LIMNOLOGY
and
OCEANOGRAPHY: METHODS

Limnol. Oceanogr.: Methods 2024

doi: 10.1002/lom3.10663

Bringing heatwaves into the lab: A low-cost, open-source, and automated system to simulate realistic warming events in an experimental setting

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Abstract

Aquatic ecosystems face increasing threats from heatwaves driven by anthropogenic climate change, necessitating continued research to understand and manage the ecological consequences. Experimental studies are essential for understanding the impacts of heatwaves in aquatic systems; however, traditional experimental methods often fail to capture real-world complexity. Here, we present a method for simulating aquatic heatwaves that match the dynamic nature of real-world heatwave events in an experimental setting. Our method allows researchers to re-create heatwaves that have happened in the past or produce entirely new heatwave scenarios based on future projections. A Raspberry Pi serves as the foundation of our autonomous, customizable temperature control system, leveraging a low-cost and open-source platform for adaptability and accessibility. We demonstrate system functionality for laboratory experiments by first simulating a hypothetical marine heatwave scenario with defined temperature parameters and then replicating a real-world marine heatwave that occurred in the Santa Barbara Channel, California, in 2015. The average difference between desired and observed temperatures was 0.023°C for the basic heatwave simulation and less than 0.001°C for the real-world heatwave simulation, with standard deviations of 0.04°C and 0.01°C, respectively. Our novel method facilitates broader access to high-quality and affordable tools to study extreme climate events. By adopting a more realistic experimental approach, scientists can conduct more informative aquatic heatwaves studies.

Anthropogenic climate change has driven increased warming in aquatic ecosystems worldwide (IPCC 2023), and thus, there is a growing need for research to better understand and predict ecosystem responses to both marine and freshwater heatwaves. Experimental approaches typically require a temperature control system to simulate warming events, an experimental design which can be cost-prohibitive for research institutions and groups with limited budgets. In this paper, we introduce a novel, low-cost, automated, and open-source method to generate aquatic heatwaves that match the dynamic nature of real-world heatwave events using a Raspberry Pi, a single-board computer, as a temperature controller.

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As an example of our method's applicability to aquatic ecosystem warming events, we focus on simulating the dynamics of marine heatwaves. Marine heatwaves have generated growing interest among scientists and the general public as warming events increase in frequency, intensity, and duration due to anthropogenic climate change (Oliver et al. 2018). Anomalously warm water events often have devastating impacts on marine ecosystems (Babcock et al. 2019; Smale et al. 2019; Smith et al. 2024) that may persist long after the heatwave subsides (Suryan et al. 2021). Crucially, these impacts extend to influence human society by disrupting socioeconomic systems (Smith et al. 2021). When marine heatwaves occur, they exhibit temporal and spatial complexity that can have important ramifications for ecosystem response and recovery (e.g., Wernberg et al. 2013; Cavanaugh et al. 2019; Fordyce et al. 2019). Marine heatwaves can exhibit variability in their duration, intensity, and frequency not only at an annual scale (Fig. 1A) but also on a weekly and daily scale (Fig. 1B). In addition, marine heatwaves have shown vertical dynamics (Zhang et al. 2023) that extend to the benthos (Amaya et al. 2023; Wyatt et al. 2023), expanding the impact of these anomalous warming events on marine ecosystems. California's kelp forest ecosystems, for instance, have

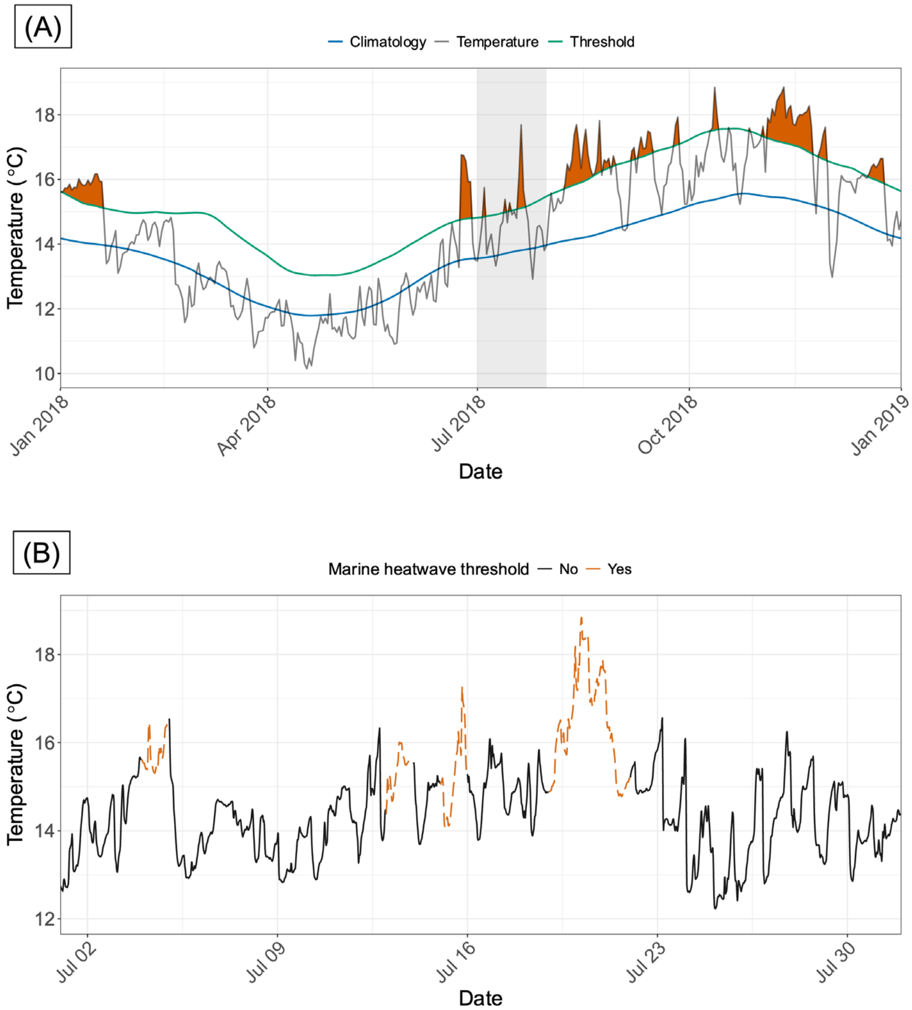

Fig. 1. Average daily temperatures measured at Naples Reef, CA, for January–December 2018 (**A**) and July 2018 (**B**). For (**A**), the black line indicates the average daily temperature, the blue line indicates the climatology based on historical data since 2001, the green line indicates the 90th percentile threshold, and shaded red areas represent marine heatwave events. For (**B**), a higher-resolution view of daily thermal conditions in July 2018 is provided: the dotted red line represents any temperatures measured above the 90th percentile threshold and therefore considered marine heatwave events. All data were collected by the Santa Barbara Coastal Long Term Ecological Research program.

responded to heatwave events with altered community structure (Rogers-Bennett and Catton 2019; McPherson et al. 2021; Michaud et al. 2022) and species range expansions (Sanford et al. 2019).

Experimental studies are a critical component of research programs aimed at broadening our understanding of the ecological impacts of marine heatwaves. While existing heatwave experiments have provided valuable insights into biological responses to elevated temperatures, traditional experimental methods often do not accurately reflect the complexity of natural conditions, including heatwave dynamics (Bass et al. 2021). Conventional approaches to warming experiments in controlled laboratory settings (e.g., He et al. 2021; Minuti et al. 2021) often exclude environmental factors such as seasonal fluctuations and diel temperature cycles which can significantly influence organismal responses both in situ (Correia-Martins et al. 2022) and in experimental settings (Jöhnk et al. 2008; Pansch et al. 2018; Atkinson et al. 2020). However, creating more realistic warming events in experimental, laboratory settings can present challenges due to the need for precise and dynamic temperature control. Lower cost, and therefore more commonly used, temperature controllers typically require more constant monitoring to perform frequent adjustments, thereby limiting long-term studies. For researchers who seek to infuse dynamic and realistic temperature fluctuations found in nature in a controlled laboratory environment, precise and dynamic temperature control often comes at a significant financial cost (e.g., Nouguier et al. 2007; Wahl et al. 2015). Moreover, these expensive systems typically utilize commercial temperature control systems that are cumbersome and offer limited customization options, hindering researchers' ability to tailor experimental conditions to address complex questions.

For our novel heatwave simulation system, we use the Raspberry Pi as a compact, cost-effective, and adaptable solution for heatwave studies thanks to its widespread popularity in the open-source community (https://forums.raspberrypi.com/). This popularity translates to an extensive online support community, making the design both user-friendly and widely accessible. Unlike commercially available systems, the Raspberry Pi is a small, inexpensive, and versatile tool that can allow researchers to generate experimental conditions that mimic the natural fluctuations of real-world aquatic heatwaves. Moreover, the Raspberry Pi supports reproducible and automated temperature control, which facilitates the generation of reliable, translatable data. By leveraging the Raspberry Pi's affordability in our design, we seek to make research more equitable by broadening access to more advanced temperature control systems. This not only empowers researchers with limited budgets, but also facilitates hands-on student learning experiences through a user-friendly, community-driven technology.

For our research, we successfully applied our novel method during a long-term marine heatwave experiment that re-created the conditions experienced by benthic marine organisms in the Santa Barbara Channel during a historic, record-breaking heatwave. In addition to reproducing heatwaves that have occurred in the past, our method can also be used by researchers to produce entirely new heatwave scenarios based on future projections. By adopting this new experimental approach, scientists can design heatwave studies that better reflect conditions in a changing ocean.

Materials and procedures

Materials

Our automated temperature control system was built using commercially available components, with a Raspberry Pi single-board computer (Raspberry Pi [Trading] Ltd 2024) at the foundation of our system (Table 1). Our temperature control system uses a 4-GB Raspberry Pi 4 Model B equipped with a 32-GB microSD card. For the purpose of testing our system, five DS18B20 temperature probes were connected to the Raspberry Pi via a perma-proto Hardware Attached on Top (HAT). We included a 4.7-kΩ pull-up resistor to ensure stable, reliable communication between the probes and the Raspberry Pi. Extension cords were used to interface heaters and pumps with the Raspberry Pi via a relay HAT, which allowed for easy, flexible reconfiguration of the system and facilitated the replacement of faulty cords without affecting the core, and more expensive, components. Our Raspberry Pi ran the Raspbian operating system (version 11.8 "bullseye"), and our heatwave simulation program was written in Python using the built-in Thonny Python IDE for software interfacing.

Table 1. Current costs for marine heatwave simulator system components.

Item	Supplier	Cost (US$)
Raspberry Pi 4 (4-GB)	Digikey	55.00
32-GB microSD card*	Digikey	7.21
Relay board HAT	Amazon	18.99
Perma-proto HAT	Digikey	4.95
DS18B20 temperature probe†	Digikey	11.25
⅛ W 4.7 kΩ resistor‡	Digikey	0.10
Extension cord‖	Digikey	6.50
Total cost§		104

*An 8-GB minimum SD card capacity required for Raspian OS.
†Purchase quantity depends on numbers of tanks.
‡Recommend ¼ W 2.2–3.3 kΩ pull-up resistors with the addition of >5 temperature probes.
‖Purchase quantity depends on number of heaters and chillers.
§Component costs were verified for accuracy at the time of manuscript submission.

To test our design, we set up three, 75-liter aquariums: one sump tank with chilled seawater, one sump tank with heated seawater, and one tank representing the experimental tank where chilled and heated seawater were mixed to achieve the desired temperature (Fig. 2). For our chilled sump tank, we used two, ⅓ HP TradeWind inline chillers paired with a 5072-L h^{-1} Resun King submersible pump. For our heated sump tank, we used one, 600-W Bulk Reef Supply titanium heater paired with one, 300-L h^{-1} Eheim submersible pump. Water from each of the sump tanks was pumped into the experimental tank by 2650-L h^{-1} Danner submersible pumps, pumping water at a rate of approximately 0.75 L min^{-1}. Water in the experimental tank was mixed using one, AquaIllumination Nero 5 wavemaker pump. All sump tanks were fed through a flow-through seawater system.

Procedures

Probe calibration

We calibrated the DS18B20 temperature probes using an ice bath (0°C) for the low reference temperature and a heated water bath (49°C) for the high reference temperature. We allowed the probes to equilibrate for at least 1 min before averaging the readings to collect calibration parameters. We verified the temperatures of each water bath using an Omega Engineering RTD Thermometer.

Temperature profile creation

Our system grants users the flexibility to create a custom temperature profile based on real-world data or user-defined parameters. Here, we demonstrate both approaches: first, simulating a hypothetical heatwave scenario with defined minimum and maximum temperatures and ramp rates, and second, replicating a real-world heatwave. For our temperature profile simulating a hypothetical heatwave scenario, we emulated traditional marine heatwave experiments and generated

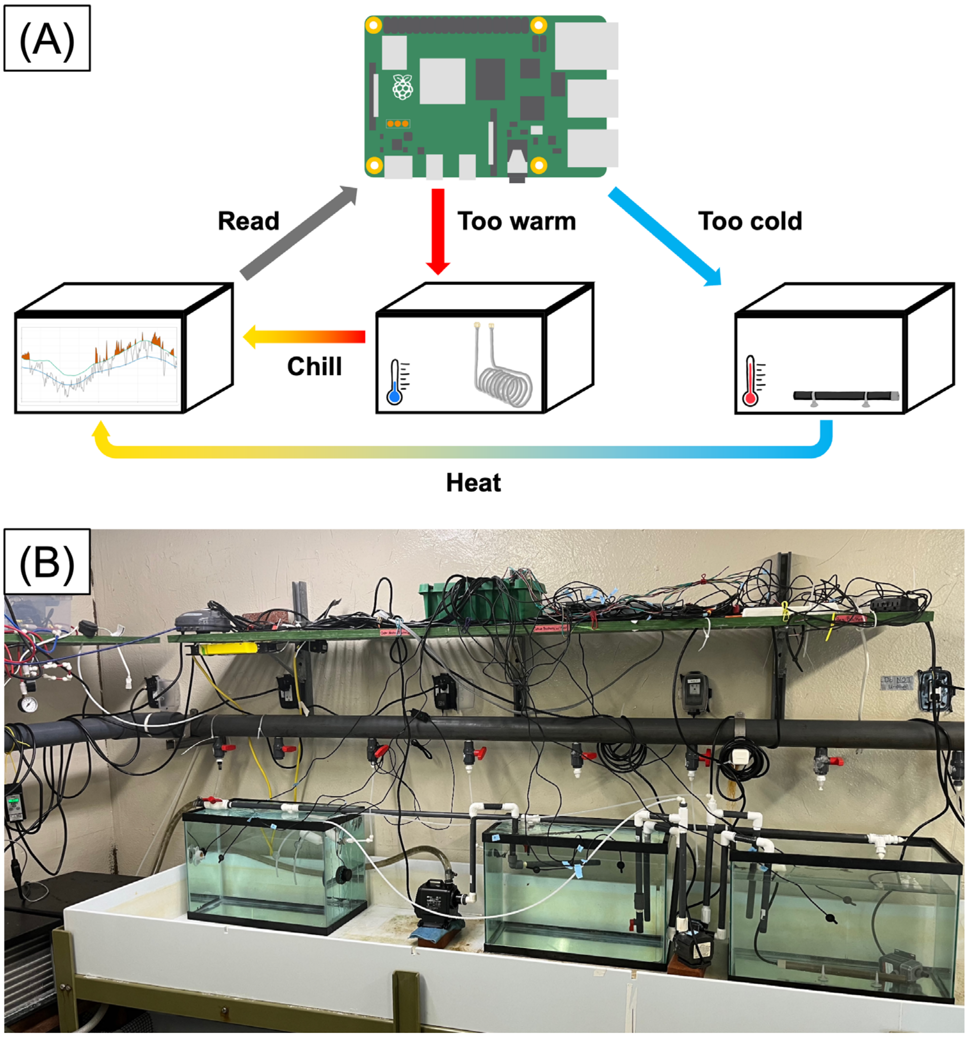

Fig. 2. Simplified schematic (**A**) and photo (**B**) of heatwave simulator system setup in the laboratory. For (**A**), the Raspberry Pi controls the system and is connected to a tank containing heated water, a tank containing chilled water, and an experimental tank where a heatwave is simulated. Water from the heated and chilled sump tanks is pumped into the experimental tank. When the program is run, the Raspberry Pi reads the temperature in the experimental tank, compares the reading to the temperature profile, and then powers on the heater or the chiller as needed to maintain the desired temperature. For (**B**) from left to right, points of interest include the chillers, the experimental tank, the chilled water sump tank, and the heated water sump tank. The Raspberry Pi assembly is on the top shelf contained within the green box.

a heatwave with a single temperature maximum of 20°C, a temperature minimum of 18°C, and a ramp rate of 2°C d^{-1}. For our temperature profile recreating a real-world heatwave, we used temperatures collected every 20 min by the Santa Barbara Coastal Long Term Ecological Research buoy at Naples Reef between March 13 and March 16, 2015 (Washburn et al. 2023). Both temperature profiles were generated in R version 4.1.1 with the lubridate package (Grolemund and Wickham 2011) which facilitated time-series data generation.

Proportional–integral–derivative controller adjustments

Although not strictly necessary for system functionality, we incorporated a proportional–integral–derivative (PID) controller in our system to improve system performance. The use of a PID algorithm greatly enhances temperature control by reducing fluctuations around the temperature set point, and is commonplace in industrial applications (Borase et al. 2021). We used a standard, iterative, empirical approach to tune the PID control parameters (Ziegler and Nichols 1942): each parameter (k_p, k_i, k_d) was individually tuned by setting a value, testing the system response, and then adjusting the value until our system achieved a desirable temperature stability. Ultimately, the decision to incorporate a PID loop depends on the researcher's needs and expertise. While PID controllers offer superior control when properly tuned, the tuning process can be time-consuming and requires an understanding of the system dynamics.

Software implementation

Our program uses both existing Python libraries (e.g., pandas, datetime) and custom libraries. When the program is initialized, the Raspberry Pi loads the temperature profile and initializes communication with the temperature probes. The main code runs in a continuous loop (Fig. 2A), the frequency of which is dictated by both a user-established value as well as the number of temperature probes connected to the Raspberry Pi. First, the current date and time on the Raspberry Pi is retrieved and cross-referenced with the closest corresponding temperature value from the temperature profile. Next, the Raspberry Pi reads the temperatures from every temperature probe in triplicate, averages the values for each probe, and then calculates the average temperature for each tank (for setups with multiple probes in a single tank for redundancy). The Raspberry Pi then utilizes a PID control algorithm to determine whether or not the tank needs to be heated, chilled, or left alone based on the difference between the temperature set point and the average tank temperature. Based on the PID output and the average tank temperature, the Raspberry Pi then turns on or off the pumps connected to either the heater or the chiller sump tanks. Finally, the Raspberry Pi saves the date and time, the temperature set point, and the average temperature reading for each probe in a .csv file before going to sleep for a preprogrammed interval (1 s for our implemented design).

The specific equipment configuration of our system necessitated the implementation of distinct temperature control strategies for each of the sump tanks. The heater used in the hot sump tank was directly controlled directly by the Raspberry Pi. Activation of the heater was based on a predefined temperature threshold relative to the experimental temperature set point. For example, for our experiment simulating a hypothetical marine heatwave scenario, the heater would turn on when the average temperature in the sump tank was less than approximately 0.5°C higher than the temperature set point. This method ensured the hot sump tank temperature remained responsive to the temperature profile throughout the experiment. In contrast, the chillers used for our system had external temperature controllers. Because they lacked the capability to dynamically respond to the temperature profile throughout the experiment, we opted to set the chillers to a fixed minimum temperature of 1°C below the minimum temperature in the temperature profile.

Optional features

The open-source nature of the Raspberry Pi platform facilitates extensive user customization. We leveraged this in our system by implementing an alarm on our Raspberry Pi, enabling it to send text message notifications upon encountering program errors. This feature may be particularly valuable for researchers working with vertebrate species who may require timely notifications about technical issues and operational failures to ensure compliance with Institutional Animal Care and Use Committee regulations.

Second, we initially interfaced with the Raspberry Pi via a 17.8-cm touch screen monitor and wireless keyboard. We ultimately established a remote connection with the Raspberry Pi using RealVNC Viewer, which allowed us to remotely access the Raspberry Pi and periodically check on system performance and make adjustments without the need to be physically present in the laboratory.

The ubiquity of the Raspberry Pi as a computing platform used across scientific disciplines (Jolles 2021) and in non-scientific applications (Monk 2022) means that there are many additional opportunities for users to customize and expand the system in a way that meets their experimental goals. For example, it is possible to integrate other sensors for measuring water quality parameters such as salinity and dissolved oxygen, or to develop a web interface or mobile application for remotely interacting with the system and plotting data in real time.

All documentation and instructions for building our heatwave simulator system are available on GitHub under the Apache 2.0 license: https://github.com/ameliaritger/MHWsim/ (Ritger 2024).

Assessment

System assembly and cost

Excluding standard experimental equipment like heaters, chillers, pumps, and tanks, the core components of our marine heatwave simulator can be purchased for just over US $100 (Table 1). The addition of more tanks to increase the number of replicates, add more treatments, or address issues such as pseudoreplication increases the system cost through the addition of (1) more thermistors and (2) a relay board HAT that can support more connections, should the system require additional capacity for these added components. The low cost of our system offers researchers a high-quality alternative to commercially available temperature control systems. While simpler controllers may be less expensive, they lack the fine-tuned temperature control necessary for simulating complex heatwave dynamics. Conversely, high-end controller systems offer precise control but at a significantly higher price point. Therefore, our system offers a middle ground, balancing affordability with the critical ability to achieve precise temperature adjustments.

While the lower cost of our Raspberry Pi-based system is a significant advantage, it is essential to acknowledge the associated time investment required by researchers. Excluding time spent on research and development, we estimate researchers interested in implementing our system will need at least 2 weeks to build and fine-tune their own heatwave simulation system.

After purchasing all the necessary materials (Table 1), the hardware can be assembled in approximately 3–4 h. The number of temperature probes and soldering skills of the researcher will impact this time estimate. Setting up the Raspberry Pi is a similar process to setting up any other computer, and fortunately, there is ample online documentation created by the

Raspberry Pi Foundation which guides users through the process. We estimate researchers should be able to set up their Raspberry Pi within a few hours, although the setup time will vary depending on the number of optional features researchers add to their system.

The system's customizability, while advantageous, necessitates an initial time investment by researchers to adapt the program for each unique heatwave experiment. Researchers will need to familiarize themselves with the code, import their temperature profile(s) to the Raspberry Pi, calibrate their temperature probes, and adjust parameters as needed. We estimate this may take the researcher anywhere between 2 and 4 d. Depending on the researcher's familiarity with Python, adjusting the code to suit their application may greatly impact this estimation. Fine-tuning the system, especially if the researcher includes the PID controller, will undeniably take the most time. Researchers must plan ahead to test how well their system works for their experiment, make adjustments as needed, and re-test until they are satisfied with system performance. We advise researchers to plan at least 1 week for system adjustments.

System performance

To test the performance of our system, we simulated two heatwave scenarios: the first, a conventional heatwave scenario with predefined minimum and maximum temperatures and ramp rates (Fig. 3A), and the second, a real-world heatwave simulation using data from a historical marine heatwave recorded in the Santa Barbara Channel (Fig. 3B). Our system configuration used five temperature probes—three probes in the experimental tank and one probe in each sump tank (Fig. 2B). Temperature control for the experimental tank was dictated by the Raspberry Pi powering on or off the pumps from the sump tanks. For these heatwave simulations, the Raspberry Pi read the temperatures from all five probes in triplicate in less than 15 s; therefore, the program looped continuously every 15 s.

For our conventional heatwave simulation (Fig. 3A), the average difference between temperature set points and observed temperatures was 0.023°C (SD = 0.040°C), with a range of 0.189°C. The difference between the set points and the observed temperatures was greatest halfway through the experiment (0.169°C), when the temperature set point reached its maximum (20°C) and the system took 38 min to reach a temperature 0.1°C away from the set point. For our simulation recreating a real-world heatwave (Fig. 3B), the average temperature difference between set points and observed temperatures was < −0.001°C (SD = 0.010°C), with a range of 0.183°C.

The limited electrical capacity of our facility, as discussed in more detail in the Comments and recommendations section, was the primary constraint of our experimental setup. With access to higher-wattage heaters and chillers, we anticipate that the temperature deviation between set points and observed values, in addition to the lag times, would have been significantly reduced.

All system testing was conducted using a flow-through seawater system; however, a flow-through system is not required for system functionality. Should researchers opt to use a closed-loop system, we anticipate improved system performance due to reduced temperature fluctuations, as the system will no longer be subjected to the constant variability of incoming water. On the other hand, should researchers have access to a flow-through system, they may take advantage of the natural temperature fluctuations by programming the Raspberry Pi to generate a dynamic, real-time heatwave. For example, by monitoring the incoming water temperature, the system could adjust to maintain a fixed temperature increase above ambient water, thus responding to changes in real time.

To assess the performance of the DS18B20 probes, we placed an Onset HOBO TidbiT temperature logger in the experimental tank for approximately 24 h at the end of the conventional heatwave simulation (Supporting Information Fig. S1). The average difference in temperature readings between the DS18B20 and HOBO TidbiT during this time period was −0.009°C (SD = 0.009°C). These achieved temperature resolutions fall well within the capabilities of the DS18B20 probes, which have a resolution of 0.0625°C (Maxim Integrated Products 2019).

System application: A long-term marine heatwave experiment

To illustrate a real-world application of our temperature control system, we tested the system in a 5-month marine heatwave experiment. For this experiment, we placed animals under experimental conditions that re-created the largest marine heatwave on global record, The Blob, using historical temperature data collected by the Santa Barbara Coastal Long Term Ecological Research program (Washburn et al. 2023). The Raspberry Pi read 18 temperature probes once every minute to monitor and control the temperature of three simultaneous treatments: ambient conditions, historical heatwave conditions (The Blob), and more severe heatwave conditions (+3°C hotter than The Blob). The temperature was successfully ramped up from ambient laboratory conditions to the simulated marine heatwave temperature at a rate that matched the onset rate (0.51°C) and decline rate (0.96°C) of the historical heatwave. In our experience, the Raspberry Pi system was able to successfully track the predefined temperature profiles of each treatment for the duration of this long-term experiment (A. L. Ritger unpubl.).

Discussion

Here, we present a low-cost and compact system capable of accurately simulating aquatic heatwave events. We have developed a novel application of a Raspberry Pi to create a fully automated and customizable temperature control system for aquatic

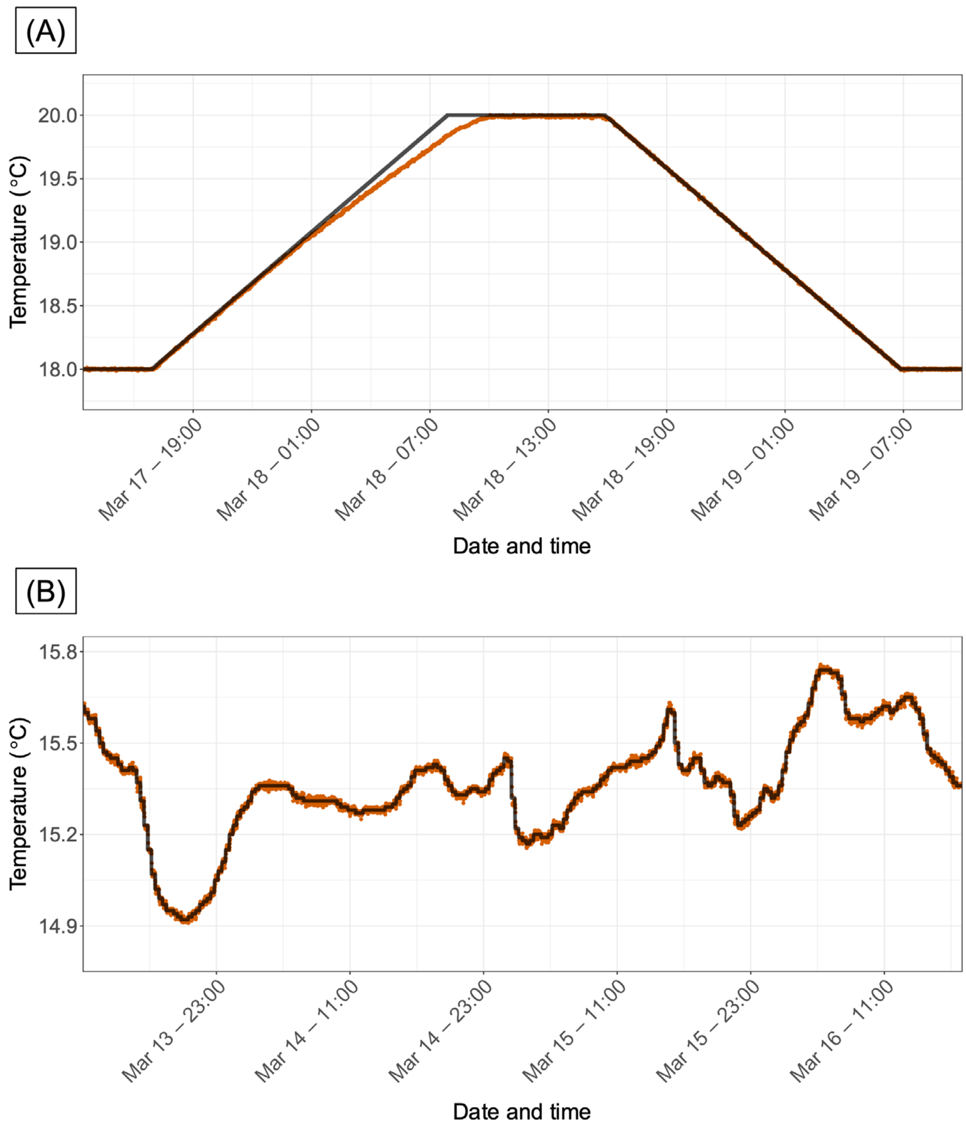

Fig. 3. Performance of the marine heatwave simulator system for a simplified marine heatwave (**A**) and a real-world marine heatwave (**B**). The black line indicates the preestablished temperature profile and the red line indicates the average temperature reading of three replicate temperature probes in the experimental tank. Data for (**A**) were generated to represent conventional, simplified marine heatwaves with a single temperature maximum value (20°C) and a ramp rate of 2°C d^{-1}. Data for (**B**) were generated using real temperature readings collected by the Santa Barbara Coastal Long Term Ecological Research buoy at Naples Reef from March 13–16, 2015.

heatwave studies that can be purchased and built for just over US$100. For those willing to dedicate the time, our system offers a high degree of customization, enabling the development of highly tailored heatwave simulations. Our system allows researchers the ability to capture daily temperature fluctuations and follow predefined heatwave profiles, enabling the creation of highly realistic experimental scenarios.

The open-source nature of the Raspberry Pi platform fosters easy access, broad user support, and reproducible research practices through Python-based code. Additionally, the system's modular, do-it-yourself (DIY) design allows for customization and self-servicing, which further reduces costs and enhances time efficiency by eliminating the need for external technicians for system maintenance and repairs. Moreover, the system's scalability accommodates experiments with various tank sizes. For scaling down to smaller organisms and water volumes, researchers only need to adjust the code to adapt the controller to the potential for more rapid temperature fluctuations. For scaling up to larger organisms and water volumes, researchers must also ensure their equipment is compatible with the power limitations of their experimental space (*see* the Comments and recommendations section).

Thanks to the open-source nature of our design, researchers are free to continue developing, improving, and adapting the system. By minimizing costs and fostering collaborative development with an open-source design, our method democratizes access to complex aquatic heatwave simulation studies and empowers continuous innovation to propel research forward.

Comments and recommendations

Our aquatic heatwave simulation system offers researchers significant flexibility and the ability to incorporate more realism into experiments. However, it is important to consider the technical limitations, time investment, and required skill set before deciding if our system is the most suitable method for a particular application.

Technical considerations

First, a critical consideration for heatwave experiments is the inherent power limitations of the electrical circuits within the chosen experimental space. All electrical circuits have a maximum load capacity which dictates the total wattage of equipment that can be safely plugged into the circuit. For example, in our application, our building's electrical grid imposed a 1600-W restriction, limiting us to no more than two, 600-W heaters per circuit. This power limitation is particularly apparent for flow-through systems where the heaters and chillers must be powerful enough to counteract the incoming water temperature to maintain the desired temperatures.

Consequently, lower wattage equipment directly translates to a reduced ability of the system to more effectively follow the predetermined temperature profile. This limitation was apparent in our own experiments, as the heater was not able to follow the temperature set point as closely at higher temperatures during the conventional marine heatwave simulation (Fig. 3A). It is noteworthy, however, that while power limitations are a critical consideration, they are not unique to our system—the Raspberry Pi itself has a negligible contribution to the overall power consumption, drawing less than 15 W (Raspberry Pi [Trading] Ltd 2024). Researchers will need to take power limitations into account for their own experiments, especially in flow-through systems where ambient temperatures may strongly influence the maximum and minimum temperatures able to be achieved by the system.

One other technical consideration is the system limitation of the Raspberry Pi and its peripherals. In our current configuration, the relay HAT has three attachment points for relays; therefore, the Raspberry Pi is able to control power to three devices (or sets of devices, as long as their combined current falls within the 10 A current rating of the HAT). For researchers seeking to implement our system as it is currently designed, they will need to decide which equipment they would like to control. For the short-term heatwave simulations described in this manuscript, the Raspberry Pi controlled the pumps to the two sump tanks, in addition to the heater in the hot sump tank. For our longer, 5-month experiment (A. L. Ritger unpubl.) with multiple, simultaneous temperature profiles, the Raspberry Pi controlled heaters in three separate sump tanks. There are options for added system capability, however, as there are alternative relay HATs available on the market with additional slots to integrate more devices.

Additionally, the number of temperature probes needed for individual applications will influence the implementation of our aquatic heatwave simulation system. First, adding temperature probes to the system increases the likelihood of occasional data loss. Because the DS18B20 probes use the 1-Wire protocol (Maxim Integrated Products 2019), whereby the probes use a single line for both data and clock signals, they are susceptible to occasional data packet loss in large sensor networks (Analog Devices 2001). To mitigate the impact of data loss events, our custom software program incorporates error-handling mechanisms designed to safeguard against program crashes due to packet loss. In the event of such an error, the Raspberry Pi automatically resets the program after 1 min. Notably, during our long-term (5-month) experiment with the Raspberry Pi continuously logging data from 18 probes in triplicate every minute, temporary probe read failures only occurred approximately once per week.

Time considerations

Time is undoubtedly the greatest tradeoff with our system over commercially available temperature controller systems, as our heatwave simulator system requires a time investment for assembly, code adjustment, and troubleshooting. First, constructing the system requires an initial time investment to purchase the components and prepare them for use with the Raspberry Pi. For example, the extension cord will need to be stripped and added to the relay HAT, and the temperature probes will need to be soldered onto the perma-proto HAT. Second, researchers will need to spend time modifying the code to fit their unique experimental design. This includes the number of temperature profiles (for experiments running multiple, simultaneous heatwaves), the number of temperature probes (depending on the number of experimental replicates), and parameters such as the frequency and quantity of temperature readings. If researchers opt for implementing a PID controller to achieve finer temperature control, then a not insignificant amount of time will be required to tune the parameters and validate system performance through trial and error. Overall, for code adjustments including PID implementation, the level of desired customization will determine the time investment required. Finally, as with all experiments, researchers will need to allocate time to troubleshoot any issues that arise–be it adjusting pump flow rates, blowing a fuse from overloading an electrical circuit, or identifying optimal heater and chiller temperature set points based on system specifications.

Skill-based considerations

While implementation of our aquatic heatwave simulation system requires some technical skills, these can be readily acquired by researchers with a willingness to learn. First, building the system involves basic soldering and access to common electronics equipment like a soldering iron. Soldering demonstrations are well documented online and skills can be learned through readily available tutorials. Moreover, many universities have electronics labs that provide researchers access to the needed tools (or the tools can be purchased with a modest budget). In addition, researchers will need basic proficiency in Python to perform code adjustments and debugging. Fortunately, the Raspberry Pi's open-source nature and the vast Python developer community offers a wealth of online resources. Moreover, the emergence of AI programs like GitHub CoPilot may offer guidance for researchers who are less confident in their Python coding skills.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available on Zenodo at http://doi.org/10.5281/zenodo.14194509 and on GitHub at https://github.com/ameliaritger/MHWsim/.

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Acknowledgments

We express our sincere gratitude to A. Baish for their invaluable support with system design, software debugging, and designing a custom three-dimensional-printed case for the Raspberry Pi. We thank J. Rohde for their assistance with software debugging. E. de Leon Sanchez provided design inspiration and financial support purchasing heaters. We would like to acknowledge M. Pessino for their contributions to the design of the system schematic in Fig. 2. We are grateful to B. Emery and T. Cabeen for their support in connecting the Raspberry Pi to the University of California, Santa Barbara WiFi network. We thank the Oakley lab for use of their water bath for temperature probe calibration. We would also like to acknowledge the assistance of University of California, Santa Barbara Energy and Electrical Services in mapping out the electrical circuits in Marine Science Research Building on campus and for their prompt response to a circuit overload that occurred during system testing. Finally, we extend our thanks to the Santa Barbara Coastal Long Term Ecological Research program for financial support purchasing chillers, and we are indebted to all Santa Barbara Coastal Long Term Ecological Research scientists and staff for their ongoing contributions to long-term temperature data collection. ALR was supported by the P.E.O. Scholar Award and the U.S. National Science Foundation Graduate Research Fellowship under Grant No. 2139319. This project was partially supported by U.S. National Science Foundation award 2131283 to GEH and U.S. National Science Foundation awards 1232779 and 1831937 to the Santa Barbara Coastal Long Term Ecological Research program (Director Dr R. Miller). Full funding for publising this article open access was provided by the University of California Libraries under a transformative open access agreement with Wiley.

Conflict of Interest

None declared.

Submitted 03 October 2024
Revised 21 November 2024
Accepted 26 November 2024

Associate editor: John P. Smol