we tested included a dead band, which was designed to extend the service of the solenoid (electromagnetic) valves. The dead band was a range of temperature differences within which the controller would not generate a signal, and as a result the solenoid valves would not be opened or closed. The purpose was to ensure that the solenoid valves did not cycle at high frequency in response to small temperature changes from the set point. Our concern was that if temperature differences remained near a threshold of 5°C, solenoid valves would continually cycle between open and closed positions and would eventually fail due to wear. In practice this was unnecessary because temperatures did not remain sufficiently close to 5°C to cause valves to cycle excessively. The dead band was not used within our final design; instead the software used a threshold system that opened the valves when the sensed temperature difference fell below 5°C and closed them when this temperature difference exceeded 5°C.

The TFX-11 is subject to a degree of offset error, which could be up to 0.5°C per channel. The magnitude of offset was measured by applying a known voltage to the amplifier inputs using a voltage calibrator (1  $\mu\text{V}$  resolution) and noting the dif-



**Fig. 1.** Simplified plumbing and wiring diagram. If the temperature difference between enclosures exceeded 5°C, the solenoid valve was closed and water flowed through the bypass loop. If the sensed temperature difference was less than 5°C, the solenoid valve was energized and water was allowed to flow through the heat exchange pipe in the warmed enclosure. Temperature differences were measured using a differential thermocouple, with a signal amplifier input into the temperature controller. The designed system included a second pair of enclosures heated using the same system with a second solenoid loop attached to the plumbing system and a second differential thermocouple attached to the TFX-11 temperature controller.

ference between the temperature reported by the controller, and the output signal (converted to temperature using standard tables). The offset for each input channel was then corrected using the program TFBasic (Onset).

A drawback of electronic temperature control is its susceptibility to lightning. A lightning strike near the enclosures on August 30, 2000, incapacitated the electronic temperature control systems by destroying controller input channels and resistors. Following the lightning strike, temperature was controlled manually (via direct valve manipulation) until repairs could be made. Avoiding lightning damage is difficult. This could be achieved by removing thermocouples from the water if a storm were predicted, although this would lead to temporary loss of electronic temperature control. Alternatively, the system could be modified to allow for easier replacement of damaged parts, and replacement equipment could be kept on-site.

*Plumbing of heat exchange system*—Hot water (approximately 45°C) generated using propane hot water heaters (150 L, 36,000 BTU/hour, attached to 100-lb propane tanks) was pumped through insulated polyethylene pipes (Oxypex) to a 10-m coil of Kitec heat exchange pipe (1.3 cm-diameter Al-Pex,

Ipxex Inc.) in the bottom of each heated enclosure. Kitec is an aluminum-imbedded pipe, with an interior and exterior polyethylene coating. It is rated for use in potable water systems and is considered chemically inert. At the output side of the coil, Kitec was coupled to Oxypex using standard crimp fittings, and water was recycled into the input side of the hot-water heater (Fig. 1). Hot-water rated, continuous-duty circulating pumps (March model 809 HS series; Little Giant CMD 100-5B) were used. Maximum pump capacity was 30 L min<sup>-1</sup> although actual flow rates were lower due to resistance within the pipes.

In this experiment, a single hot water heater system was used to heat two enclosures. Water could therefore follow one of three routes: through enclosure 1, enclosure 2, or through the bypass loop. If closed solenoid valves prevented water from entering the heat exchange pipe in the enclosures, water would travel through the bypass loop. This design minimized the frequency of pump start up and shut down and prevented unnecessary wear. The bypass line was considerably shorter than the enclosure routes and hence had lower resistance. The length of pipe leading to each enclosure also differed, again translating

to varied resistance. To prevent the water from preferentially flowing through the bypass loop, ball valves were installed to increase resistance on the bypass line and to equalize flow through each of the enclosure lines. These valves also permitted manual temperature control when the electronic system was disabled.

We installed an air trap where gases, released upon initial heating of the water, could accumulate and escape without creating a vapor lock. The trap consisted of a length of 2-in diameter ABS pipe located at the hot water outlet of the hot water heater, the high point of the system. The pipe was oriented vertically, capped at both ends, and fitted such that water would enter near the top and exit at the bottom. This arrangement sufficiently slowed the flow of water to allow gasses to accumulate at the top where they were vented by an automatic air vent of the type used in hot water heating systems (float valve or radiator valve). It also facilitated initial charging of the system.

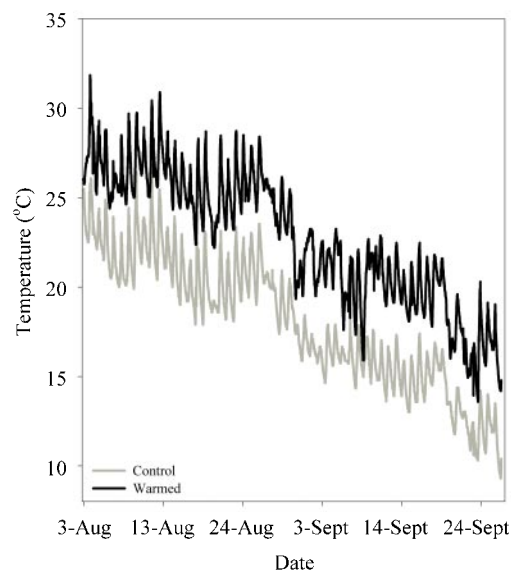
A pressure tank and gauge were used to maintain and monitor pressure within the system, assuring sufficient reserve volume and forcing the release of excess gas. The system ran effectively at pressures from 0 to 30 psi without pressure loss or airlocks (we did not test beyond 30 psi). The system was filled with water from Lake 239 and pressurized using a jet pump (Red Lion Model RJC 33). Periodic inspection of the inside of pipes showed minimal biofilm growth and flushing was not required.

The placement of heat exchange pipes on the bottom of the enclosures was expected to increase vertical mixing within the experimental enclosures; however, this was necessary to allow complete heating of the enclosures. Preliminary experiments (performed in the Lobstick River, Alberta) had shown that strong thermal stratification resulted when heat exchange pipes were located near the top or middle of an enclosure. This was of particular concern in this experiment, as the community of interest was benthic, and stratification would limit the amount of heating reaching the bottom of the enclosures.

**Energy efficiency**—Propane consumption varied from approximately 120,000–540,000 BTU per enclosure per day (mean = 220,000 BTU per enclosure per day). Energy efficiency could be improved by reducing the rate of water exchange between the enclosures and the lake, either by improving the seal between the enclosure and substratum, or by using a closed-bottom enclosure. With more effective insulation and reduced water exchange, a single propane hot water heater might warm four enclosures of this size. A boiler-driven system that adjusts the temperature of circulating hot water based on heat demand would further improve efficiency, but was considered too complicated for this field application.

### Assessment and Discussion

**System performance**—The heating system performed quite well, and temperatures within warmed enclosures generally paralleled diurnal temperature variation within control enclo-



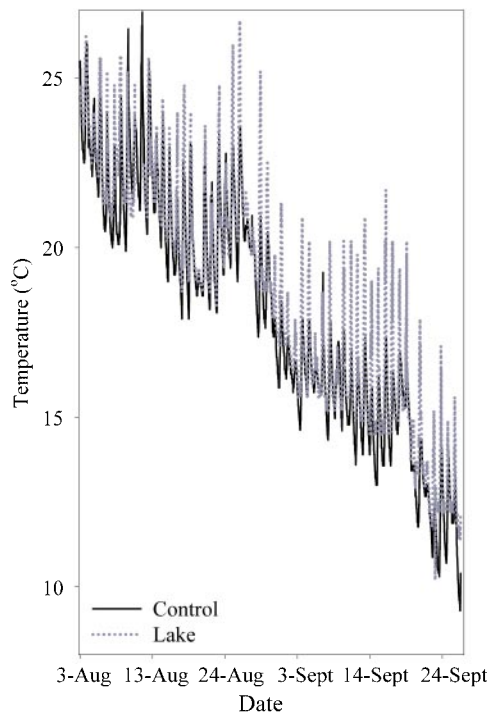
**Fig. 2.** Mean temperature in warm and control enclosures. Temperature was monitored every 15 min.

ures (Fig. 2). The average temperature difference between warmed and control enclosures was 4.5°C, slightly below the target temperature difference of 5°C. However, this is within the range of temperatures predicted following a doubling of atmospheric carbon dioxide (Hostetler and Small 1999), and is also within the range of natural spatial variation in littoral temperatures (Finlay et al. 2001).

Temperature was controlled manually and therefore less precisely during the period following the lightning strike on August 30 before repairs were completed September 7. Temperatures within control enclosures were quite similar to temperatures within the lake (Fig. 3), although on average, control enclosures were 0.6°C cooler than adjacent areas of the lake. Maximum temperatures within control enclosures showed greater deviation from lake temperatures than minimum temperatures. This suggests that shading from the enclosure walls had a cooling effect on the control enclosures.

The large variation in rates of propane consumption meant that periodically a tank ran empty, and the problem remained undiscovered for up to 8 h. Temperature control could be improved by linking multiple propane tanks, using larger volume gauged tanks, or using a telemetry system with alarm settings.

**Enclosure effects**—Enclosure fabric and heat exchange pipes showed considerable carbon accumulation by the end of the experiment (details of methods and analyses in Baulch 2002). Particulate carbon accumulation on fabric did not differ between warm ( $16 \pm 8 \mu\text{g cm}^{-2}$ ; mean  $\pm$  SD) and control enclosures ( $17 \pm 18 \mu\text{g cm}^{-2}$ ). On average, more particulate carbon accumulated on hot water pipes ( $273 \pm 100 \mu\text{g cm}^{-2}$ ) than on pipes within control enclosures ( $106 \pm 62 \mu\text{g cm}^{-2}$ ;  $F_{1,3} = 9.67$ ,  $P = 0.053$ , randomized block analysis of variance). Given that



**Fig. 3:** Mean temperature in control enclosures and temperature in the lake adjacent to the enclosures. Temperature was measured every 15 min.

the pipe surface area was approximately 20% of the bedrock surface area, an increase in biofilm accumulation could have led to accelerated nutrient depletion in warmed enclosures if water exchange had not occurred between enclosures and the lake.

In addition, we expected that the algal community on hot water pipes would differ from the community on pipes within control enclosures. Specifically, we expected to see an increase in the biomass of thermophilic taxa such as cyanobacteria (DeNicola 1996). On heated pipes, we observed increased accrual of chlorophyll *a* and  $\beta$ -carotene, two pigments frequently used to estimate total algal biomass (Baulch 2002; Vinebrooke and Leavitt 1999). We also observed increased accrual of fucoxanthin (a pigment of chrysophytes, diatoms, and some dinoflagellates), canthaxanthin (cyanobacteria), chlorophyll *b* (chlorophytes, euglenophytes), and violaxanthin (chlorophytes). These results suggest that the algal community of the pipes within control and warmed enclosures differed. However, algal pigment accrual also can be affected by a number of other factors that alter cellular pigment content such as temperature (Coles and Jones 2000). Therefore, algal pigment signals may have been attributable to increases in total abundance, higher cellular pigment content on the heated pipes, or both factors.

Differences in the abundance of carbon and pigments on warm and control pipes indicate that it is important that the community of interest is physically distinct from the pipes. To minimize the effects of the high-temperature adapted community on study communities, we ensured that study tiles were

separated from pipes by at least 10 cm. In the future, studying the algal community at varying distances from the heating pipes would be advantageous to determine whether a 10-cm separation is sufficient to prevent study communities from being affected by communities on the heat exchange pipes. In addition, changes to the apparatus could reduce the magnitude of temperature difference between the circulated water and the enclosure water without affecting heating performance. If the length of pipe or flow rate within the pipe is increased, lower temperature water could be circulated and still produce the desired temperature difference within enclosures.

*Effects of the heat treatment on the benthic boundary layer*—We were concerned that the heat treatment would increase vertical mixing patterns and reduce the thickness of the benthic boundary layer. The benthic boundary layer restricts nutrient transport into benthic communities, and as a result, differences in boundary layer thickness can affect the nutrient status and photosynthetic rates of bottom-dwelling communities (Riber and Wetzel 1987; Turner et al. 1991). Benthic boundary layer thickness, measured by monitoring the dissolution of weighted gypsum blocks (Turner et al. 1991) was not significantly different between warm and control enclosures when measured during the daytime. Interestingly, boundary layer thickness in warmed enclosures was 18% greater than in control enclosures when measured at night (1-way analysis of variance,  $P = 0.02$ ) (Baulch 2002). However, thickness of boundary layers in warmed and control enclosures were within the range observed in adjacent areas of the lake. Nonetheless, the thickness of the benthic boundary layer should be monitored in any application of this experimental design.

### Comments and recommendations

This experimental apparatus was used successfully in an experiment (August–September 2000) designed to assess climate-warming effects on littoral community composition and metabolism (Baulch 2002). The design can be easily applied to other littoral sites or could be modified to allow study of the effects of increased temperature within the pelagic zone. The design could also be modified to allow study of altered stratification patterns on planktonic communities. For example, the heating apparatus could be installed at the top of pelagic enclosures to simulate near-surface thermoclines or increased stratification strength. Alternatively, bottom heating in deep pelagic enclosures could be used to delay the onset of thermal stratification. The demand for electrical power was relatively minor, and could be met with a series of solar panels, making this system suitable for remote applications.

Effects of the experimental apparatus on study communities should be considered in any application of this experimental design, and biofilm development on enclosures and pipes should be monitored.

This system is adaptable to larger and smaller scale experiments and can provide fixed or differential temperature control. Target temperatures or temperature differences are easily

adjusted via a simple software change. In the current application, differential control was deemed important, because the lake temperatures showed strong diurnal variation, and because fecundity and development rates of invertebrates can differ under fluctuating and constant temperature regimes (Bradshaw 1980).

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