PLOS CLIMATE

RESEARCH ARTICLE

Widespread inconsistency in logger deployment methods in coral reef studies may bias perceptions of thermal regimes

Walter A. Rich[1]*, Jess S. Glanz[1], Gage Mele[1], Nicole J. Burt[1], Susana Carvalho[1], Steve S. Doo[1¤], Elizabeth A. Goergen[2], Erik C. Krieger[1], Lena Li[1], Eslam O. Osman[1], David J. Suggett[1,2,3], Maggie D. Johnson[1], Michael. D. Fox[1]

1 Biological and Environmental Sciences and Engineering Division, King Abdullah University of Science and Technology, Thuwal, Kingdom of Saudi Arabia, **2** KAUST Coral Restoration Initiative, King Abdullah University of Science and Technology, Thuwal, Kingdom of Saudi Arabia, **3** Climate Change Cluster, University of Technology Sydney, Ultimo, Australia

¤ Current address: Marine Science Department, University of Hawai'i, Hilo, Hawai'i, United States of America
* walter.richiv@kaust.edu.sa

Citation: Rich WA, Glanz JS, Mele G, Burt NJ, Carvalho S, Doo SS, et al. (2024) Widespread inconsistency in logger deployment methods in coral reef studies may bias perceptions of thermal regimes. PLOS Clim 3(12): e0000517. https://doi.org/10.1371/journal.pclm.0000517

Editor: Djanaguiraman Maduraimuthu, Tamil Nadu Agricultural University Agricultural College and Research Institute, INDIA

Received: May 31, 2024

Accepted: November 4, 2024

Published: December 27, 2024

Data Availability Statement: Data and metadata are available in the Environmental Data Initiative data repository (DOI: https://doi.org/10.6073/pasta/2d529777840c0c7ca2ff7228b061c9e2).

Funding: Funding for this work was provided through the KAUST Coral Restoration Initiative (KCRI) Research and Development program to MDF and MDJ. The funders had no role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Abstract

Ocean warming is the greatest threat to coral reefs, prompting a need to accurately monitor in situ temperatures. Advancements in sensing technologies have led to a proliferation of temperature loggers being deployed globally. However, appropriate deployment of loggers–essential for measurement accuracy in an ecosystem where changes of 1ºC can cause widespread mortality–is often overlooked. For example, loggers deployed in direct sunlight are known to overestimate temperature, but the prevalence of shading loggers is unknown. Here, we survey recent literature to assess the current state of temperature logger use on coral reefs. We then performed lab and field trials on 10 models that span a range of prices and accuracies to evaluate logger performance and assess efficacies of shading techniques. Of the 329 studies we reviewed, >40% of studies deployed loggers shallower than 5 m, yet <5% reported shading loggers, revealing the potential for bias in existing datasets. In field tests, solar bias varied significantly across loggers; the most popular model suffered the largest bias of >2.5ºC, while other models were less affected by irradiance. Wrapping loggers in tape reduced temperature bias, but under high irradiance measurement error still exceeded 0.8ºC. Shading loggers under an opaque object completely eliminated solar bias. We demonstrated a strong linear relationship between in situ irradiance and temperature error and quantified irradiance thresholds for which error >0.5˚C can be expected. We then modeled the temperature bias expected for the most popular logger model using in situ irradiance data, showing that errors >2ºC can exist across multiple depths. Our findings reveal pervasive underreporting of logger deployment methods in coral reef studies, highlighting the need to consider the possibility of bias when comparing studies or integrating different in situ temperature records. Future studies should strive to transparently describe deployment methods and appropriately shade loggers.

Competing interests: The authors have declared that no competing interests exist.

Introduction

Rising ocean temperatures have triggered more frequent and intense heatwaves, with devastating effects on marine ecosystems worldwide [1]. The need to understand rapidly changing ocean temperatures has increased demand and urgency for expanded ocean monitoring capacity, particularly in coastal habitats. Coral reefs are among the most vulnerable ecosystems to ocean warming, because their physical and ecological functioning is underpinned by thermally sensitive reef-building corals [2]. Most tropical corals live near their thermal limit, such that increases as small as 1°C beyond their local maximum summer temperatures can cause coral bleaching and mortality [3]. Currently, due to record-high ocean temperatures, the fourth global coral bleaching event is underway, severely impacting coral reefs across multiple ocean basins [4]. Given the severe ecological impacts of slight temperature variation and the ongoing impacts of global bleaching, it is imperative that in situ temperatures on coral reefs are measured accurately.

Techniques for measuring ocean temperature have evolved over the last several decades, from handheld thermometers to remotely sensed satellite observations. Whilst the scale of remote temperature sensing is invaluable, it fails to capture the dynamic temperatures of coastal habitats. By contrast, underwater temperature monitoring enables continuous data collection at finer spatial and temporal resolution. Electronic temperature measurements have been made on coral reefs since the 1970s [5]. However, technological advancements and development of Onset Hobo loggers in the early 2000s led to more widespread use of continuous in situ temperature recorders [6–9]. The recent acceleration of widespread bleaching events [10] and coral restoration efforts [11], combined with technological advances that make waterproof temperature sensors more accessible, have coincided with the proliferation of new, easily-deployed temperature loggers on the market. The result has been a profusion of in situ temperature records for reefs worldwide, but with an added element of measurement uncertainty that must be considered when comparing data across different products and applications.

Most commercial loggers are marketed as "ready to use", with no calibration or assembly required. Thus, loggers are frequently deployed with little attention paid to calibration or deployment technique. It is well-documented that not shading certain Onset Hobo loggers from direct sunlight can cause false temperature measurements up to 3˚C above the true temperature [9,12]. In sunny, tropical ecosystems where increases of 1˚C can have severe biological consequences, biased measurements could promote inaccurate estimates of coral bleaching thresholds with significant consequences for management and restoration decisions.

Although shading of temperature loggers can dramatically improve their accuracy, this protocol is not consistently applied by the broader community of coral reef scientists, managers, and restoration practitioners. As monitoring and restoration efforts expand [11], the diversity of temperature loggers and multiparameter environmental sensors has grown to meet demand. Despite the known solar bias of some popular logger models [9,12], it is necessary to quantify the extent to which recommended precautions against measurement error are followed by the coral reef community and to determine the potential error associated with new logger models.

Here we review the current state of temperature measurements on coral reefs to evaluate the potential for widespread bias in global in situ temperature records and quantify actionable irradiance thresholds to promote accurate data collection using a variety of loggers. First, to evaluate the adoption of earlier recommendations to shade and calibrate loggers, we reviewed temperature-focused studies over the past decade since the first paper alerting the community to solar bias was published [12]. Second, we assessed the accuracy and solar bias of 10 loggers across six manufacturers to evaluate performance and determine irradiance thresholds to reduce biases <0.5˚C. Finally, we modeled the temperature error expected for a popular logger (Onset Hobo Pendant) using in situ irradiance data from multiple depths spanning a range of conditions. Our findings reveal extensive shortcomings in how temperature data are collected and reported, emphasizing that biases of 1–3˚C may be embedded in some published temperature records. Given the immense resources being allocated to coral reef research [13], these issues must be urgently addressed to improve future integration of in situ temperature records and ensure research and management decisions are based on accurate data.

Materials and methods

Evaluating logger usage in the literature

We conducted a literature review of papers published between 2013 and 2022 using Web of Science to determine the diversity of loggers used and if the coral reef research community has adopted past recommendations to shade temperature loggers [9,12]. Most studies do not discuss temperature loggers in the paper title or abstract, which necessitated a very broad search and subsequent narrowing of the results. This effort was not intended to be an exhaustive literature search, but rather a broad survey to see how frequently researchers are reporting the details of their temperature logger deployments since the first study alerting the community to potential bias due to irradiance was published [12]. We used the following search terms ((ALL = ((coral* OR reef))) AND ALL = ("Seawater Temperature" OR Temperature*)). Given the necessary breadth of this search, we refined the total records (n = 7834) to the top four top categories: marine and freshwater biology, ecology, environmental sciences, and oceanography, which contained 52% of all records (n = 4046). From these, we individually screened each study to remove those 1) conducted in mesocosms, aquarium tanks, or other ex situ settings, 2) relying solely on remote sensing measurements, 3) measuring temperature manually without deploying a logging sensor (e.g., periodically measuring temperature with a handheld multiparameter probe), or 4) using temperature data from monitoring networks that do not clearly state the type of sensor employed. Following this screening, we identified 329 temperature-focused studies that used 397 unique loggers to measure temperature on reefs across 51 countries (S1 Table). We collated information from these studies on which loggers were used and if details on shading or calibrating loggers were reported.

Standardizing performance across common logger models

To evaluate the performance of commercially available temperature loggers, we deployed 10 models from six manufacturers (n = 3 replicates per logger; model details in Table B of S1 Text) in a controlled, high precision calibration bath (model 7012, Fluke Corporation, American Fork, UT, USA). The bath ramped from 17–41ºC (8-hr period, 2˚C intervals) to capture the range of temperatures coral reefs experience globally. Each temperature step was ramped over 10 min and held for 30 min to compare the accuracy of measurements as a function of logger response time. Accuracy was assessed at multiple time points within each hold to account for differences in logger deployment parameters (i.e., sampling frequency) from the literature: once at the start of the hold (within 1 min of stabilizing at the next temperature), and at 5, 15, and 30 min into the hold. To assess overall accuracy of different loggers, we calculated the root mean square error (RMSE) across all temperature steps using the 5-min time point (n = 3 measurements per temperature), with lower RSME values indicating greater accuracy.

Quantifying irradiance thresholds to minimize solar bias

Loggers were deployed on a fringing reef adjacent to King Abdullah University of Science and Technology (KAUST) in the central Red Sea (22.340˚N 39.087˚E). Permits to access to the field site were granted by KAUST marine security services. All models used in the lab calibration were field tested except for Electric Blue EnvLogger T7.3. Logger units were all newly-purchased and had not yet been deployed. Replicates for each logger (n = 3 shaded and 3 unshaded, 5-min sampling intervals) were deployed at 2–3 m depth, 3–7 February 2023. This period corresponds to the boreal winter in the Red Sea when conditions more accurately reflect non-stressful temperatures experienced by many coral reefs worldwide (e.g., 24-26ºC). Although deployed in a shallow habitat, the site is relatively turbid and not indicative of extreme irradiance. Loggers were mounted on two adjacent racks (Fig A in S1 Text). One rack was shaded with a black acrylic panel fastened ∼15 cm above the loggers blocking sunlight without restricting water flow. Irradiance was measured during the deployment with PAR (photosynthetically active radiation) loggers (Odyssey Xtreem PAR, Dataflow systems, Christchurch, New Zealand). PAR is visible light between the wavelengths 400–700 nm and is frequently used to monitor irradiance in marine habitats. The average irradiance values from Odyssey Xtreem PAR loggers (n = 3) in the unshaded treatment were used to evaluate irradiance-specific heating bias across all loggers. The Odyssey Xtreem PAR loggers were calibrated against a LI-COR LI-1500 cosine light meter before deployment.

We quantified logger performance as the difference from the mean value of the shaded SBE-56 Temperature loggers (Sea-Bird Scientific, Bellevue, WA, USA) (n = 3), which are considered the industry standard for high-precision temperature measurements. In pilot studies, we determined SBE-56 loggers exhibit no detectable solar heating bias (Figs B, C in S1 Text). We then calculated logger-specific irradiance thresholds for a bias of 0.5˚C using linear regression.

While many practitioners may wrap loggers in electrical tape but not report it, this may not completely remove bias from temperature measurements. To ascertain the extent of bias that may still be present even in taped loggers, we conducted a second deployment during the high-temperature and bright conditions of the boreal summer (June 2023) in a shallow (1 m) site (maximum temperature > 35ºC; maximum PAR > 2000 μmol m^{-2} s^{-1}) using the popular (and solar sensitive) Onset Hobo Pendant loggers (UA-002-64). We calculated deviations of temperature measurements from shaded, taped, and unshaded loggers relative to a co-deployed Sea-Bird SBE-56. White electrical tape [12] and aluminum foil tape [9] have been proposed as alternatives to full coverage with a PVC pipe. We therefore evaluated the increase in measurement accuracy afforded by shading loggers using a white PVC pipe (schedule 40 PVC, ⌀ = 4.5 cm), white and black electrical tape (to determine if tape color matters), or aluminum foil tape (n = 2 per shading treatment).

Evaluating the dependence of temperature error on irradiance and modeling potential bias

We empirically assessed the consistency of the linear relationship between irradiance and temperature measurement error across a range of irradiance levels typical of coral reefs. We performed two trials to validate the linearity of temperature bias under extreme irradiance on Onset Hobo Pendant loggers (n = 3 for both trials). In an outdoor tank experiment, we placed loggers in shallow water (<10 cm depth). The tank was subject to natural sunlight and the experiment was conducted from dawn until mid-afternoon, after peak irradiance was reached. We repeated this experiment in the lab using aquarium lights (Hydra 64HD, AquaIllumination, Bethlehem, USA) simulating the natural spectrum of sunlight. We ramped irradiance over a period of 5 hours simulating the increase of irradiance from sunrise to midday at a rate that increased by 12 μmol photons m^{-2} s^{-1} every minute (total range 0–3823 μmol photos m^{-2} s^{-1}). Both experiments used a PAR logger (MiniPAR, PME, Vista, CA, USA) to track irradiance and an SBE-56 temperature logger to record true water temperatures.

Using the observed relationships between irradiance and temperature error for unshaded Hobo Pendant loggers, we modeled the bias expected from different habitats using in situ irradiance data. To showcase the range of potential bias of loggers from a more globally-representative selection of habitats, we provide four datasets spanning shallow, high-irradiance environments to deeper, more turbid sites. Specifically, we leveraged data from co-located irradiance and temperature loggers (collected via MiniPAR and SBE-56 loggers, respectively) from two reefs in different ocean basins: for 1 m and 5 m depths, we use data from Palmyra Atoll, an equatorial reef in the central Pacific that experiences high irradiance and low light attenuation; and for 15 m and 30 m depths, we model data from a central Red Sea reef that experiences lower overall irradiance and moderate turbidity. We modeled data from four logger deployment scenarios: 1) an unshaded, uncalibrated logger, 2) an unshaded logger that has been calibrated prior to deployment, 3) an uncalibrated logger that has been wrapped in tape, and 4) a calibrated logger wrapped in tape.

Results

Literature review

Across 329 coral reef studies published between 2013–2022, researchers deployed 28 brands of temperature loggers, highlighting the variety of available products. Onset Computer Corporation accounted for more than 60% of loggers used, with the most common models being the Hobo Pendant (UA series) and Hobo Pro (U22-001) (33% and 31% of Onset loggers, respectively) (Fig 1A). The second most popular manufacturer used was Sea-Bird Scientific, comprising nearly 20% of the reviewed studies. Of the studies that report logger deployment depths, the majority (64%) were in ≤10 m of water (median deployment depth = 8 m) (Fig 1B). A large proportion of studies deploy loggers at even shallower depths, with 41% at ≤5 m and 17% at ≤2 m. More than one in ten loggers were deployed at depths of ≤1 m (11.5% of logger deployments). Yet, despite the widespread use of temperature loggers in shallow, high-irradiance habitats, only 5 and 14% of all studies reported shading or calibrating loggers, respectively (Fig 1B, Table A in S1 Text).

Comparative performance of popular loggers

Significant variability in measurement accuracy was evident across the 10 loggers evaluated in the calibration bath (Fig 1C). Overall, measurement error (RMSE) was greatest at the initial timepoint for each new temperature hold, ranging from 0.042°C for the Sea-Bird SBE-56s to 1.248°C for the Odyssey Xtreem PAR loggers (Table B in S1 Text). Measurement accuracy generally stabilized by 15 min into the temperature hold (Fig 1C).

Certain logger models measured temperature with a consistent bias. The Onset Hobo Pendant Series (UA-001-64, UA-002-64, and MX2202) and Electric Blue EnvLogger T7.3 slightly overestimated the true temperature (∼0.2°C), while the Odyssey Xtreem PAR loggers regularly underestimated true temperature by ∼0.5°C. Notably, this was the only logger model to consistently underestimate temperatures across the range tested, resulting in the highest error (RMSE = 0.641°C). The PME MiniDOT logger exhibited low error for temperatures under 35°C (RMSE = 0.034°C). However, consistent with manufacturer specifications, the logger could not resolve temperatures above this threshold (Fig D in S1 Text).

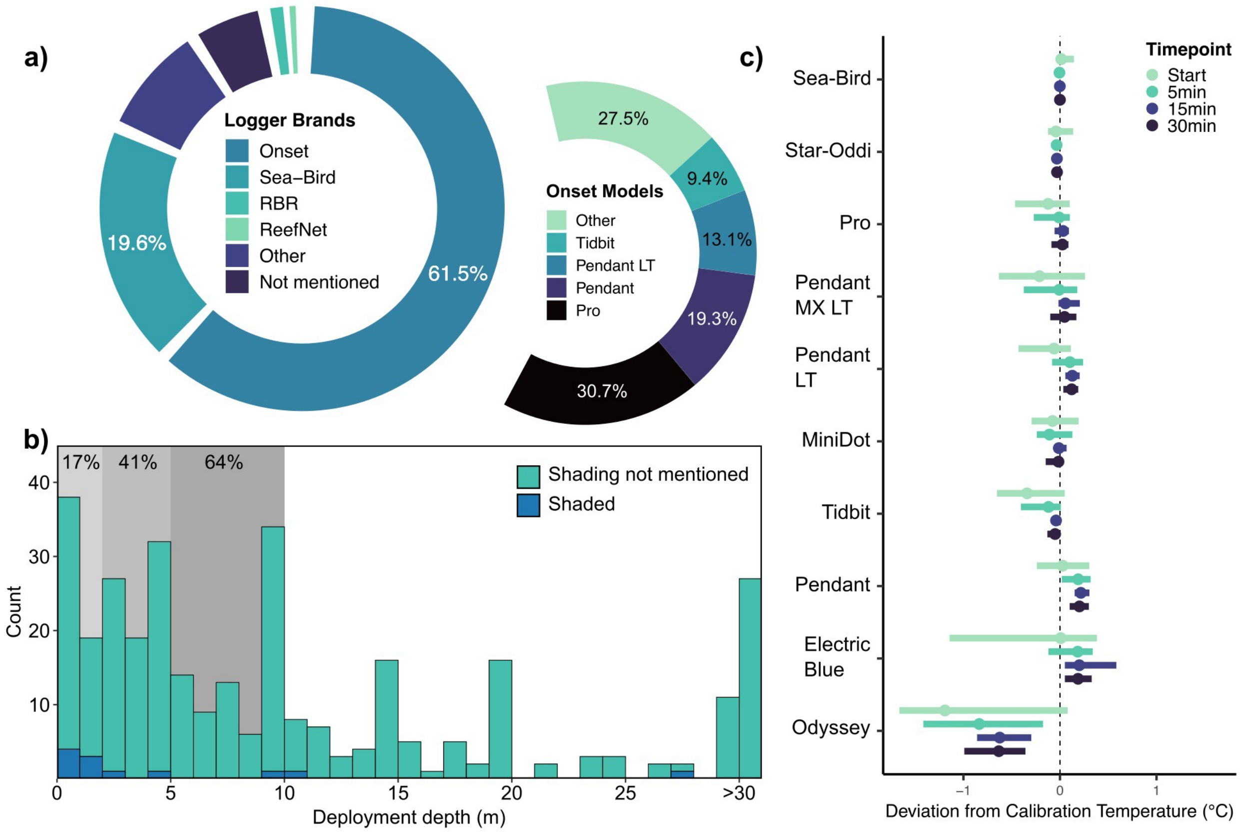

Fig 1. Temperature measurements on coral reefs are made using a wide array of products with differing accuracies and at a range of deployment depths. (a) Breakdown of logger brands most commonly used across 329 studies from 2013–2022. The most popular brand, Onset, is further broken down into the proportion of studies using various models. (b) Studies report deploying loggers across a range of depths in coral reefs. Shaded grey boxes denote the cumulative proportion of studies that deployed loggers in sites shallower than or equal to the respective depth between 0 and 10 m (absolute percentage of studies per depth bin: 17% in 0-2m, 24% in 2-5m, 23% in 5-10m). Despite the majority of logger deployments occurring in less than 10m of water, where the potential for solar heating bias is high, less than 5% of studies report shading loggers (dark blue bars). (c) Logger accuracy at different sampling frequencies show as the mean (point) and total range (bar) of deviation from the calibration bath temperature with increasing time at each temperature (17–41˚C). For all loggers, n = 3 except Electric Blue (n = 6), and data for the PME MiniDOTs and Electric Blue EnvLogger T7.3 3are only shown to 35˚C. Model numbers of loggers are provided in Table B of S1 Text.

https://doi.org/10.1371/journal.pclm.0000517.g001

Determination of irradiance thresholds to reduce heating bias

Field deployments revealed the potential error embedded within temperature time series using improperly deployed loggers. The range of temperatures recorded by the Sea-Bird SBE-56s was 24.66–26.64ºC during the shallow deployment; however, other loggers recorded temperatures as low as 23.94ºC and as high as 28.06ºC (maximum offset of +1.86˚C in Onset Hobo Pendant UA-001-64) (Fig 2A). Most loggers exhibited a positive temperature bias during daylight hours, which correlated to irradiance (Fig 2B, Table C in S1 Text). Conversely, Odyssey Xtreem PAR loggers regularly underestimated temperatures by ∼0.5ºC, consistent with the results of the lab calibration bath.

The degree to which solar irradiance affected temperature bias differed between loggers (Fig 3, Table C in S1 Text). To isolate the effect of irradiance alone (i.e., remove the effect of calibration offsets), we presented irradiance thresholds for loggers calibrated in the laboratory calibration bath. However, given the low reporting rates of calibration in our literature survey, we also show the range of bias for uncalibrated, "out of the box" loggers (grey shaded regions in Fig 3). Some uncalibrated loggers tended to slightly overestimate temperature even under

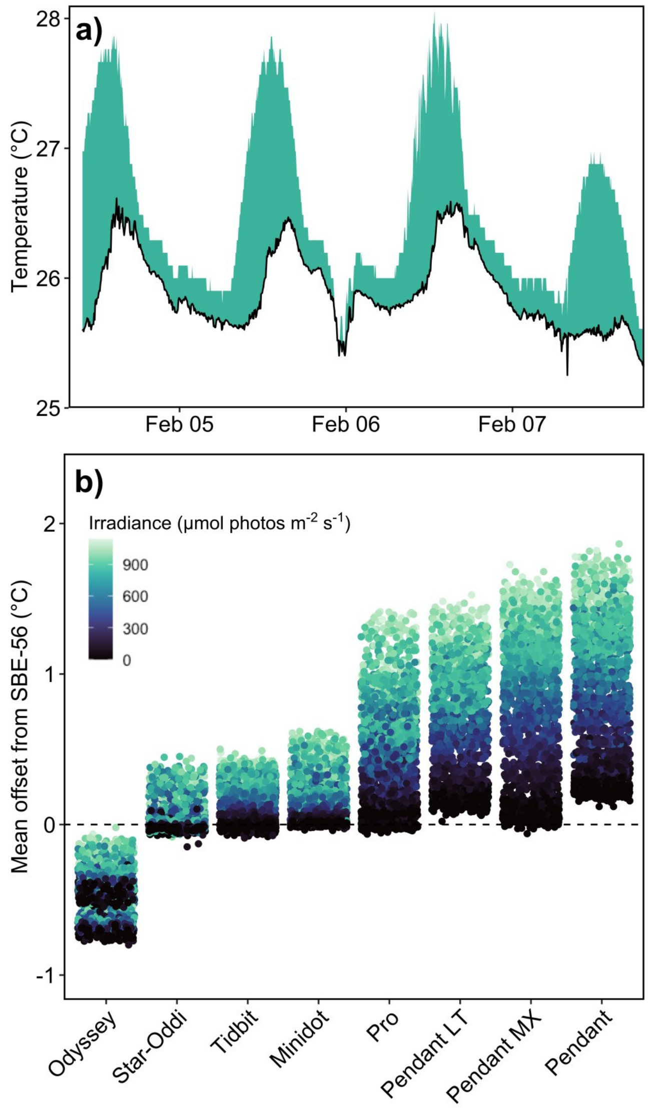

Fig 2. Temperature bias is directly related to solar irradiance. (a) The maximum potential range of measurement error in unshaded, uncalibrated loggers across four days during February 2023 (2–3 m depth). The black line indicates the mean temperature of three shaded Sea-Bird Scientific SBE-56 loggers and the upper bound of the shaded region corresponds to the unshaded Onset Pendant logger (UA-001-64) temperature, which had the largest positive temperature bias of loggers tested. (b) The effect of solar irradiance on temperature bias relative to shaded Sea-Bird SBE-56 for unshaded, uncalibrated loggers. All measurements during daylight hours (06:00–19:00) are paired with in situ irradiance data from the Odyssey Xtreem PAR loggers for the field deployment period. Model numbers of loggers are provided in Table B of S1 Text.

https://doi.org/10.1371/journal.pclm.0000517.g002

no irradiance (Fig 2B), effectively reducing the irradiance threshold to reach 0.5°C bias (e.g., Hobo Pendant threshold is reduced from 399 to 208 μmol photos m^{-2} s^{-1} when deployed uncalibrated). Conversely, the Odyssey Xtreem PAR logger exhibited a negative calibration offset, resulting in underestimating true temperature when uncalibrated. Thus, calibrating loggers in the lab before deployment generally improved logger accuracy and increased the irradiance required to exceed the 0.5°C error threshold by 8–92% depending on model. The strongest solar bias occurred in many of the Onset models, with the Hobo Pendant series (UA-001-64, UA-002-64, MX2202) and Hobo Pro (U22-001) loggers suffering a 0.5°C bias at

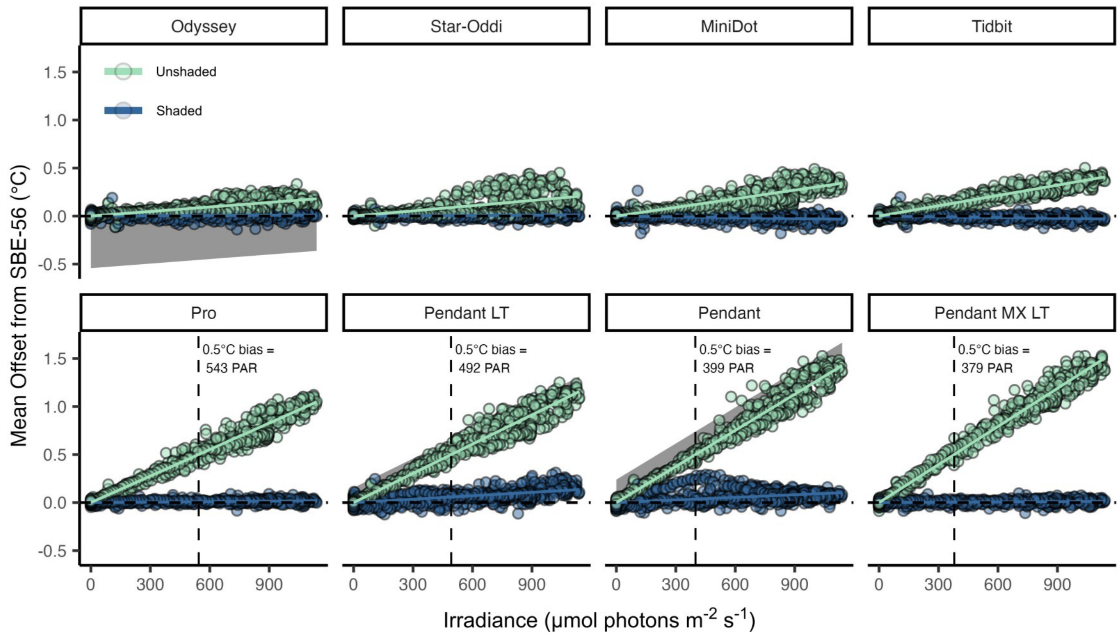

Fig 3. Solar heating and measurement error varies widely across temperature loggers. Each panel represents the average deviation of three replicate lab-calibrated loggers from the mean temperature recorded by three shaded Sea-Bird SBE-56s at 2–3 m depth. Data shown here represent loggers cross-calibrated to the SBE-56 temperature to remove calibration biases and isolate the effect of solar heating for each model. All logger models exhibited, to some degree, temperature error as a function of irradiance (green points). In all cases, shading reduced the effect of solar heating (blue points). Green and blue lines represent the model fit lines of temperature error as a function of irradiance for unshaded and shaded loggers, respectively. Irradiance thresholds were estimated from linear regression (Table C of S1 Text) of the unshaded and calibrated loggers to quantify irradiance values above which temperature bias of at least 0.5˚C can be expected (vertical dashed lines). Loggers that did not experience a bias of 0.5˚C or greater within the range of irradiance experienced during the deployment period do not have thresholds shown. Grey shaded regions parallel to the unshaded model fit lines depict the temperature bias of uncalibrated loggers. As each logger model had different calibration coefficients (i.e., intercepts), some models show minimal difference between uncalibrated and calibrated loggers, while others show substantial offsets when loggers are not calibrated. Odyssey loggers were the only model to exhibit a negative calibration coefficient, resulting in underestimation of true temperature for uncalibrated loggers. Horizontal dashed lines represent 0 or no difference from Sea-Bird SBE-56 temperature. All measurements shown are during daylight hours only (06:00–19:00). Model numbers of loggers are provided in Table B of S1 Text.

https://doi.org/10.1371/journal.pclm.0000517.g003

irradiance values between 399–543 μmol m^{-2} s^{-1} when calibrated (Fig 3). However, calibrating loggers prior to deployment did not completely remove solar bias for unshaded loggers. Onset Hobo Tidbit (MX2203), PME MiniDOT and Star-Oddi DST CT loggers exhibited measurement error with increasing irradiance (Table C in S1 Text), but never reached a 0.5ºC bias within the irradiance range experienced during the field trial.

Efficacy of different shading methods

In warm, high-irradiance conditions, logger biases can be greatly exacerbated.

Unshaded and uncalibrated Onset Hobo Pendant UA-002-64 loggers in the summer trial exhibited temperature biases nearly 2.5ºC higher than the co-deployed Sea-Bird SBE-56 at 1 m depth (Fig 4A and 4B). By contrast, loggers deployed in PVC tubes showed no solar bias and recorded temperatures consistent with the SBE-56, although they retained a slight positive bias (~0.2ºC) as observed in the calibration bath test (Fig 1C) and February field deployment (Fig 2, Table C in S1 Text). Thus, calibrating loggers reduces error (Fig 4C and 4D). Loggers wrapped in tape were less affected by irradiance than unshaded loggers, but still showed a detectable positive bias compared to the PVC treatment (Fig 4B and 4D). Notably, there was

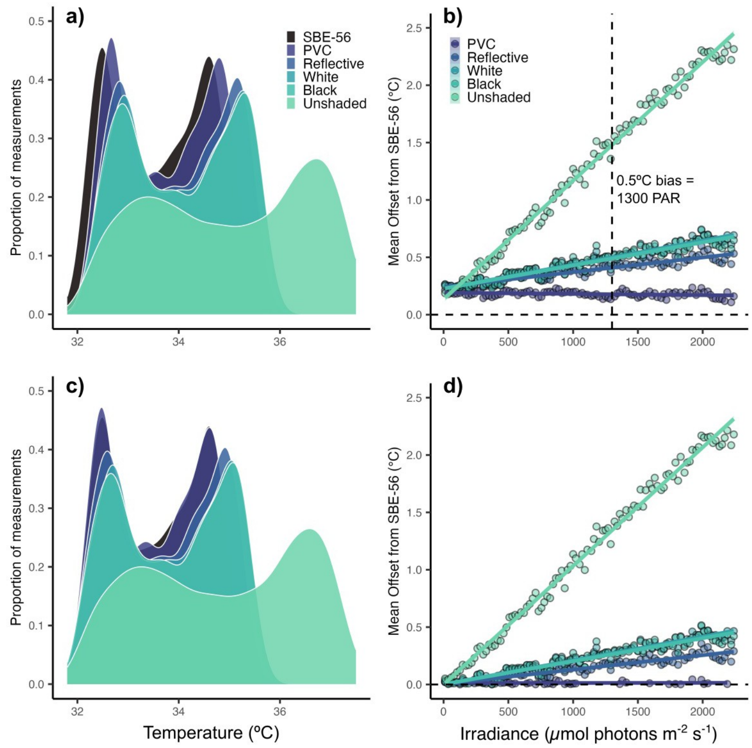

Fig 4. The effect of irradiance on Onset Hobo Pendant (UA-002-64) loggers varies under different shading methods. Panels (a) and (b) depict data from uncalibrated loggers while panels (c) and (d) show the same data when loggers have been calibrated. (a) The proportion of temperature measurements recorded by uncalibrated loggers under each shading method. The Sea-Bird SBE-56 temperature is considered the "true" water temperature and exhibits peaks around 32ºC (night) and 35ºC (day), while the unshaded logger reported false daytime high temperatures. Nighttime error exists due to lack of lab calibration. (b) Shading by PVC removes the effect solar heating, but due to calibration offsets, uncalibrated loggers show a consistent offset from Sea-Bird SBE-56 (horizontal dashed line). Shading with reflective, white and black tape wrapped around the logger housing improves accuracy but can still result in measurement bias of >0.5˚C (vertical dashed line) under high irradiance when loggers are uncalibrated. (c) Calibrating loggers improves their accuracy, but they are still affected by irradiance. (d) The 0.5ºC threshold for calibrated, taped loggers exceeds the range of irradiance experienced during the field trial and is not depicted.

https://doi.org/10.1371/journal.pclm.0000517.g004

no appreciable difference between types of tape used to shade loggers (white, black, or reflective foil tape), suggesting that presence of a physical barrier between the logger and sunlight is more important than the color of the shading material. By calibrating loggers before deployment, the 0.5ºC threshold for taped loggers is increased from 1300 to 2500 μmol photos m^{-2} s^{-1}, which is out of the range of the summer field trial (Fig 4D).

Modeling expected temperature error under different irradiance scenarios

We assessed the linearity of the relationship between temperature error and irradiance under the full range of plausible in situ irradiance for the most popular logger model, the Onset Hobo Pendant series. In the outdoor tank and lab trials, maximum irradiance levels were 2423 and 3823 μmol photos m^{-2} s^{-1}, respectively. Unshaded and uncalibrated Hobo pendants exhibited severe solar bias in both trials, reaching 3.42 and 5.61ºC in the outdoor tank and lab trials, respectively (Fig E in S1 Text). In both trials, the linear relationships observed were consistent across the broad range of irradiance intensities (r^2 of 0.967 and 0.999 for outdoor tank and lab trials, respectively). The measurement error did not show evidence of reaching an asymptote, even under extreme irradiances. Using in situ irradiance data paired with SBE-56 temperature data from four depths at two reefs from different ocean basins, we modeled the expected temperature error due to irradiance in different scenarios. Observed maximum irradiance from these datasets ranged from 241 to 2873 μmol photos m^{-2} s^{-1} across 1–30 m depths (Fig F in S1 Text). Uncalibrated and unshaded Hobo Pendants can overestimate temperatures substantially in shallow deployments–up to 3.83ºC at 1 m and up to 2.19ºC at 5 m (Fig 5). Even deeper deployments for uncalibrated and unshaded Hobo pendant loggers can result in maximum

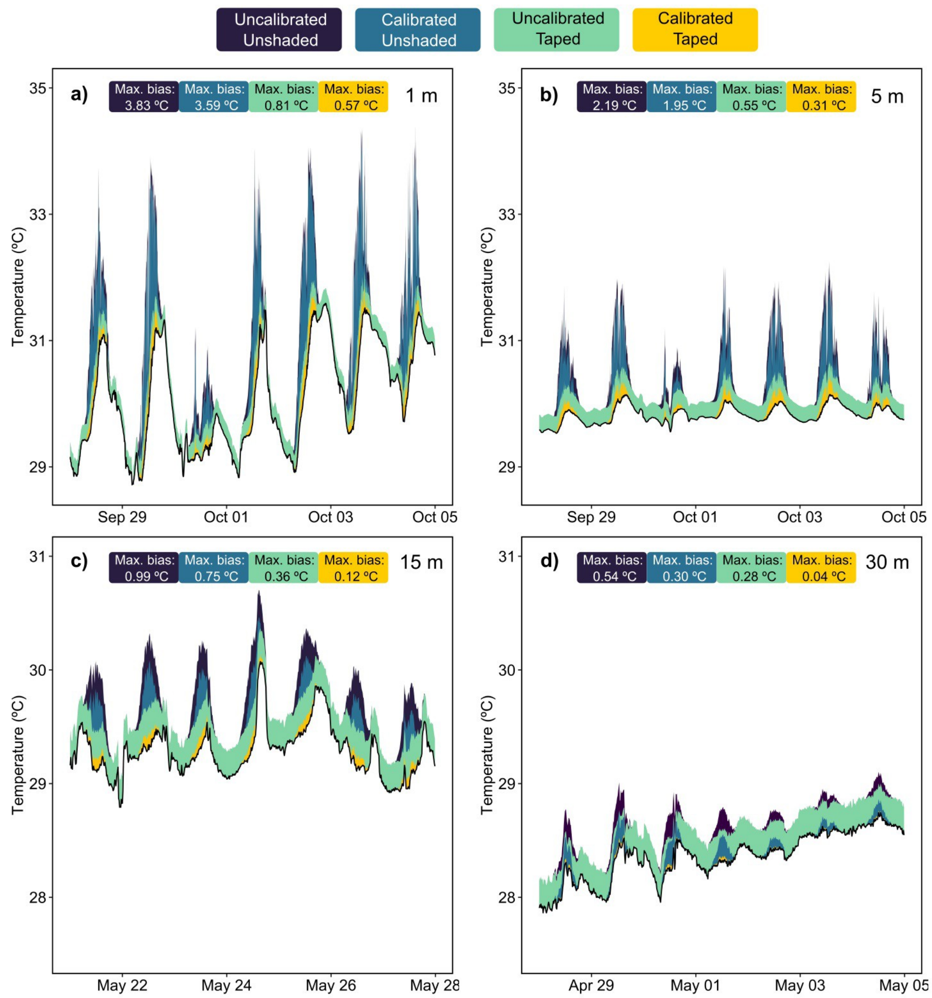

Fig 5. Estimated reductions in temperature error associated with lab-calibration or taping of Hobo Pendant loggers (UA-002-64) using in situ irradiance and temperature data from depths of 1m **(a)**, 5m **(b)**, on Palmyra Atoll, an equatorial central Pacific reef that experiences high irradiance and low light attenuation and from 15 m **(c)** and 30m **(d)** from a midshore reef in the central Red Sea with moderate turbidity and higher light attenuation. True temperature is represented by the black line (measured with Sea-Bird SBE-56) and shaded areas represent modeled error associated with different deployment methods. We modeled temperature error using the empirically-measured linear relationship derived between irradiance and temperature bias from the field shading trials (Fig 3, Table C of S1 Text). Completely unshaded and uncalibrated loggers (dark purple) suffer substantial error when irradiance is high, particularly in shallow deployments. Taping uncalibrated loggers to reduce biofouling (light green) can reduce error due to irradiance, but in shallow deployments the error can still exceed 0.8ºC. Since uncalibrated Hobo Pendant loggers tend to overestimate temperatures, calibrating loggers (blue-green) before deployment can reduce error, but loggers will still be affected by irradiance. Calibrating loggers and taping them (orange) further reduces error due to irradiance. Scales are adjusted to highlight differences between shading methods within depths rather than compare across depths. Text boxes in each panel state the maximum modeled temperature bias for each treatment based on the maximum observed irradiance for each site during the deployment period (Fig F in S1 Text).

https://doi.org/10.1371/journal.pclm.0000517.g005

bias of 0.99°C and 0.54°C at 15 m and 30 m, respectively. Calibrating loggers prior to deployment can reduce this error by ∼0.2°C, as the loggers we tested tended to overestimate temperature even under no irradiance. However, a more impactful increase in accuracy can be achieved by taping loggers, especially in shallow, high irradiance habitats. Taping a logger reduces error between roughly 50–80% depending on irradiance and depth of deployment. Nevertheless, in the high-irradiance habitats of 1 m and 5 m depths, these precautions still result in maximum bias of 0.81 and 0.55°C, respectively.

Discussion

As warming and marine heatwaves continue to transform ocean ecosystems, reliable and standardized monitoring of coastal ocean temperatures is essential. This study provides a timely update and expands on previous work that has demonstrated solar bias in commonly used in situ loggers [9,12]. We show that the recommendations from those seminal works are not being reported for most logger deployments, and concerningly, recent studies are primarily deploying loggers in shallow habitats where the risk of solar bias is high. Using standardized tests of logger performance, our findings reveal that solar bias exists, to some degree, in eight of the nine logger models we field tested. The risk of solar bias is therefore possible in many logger models, but the magnitude of bias varies between them, which has important implications for contextualizing published in situ temperature records. We hope our results serve as a call-to-action for the coral reef community to take deployment methods into consideration and to explicitly state these details when publishing in situ temperature datasets. Moreover, our findings of solar bias at low irradiances for some models suggest that even studies conducted in turbid or deep habitats may also be at risk of overestimating temperatures. This has broad implications for coral restoration, research, and conservation, given that most metrics of coral heat stress are based on the maximum temperatures they experience. As marine heatwaves continue to cause unprecedented maximum temperatures, it is imperative the coral reef community accurately measures the magnitude of these events by responsibly deploying loggers to avoid potential bias.

Beyond considering solar bias, logger performance should be appropriately matched to study objectives in order to accurately capture the temperature dynamics of interest. Logger performance in the calibration bath trial broadly reflected manufactures' specifications. Our literature survey revealed that only 14% of studies report calibrating loggers before deployment (Table A in S1 Text). Notably, across the range of logger affordability, most models exceeded their manufacturer-stated accuracies, implying most loggers can reliably measure temperatures on coral reefs if deployed properly. Most loggers had a higher error early in the temperature hold (<5 min), but stabilized with increased measurement accuracy within 10–15 min. Logger response time and accuracy is important to consider for researchers interested in high-frequency temperature variability in coral reef systems, such as upwelling [14] and shallow coastal lagoons [15]. In general, we recommend practitioners calibrate their loggers prior to deployment, particularly models that show a consistent offset from true temperatures, and to clearly report such details (see [16] for example of detailed reporting).

The magnitude of solar bias varied widely across all logger models. While some experienced no detectable temperature bias (e.g., Sea-Bird SBE-56) or only minor bias (e.g., Star-Oddi DST CT, Odyssey Xtreem PAR, and PME MiniDOT), several loggers were affected by even moderate irradiance levels. Special attention to shading must be given to all loggers deployed in shallow, clear-water habitats where irradiance often exceeds 1000 μmol m^{-2} s^{-1} (e.g., [17,18]. However, due to low light attenuation in many coral reefs, even deeper or more turbid sites can experience irradiance levels that may result in overestimations of temperature. For example, Palmyra Atoll can experience a mean irradiance of 372 μmol m^{-2} s^{-1} at 20 m depth [14], which exceeds the 0.5°C bias threshold for uncalibrated Onset Hobo Pendant, Pendant LT, and Pendant MX LT models. Our in situ irradiance data from Palmyra Atoll showed far higher irradiance for depths of 1 m or 5 m, peaking at 2873 and 1561 μmol m^{-2} s^{-1}, respectively. Unshaded loggers in those sites would drastically overestimate temperature, and even taped loggers would suffer solar bias of 0.55–0.81°C (Fig 5). Considering that >40% of recent studies report deploying loggers in these depths (Fig 1B), it is critical that loggers used in future deployments are properly shaded. While taping loggers greatly reduced the possible bias due to irradiance, it still resulted in an error exceeding 50% of the typical 1°C threshold used in metrics of thermal stress. This level of error has major implications for the interpretation of thermal stress to coral reef organisms. Besides maximum observed temperatures, heating rate (e.g., °C hr^{-1}) is an important metric that influences the coral stress response [19,20]. Given the strong linear relationship between temperature bias and irradiance of unshaded loggers, high-irradiance habitats would be incorrectly assumed to experience exceedingly high heating rates.

There is an inherent appeal to deploying loggers that can measure more than a single parameter, but such instruments must be deployed with greater attention to detail. We determined that Odyssey Xtreem PAR loggers exhibited very low bias due to irradiance but they consistently underestimated the true water temperature by 0.5–1.5˚C and therefore must be calibrated before deployment. In addition, some sensors are unsuited for deployment in "extreme" conditions, such as the PME MiniDOTs which cannot accurately record temperature higher than 35°C per the manufacturer's recommendation (Fig D in S1 Text). Researchers working in extreme habitats, including reef flats or tidal pools that regularly experience high temperatures [21–23], must carefully choose the appropriate instrumentation.

While we tested a range of brands and models, we were not able to acquire all possible options of temperature loggers and evaluate them here. Furthermore, new companies and models will inevitably continue to enter the market in the future. We encourage practitioners to assess new models for their specific needs by performing similar evaluations that we have done in this study, if possible. Comparing logger readings across a range of temperatures in a high-precision calibration bath or against a high-precision logger (e.g., SBE-56) can improve the accuracy of loggers and ensure reliable data are collected, assuming proper deployment practices are followed (e.g., shading).

Coral reefs are experiencing unprecedented heat, with 2023 temperatures on western Atlantic reefs reaching an alarming 38°C [24]. As ocean warming continues to stretch the thermal limits of coastal habitats, it is imperative that temperature measurements are accurate in order to ensure robust scientific conclusions and make informed management decisions. Loggers recording erroneously high temperatures may lead researchers to incorrectly assume that unbleached corals have exceptionally high thermal tolerances, which has direct implications for selection of individuals to use in management approaches such as assisted evolution [25]. Likewise, loggers reporting erroneously low temperatures may cause reef restoration practitioners to underestimate temperature stress at a chosen site, dooming future coral outplants. Either scenario could jeopardize research and conservation during this critical period of coral reef degradation. Our assessment reveals widespread underreporting of important details in logger deployment as well as high variability in solar bias and temperature accuracy across logger models. Based on recent literature and our evaluation of loggers, it is possible that many current temperature records are biased by at least 0.5°C, and possibly up to 2-3°C. We acknowledge it is possible that many researchers did tape or shade loggers but did not explicitly report it in their methods, and therefore solar bias in existing datasets may not be as widespread as our literature survey suggests. Furthermore, "natural" shading by biofouling organisms may mitigate the most extreme temperature errors, but the biofouling progression within deployment periods, stability of the biofouling community, and shading effect of different types of organisms would undoubtedly vary between scenarios and be difficult to quantify. In the absence of reported deployment methods, the true extent and magnitude of error cannot be evaluated. Future efforts to integrate and synthesize such data should take this uncertainty into account for datasets where logger deployment details are not provided. While wrapping loggers in tape can somewhat reduce solar bias, we recommend that shading loggers under an opaque object (e.g., in a PVC tube), as well as calibrating loggers prior to deployment, should become standard practice. We call on coral reef researchers to clearly detail their deployment methods to ensure comparable measurements between independent datasets. Implementation of these simple actions will facilitate the continued expansion of temperature monitoring by a range of stakeholders and improve our capacity to assess the ongoing impacts of ocean warming on the world's coral reef ecosystems.

Supporting information

S1 Table.
(CSV)

S1 Text.
(DOCX)

Acknowledgments

We thank Anita Giraldo-Ospina for illuminating discussions. We are grateful to Andres Espinoza and Samar Mahmoud with the KAUST Coastal Marine Resource core lab for assisting with the lab calibration bath. We thank the U.S. Fish and Wildlife Service and The Nature Conservancy for logistical support and access to the Palmyra Atoll National Wildlife Refuge (special use permit no. 12533–23016).

Author Contributions

Conceptualization: Walter A. Rich, Susana Carvalho, Steve S. Doo, Maggie D. Johnson, Michael. D. Fox.

Data curation: Walter A. Rich, Steve S. Doo, Michael. D. Fox.

Formal analysis: Walter A. Rich, Jess S. Glanz, Michael. D. Fox.

Funding acquisition: Maggie D. Johnson, Michael. D. Fox.

Investigation: Walter A. Rich, Jess S. Glanz, Gage Mele, Nicole J. Burt, Steve S. Doo, Erik C. Krieger, Lena Li, Eslam O. Osman, Michael. D. Fox.

Methodology: Walter A. Rich.

Resources: Susana Carvalho, Elizabeth A. Goergen, David J. Suggett, Maggie D. Johnson, Michael. D. Fox.

Supervision: Maggie D. Johnson, Michael. D. Fox.

Visualization: Walter A. Rich, Jess S. Glanz, Gage Mele, Michael. D. Fox.

Writing – original draft: Walter A. Rich, Michael. D. Fox.

Writing – review & editing: Walter A. Rich, Jess S. Glanz, Gage Mele, Nicole J. Burt, Susana Carvalho, Steve S. Doo, Elizabeth A. Goergen, Erik C. Krieger, Lena Li, Eslam O. Osman, David J. Suggett, Maggie D. Johnson, Michael. D. Fox.

References

1. Oliver EC, Benthuysen JA, Darmaraki S, Donat MG, Hobday AJ, Holbrook NJ, et al. Marine heatwaves. Annual Review of Marine Science. 2021; 13:313–42. https://doi.org/10.1146/annurev-marine-032720-095144 PMID: 32976730
2. Hughes TP, Kerry JT, Baird AH, Connolly SR, Dietzel A, Eakin CM, et al. Global warming transforms coral reef assemblages. Nature. 2018; 556(7702):492–6. https://doi.org/10.1038/s41586-018-0041-2 PMID: 29670282
3. Hoegh-Guldberg O. Climate change, coral bleaching and the future of the world's coral reefs. Marine and Freshwater Research. 1999; 50(8):839–66.
4. Reimer JD, Peixoto RS, Davies SW, Traylor-Knowles N, Short ML, Cabral-Tena RA, et al. The Fourth Global Coral Bleaching Event: Where do we go from here? Coral Reefs. 2024;1–5.
5. Jokiel PL, Coles S. Effects of temperature on the mortality and growth of Hawaiian reef corals. Marine Biology. 1977; 43:201–8.
6. Craig P, Birkeland C, Belliveau S. High temperatures tolerated by a diverse assemblage of shallow-water corals in American Samoa. Coral reefs. 2001; 20:185–9.
7. Smith LW, Birkeland C. Effects of intermittent flow and irradiance level on back reef *Porites* corals at elevated seawater temperatures. Journal of Experimental Marine Biology and Ecology. 2007; 341 (2):282–94.
8. Oliver T, Palumbi S. Do fluctuating temperature environments elevate coral thermal tolerance? Coral reefs. 2011; 30(2):429–40.
9. Bahr KD, Jokiel PL, Rodgers KS. Influence of solar irradiance on underwater temperature recorded by temperature loggers on coral reefs. Limnology and Oceanography: Methods. 2016; 14(5):338–42.
10. Hughes TP, Anderson KD, Connolly SR, Heron SF, Kerry JT, Lough JM, et al. Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. Science. 2018; 359(6371):80–3. https://doi.org/10.1126/science.aan8048 PMID: 29302011
11. Boström-Einarsson L, Babcock RC, Bayraktarov E, Ceccarelli D, Cook N, Ferse SC, et al. Coral restoration–A systematic review of current methods, successes, failures and future directions. PloS one. 2020; 15(1):e0226631. https://doi.org/10.1371/journal.pone.0226631 PMID: 31999709
12. Lentz SJ, Churchill JH, Marquette C, Smith J. Evaluation and recommendations for improving the accuracy of an inexpensive water temperature logger. Journal of Atmospheric and Oceanic Technology. 2013; 30(7):1576–82.
13. Hein M, Banaszack A, Dallison T, Deri W, Grimsditch G, Jacob F, et al. Mapping the global funding landscape for coral reef restoration. International Coral Reef Initiative. 2021;1–23.
14. Williams GJ, Sandin SA, Zgliczynski BJ, Fox MD, Gove JM, Rogers JS, et al. Biophysical drivers of coral trophic depth zonation. Marine Biology. 2018; 165:1–15.
15. Camp EF, Schoepf V, Mumby PJ, Hardtke LA, Rodolfo-Metalpa R, Smith DJ, et al. The future of coral reefs subject to rapid climate change: lessons from natural extreme environments. Frontiers in Marine Science. 2018; 5:4.
16. DeCarlo TM, Carvalho S, Gajdzik L, Hardenstine RS, Tanabe LK, Villalobos R, et al. Patterns, drivers, and ecological implications of upwelling in coral reef habitats of the southern Red Sea. Journal of Geophysical Research: Oceans. 2021; 126(2):e2020JC016493.
17. Stewart HA, Kline DI, Chapman LJ, Altieri AH. Caribbean mangrove forests act as coral refugia by reducing light stress and increasing coral richness. Ecosphere. 2021; 12(3):e03413.
18. Winters G, Loya Y, Röttgers R, Beer S. Photoinhibition in shallow-water colonies of the coral *Stylophora pistillata* as measured in situ. Limnology and Oceanography. 2003; 48:1388–93.
19. McLachlan RH, Price JT, Solomon SL, Grottoli AG. Thirty years of coral heat-stress experiments: a review of methods. Coral Reefs. 2020; 39(4):885–902.
20. Voolstra CR, Alderdice R, Colin L, Staab S, Apprill A, Raina JB. Standardized Methods to Assess the Impacts of Thermal Stress on Coral Reef Marine Life. Annual Review of Marine Science. 2024; 17. https://doi.org/10.1146/annurev-marine-032223-024511 PMID: 39116436
21. Coles SL, Riegl BM. Thermal tolerances of reef corals in the Gulf: A review of the potential for increasing coral survival and adaptation to climate change through assisted translocation. Marine pollution bulletin. 2013; 72(2):323–32. https://doi.org/10.1016/j.marpolbul.2012.09.006 PMID: 23058810
22. Dandan S, Falter J, Lowe R, McCulloch M. Resilience of coral calcification to extreme temperature variations in the Kimberley region, northwest Australia. Coral Reefs. 2015; 34:1151–63.
23. Rich WA, Carvalho S, Cadiz R, Gil G, Gonzalez K, Berumen ML. Size structure of the coral *Stylophora pistillata* across reef flat zones in the central Red Sea. Scientific Reports. 2022; 12(1):13979.

24. Hobday AJ, Burrows MT, Filbee-Dexter K, Holbrook NJ, Sen Gupta A, Smale DA, et al. With the arrival of El Niño, prepare for stronger marine heatwaves. Nature. 2023; 621(7977):38–41.

25. Humanes A, Beauchamp EA, Bythell JC, Carl MK, Craggs JR, Edwards AJ, et al. An experimental framework for selectively breeding corals for assisted evolution. Frontiers in Marine Science. 2021; 8:626.