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Use of open-top chambers to study the effect of climate change in aquatic ecosystems

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Abstract

The aim of this research was to explore the possibility to use inexpensive open-top chambers (OTCs) as passive artificial warming devices in experimental aquatic studies. Our results show that OTCs give a significant temperature increase compared with the control. The measured increase (up to an average of 2.3°C) corresponds with predicted climatic warming. Due to their open top, the light quantity and quality is only minimally reduced. We found that OTCs are especially suited for studying the effect of climate change in small waters as the vertical temperature gradients remain unchanged. They can also easily be transported to remote environments. We discuss other advantages and disadvantages of these devices for aquatic studies and compare them with other warming devices.

Due to climate change, temperature is currently increasing worldwide. Most recent temperature predictions for the 21st century range from an increase of 1.1°C (minimum low scenario) to 6.4°C (maximum high scenario) (IPCC 2007). For the near future, a temperature rise of 0.1°C per decade is predicted. Temperature increase and other factors of climate change (e.g., precipitation, atmospheric CO_2 concentration) can change community structure and functioning of ecosystems (see e.g., Walther et al. 2002). Shallow freshwater ecosystems will closely follow prevailing air temperature during climate change (Gerten and Adrian 2001; McKee et al. 2002*a*).

Because the effect of climate change on ecosystems is complex, it is the subject of many studies (e.g., Carpenter et al. 1992; Santamaria and Van Vierssen 1997; Moss et al. 2003). Experimental mesocosm studies are often used to understand the potential effect of climatic warming on shallow freshwater bodies (e.g., McKee et al. 2000; Baulch et al. 2003; Burnett et al. 2007). As Feuchtmayr et al. (2007) posed, artificial outdoor open-air mesocosms are a good intermediate between laboratory and natural conditions.

Experimental mesocosm studies generally use two different experimental set-ups for artificial warming. One option is either to place the treatment mesocosms in a warmed (active or passive), closed greenhouse and untreated mesocosms outside the greenhouse (Braley et al. 1992; Kankaala et al. 2000) or to place both treatments in a greenhouse but under different air temperature regimes (Beisner et al. 1997) or different ventilation regimes to cool the system (Strecker et al. 2004; Christensen et al. 2006). Apart from active warming being expensive and susceptible to break down, the greenhouse approach has the disadvantage that in closed-canopy systems, light, gas exchange, invertebrate access, and precipitation are hampered.

Another option is to place heating elements on top of the sediment. Heating is performed either by electrical elements (Liboriussen et al. 2005; Burnett et al. 2007; Nouguier et al. 2007) or by running hot water through elements (McKee et al. 2000; Baulch et al. 2003). To prevent a vertical gradient, the water column can be mixed by pumping (McKee et al. 2000) or by stirring with paddles (Liboriussen et al. 2005). One drawback of this design is that the heating elements result in locally higher temperatures. In addition, these systems are expensive to set up and run and are susceptible to break down.

Water temperatures in untreated mesocosms and in small natural waters (e.g., ponds, ditches) show a clear profile during most of the year (Young 1975; Dale and Gillespie 1977; personal observation). With the above-described warming devices, the temperature profile may be disturbed if there is

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side heating, mixing of the water column or heating from the bottom. In addition to water temperature, the fact that solar irradiation is coming from above is important for biological communities (e.g., Jöhnk et al. 2008). To study the effects of climate change with minimal unwanted ecological effects, we think it important that the warming device preserves the vertical temperature profile.

Molau and Mølgaard (1996) and Marion et al. (1997) designed open-top chambers (OTCs), cone-shaped transparent structures with an open top to study the effect of increased temperature in tundra ecosystems. Because of their open top, OTCs allow direct solar irradiation into the chamber. The inwardly inclined sides trap part of incoming heat like a greenhouse. Molau and Mølgaard (1996) found multiple advantages of OTCs over greenhouses: lower temperature extremes, better light quantity, better light quality, and invertebrate access. Moreover, no significant differences are found in CO_2 concentrations (Marion et al. 1997) and H_2O/CH_4 fluxes (Kanerva et al. 2005) inside and outside the OTC. They concluded that OTCs alter the temperature significantly with little unwanted ecological effects.

Here, we explore whether open-top chambers can be used as artificial warming devices of aquatic mesocosms. Specifically, we study the effects of open-top chambers with different heights on the daily water temperature course of outdoor mesocosms

Materials and procedures

Experimental site—The experiment was conducted in ten, white polyethylene cylindrical mesocosms (height: 67 cm, internal diameter: 45 cm) located at an outdoor research facility near Renkum, the Netherlands. From the bottom up, the mesocosms were filled with 7 cm clay, 2 cm sludge, 2 cm washed sand, and 45 cm rain water (on average 70 L), respectively. For insulation, mesocosms were completely sunk in the ground to the water surface level. During this experiment no plants were present in the mesocosms.

Chamber design and experimental set up—The design of the open-top chamber (OTC) was similar to the cone design described in Molau and Mølgaard (1996) and Marion et al. (1997) (Fig. 1). The OTCs are made of 1 mm thick Sun-Lite HP™ Fiberglas (Solar Components Corp.). Molau and Mølgaard (1996) show that this material is highly suitable due to a low transmittance of infrared (<5%) and a high solar transmittance for the visible wavelengths (87%). Spectral transmittance of the canopy material is assessed with a fiber optic spectrometer (AvaSpec-2048, Avantes BV). PAR light at different water depths and locations is assessed for the control and the tallest OTC with a Li-Cor sensor.

The effect on water temperature of different heights of open-top chamber was evaluated. The different treatments were no OTC and OTCs with heights of 10, 15, 20, and 25 cm. Treatments were carried out in duplicate, but due to failure of data logging equipment, some treatments have less data. OTCs were randomly assigned to the mesocosms, placed on top, connected with duct tape to the mesocosms, and left there for 2 days to let the water adapt to the new situation. In advance of the experiment, we measured wind speeds just above the water layer on several occasions in mesocosms with and without an open-top (all heights). No difference in wind speed was found.

Measurements—To test the water temperature elevation in mesocosms covered with OTCs of the different heights, two 48-h measuring sessions were performed. The first session ran from 3 May 2007 13:27 to 5 May 2007 12:27, which were clear, sunny days (mean temperature: 14.90°C ± 5.03; 1412.1 min of sun, no precipitation). The second session ran from 7 May 2007 13:21 to 9 May 2007 12:21, which were overcast days (mean temperature: 12.45°C ± 1.46; 303.5 min sun, 3 cm precipitation [mainly drizzle]). The mean net solar irradiance of the sunny days (108.7 W m^{-2}) was almost double the solar irradiance of the overcast days (56.2 W m^{-2}).

Hourly water temperature measurements were recorded with data loggers (Type: Grant 1200, Grant Instruments). Thermocouples were placed in the center of the mesocosm, 3 cm under the water surface. Weather conditions and irradiance (Kipp and Zonen solarimeter CM11) were described using data from a nearby meteorological station. Additional measurements of vertical temperature profiles were conducted in the same mesocosms in August 2007.

Statistical analysis—Hourly repeated measurements of water temperature of the different treatments were analyzed using repeated-measures analyses of variances (ANOVA). When the repeated-measures ANOVA resulted in a significant effect, multiple comparisons were carried out with a Tukey post hoc test with Kramer's (1956) approximation for unbalanced data. Sampling time was handled as a repeated measure within-subject factor and treatment was handled as a between-subject factor (SAS 9.1.3, SAS Institute Inc.). Statistically significant difference was defined as $P < 0.05$.

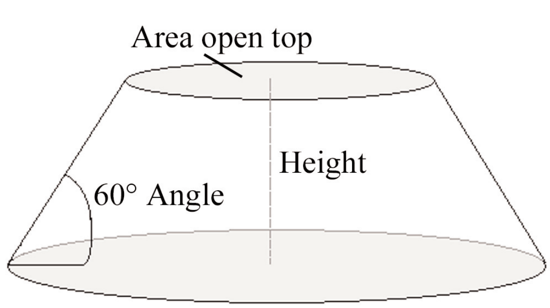

Fig. 1. Design of cone-shaped open-top chamber

Assessment

Spectral transmittance of the canopy material is assessed by comparing the light spectrum of direct sunlight with sunlight

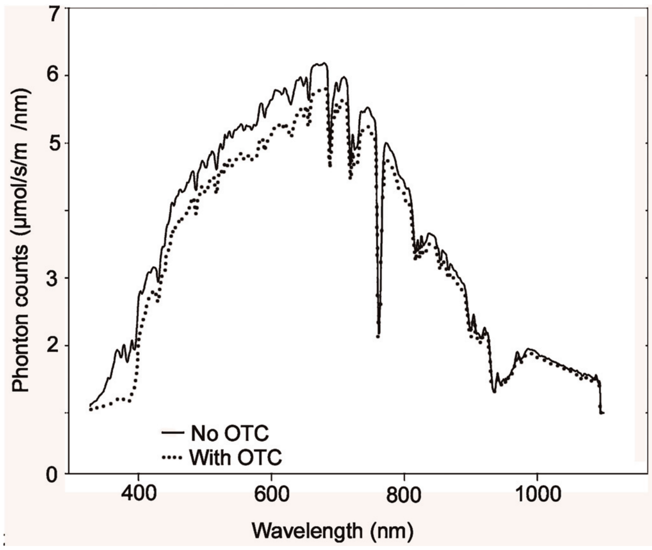

Fig. 2. Light spectrum of direct sunlight (solid line) and sunlight coming through the canopy material of the open-top chamber (dotted line).

coming through the canopy material of the open-top chamber (Fig. 2). We found on average a transmittance of 30%, 89%, and 94% for UV, PAR, and IR light, respectively, which is similar to the findings of Molau and Mølgaard (1996). As the OTC has an open top, light level in the device is much higher. Measurements of PAR light at different water depths showed a reduction of only 3% at the water surface to no measurable reduction of PAR at 20 cm depth in the mesocosm under the OTC.

Data from sunny days show a clear diurnal pattern in water temperature (Fig. 3a). Treatments differed most around noon, as the between-subjects standard deviation (n = 9) then is maximal (Fig. 3c). On overcast days, water temperature also shows a diurnal pattern, although less regular (Fig. 3b). The between-subjects standard deviations (n = 8) now show no diurnal pattern, indicating that the differences between the treatments are more constant over time (Fig. 3d).

Both measuring sessions consistently show that OTCs result in a higher mean water temperature (Table 1). Moreover, the effect clearly increases with the height of the OTCs. Temperature increase of the water and the within-subject standard deviation are higher on sunny days than on overcast days.

Under sunny conditions all heights of OTCs show a significantly higher water temperature than the control treatment (F = 68.895, $P < 0.001$ Table 1: Tukey post hoc). Furthermore, water temperature is significantly higher with a 25-cm–high OTC than other treatments. Under overcast conditions, only 20- and 25-cm–high OTCs show significantly higher water temperature than the control treatment (F = 34.821, $P = 0.008$). Again, significantly higher water temperature is apparent in the 25-cm–high OTC over all other treatments.

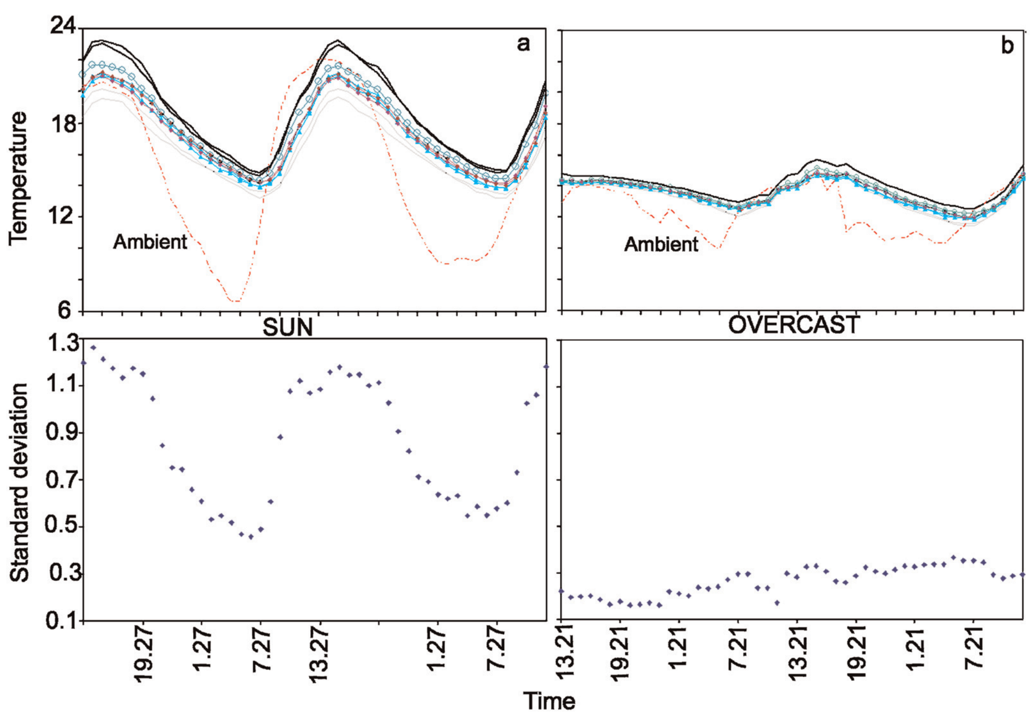

Fig. 3. Temperature data (a,b) and between-subject standard deviations (c,d) for 48 h under sunny weather conditions (left panels) and overcast weather conditions (right panels). Dashed line is ambient air temperature. Solid black line: 25 cm high OTC, open circles: 20 cm high OTC, closed diamond: 15 cm high OTC, triangle: 10 cm high OTC, solid gray line: control.

Table 1. Water temperature data of open-top chambers (OTCs) over 48 h

Open-top chamber		Sun		Overcast	
Height (cm)	Fraction covered	Mean ±SD (*n*)	Post hoc	Mean ±SD (*n*)	Post hoc
0 (control)	0.00	16.40 ± 2.20 *(96)*	a	13.26 ± 0.96 *(96)*	d
10	0.45	0.88 ± 2.45 *(96)*	b	0.16 ± 0.82 *(96)*	de
15	0.62	0.99 ± 2.33 *(96)*	b	0.28 ± 0.83 *(48)*	de
20	0.76	1.50 ± 2.51 *(48)*	b	0.34 ± 0.81 *(96)*	ef
25	0.87	2.33 ± 2.84 *(96)*	c	0.76 ± 0.86 *(48)*	f

Fraction covered = 1 – (area open top/area mesocosm). Post hoc results follow a Tukey-Kramer approximation of repeated measures analysis of variance (ANOVA).

The relationship between the temperature increase and the area fraction that is covered by the OTC (fraction covered = 1 – [area open top / area mesocosm]) can be described by the following power functions (Sigmaplot 2000, SPSS Inc.) (see also Fig. 4):

$$\Delta t_{Sun} = 2.84\ c^{1.90} \quad (1)$$

$$\Delta t_{Overcast} = 1.11\ c^{3.16} \quad (2)$$

These results suggest that under both weather conditions the OTC of 25 cm height and corresponding covered fraction of 0.87 results in a significant mean water temperature increase of 0.76°C on overcast days and 2.33°C on sunny days. Cloud cover during overcast days may explain a lower water temperature increase and irregular pattern of between-subject standard deviation over time, due to scattering and absorption processes that result in a more variable surface irradiance (Orsini et al. 2002).

Additional temperature measurements at different depths show that although the temperature increase of the water was rather small because of the strong overcast weather conditions, the vertical temperature profiles of the control treatment and the 25 cm high OTC are very similar (Fig. 5).

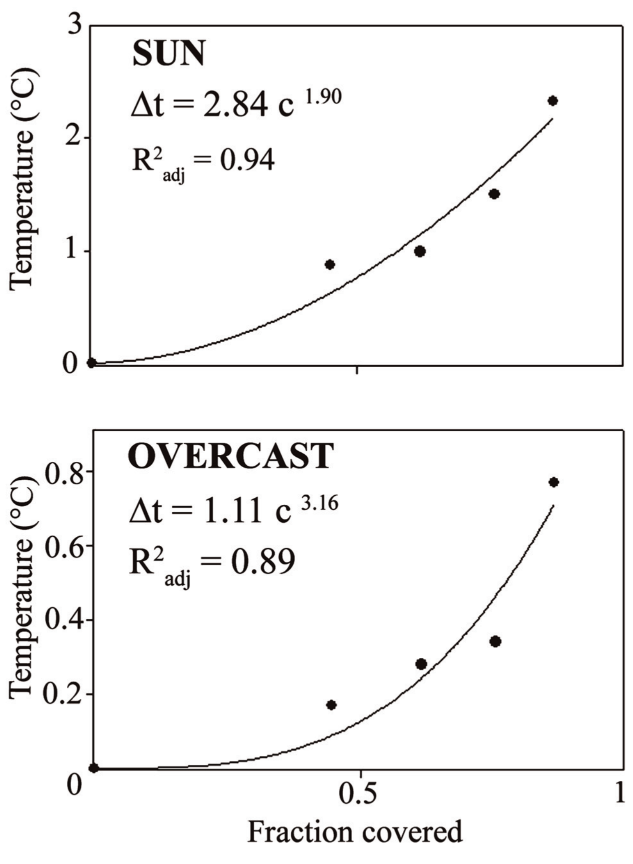

Fig. 4. Relationship between the fraction covered by the OTC and absolute water temperature increase under sunny (a) and overcast (b) weather conditions can be described by a power function in which Δt is the absolute water temperature increase compared with the control treatment and c is the fraction covered of the OTC (c = 0 is the control treatment without OTC).

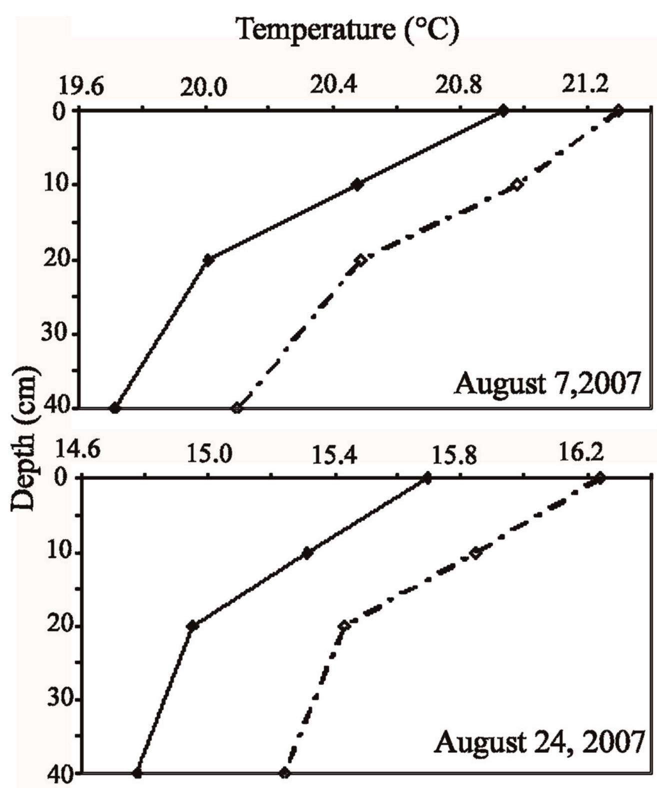

Fig. 5. Mean temperature profile of the water column on two different dates. Solid line is the control treatment and the dashed line is the 25 cm OTC treatment. Horizontal axis is the absolute temperature in the water column and the vertical axis is the depth (0–40 cm).

Table 2. Artificial warming devices for mesocosms

Design	Specs	Advantages	Disadvantages	Users
Greenhouse	Active warming	Predefined temperatures	Expensive (money, manpower)	Beisner et al. 1997
		Higher temperature increase	Limits light	Kankaala et al. 2000
		Temperature profile	(Limits gas exchange)	
			Limits precipitation	
			Limits invertebrate access	
			Susceptible to break down	
	Passive warming	Inexpensive	Limits light	Yuschak and Richards 1987
		No supervision required	(Limits gas exchange)	
		Easy to construct/transport	Limits precipitation	Braley et al. 1992
		Temperature profile	Limits invertebrate access	Strecker et al. 2004
		Solid construction	Warming uncontrolled and limited	Christensen et al. 2006
Heating elements	Electrical/hot water	Predefined temperature	Expensive (money, manpower)	
		Higher temperature increase	No temperature profile	McKee et al. 2000, 2002*a*,*b*, 2003
		Invertebrate access	Susceptible to break down	
		Normal precipitation	Locally higher temperatures	Baulch et al. 2003
				Liboriussen et al. 2005
				Burnett et al. 2007
Open-top chambers		Inexpensive	Warming uncontrolled and limited	Present study
		No supervision required	Limits light slightly (3%)	
		Easy to construct/transport	Limits precipitation quantity	
		Temperature profile		
		Invertebrate access		
		Solid construction		

Discussion

In this study, we explored the potential use of open-top chambers (OTCs) as artificial warming devices for aquatic mesocosms. To be useful for climate change studies, it is obviously necessary that the device yields consistently higher temperatures and that these are comparable with the IPCC predictions for the coming decades (IPCC 2007). Second, the device should have minimal unwanted ecological effects and maintain a natural vertical temperature profile. Of course, practical considerations are important, like feasibility, costs, and stability. Below we discuss these points, comparing OTCs with other devices (see also Table 2).

Our results show that with OTCs a significantly higher temperature is reached compared with the control. The measured increase (up to an average of 2.3°C) corresponds with predicted global warming. If the temperature change needs to be higher or more controlled, an active heating system is more appropriate (e.g., McKee et al. 2000; Kankaala et al. 2000; Liboriussen et al. 2005). Furthermore, there might be some scale-dependent limitations of the size of the open-top chamber on really large mesocosms in relation to the warming capacity of the open-top chamber. Thus, for much larger ecosystems, the warming effect of the OTC on a larger volume of water should be investigated to determine whether another approach should be followed.

Each possible device used to increase temperature will have some unwanted effects, making the control treatment differ in more aspects than temperature alone (Kennedy 1995; Marion et al. 1997). The consequence of the effects is determined by the purpose of the study. Some unwanted effects of open-top chambers are similar to, but less severe than closed-canopy greenhouses. These unwanted effects are hampering of light, precipitation, (possible) invertebrate access, and wind, in comparison to control mesocosms. The open-top still gives free access to the inside of the chamber for e.g., direct light, precipitation, and invertebrates. The fraction covered (1 – [area open top/area mesocosm]) by the OTC determines the trade-off between the temperature increase and the degree of unwanted effects.

Regarding the reduction of light, the Fiberglas material of the OTCs reduced incoming PAR light at most by 11%. But because OTCs are partly open, the real light reduction inside the chamber is much less. We measured on a sunny day only 3% light reduction. This is however dependent on the time of the day and the weather conditions. Note also that for many processes, the effect of light reduction will be opposite to the effect of temperature increase (for instance on primary production). Therefore, the small reduction in light will in many cases only lead to a slightly conservative estimate of the temperature effect. In environments with a strong photoinhibition (e.g., high altitude tropical areas), the shading by OTCs can have an unwanted positive effect on photosynthesis. In such cases, it will be necessary to shade the controls in a similar way or use different canopy material.

Precipitation is a natural disturbance of water bodies at water surface level and can mix the water column. The open-top of the OTC still allows the intensity of direct precipitation on the water surface determine the mixing. During our experiment, we did not encounter large quantities of precipitation. An overflow in our mesocosm system ensured a maximal water level. In areas with heavy precipitation over a longer period, OTCs might be less effective because larger quantities of precipitation in the control over a longer time might cool down and mix the mesocosm to a higher degree. Possible evaporative losses, which we almost did not encounter during our experiment, can be replaced gently with, e.g., rain water.

The species exchange of invertebrates between water bodies occur mainly by air. Airborne animals seem to have no problem getting in and out of the open-top chamber (personal observation). This might be different in systems with an almost closed open-top. A proper evaluation should be done if the purpose of the study demands this. Other invertebrates, such as gastropoda or crustacean, depend on other modes of transportation e.g., by waterfowl or humans. We tried to avoid this other mode of transportation by, e.g., covering the mesocosms with chicken wire and cleaning the sensors before measuring in the next mesocosm. We therefore think that colonization of invertebrates is likely to be comparable for the control and the open-top chamber treatment.

OTCs obviously protect mesocosms from wind. In terrestrial systems, this can be an important disadvantage (Marion et al. 1997). In our mesocosms, however, we could not measure differences in wind speed just above the water surface between control and treatment. Because in our experimental mesocosms the wind fetch was small, the wind effect was limited. In larger scale experiments, the wind effect of OTCs might be more problematic.

A possible advantage that OTCs have over most other devices is that OTCs maintain the natural vertical temperature profile in the water column. This is useful for studying ecological effect of climate change in small water bodies, but it might be unwanted for studies on large well-mixed systems. The use of heating elements result in locally higher temperatures near the elements (e.g., Baulch et al. 2003), which is not the case when using OTCs. Another approach would be to use a greenhouse and sink the mesocosms in the ground. But, as described before, the unwanted effects caused by the chamber effect are stronger with these closed-canopy greenhouses than with the OTCs.

Finally practical considerations can be important. Active warming devices, such as active greenhouses and heating elements, are more expensive to construct and to maintain (energy and personnel) (e.g., Liboriussen et al. 2005). Furthermore, active heating has a risk of equipment failure (e.g., Baulch et al. 2003). OTCs are easy and inexpensive to construct, can withstand time and extreme weather conditions, and are, therefore, highly reliable, feasible, and also suitable for use in remote and harsh areas. Due to their robustness, they are especially suitable for long-term experiments.

Many of the advantages and disadvantages of OTCs are shared with other passive warming systems (Yuschak and Richards 1987; Braley et al. 1992; Strecker et al. 2004; Christensen et al. 2006). Yuschak and Richards (1987) built an entire passive solar building in which they placed tanks. Although the construction is very robust, it is a rather complex and expensive design. Furthermore, this design is closed for light and precipitation. Strecker et al. (2004) used a conical design but with a closed canopy. Advantage of this system is that the control and treatment are both almost closed in a similar way. Disadvantage is that the system of Strecker et al. (2004) is closed for light, invertebrates, and precipitation. Furthermore, the OTC is a simpler and possibly a more robust design. Braley et al. (1992) and Christensen et al. (2006) used a completely sealed canopy with no gas-exchange possibilities. These designs could result in a difference in CO_2 and O_2 level between treatment and control and are also completely closed for light, invertebrates, and precipitation.

In conclusion, open-top chambers can be used as inexpensive artificial warming devices for aquatic mesocosms. They are especially suited for studying climatic warming in small water bodies. Future studies can combine temperature increase with other factors of global change (e.g., eutrophication, species interaction) to give a more elaborate assessment of the cumulative impacts of global change on these kind of ecosystems. The largest OTC can yield temperature increases that correspond with predicted climatic warming. Main limitations are that the temperature increase cannot be controlled and is rather limited. The open-top and the angle of the canopy material make it possible to receive direct light. Because the light quality and light quantity within the OTC are slightly hampered, the use of OTCs might result in a slightly conservative estimate of the effects of climatic warming. Also precipitation quantity is altered although not as much as in greenhouses.

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