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Methods in Ecology and Evolution

PRACTICAL TOOLS

Effective heating chamber design to simulate acute heatwaves and night-time warming for ecological communities under natural field conditions

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Abstract

1. Heatwaves are increasing in intensity, duration and frequency. The impacts of such events can be extensive for natural ecosystems, but studying heatwaves in field conditions (in situ) remains challenging.
2. Chambers that passively increase air temperatures have been used widely for studying climate warming in field experiments, but they cannot simulate warming at night and rarely achieve more than +3°C above ambient air temperature. Simulating heatwaves requires active heating. As a result, most studies of heatwaves have been applied ex situ to potted plants or mesocosms, which can yield results that do not reflect outcomes in natural systems.
3. We designed and built equipment for simulating an extreme heat event under field conditions that combines passive warming in semi-enclosed chambers and active convective heating, using portable diesel heaters to supply warm air to 1.5 m diameter cylindrical chambers. The active heating systems can be programmed with target temperature profiles to heat day and night.
4. Through two case studies in high elevation ecosystems in Australia, we demonstrated the capacity for an actively heated chamber to increase air temperature by up to +14°C above ambient during the day and +17°C at night, then identify optimal operating conditions and limitations during challenging field conditions.

5. Our active heating chamber design can be applied to simulate an array of extreme heat scenarios on ecological communities, including night-time warming, daytime extremes, varying heat intensity, duration, event frequency, recovery period lengths and combinations thereof. We hope that researchers will be inspired to make use of this active heating chamber system to study the impacts of heat in the field.

KEYWORDS
climate change, extreme climatic event, field ecology, heat stress, heatwave, in situ, night-time warming, open-top chamber

1 | INTRODUCTION

Global climate change is increasing average temperatures and the frequency, intensity and duration of extreme climatic events (Cowan et al., 2014; Perkins-Kirkpatrick & Lewis, 2020; Zhang et al., 2022). Heatwaves (often defined as three or more consecutive days above the 90th percentile for maximum temperatures) have substantial detrimental effects on species and ecological communities (Breshears et al., 2021; Perkins et al., 2012; Perkins & Alexander, 2013; Smith et al., 2023). However, studying the impact of heatwaves in natural terrestrial systems remains challenging (Thakur et al., 2022; Ummenhofer & Meehl, 2017).

Research on the effects of climate warming and heatwaves is typically done using opportunistic studies of extreme events, ex situ studies or open-top chambers (Altwegg et al., 2017; Ettinger et al., 2019). However, accurately predicting natural extreme events well in advance is impossible. Therefore, implementing appropriate controls and replication is difficult, often requiring long-term monitoring with appropriate temporal and spatial controls (Altwegg et al., 2017). Other studies apply heatwaves to organisms in glasshouses or controlled environments (ex situ) (e.g. Andrew et al., 2023; Aspinwall et al., 2019; Marchin et al., 2022). A substantial problem with ex situ studies of plants is that their responses to heat depend on soil moisture, such that plants growing with natural soil moisture may have different responses to potted plants with artificial watering regimes (Karitter et al., 2023; Poorter et al., 2016). Field (in situ) studies that retain intact plant assemblages and natural microclimate (including light, soil water availability and weather variability) are crucial for understanding the complexities of biological responses to increased heat.

Passive heating methods have been used widely for decades. The most well-known approach is the open-top chamber (OTC): a simple, cost-effective and replicable tool for field experiments that allows for natural precipitation, light and gas exchange, while increasing daytime temperatures by generating a greenhouse effect (Hollister et al., 2023; Marion et al., 1997; Vázquez-Ramírez & Venn, 2024; Welshofer et al., 2018). Open-top chambers allow the transmission of short-wave solar radiation but trap outgoing long-wave radiation and limit heat loss through air movement (advection and convection), resulting in warmer surface temperatures, typically around +1–3°C (Hollister et al., 2023), depending on external conditions and solar input (Vázquez-Ramírez & Venn, 2024). However, there are significant drawbacks to passive open-top chambers for studying important aspects of climate change, particularly extremes (Kennedy, 1995).

Open-top chambers have difficulty achieving and sustaining moderate warming except during periods with very high solar input, and they are not effective for studying heatwaves as they provide a modest increase to ambient temperatures (Hollister et al., 2023; Welshofer et al., 2018). Open-top chambers have limited capacity for night-time warming and have highly variable humidity and condensation that affect vapour pressure deficit (VPD). Improvements can be made by adding a radiant object with large thermal mass to radiate heat at night-time, or reflective material covering a chamber at night can prevent the loss of heat (Speights et al., 2018). However, the precision of temperature control is low and depends on daytime solar input, which does not ensure warmer simulated temperatures at night. Nights are warming even more rapidly than days through climate change (Davy et al., 2017), and typical heatwaves increase both daytime and night-time temperatures. Night-time warming can have different (often more negative) impacts on the function and fitness of organisms than daytime warming (Barton & Schmitz, 2018; Kundu et al., 2024; Posch, Hammer, et al., 2022). Open-top chambers do not substantially increase night-time temperatures (Speights et al., 2018), thus studying the effects of night-time warming on ecological communities has had practical limitations (Barton & Schmitz, 2018).

Active heating of in situ communities is effective for night-time warming and can allow researchers to study heatwaves. The use of infrared, electric or combustion heaters to warm enclosed chambers allows for relatively high precision in temperature control (Speights et al., 2018; Wang et al., 2008). Electric infrared heaters (e.g. heat lamps) can achieve precise and substantial warming and have predictable operation under different ambient temperatures and wind conditions (Kimball et al., 2008). However, infrared heaters can expose ecological communities to uneven thermal treatments: the highest leaves on plants reach unnaturally high temperatures, while shaded leaves receive very little warming. Convection heaters are considered inefficient under field conditions due to heated air escaping through convection, resulting in uneven heating across the target community (Speights et al., 2018). However, convection heaters in combination with a chamber can greatly improve the overall heating capability and evenness (Frei et al., 2020; Wang et al., 2008).

Here, we propose a design that will allow ecologists to simulate more realistic heat events in the field by combining a controllable convection heater system with a semi-enclosed chamber with adjustable vents. Our overall aims were to (1) design and build an effective, portable system for simulating a heatwave or extreme heat event; (2) compare temperature profiles of actively and passively heated chambers relative to target temperatures; and (3) evaluate the performance and consistency of actively heated chambers at reaching and maintaining heat targets during the day and night under field conditions. We developed equipment that combines design elements of both passive and active warming methods and tested it in Australia's alpine region. We present two case studies to showcase the equipment and how it could enable research on biological responses to realistic heatwaves in situ across ecological communities.

2 | MATERIALS AND METHODS

2.1 | Heating chamber design

We used large cylindrical semi-enclosed chambers (Case study 1: diameter = 1.5 m, height = 700 mm, internal air volume ≈ 1.24 m^3; Case study 2: diameter = 1.5 m, height = 550 mm, internal air volume ≈ 0.97 m^3), which comprised a wall and a circular lid, both constructed from 3 mm thick translucent polycarbonate sheets (Huili TUVLITE, Huili-Tuvgal Sheets Co. Ltd., Shanghai, China). The chamber lid included six portholes (diameter = 300 mm) that could be manually opened to access the chamber interior and adjusted to provide variable ventilation or closed to prevent heat loss. The chamber was secured to the ground using nylon rope and tent pegs attached to the chamber lid. Air within the chamber was circulated using three 120 mm 12 V fans (AP120i, SilverStone Technology Co., Ltd., Taiwan) 300 mm above the vegetation surface (Figure 1).

Active heating of chamber air space was achieved using a diesel-fuelled heater with a 10 L fuel tank (5 kW Caravan Heater; OnTrack Outdoor Pty Ltd., QLD, Australia), which forced warmed air into the chamber via a fan and insulated ducting that was secured to the chamber using adjustable hose clamps. A T-junction duct diverted warmed air to two separate chambers at any given time. Warmed air entered each chamber through a duct at a height of 400 mm, ~300 mm above the vegetation. Each chamber utilised an independent temperature feedback system to maintain chamber interior air temperature according to a target temperature setpoint. Warmed air passed through a 75 mm diameter aluminium bypass valve with two output channels: to the chamber interior or the atmosphere (Figure 1a). The bypass valve had opposingly set valve closures controlled by an actuator (24 V; LM24A-SR, Belimo Actuators Pty Ltd., Switzerland) and an automated temperature controller (24 V; PXU400B0, Red Lion, PA, USA), which measured air temperature each second using a type-K thermocouple positioned 100 mm above the vegetation, sheltered by a Stevenson screen. A signal based on the difference between air temperature and target temperature was relayed from the controller to the actuator, which incrementally adjusted the bypass valve position according to the temperature difference.

Further technical details of the active heating system, along with generalised safety considerations, risk management and a generalised setup guide with annotated images are provided in Text S1. Notably, for safe use in the field, the actively heated chamber systems should be continuously monitored by appropriately trained personnel.

2.2 | Environmental measurements

The chambers were deployed for the two field case studies on Mt. Hotham, Victoria (VIC), Australia (36.98° S 147.13° E) in 2022 (hereafter, Hotham) and Perisher Valley, Kosciuszko National Park, New South Wales (NSW), Australia (36.41° S 148.41° E) in 2023 (hereafter Perisher). Both sites are located on commercially leased (ski resort) land, and scientific licences for fieldwork were not required. We assessed the relative performance of the heating chamber under different environmental conditions, which was quantified by measuring a series of microclimatic variables within each plot. A plot was defined as the 1 m central circle within the 1.5 m circular area of the chamber (i.e. there was a 250 mm buffer zone to reduce edge effects from the chamber walls). In both studies, we measured air temperature and relative humidity within the plots (details in Text S2).

2.3 | Case study 1: Hotham

The first chamber deployment was conducted in early March 2022 on Mt. Hotham at 1840 m elevation (Figure 1b,c), which was located adjacent to an Australian Bureau of Meteorology weather station (#083085). Climate conditions for the site are reported in Text S2. At Hotham, we investigated the effectiveness of active and passive heating approaches using the semi-enclosed chambers. We subjected 25 plots distributed across seven replicate blocks to one of three treatments: actively and passively heated ($n = 14$), passively heated only ($n = 3$) and ambient, unheated control ($n = 8$). Hereafter, we refer to these treatments as actively heated, passively heated and control. The numbers of replicate plots for each treatment were uneven because the initial design used eight blocks (physical locations within the site). Each block contained a randomised layout of one control plot and two heated plots. However, the heating system in one block had technical issues and was excluded. The two heated plots per block were originally intended to be used for heat events of different durations. However, inclement weather necessitated altering the experimental design. Three passively heated plots were included as an alternative control, accounting for the passive warming effect of the physical chamber structure (see also Section 4 about controls). We recommend that future implementations of these

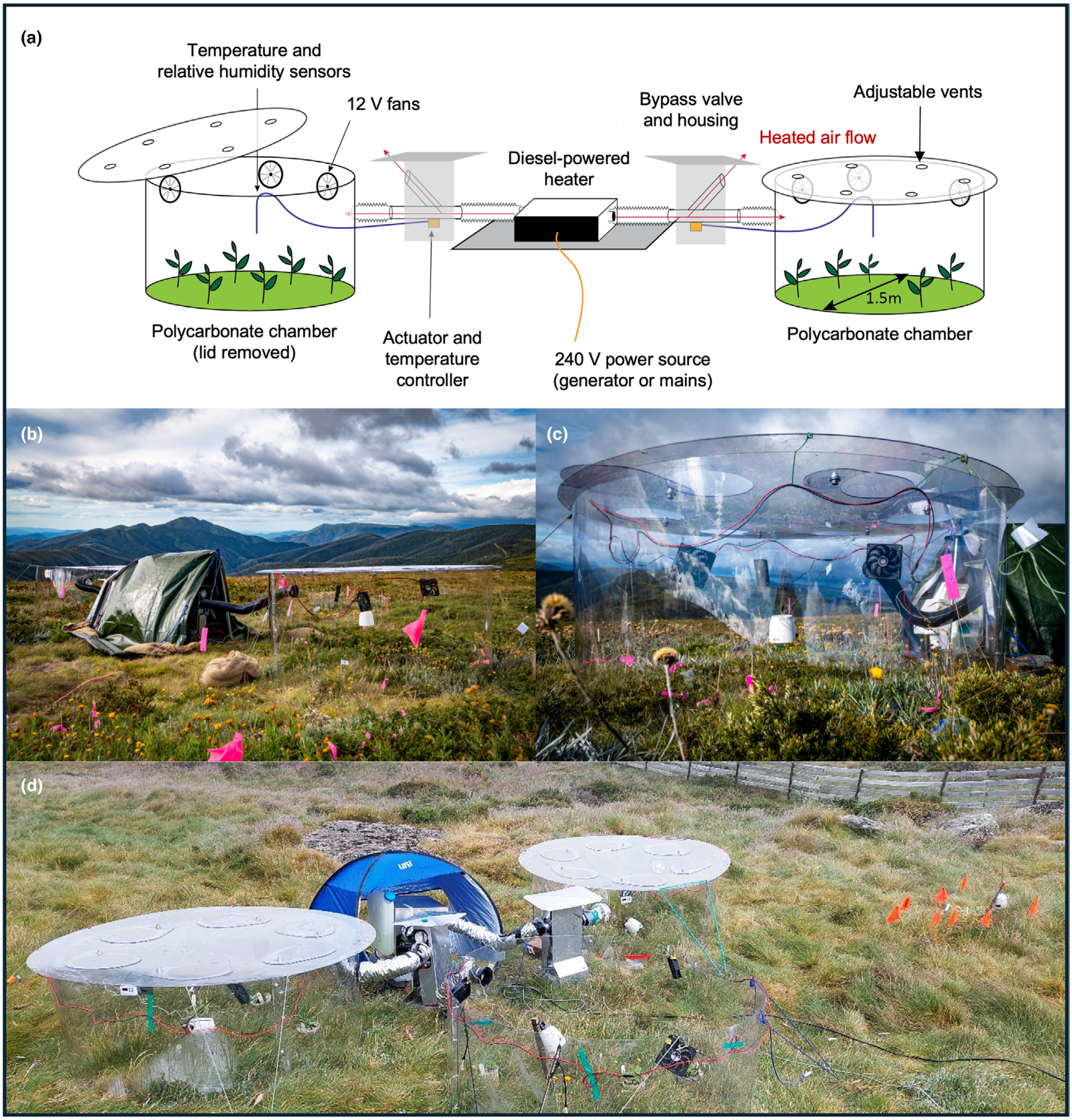

FIGURE 1 Images of the chamber and active heating system. (a) Annotated detail image of the heating system, electrical components, and chambers (not to scale). Field photos from Mt. Hotham, VIC, Australia (Case study 1): (b) two polycarbonate chambers attached via black ducting to one heating system under a tarpaulin for protection from the weather; and (c) side view of a chamber with its semi-enclosed, overhanging lid with adjustable portholes, circulating fans, and Stevenson screen housing thermocouples. (d) Field photo from Perisher Valley, NSW, Australia (Case study 2). The heating system attached to three chambers showing improved insulative ducting and open tent protecting and ventilating the heating system. Note that chamber lids are transparent like the chamber sides but appear grey due to reflections of cloud cover.

heating chambers use equal replicates of each treatment (as in Case study 2).

The experiment was conducted over 6 days and nights from 2 March 2022 14:00 through to 8 March 2022 07:30, where active heating treatments persisted throughout both day and night. The local average daytime (08:00–20:00) air temperature during the experiment was 15.5 ± 3.7°C, while the average night-time (20:00–08:00) air temperature was 9.4 ± 1.9°C, with an average windspeed of 0.5 $m\,s^{-1}$ (range: 0.0–7.1 $m\,s^{-1}$). An electrical storm with high wind, heavy precipitation and cold temperature occurred on 5 March 2022

07:00–19:00, during which time chambers were left in place but active heating was paused to ensure occupational safety.

For this case study, our focus was daytime warming. The daytime setpoint of 32°C for actively heated plots was chosen to simulate severe end-of-century warming of +4°C above the highest recorded daytime February air temperature. The night-time setpoint of 22°C represents a hot night (well above the mean minimum air temperature of 8.0°C and near the highest minimum air temperature for February; 19.6°C in 2020). The weather conditions during this fieldwork were unseasonably cold and included periods of precipitation and strong winds (Table S1). Leaf temperatures were also measured in control and actively heated plots during Case study 1 (details in Text S2).

2.4 | Case study 2: Perisher

The second chamber deployment was conducted in January 2023 in the Perisher Valley at 1740 m elevation (Figure 1d), within 1 km of an Australian Bureau of Meteorology weather station (#071075). Climate conditions for the site are reported in Text S2. The Perisher experiment investigated factorial combinations of diurnal and nocturnal heating: warm days with warm nights (W); warm days with ambient nights (D); ambient days with warm nights (N); and a control plot (no chamber) with ambient days with ambient nights (C). There were five replicate blocks that each contained three chambers (one for each type of heat treatment) and one control plot. The ducting that distributed heated air to the chambers could heat two chambers simultaneously. One heating duct was constantly connected to the W treatment. A second duct was connected to the D treatment from 06:30 to 18:00. From 18:00 to 06:30, the second duct was detached from the D treatment and moved to the N treatment (Figure S1). During the day, the N treatment had its lid removed, and the chamber was propped up from the ground by 100 mm to allow extra air circulation. The D treatment had the six lid portholes opened overnight.

The experiment was conducted for 4 days and nights, with heating from 19 January 2023 18:00 until 23 January 2023 18:00, including one shut-off period between 17:30–20:50 on 22 January 2023 due to storm activity. Our target treatment temperatures were chosen to simulate severe end-of-century warming of approximately +4°C above the highest recorded January air temperature. We therefore programmed heating to reach 34°C for warm day treatments, following a ramping profile to simulate elevated temperatures over a typical alpine temperature profile on a hot summer day (i.e. target changes: 08:00 = 28°C, 11:00 = 30°C, 13:00 = 32°C, 14:00 = 34°C, 19:00 = 22°C).

2.5 | Statistical analyses

Data processing and analyses were conducted in the R Environment for Statistical Computing v4.3.1 (R Core Team, 2023). For Case study 1 (Hotham), due to unexpectedly harsh weather conditions, we opted to evaluate days that were not strongly affected by severe weather (e.g. significant precipitation and very strong wind) when analysing the performance of the heating treatments. Analyses were therefore conducted on data from days 2, 3, and 6 of the installation. These 3 days were relatively clear days (not heavy rain but still unseasonably cool with periods of high winds) and had daily global solar exposure that was above average (≥15.5 MJ m^{-2}; Table S1; Solargis, 2019). For analyses, we excluded 2 h transition periods between day and night targets (07:00–09:00 and 19:00–21:00). We calculated mean hourly temperatures and fitted linear mixed effects regression (LMER) models to daytime and night-time temperatures separately, where treatment was a fixed factor and random effects included hour nested within day to account for repeated measurements and plot nested within block to account for spatial replication. We repeated these models with mean daily temperatures instead of hourly, where random effects were the same except without hour. We also repeated these analyses for all days including the poor weather conditions. We then calculated temperature differences between control plots and both actively and passively heated plots (ΔT relative to control). To assess the performance of the actively heated chambers relative to set target temperatures, we calculated the difference between air and target temperature (ΔT relative to target) and regressed these against air temperature.

For Case study 2 (Perisher), all data except for the period with storm activity were included for analyses, since all days exceeded average daily global solar exposure for the site (≥16.5 MJ m^{-2}; Table S2; Solargis, 2019). To assess the performance of chambers through day and night relative to target temperatures, we calculated ΔT relative to target as above. We calculated temperature differences between the unheated control plots and the three heating treatments (ΔT relative to control), then fitted LMER models at hourly and daily scales for daytime and night-time temperatures between treatments as above.

3 | RESULTS

3.1 | Case study 1: Hotham. Actively heated chambers are effective under field conditions

The air temperature profile averaged over the 3 days showed clear differences among the treatments (Figure 2). The air temperature in passively heated chambers lagged behind actively heated chambers during the daytime. Passively heated chambers did not retain heat overnight and only achieved similar heating to actively heated chambers when solar input and daytime temperatures were highest (Figure 2). Thermal variability was much lower in actively heated plots, but both heating treatments responded to changes in ambient air temperature and cloud cover (Figure S2). Like temperature, relative humidity was most stable in the actively heated chambers and remained relatively high despite the active heating process (Table 1). Temperature, relative humidity and

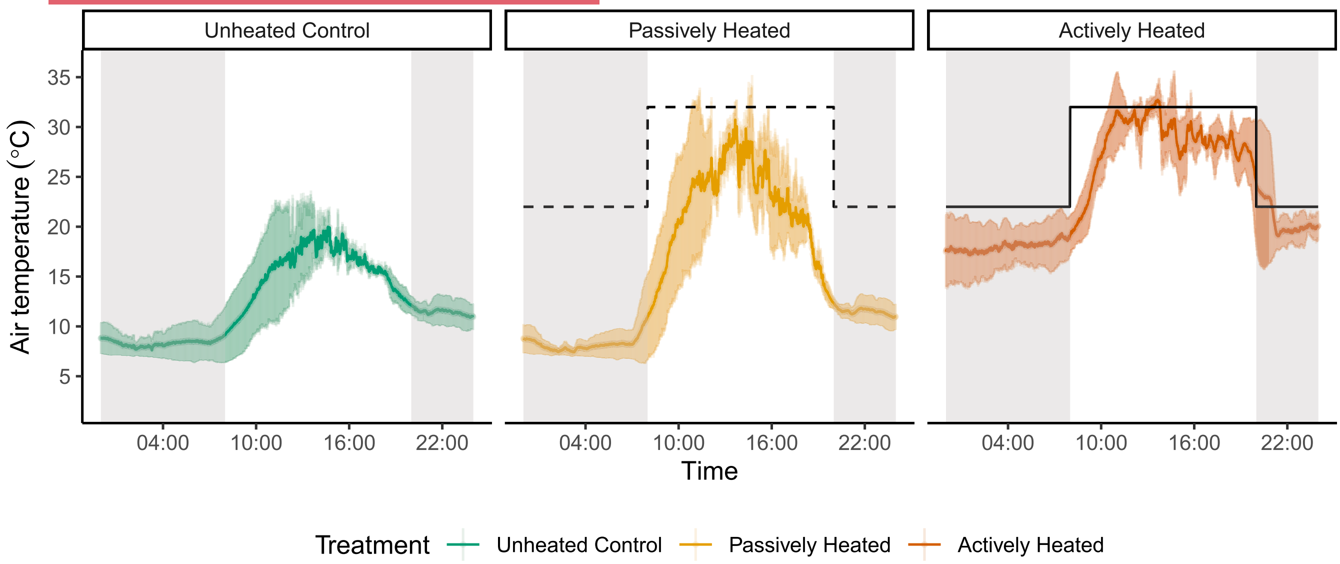

FIGURE 2 Air temperature time profiles the heatwave experiment at Mt. Hotham, VIC (Case study 1). Solid lines and coloured shading indicate the mean ± SD for the average temperature profile across seven blocks over 3 days. Dashed black lines on the passively heated panel (reference for comparison) and solid black lines on the actively heated panel indicates the set target for the actively heated treatment. Shaded grey background indicates hours of night-time.

TABLE 1 Summary of air temperature (T_{air}) and relative humidity (RH) conditions in each treatment during day and night periods at Mt. Hotham, VIC (Case study 1).

Treatment	Period	Hours	Mean T_{air} ± SD (°C)	Mean T_{air} range (°C)	Mean RH ± SD (%)	Mean RH range (%)
Unheated control	Day	09:00–19:00	16.3 ± 4.0	10.5–23.9	72.3 ± 10.8	45.2–98.9
Passively heated	Day	09:00–19:00	23.3 ± 5.1	13.1–34.2	71.9 ± 15.7	34.2–100
Actively heated	Day	09:00–19:00	29.0 ± 4.2	18.5–37.9	55.2 ± 6.2	40.3–82.2
Unheated control	Night	21:00–07:00	9.2 ± 2.0	7.2–11.9	90.7 ± 9.5	73.3–99.4
Passively heated	Night	21:00–07:00	9.1 ± 1.9	7.3–11.9	94.6 ± 9.2	73.7–100
Actively heated	Night	21:00–07:00	18.5 ± 3.9	13.4–26.2	62.5 ± 5.2	43.8–73.6

Note: Range is based on the mean of each minimum and maximum values measured in each replicate plot. Mean and standard deviation (SD) are calculated from measurements taken at 1-min intervals across all replicate plots during the three-day subset (n = 600 per treatment per block per day for daytime and n = 600 per treatment per block per day for night-time).

vapour pressure deficit patterns across the 3 days individually, and the relationship between vapour pressure deficit and temperature are shown in Figure S2.

In the 3-day subset, daytime (09:00–19:00) mean air temperature in unheated control plots was 16.3 ± 4.0°C, where actively heated chambers achieved +12.7°C warming over the control (Figure 3a; Table 1, Tables S3 and S4), and passively heated chambers reached +7.0°C warming over the control (Figure 3b; Table 1, Tables S3 and S4). During the night-time (21:00–07:00), unheated control plots reached 9.2 ± 2.0°C and passively heated chambers were not significantly different from the control (−0.2°C cooler; Figure 3b; Table 1, Tables S3 and S4), but the actively heated chambers achieved +9.3°C warming over the control (Figure 3a; Table 1, Tables S3 and S4). By using either hourly or daily averaged temperature data, and including data from all days, did not significantly alter the differences among the treatments (Tables S3–S6).

Mean temperature ramping rate during the first 3 h of active daytime heating was 4.2°C h^{-1}.

Aiming to maintain daytime warming of 32°C when peak daytime ambient air temperature was very cool, coupled with strong wind and relatively low solar input, represented a strenuous test of the heating chamber capability. The air temperatures for each treatment across all days are shown in Figure S3. The achieved air temperature relative to target temperature (ΔT) was fairly stable for the actively heated treatment across the range of ambient air temperature (~7–20°C): Target temperatures were achieved frequently when daytime air temperature exceeded 16°C and night-time air temperature exceeded 10°C (Figure 3c), whereas passively heated chambers did not reach warming targets even at the warmest ambient temperatures and the ΔT was substantial across the air temperature range (Figure 3d). The actively heated treatment had an initial heating phase to reach the target temperature but

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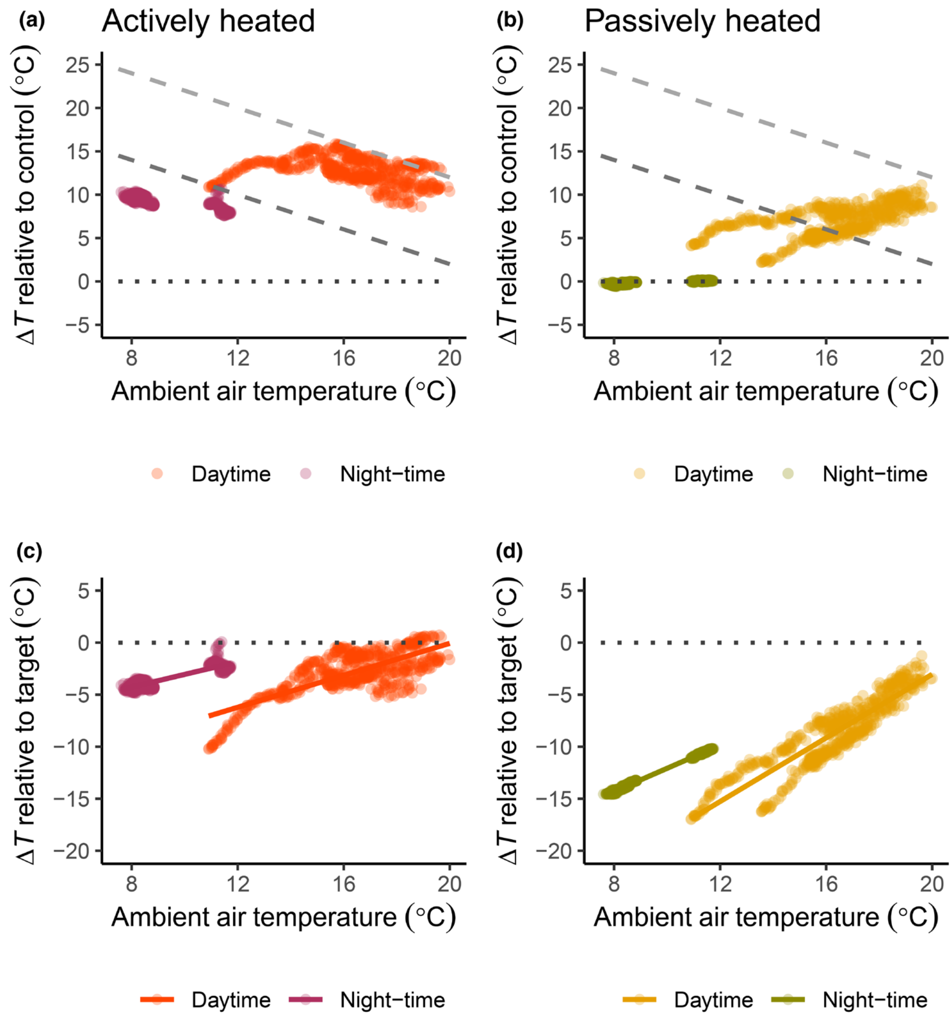

FIGURE 3 Temperature differences (ΔT) in the heated treatments relative to the unheated control and relative to the set targets (22°C night-time and 32°C daytime) at Mt. Hotham, VIC (Case study 1). Panels on the left side are data from actively heated chambers and on the right are from passively heated chambers. ΔT relative to the control across ambient air temperature in (a) actively heated and (b) passively heated chambers. The ΔT of the daytime and night-time target temperature relative to the ambient temperature are indicated in diagonal light grey and dark grey dashed lines respectively, that is at ambient air temperature = 8°C, the ΔT to the daytime target (32°C) is 24°C and ΔT to the night-time target (22°C) is 14°C. ΔT relative to the target across ambient air temperature in (c) actively heated and (d) passively heated chambers. Linear regression model fits are shown overlaying the data. Dotted black lines on all panels show when $\Delta T = 0$, that is control or target temperatures are the same as ambient air temperature.

thereafter remained relatively stable and reached close to or a few°C below target temperatures (Figure S4a). Both heating treatments had smaller ΔT during warmer and sunnier periods and followed a typical diurnal air temperature profile (Figure S4), but ΔT in the passively heated treatment was clearly more dependent on the external environmental conditions (Figure S4b). Leaf temperatures of six dominant plant species were, on average, 20.5 ± 3.6°C in the unheated control treatment when (air temperature = 17.9°C at time of measurement), and leaf temperatures were 29.8 ± 5.2°C in the actively heated treatment (air temperature = 31.2°C at time of measurement). Leaf temperatures of representative species under both treatments are shown in Figure S5 and discussed further in Text S3.

3.2 | Case study 2: Perisher. Effective daytime and night-time heating

This experiment investigated the effectiveness of differential diurnal temperature elevation factorially: an unheated control without chamber and three actively heated treatments applied during the day only, night only and both day and night. All three heated treatments were also passively heated with the semi-enclosed heating chamber during the phases when active heating was not applied. The heated treatments were each highly effective at reaching and maintaining target temperatures during their active phases (Figure 4). Mean temperature ramping rate during the first 3 h of active daytime heating was 4.0°C h^{-1} in the heated both day

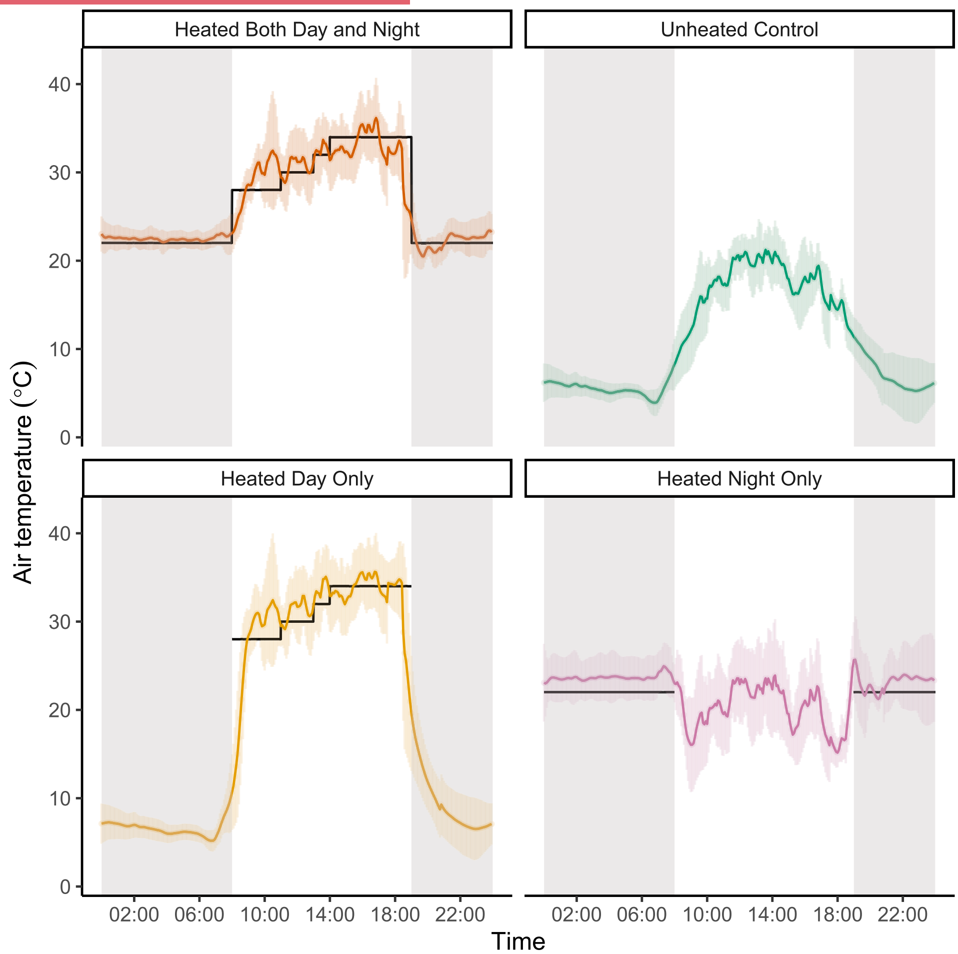

FIGURE 4 Air temperature time profiles the heatwave experiment at Perisher Valley, NSW (Case study 2). Solid coloured lines and shading indicate the mean ± SD for the temperature profile across five blocks. Solid black lines indicate the set target temperatures for the actively heated treatments when they are applied. Shaded grey background indicates hours of night-time.

and night treatment and 11.1°C h^{-1} (due to lower initial temperatures) in the heated day only treatment (Figure 4). Hourly and daily analyses of treatment differences were all significant (Tables S7 and S8).

The air temperature, relative humidity and vapour pressure deficit profiles for the four-day fieldwork period across the four treatments are presented in Figures S6–S8. Daytime (09:00–19:00) mean air temperature in unheated control plots was 17.5°C, where heated chambers that were active during the day achieved an average of +14.8°C warming over the control during daytime (Figure 5a; Table 2, Tables S7 and S8). The heated night only treatment was passively heated during the day and still achieved +2.6°C warming over the control (Figure 5a; Tables S7 and S8). At night (21:00–07:00), unheated control plots reached 5.7 ± 2.2°C and the heated day only chambers were +1.1°C warmer than the control, but the heated chambers that were active during the night achieved +17.5°C warming over the control (Figure 5a; Tables S7 and S8).

The ΔT relative to target temperature was maintained very tightly around zero during phases when heating was active, which was independent of ambient air temperature (Figure 5b). The ΔT relative to target temperature was stable over time, with minor fluctuations through the day due to changes in cloud cover (Figure S9). In phases when active heating was off, the ΔT relative to target temperature was well below zero, which increased with ambient air temperature due to the passive heating effect (Figure 5b). Heating that was not active during the day and night had larger fluctuations with external environmental conditions (Figure S9).

4 | DISCUSSION

The rapid pace of global climatic change means that there is an urgent need to develop practical tools for researchers to replicate realistic heatwaves in the field to more accurately assess biological responses. Here we designed, implemented and evaluated the performance of active heat chambers under challenging field conditions.

Both our case studies show that this active heating system effectively regulates temperature to achieve sustained >+10°C warmer than ambient conditions even overnight, in the field, which is exceptional compared to other manipulative mesocosm or field approaches (e.g. Barton & Schmitz, 2018; Frei et al., 2020; Qu et al., 2020; Speights et al., 2018; Wang et al., 2008). Heatwaves

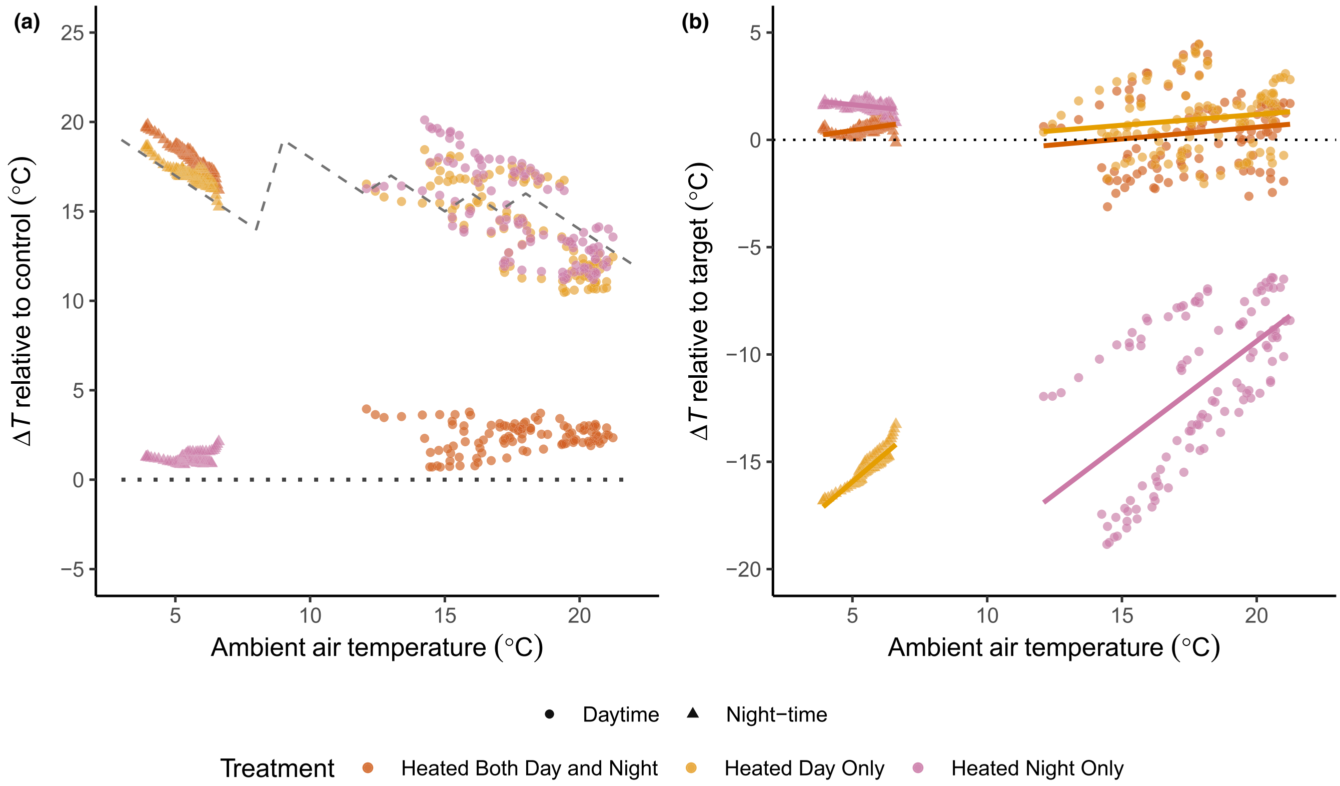

FIGURE 5 Temperature differences (ΔT) in the three heated treatments relative to the unheated control and relative to the ramped target temperatures at Perisher Valley, NSW (Case study 2). (a) ΔT relative to the unheated control across ambient air temperature. The ΔT of the daytime and night-time target temperature relative to the ambient temperature are indicated by the grey dashed lines at ambient air temperature = 15°C, the ΔT to the peak daytime target (34°C) is 19°C and ΔT to the night-time target at (22°C) at ambient air temperature = 8°C is 14°C. (b) ΔT relative to the target across ambient air temperature. Linear regression model fits are shown overlaying the data. Dotted black lines on all panels show when $\Delta T = 0$, that is control or target temperatures are the same as ambient air temperature.

TABLE 2 Summary of air temperature (T_{air}) and relative humidity (RH) conditions in each treatment during day and night periods at Perisher Valley, NSW (Case study 2).

Treatment	Period	Hours	Mean T_{air} ± SD (°C)	Mean T_{air} range (°C)	Mean RH ± SD (%)	Mean RH range (%)
Unheated control	Day	09:00–19:00	16.5 ± 4.7	7.3–21.0	65.6 ± 15.4	48.6–94.2
Heated day (D) only	Day	09:00–19:00	30.0 ± 7.6	9.5–35.4	58.5 ± 16.5	40.1–94.1
Heated night (N) only	Day	09:00–19:00	20.5 ± 5.0	12.8–28.8	54.5 ± 12.8	36.5–83.1
Heated both D + N	Day	09:00–19:00	30.6 ± 5.0	19.4–37.3	55.4 ± 11.4	36.2–83.2
Unheated control	Night	21:00–07:00	5.7 ± 2.2	2.2–8.8	96.7 ± 3.8	86.9–94.1
Heated D only	Night	21:00–07:00	7.0 ± 2.4	3.6–11.9	93.6 ± 5.0	82.0–97.2
Heated N only	Night	21:00–07:00	23.5 ± 3.0	19.7–27.1	47.3 ± 9.3	38.9–65.9
Heated both D + N	Night	21:00–07:00	22.5 ± 1.6	19.9–25.3	54.2 ± 8.3	45.9–70.0

Note: Range is based on the mean value of each minimum and maximum values measured in each replicate plot. Mean and standard deviation (SD) are calculated from measurements taken at 5-min intervals across all replicate plots over the experimental duration ($n = 548$ per treatment per block for daytime and $n = 566$ per treatment per block for night-time).

and other heat events are characterised by sunny, dry conditions where temperature rapidly ramps up to extreme values, which are sustained, resulting in a high heat sum, and often do not cool substantially overnight (De Boeck et al., 2010). Most field manipulative experiments aim for longer-term mild warming (months or years) rather than short-term heatwaves (Kimball et al., 2008). Few studies report system performance variables (e.g. heat ramping rates) other than deviation from target temperatures or maximum temperatures reached. As an exception, Frei et al. (2020) report effective and relatively homogenous ~2–3°C warming during day and night in very large (5 m wide, 2 m high) open-top chambers supplemented by either an electric heater or warming cables, with

~13% decrease in relative humidity. Wang et al. (2008) report reaching 40.5 ± 2.8°C (~10°C higher than average ambient, target 41°C) with a 1500 W electric heater in 1 m^3 top-vented plastic chambers, which seem to be a comparable size and style to ours, but little other information is provided. De Boeck et al. (2010) reported average maximum temperatures during their experimental heatwaves via infrared heaters deviated −0.5°C, +3.2°C and +0.5°C from target temperatures in spring, summer, and autumn, respectively. Ettinger et al. (2019) reviewed 15 active warming experiments and found that most were open-top, using infrared heaters, soil warming cables or forced air warming types. They found that few warming experiments achieved above-ground warming above +4°C and that systems that used feedback to control the extent of warming (like our actuator bypass valve) could minimise thermal variability. The effectiveness of warming type and recommendations for future field ecology manipulation studies in general are discussed extensively in Ettinger et al. (2019), so hereafter we largely discuss the performance of our specific heating system.

The semi-enclosed heating chamber reduces the energy required for active heating, allows for gas exchange while minimising heat loss, and reduces incident precipitation that would be unwanted during an experimental heatwave. The chamber lid portholes provide practical access for measurement tools and plant sampling without significant heat loss. Being semi-enclosed, the chamber also has a relatively strong passive warming effect during the day (more than most open-top chambers; Hollister et al., 2023; Vázquez-Ramírez & Venn, 2024; Welshofer et al., 2018), which improves thermostability and efficiency of the active heating.

The two case studies showcase optimal operating conditions for the equipment. Maintaining air temperature at set target temperatures is challenging during intermittent clouds because rapidly changing solar conditions result in peaks and troughs in air temperature due to temporal lags between heater adjustments and solar conditions. Optimal operation is achieved when external environmental conditions are stable (e.g. full sun, full cloud or at night), wind and precipitation are absent, and ambient air temperature is not cold. At Hotham, ambient air temperature needed to be above 16°C, ideally 20°C, to maintain target temperature. Here, measured leaf temperatures suggest that the plant communities were heated relatively evenly, most reaching nearly 30°C (at a 32°C air temperature target), even for plants of different heights and positions within the actively heated plots (Text S3). Relative humidity was unsurprisingly lower in the actively heated plots due to the influx of heated dry air. Yet, relative humidity was still maintained at relatively high levels in both case studies during the day but was generally lower at night. Water released by evapotranspiration during heating was retained or recondensed in the chambers when vents were fully closed, while humidity decreased when the heaters were operating, but not to the point where chamber air would be considered especially dry. Rising vapour pressure deficit is an important component of climate change and extreme heat events due to the interdependence of vapour pressure deficit from temperature (Grossiord et al., 2020). Vapour pressure deficit levels reached, in our case studies, were within expected realistic values during a heatwave in other mountainous ecosystems (De Boeck et al., 2016).

At Perisher, when conditions were mostly clear, wind and precipitation were absent, the heaters could achieve their target temperature even when the ambient air temperature was around 5°C. Heaters were covered by tarpaulins for protection from harsh weather at Hotham, but they operated far better when well-ventilated, which was achieved using open tents at Perisher. The performance of the heating chambers in Perisher exceeded our expectations from Hotham. This was likely due to five factors that improved operating efficiency: (1) favourable weather conditions; (2) well-ventilated heaters; (3) reducing chamber height to reduce internal air volume by ~20%; (4) shorter distances between heaters and chambers; and (5) improved ducting insulation to minimise heat loss of air in transit to the chamber.

We tested the capacity of the active heating chambers to apply different heat treatments. Perisher used a factorial day and night warming experiment using a ramped temperature profile to simulate more natural transition temperatures. This active heating design is an excellent option for stable temperature manipulation for experiments that include night-time warming, which is an underappreciated component of global change that is likely to have substantial impact on the capacity for plants to repair accumulated damage during a heatwave (Davy et al., 2017; Kundu et al., 2024; Posch, Zhai, et al., 2022). The degree of night-time warming can be readily controlled and combined with different daytime conditions.

Effective ‘controls’ in field ecology experiments are challenging (Ettinger et al., 2019; Hurlbert, 1984). Here, the unheated control plots were subject to natural weather variability and no chambers, serving as an undisturbed, natural vegetation patch against which to compare the active heating effects. It could be argued that one should control for the other effects of the physical chamber (i.e. reducing air flow and incident precipitation); however, these effects are clearly coupled with a large passive warming effect, especially during clear conditions and thus are also receiving a treatment. For manipulative ecological field studies, defining the question and comparison being made is essential for ‘controls’ to be meaningful, since infrastructure can have indirect effects on ecological responses that may be experimental artefacts either muting or exaggerating a temperature effect (Ettinger et al., 2019). For future applications of in situ heat experiments, replication of treatment(s) and control plots (e.g. with a randomised block design) will be necessary for adequate power to detect effects, where five replicate blocks would be a recommended minimum.

There are many other potential combinations of study treatments for which this equipment could be effective. For example, climate change is generating ‘press-pulse’ scenarios where organisms are exposed to background levels of warming (press) followed by extreme events like heatwaves (pulse) (Harris et al., 2018). Studying both factors concurrently has relied on controlled environments;

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however, chamber performance here suggests that it could be done in situ. A chamber could be deployed with the lid off (like an open-top chamber) for simulating longer-term passive warming, and an acute pulse could be added by closing the lid and attaching active heating operations for the desired pulse duration to the same community. However, long-term applications with these chambers will need to consider how they will manage water (natural precipitation or supplementary watering), with appropriate controls for the specific ecosystem type and scientific questions.

We see these chambers primarily being used by researchers interested in studying the effects of key factors of worsening future extreme events. Researchers could use these actively heated chambers in situ to study: (1) duration, by altering the number of actively heated days; (2) intensity, by altering the set target temperature profile and upper limit; (3) frequency, by repeating acute events; and (4) recovery, including by manipulating interim conditions between acute events. The active heating chamber system is flexible for many practical applications through programmable set target temperatures, switching between passive and active heating, and manual adjustments can be made via the portholes in the semi-enclosed top, or the top could be removed to effectively be an open-top chamber.

5 | CONCLUSIONS

The active heating chamber system works exceptionally well under stable conditions for warming both day and night. It is capable of acutely heating terrestrial communities in situ by >10°C above ambient air temperature, with few drawbacks compared to open-top chambers and other active heating approaches. Extreme climatic events like heatwaves have major impacts on species and ecological communities (Breshears et al., 2021) and are strong selective agents for evolution (Kingsolver & Buckley, 2017), but are challenging to study in nature. It is imperative that researchers can effectively study biological responses to heatwaves in nature as climate change progresses. Achieving this goal requires the application of practical tools like these active heating chambers that can simulate realistic heat scenarios in the field. We hope that researchers will be inspired to make use of this active heating design to study the impacts of heatwave and night-time warming on diverse terrestrial ecosystems: plants, invertebrates, microbes and communities alike.

AUTHOR CONTRIBUTIONS

Adrienne B. Nicotra, Susanna E. Venn, Angela T. Moles, Andrea Leigh, and Zachary A. Brown conceived the ideas and designed methodology; Freya M. Brown and Zachary A. Brown developed the equipment and led the fieldwork campaign at Mt. Hotham; Lisa M. Danzey and James L. King led the fieldwork at Perisher Valley; Sabina M. Aitken, Xuemeng Mu, Lisa M. Danzey, James L. King, Thomas C. Hanley, Adrienne B. Nicotra, Inna Osmolovsky, Emma E. Sumner, Susanna E. Venn, Virginia G. Williamson, and Zoe A. Xirocostas collected the data; Pieter A. Arnold and Freya M. Brown analysed the data; Pieter A. Arnold led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

None of the authors have a conflict of interest to declare.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

Data and R code to reproduce the figures and analyses of heat chamber performance in both case studies are available from the figshare repository via https://doi.org/10.6084/m9.figshare.27998534 (Arnold et al., 2025).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1. Case study 1 Mt. Hotham VIC weather station data.

Table S2. Case study 2 Perisher Valley NSW weather station data.

Table S3. Case study 1 Mt. Hotham VIC summary from hourly LMER analysis of subset.

Table S4. Case study 1 Mt. Hotham VIC summary from daily LMER analysis of subset.

Table S5. Case study 1 Mt. Hotham VIC summary from hourly LMER analysis of all days.

Table S6. Case study 1 Mt. Hotham VIC summary from daily LMER analysis of all days.

Table S7. Case study 2 Perisher Valley NSW summary from LMER analysis of all days.

Table S8. Case study 2 Perisher Valley NSW summary from LMER analysis of all days.

Figure S1. Diagrams of heater layouts for both case studies.

Figure S2. Case study 1 Mt. Hotham VIC environmental parameter-time profiles.

Figure S3. Case study 1 Mt. Hotham VIC temperature profiles for all days.

Figure S4. Case study 1 Mt. Hotham VIC air temperature relative to target-time profiles.

Figure S5. Case study 1 Mt. Hotham VIC leaf temperature assessments.

Figure S6. Case study 2 Perisher Valley NSW air temperature–time profiles.

Figure S7. Case study 2 Perisher Valley NSW Relative humidity-time profiles.

Figure S8. Case study 2 Perisher Valley NSW vapour pressure deficit-time profiles.

Figure S9. Case study 2 Perisher Valley NSW air temperature relative to target-time profiles.

Text S1. Active heating system technical details, costs, risk management, and setup guide.

Text S2. Additional methodological details for the Case Studies.

Text S3. Leaf temperature and vapour pressure deficit discussion.

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