

TECHNICAL NOTE

A low-cost environmental chamber to simulate warm climatic conditions

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Funding information

Bundesministerium für Bildung und Forschung, Grant/Award Number: 57156376; German Academic Exchange Service

Abstract

Environmental chambers are used for a variety of experiments in multiple disciplines but are often prohibitively expensive. In this study, we developed an environmental chamber that allows reliable regulation of temperature and relative humidity in a range typical for warm climatic conditions. As we have only used consumer products, which are readily available off the shelf, the device is affordable (<€900) and easy to replicate. The presented chamber has inner dimensions of 1,790 × 970 × 520 mm (height × width × depth). It is heated with two infrared lamps, and for moistening, an ultrasonic mister is used. Air dehumidification and cooling down to ambient temperature are realized with inflowing compressed laboratory air. Additionally, we installed a Peltier element cooling system to enable temperatures below the ambient laboratory temperature. The chamber works in a temperature and humidity range of 15–50 °C and 10–95%, respectively.

1 | INTRODUCTION

Environmental chambers (also termed climate or climatic chambers) enabling temperature and relative humidity regulation during laboratory experiments are required in a range of disciplines, including ecology, geology, and hydrology. They are, for example, used to study salt weathering of rocks (Goudie & Parker, 1998), nutrient leaching in soils (Grant, Macrae, Rezanezhad, & Lam, 2019), and water repellency of soils (Jiménez-Pinilla et al., 2016), or in evaporation studies (Huang, Bruch, & Barbour, 2013; Merz et al., 2018; Qazi, Bonn, & Shahidzadeh, 2018; Shokri-Kuehni, Norouzi Rad, Webb, & Shokri, 2017; Song, Cui, Tang, Ding, & Tran, 2014). Moreover, environmental chambers serve to test monitoring equipment (Papapostolou, Zhang, Feenstra, & Polidori, 2017; Prechsl, Gilgen, Kahmen, & Buchmann, 2014; Windhorst, Waltz, Timbe, Frede, & Breuer, 2013). However, commercial devices are often prohibitively expensive (Greenspan et al.,

2016), particularly for laboratories that do not use them on a routine basis. Consequently, scientists tend to improvise (Michelsen et al., 2018; Schulz et al., 2015), and although improvisation has helped in these cases, a fully functional but affordable environmental chamber would be a useful addition to the researcher's toolbox.

Some researchers have designed affordable environmental chambers, but often they only propose solutions for the control of temperature (Greenspan et al., 2016; Song et al., 2014). Others have constructed working models for the control of both temperature and humidity, yet they mostly focused on plant growth chambers simulating moderate environmental conditions (Bernard, Pitz, Chang, & Szlavecz, 2015; Katagiri et al., 2015). Katagiri et al. (2015), for instance, aimed for a temperature of 22 °C and a relative humidity of 75%, and they generally assumed that the temperature in their chamber would be within 8 °C of the ambient temperature.

In view of much harsher conditions prevailing in nature, we developed a robust climate chamber that can mimic a relatively wide range of warm environmental conditions, in

Abbreviations: DIY, do-it-yourself.

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terms of temperature and humidity. We describe a simple, affordable (<€900) do-it-yourself (DIY) chamber that mainly consists of off-the-shelf equipment. After providing an overview of the design, we present the results of a rigorous multiweek test of the device. A bill of materials, including suppliers and prices, a construction manual, and a comparison with commercially available environmental chambers is given in Supplemental Materials 1 and 3, respectively.

2 | DESIGN

Aiming at a versatile tool for multiple applications such as larger column experiments (Schulz et al., 2015) or tests of equipment (Michelsen et al., 2018), we designed an environmental chamber with inner dimensions of 1,790 × 970 × 520 mm (height × width × depth). Although we generally acknowledge the usefulness of microcontrollers, we deliberately avoided this tool (and the associated coding) and entirely relied on readily available consumer products to allow for easy replication and operation.

The chamber itself consists of 16-mm polycarbonate twin-wall sheets framed by a heavy-duty shelf. The front has an opening of about 900 × 400 mm, which is covered by a transparent acrylic glass panel (Figure 1a). To guarantee a homogeneous temperature and humidity distribution, an air circulation system with a fan ensures a gentle but constant air flow through the chamber (Figure 1b).

The temperature is controlled by a dual-relay thermostat. If the temperature in the chamber falls below a defined threshold, two infrared lamps (2 × 150 W or 2 × 300 W) are switched on. If the temperature exceeds a threshold, the lamps are switched off and a valve opens so that cool and dry air, provided by the compressed air system in the laboratory, flows into the chamber. Here, a pressure-reducing valve, set to 0.5 bar, maintains a constant flow rate of 0.14 L s⁻¹. Our compressed laboratory air is dehumidified and has a constant temperature of 21–22 °C, which in turn constitutes the minimum temperature that can be reached in this setup. For most experiments targeting warm arid conditions, this would be cold enough. Nevertheless, we installed an additional cooling system, which replaces the previously described one, if temperatures below the compressed air temperature must be reached. This system is based on eight 60-W Peltier elements that are installed into the back wall of the chamber. On top of the cooling side of the Peltier elements (inside of the chamber), a fan is mounted for the cold air distribution. On the warming side (outside of the chamber), a water-cooling block is attached. Nonetheless, for the simulation of warm arid conditions, the cooling system using compressed laboratory air should be sufficient. Hence, the cooling method based on Peltier elements can be considered as an optional add-on.

Core Ideas

- We develop a low-cost environmental chamber to simulate warm climatic conditions.
- It allows the regulation of temperature (15–50 °C) and relative humidity (10–95%).
- All parts are available off the shelf.
- It is affordable (<€900) and easy to replicate.

Simultaneously to temperature, relative humidity is controlled by a dual-relay hygrostat. When the relative humidity falls below or exceeds a threshold, the air inside the chamber will be moistened or dehumidified, respectively. Air moistening is realized with a fan-driven air circuit passing an external humidifier (Figure 1a). This humidifier consists of a polypropylene container with deionized water and an ultrasonic mister (Hannusch, 1995; Katagiri et al., 2015). Air dehumidification works the same way as the firstly described cooling method (i.e., via inflow of cool and dry compressed air). For both cooling and drying, the compressed air flows into the internal air tubing system for quick distribution.

The thermostat and the hygrostat are simple plug and play devices, which allow intuitive programming and, in case of the thermostat, even for different time windows per day. To avoid a permanent on-and-off switching of the cooling–heating or moistening–drying systems, a buffer can be applied to the target values for temperature and humidity.

3 | TEST

To explore the chamber's capabilities and limits, it was tested with various temperature and relative humidity settings for several weeks. For monitoring purposes during this test, we additionally installed a CS215 temperature and relative humidity probe (Campbell Scientific) next to the sensors of the thermostat and the hygrostat, which are located in the center of the chamber about 60 cm below the infrared lamps. Measurements were recorded with a CR800 datalogger (Campbell Scientific) with a 1-min logging interval. The laboratory in which the test was performed has an ambient temperature of 21–22 °C and a relative humidity between 50 and 60%. These conditions correspond approximately to the test standard (i.e., most commercial chambers are tested at 23 °C ambient temperature and about 65% relative humidity; ESPEC CORP, 2019a, 2019b; Memmert, 2019; Russells Technical Products, 2019).

In a series of pre-tests, we figured out that depending on the target temperature, different hardware configurations of the environmental chamber are required. For target temperatures of 25–35 °C, two 150-W infrared lamps are suitable. For

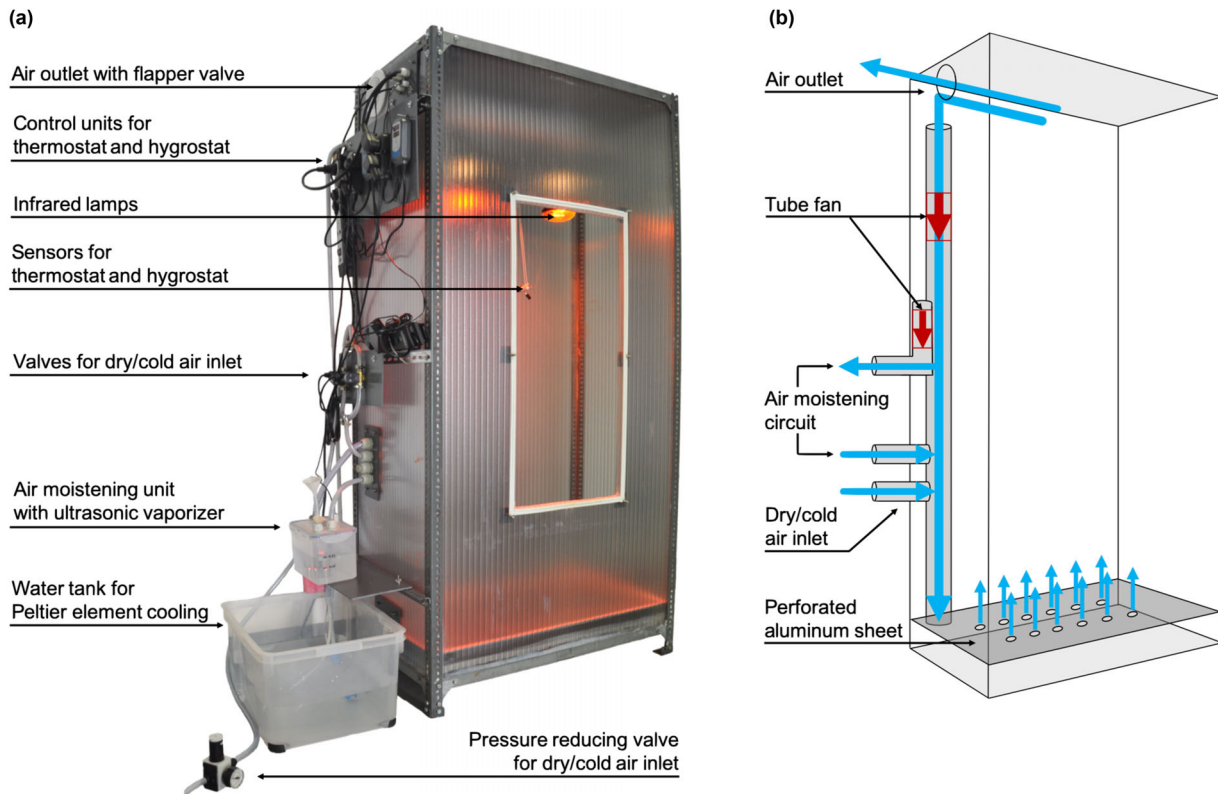


FIGURE 1 (a) Operating environmental chamber with activated infrared lamps. The opening can be closed with a transparent acrylic glass panel (for bill of materials and construction manual, see Supplemental Material 1). (b) Schematic sketch of the air circulation

higher target temperatures of up to 50 °C, the 150-W lamps should be replaced by two 300-W bulbs. For both temperature ranges, the cooling is realized with inflowing compressed laboratory air. In the case of lower desired temperatures, ranging from ambient laboratory temperature down to 15 °C, the compressed air-cooling system has to be replaced by the Peltier element cooling system (see above).

The test was conducted with target temperatures of 15, 20, 25, 30, 35, 40, 45, and 50 °C. For each temperature setting, the relative humidity was initially set to 5% and subsequently increased to 10, 30, 50%, etc., until a temperature-dependent limit was reached. As soon as the feasible relative humidity setting was exceeded (indicated by unstable relative humidity records and condensed water at the acrylic glass), we gradually lowered the target humidity until the values stabilized (Figure 2). The buffers for the thermostat and the hygostat (see the section above) were set to ± 0.5 °C and $\pm 1\%$, respectively. Each selected temperature–humidity combination was tested for 24 h, resulting in a total test period of 48 d.

The test yielded several findings. First, it showed how long it takes to reach a given target value (lag time). Generally, temperature increases by 5 °C are associated with lag times of <10 min. In the case of relative humidity, lag times are not that constant. For the increases from 10 to 30%, 30 to 50%, and 50 to 70%, lag times of about 30, 60, and 120 min were

noted, respectively. The strong decrease in relative humidity at the start of a new temperature setting lasted even longer. In the case of the transition from 90 to 5% (at 25–30 °C), it took about 8 h. This is caused by the condensation of water drops and the relatively long time required for their evaporation.

As soon as a target setting was reached, temperature and relative humidity records were rather stable. Small fluctuations are usually within the buffer range of the thermostat and hygostat. An exception is the period in which the Peltier elements were used for cooling. Here, stronger fluctuations were noticed (Figure 2).

The test of the environmental chamber showed that temperature as well as humidity measurements of the thermostat and hygostat differ from those recorded by the independent CS215 probe (Figure 2). The latter is a tested device with a temperature accuracy of ± 0.4 °C (5–40 °C), a relative humidity accuracy of $\pm 2\%$ (10–90%), and a temperature dependency of $\pm 2\%$ (20–60%) for the relative humidity sensor (Campbell Scientific, 2016). For our purposes, these are satisfying accuracies. Hence, we consider the measurements of the CS215 probe as true reference values. For future applications of the environmental chamber, we would like to have the possibility to omit the somewhat expensive reference probe and datalogger. Therefore, we developed correction functions for the measurements of the thermostat and the hygostat.

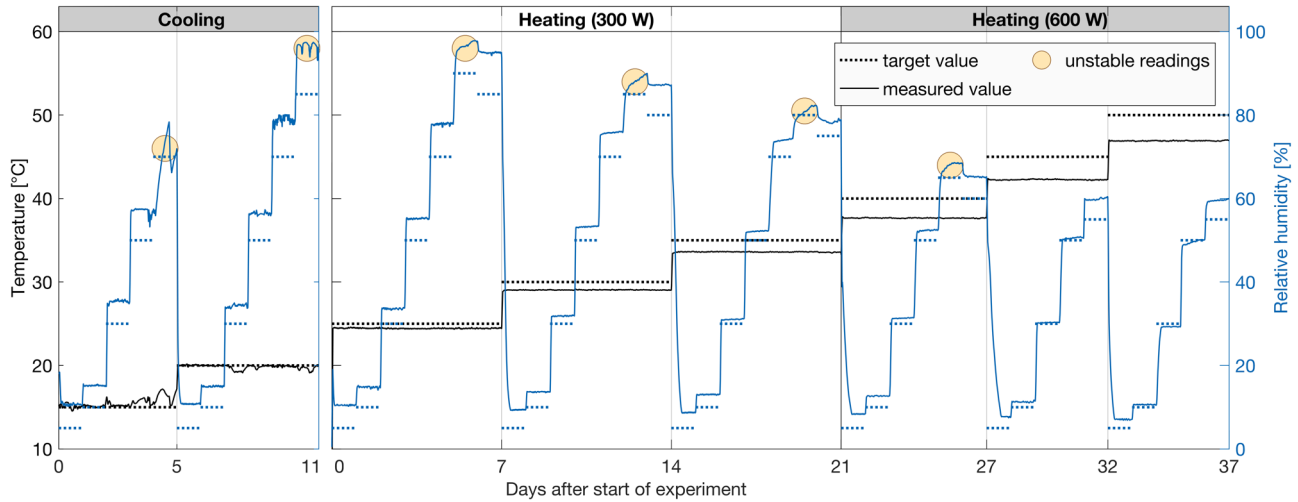


FIGURE 2 Target and measured temperature (left axis) and relative humidity (right axis) over the 48-d testing period

The temperature sensor deviation is independent from humidity and only depends on the temperature itself. The relation between true temperature and target temperature can be described by a simple linear regression model:

$$\vartheta = 0.901\vartheta_{\text{tar}} + 1.843 \quad (1)$$

with $n = 8$ and $R^2 = 1.00$, where ϑ is the true temperature ($^{\circ}\text{C}$) and ϑ_{tar} is the target temperature ($^{\circ}\text{C}$).

The relative humidity sensor drift depends on both temperature and relative humidity. The relation between true relative humidity and target temperature and target relative humidity can be described by a multivariate linear regression model:

$$\varphi = 1.008\varphi_{\text{tar}} - 0.175\vartheta_{\text{tar}} + 8.957 \quad (2)$$

with $n = 42$ and $R^2 = .99$, where φ is the true relative humidity (%) and φ_{tar} is the target relative humidity (%).

Finally, this test shows the range of feasible temperature and relative humidity settings. Although the temperature range seems to be independent from the relative humidity, the range of the relative humidity is very sensitive to the temperature. The presented environmental chamber can simulate a temperature window from 15 to ~ 50 $^{\circ}\text{C}$. A low relative humidity of 10–60% is possible over the entire temperature range. However, a higher relative humidity of up to 95% is only feasible with moderate temperatures around 25 $^{\circ}\text{C}$. From this optimum, the maximum possible relative humidity continuously decreases to 60% towards the minimum and maximum temperature limits (Figure 3). For high temperatures, this can be explained by increasing gradients to the ambient laboratory temperature. The higher the gradient, the lower the relative humidity, which leads to condensation (i.e., reaching of the dew point) at the inner walls.

In addition, we performed a second series of tests to analyze the homogeneity of the temperature distribution within

the chamber for the target temperatures of 25, 30, 35, 40, 45, and 50 $^{\circ}\text{C}$. To analyze the vertical temperature distribution, we installed eight temperature sensors in two arrays below the infrared lamps at different levels. It is not surprising that the upper sensors, which were closest to the lamps, showed the highest temperatures, whereas the lowest sensors showed the lowest temperatures. Here, the largest difference (4.3 $^{\circ}\text{C}$) was recorded for the target temperature of 50 $^{\circ}\text{C}$ (Supplemental Figure S2.2). We then repeated the test with the same target temperatures but placed 21 sensors aligned on a horizontal plane 80 cm above the bottom of the chamber to map out the lateral homogeneity. In general, the recorded temperatures differ less with this sensor arrangement. Again, the largest difference (1.7 $^{\circ}\text{C}$) was recorded for the highest temperature setting of 50 $^{\circ}\text{C}$ (Supplemental Figure S2.4). A more detailed description of this test can be found in the Supplemental Material 2.

We also point out that there might be a difference between air temperature and sample temperature (caused by the infrared radiation emitted by the heating system), which implies that researchers would have to decide where to place the sensors of the thermostat and hygostat. Using the example of a soil column experiment, one has to consider which temperature is relevant—air or soil temperature. Accordingly, one has to place the sensor in the air or on the soil surface. For a simple test case, we observed a surface of a soil column (fine quartz sand, 10-cm diam., 20-cm height), which was ~ 1 $^{\circ}\text{C}$ warmer than the air temperature (shielded sensor, 40 $^{\circ}\text{C}$).

4 | CONCLUDING REMARKS

The presented environmental chamber has proven to be a reliable and affordable tool to mimic warm arid conditions. All necessary parts are consumer products and readily available

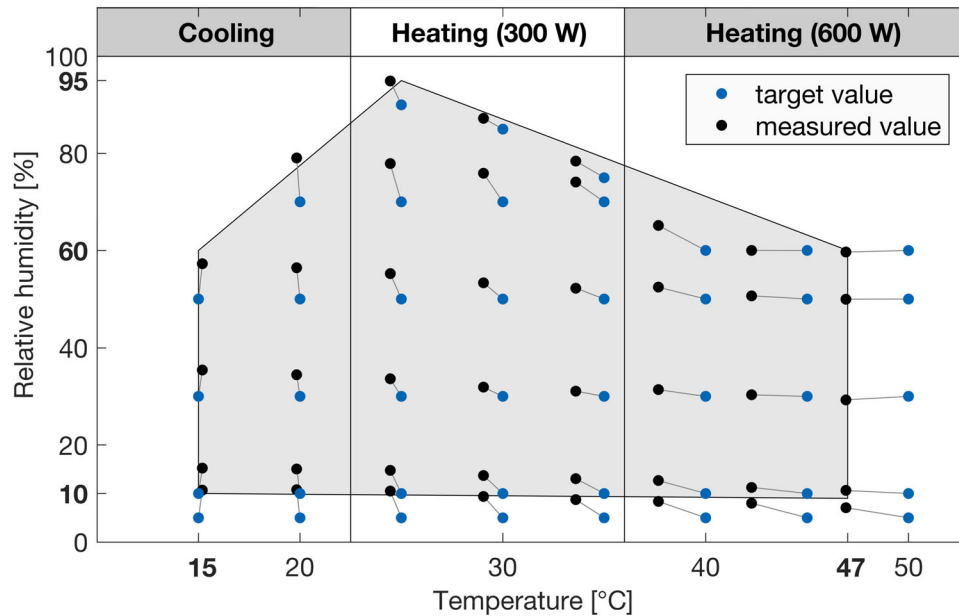


FIGURE 3 Temperature and relative humidity ranges that can be simulated with the environmental chamber (gray box)

off the shelf. Moreover, the setup does not require microcontroller coding or difficult wiring, enabling replication with reasonable effort.

Nevertheless, the test of the chamber also revealed some limitations. The simulation of temperatures below ambient laboratory temperature requires a hardware modification (i.e., Peltier elements have to be used for cooling instead of compressed air). In our case, this enables only a minor temperature decrease of 6–7 °C below ambient temperature. Moreover, higher relative humidities are only possible for moderate temperatures. For example, 80% are only possible in the range of 20–35 °C. In most of the tested cases, the target settings are reached relatively quickly, which allows to simulate diurnal cycles. However, a strong decrease of relative humidity from its temperature-dependent maximum down to the minimum takes several hours. For some applications (e.g., short-term humidity fluctuation during the simulation of diurnal cycles), these long equilibration times might be not acceptable. In such cases, the total possible humidity range cannot be used (i.e., one must stay below the upper humidity limit to prevent condensation at the inner chamber walls). A further limitation is the slightly inhomogeneous temperature distribution, which is due to the small number of lamps, acting as a point heat source.

Given these limitations, commercial environmental chambers may still be the better choice for some applications. For example, various commercial chambers can simulate temperatures that exceed our 50 °C limit while maintaining relative humidity of up to almost 100%. However, many of these are unable to simulate low temperatures (<30 °C) and low relative humidities (<20%, Supplemental Figure S3.1). Others cover a

wide temperature and humidity range but may not provide sufficient space for the planned experiment (Supplemental Table S3.1). Eventually, the right choice depends on individual and demand-specific needs. To check whether our DIY chamber is suitable for one's purpose or which commercial chamber would be an alternative, we provide a comparison of selected environmental chambers in the Supplemental Material 3.

For the simulation of warm arid conditions, the presented environmental chamber shows a satisfying performance. Moreover, its design leaves margin for demand-specific adaptations (e.g., in terms of [a] chamber size, [b] number, distribution and power of cooling or heating units, or [c] improved insulation). Such an improved insulation could potentially remedy some limitations and enhance cooling capabilities or increase relative humidity limits for higher temperatures, if necessary.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

AUTHOR CONTRIBUTIONS


S.D., N.M., and S.S. designed the research; S.D. and S.S. constructed the environmental chamber; S.D. tested the chamber; all authors wrote and reviewed the manuscript.

ACKNOWLEDGMENTS

The first author acknowledges the support from the German Academic Exchange Service (DAAD) programme "Sustainable Water Management (NaWaM) Study Scholarsips and

Research Grants 2015” (57156376) funded by the German Federal Ministry of Education and Research (BMBF). We thank the two anonymous reviewers for their constructive comments.

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SUPPORTING INFORMATION

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

How to cite this article: Darehshouri S, Michelsen N, Schüth C, Schulz S. A low-cost environmental chamber to simulate warm climatic conditions. *Vadose Zone J.* 2020;19:e20023. <https://doi.org/10.1002/vzj2.20023>