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Key Points:

- Quantified biogeochemical and carbonate system dynamics using autonomous sensors in an understudied region
- Sensor pH-DO and total alkalinity (TA) observations show net autotrophic reef, with net community production accounting for 87% of carbonate variability
- Red Sea reef TA–DIC slopes in 2023 match 1997–2013 values, suggesting persistent metabolism amid globally shifting reef dynamics

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Metabolic Dynamics of an Offshore Coral Reef in the Central Red Sea: Observations From Autonomous Sensors

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Abstract Coral reefs are increasingly threatened by local and global stressors. Traditional visual reef monitoring methods are time-intensive and provide only a snapshot of reef condition. Recent efforts aim to measure reef metabolism, or the balance of net community production (NCP) and net community calcification (NCC), as coral reef carbonate budgets shift globally toward declining NCC and greater NCP influence. Resolving these metabolic changes requires comprehensive, high-resolution biogeochemical measurements unattainable by traditional sampling alone. This work reports the novel multi-month deployment of a high-resolution, autonomous total alkalinity (TA) sensor alongside pH, partial pressure of CO₂, and dissolved oxygen (DO) sensors at Cement Wreck, a central Red Sea offshore reef. Observations from the back reef and fore reef revealed strong diel variability and distinct reef-zone biogeochemical dynamics linked to contrasting benthic compositions. On the back reef, pH and DO were tightly coupled and closely matched a Redfield-based model ($R^2 = 0.943$), while the fore reef relationship was weaker ($R^2 = 0.145$). TA observations allowed characterization of the back reef carbonate system, with TA–DIC stoichiometry yielding a slope of 0.26, indicating NCP accounted for approximately 87% of observed carbonate system variability. Compared to global reefs, Cement Wreck exhibits high % NCP contribution. However, the observed 2023 TA–DIC slope closely matches those from Red Sea observations from 1997 to 2013, suggesting that while reefs around the world shift, Red Sea reefs like Cement Wreck represent a persistent metabolic state. Scaled-up autonomous deployments, like the one presented here, will better enable predictions of global reef health in future conditions.

Plain Language Summary Globally, coral reefs are threatened by rising temperatures, changes in seawater chemistry, pollution, and overfishing. The health of coral reefs is traditionally monitored by reef community composition through visual analysis, however changes in surrounding seawater chemistry can provide insight into reef processes and holistically monitor reef health. Here, we deploy a newly developed total alkalinity (TA) sensor, alongside commercially available pH and oxygen sensors on a coral reef in the Red Sea. Autonomous sensors allow the collection of high-resolution data on reef seawater chemistry, including daily cycles and changes over time, with a cost per data point much lower than traditional discrete samples. Furthermore, the TA sensor allows us to evaluate the relative balance between the reef-building processes and reef-eroding processes occurring, which are important parameters when evaluating a reef's present and future health. We found that the reef studied here was strongly influenced by organic production, and that this signal closely matched Red Sea observations from the last 25 years. This suggests that some Red Sea reefs may represent a persistent metabolic state rather than a recent shift. The Red Sea lacks high-resolution carbonate-system observations, and this deployment contributes to baseline understanding of Red Sea reef metabolism and carbonate budgets.

1. Introduction

Coral reef ecosystems are among the most biodiverse and valuable ecosystems in the world, supporting human livelihoods through fisheries and tourism, while also providing coastal protection (Bruckner, 2002; Moberg & Folke, 1999). Reefs are biogeochemical hotspots, where metabolic processes such as photosynthesis, respiration, calcification, and dissolution recycle carbon and nutrients across a range of timescales (Wagner et al., 2020; Reaka-Kudla, 1997; S. V. Smith, 1973; Gattuso et al., 1998; Cyronak et al., 2018). Organic carbon is fixed via

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photosynthesis by symbiotic algae (zooxanthellae) and other primary producers, while inorganic carbon is precipitated through calcium carbonate (CaCO_3) production (calcification). Hard corals build skeletons with aragonite, while calcifying algae precipitate aragonite or calcite (Cabioch & Giraud, 1986; Constantz, 1986). On coral-dominated reefs, calcification is typically biogenic, although abiotic calcification exists through the precipitation of CaCO_3 in favorable thermodynamic conditions (Bialik et al., 2022; Courtney & Andersson, 2025). Collectively, biogenic calcification by reef-building taxa construct and maintain reef structural foundation (Erez et al., 2011; Pilcher, 2001). Conversely, reef structure is reduced when calcium carbonate dissolves (dissolution) and/or removed through erosion. During the day, coral reefs sequester CO_2 and produce oxygen (O_2) through photosynthesis, while simultaneously releasing CO_2 through calcification and respiration. Calcification rates decrease at night (Moya et al., 2006), making respiration the dominant metabolic process and increasing seawater CO_2 at night. The cyclic succession of photosynthesis and respiration drives pronounced diel signals in oxygen and CO_2 (and consequently pH) (Cryer et al., 2023; Suzuki et al., 1995). The magnitude of these cycles is determined by the relative balance of net community production (gross primary production minus respiration; NCP) and net community calcification (gross calcification minus dissolution; NCC). This balance of NCP and NCC indicates whether a reef is a net source or sink of CO_2 to the atmosphere at any given time and is often considered to be a vital signal of reef health (Kayanne, 2025).

Reef health is defined by both benthic characterization and biogeochemical function. For a coral reef to maintain its structure and support the diverse communities dependent on reef structures, calcification rates must exceed those of dissolution, erosion (Andersson & Gledhill, 2013; Erez et al., 2011; Kleypas et al., 1999) and sea level rise (Perry et al., 2018). Reefs with high coverage of hard coral and crustose coralline algae (CCA) are often NCC-driven, while algal-dominated reefs are NCP-driven (J. E. Smith et al., 2016). Additionally, reduced NCC often reflects a stressed or degraded reef that may be undergoing a phase shift to macroalgal dominance (Hughes et al., 2007). A healthy reef not only has high coral cover, but also active net reef growth and accretion over time (Andersson & Gledhill, 2013). It is important to note however, that the metabolic balance of a reef is highly dependent on many other factors including geomorphology, water flow, and residence time (Falter et al., 2013). So, while it is logical to consider that reefs with a greater abundance of active reef-builders (hard corals, CCA) will be “healthier,” reef condition is best understood by holistic metrics that characterize functions and trajectories of the whole ecosystem.

Reductions in calcification are increasingly linked to anthropogenic-induced environmental stressors, including ocean acidification (OA) and rising sea surface temperatures (SST) (Erez et al., 2011; Hoegh-Guldberg et al., 2007). Rising SST often result in coral bleaching, the process during which corals expel their zooxanthellae symbionts, removing their ability to photosynthesize and reducing their ability to calcify (Heron et al., 2016; Hughes et al., 2017). As ocean pH decreases, through the continuous absorption of anthropogenic CO_2 (Doney et al., 2009), saturation states of calcite and aragonite decline. Lower saturation states make calcification energetically expensive for corals and make dissolution more likely, especially at night (Erez et al., 2011; Eyre et al., 2018; Hoegh-Guldberg et al., 2007). Additionally, during stress events (e.g., heat waves), corals tend to maximize their chances of survival by temporarily reducing calcification (Schoepf et al., 2015; D’Olivo & McCulloch, 2017), showing that even without a net loss of benthic calcifiers, these events impact metabolic processes. Globally, coral reef ecosystems are exhibiting declining NCC and increasing NCP (K. L. Davis et al., 2021). Between 1998 and 2015, net calcification rates have declined ~26% in the Red Sea in part due to declining coral cover and coral calcification rates (Steiner et al., 2018).

In a reef system, metabolic processes drive changes in the seawater’s carbonate chemistry. NCP mainly affects dissolved inorganic carbon (DIC) concentration through photosynthesis and respiration, while NCC changes both DIC and total alkalinity (TA) in a 2:1 ratio (Cyronak et al., 2018; Gattuso et al., 1998). Characterizing the carbonate system of a coral reef environment at a high temporal resolution can therefore shed light on the dominant metabolic processes and their rates. Characterizing the marine carbonate system requires knowledge of two of the four measurable carbonate system variables (DIC, TA, pH, and the partial pressure of carbon dioxide (pCO_2)), along with temperature, salinity, and pressure (Millero, 1995, 2007; Park, 1969). Currently, only pH and pCO_2 sensors are widely available for autonomous in situ observations (Martz et al., 2015). However, the environmental covariance of pH and pCO_2 makes them the least desirable combination because this pairing can result in substantial uncertainties in derived TA and DIC, which is sub-optimal for NCP and NCC calculations (Orr et al., 2018; Raimondi et al., 2019; Sutton & Sabine, 2023). In the open ocean, TA can often be estimated from its

conservative relationship with salinity (Cai et al., 2010; Lee et al., 2006; Millero et al., 1998; Takahashi et al., 2014), but such approaches are unreliable in coastal reef environments where mixing, riverine input, and strong metabolic activity decouple TA from salinity. Therefore, direct in situ observations of TA or DIC, alongside pH or pCO₂, are essential for characterizing reef metabolism.

The ability to monitor the biogeochemical processes occurring on coral reefs provides crucial insights into ecosystem function by capturing natural variability, as well as establishing baselines for detecting long-term changes or climatic effects. Visual indicators, such as reef benthic community composition, often show threshold responses to environmental stressors, whereas shifts in seawater biogeochemistry provide a more reliable early detection of reef health (Hughes et al., 2010). This is particularly important because global net calcification rates are decreasing at a faster rate than the concurrent decline in calcifier cover (K. L. Davis et al., 2021). Yet, high-resolution observations from coral reefs remain scarce. In addition, complex reef geomorphology and shallow bathymetry (Blanchon, 2011) hinder high-resolution data via traditional discrete sampling. Advances in autonomous sensors offer improved capabilities, including providing sustained, fine-scale measurements (Cryer et al., 2020; Hammermeister et al., 2025; Schaap et al., 2025; Takeshita et al., 2018; Yin et al., 2021). While sensor technologies have continued to develop over the past several years, expanding high-frequency reef pH data (e.g., Cryer et al. (2023); Cyronak et al. (2020); McMahon et al. (2018); Saderne et al. (2019)), autonomous carbonate measurements and parameter-relationship records from coral reef observations are still limited, particularly in the Red Sea, where the carbonate system remains understudied.

Here, we investigate reef metabolism and carbonate dynamics at an offshore central Red Sea reef using novel autonomous sensors. By collecting a continuous high-resolution multi-month data set, we capture seasonal trends, resolve diel variability, and examine biogeochemical relationships between two different sites and their benthic compositions. We are able to fully constrain the carbonate system of the back reef zone and derive its metabolic balance. Additionally, we report the novel sustained deployment of an autonomous Lab-On-Chip TA sensor on a Red Sea coral reef building on previous autonomous TA reef system deployments (Briggs et al., 2020; Pezner et al., 2021). This work provides a unique benchmark for evaluating reef carbon cycling under extreme thermal and saline conditions and offering new insights into coral reef responses to ongoing ocean and climate change.

2. Materials and Methods

2.1. Study Site

Sensor mooring observations were conducted at Cement Wreck Reef (22°23' N, 38°51' E), located approximately 20 km off the coast of Saudi Arabia in the central Red Sea (Figure 1). The Red Sea basin spans 2,270 km from 30°N to 12°N, dividing Africa and Asia, and offers a natural test site for reef carbonate cycling under extreme conditions. It is characterized by its high seawater temperature and salinity, and is home to some of the world's most productive, endemic, and diverse coral ecosystems, with reef frameworks spanning its coastline (DiBattista et al., 2016; Fine et al., 2019). In the central Red Sea, year-round temperatures for an offshore reef range from 25 to 32°C, but can exceed 37°C in certain reef zones, such as the reef flat, back reef, or other protected regions (Roik et al., 2016; K. A. Davis et al., 2011; Rich, Carvalho, Cadiz, et al., 2022). Cement Wreck is an offshore coral reef that is part of the Shib Nazar reef system, which spans approximately 10 km in the North–South direction (Rich, Carvalho, & Berumen, 2022; Roik et al., 2018). Cement Wreck was chosen as the study site for this work because of its protected, shallow (~1.5 m) back reef, and its exposure to offshore seawater exchange. The reefs within the Shib Nazar system are dominated by the hermatypic coral species *Stylophora pistillata*, which are the sole branching coral species found on the Cement Wreck back reef (Rich, Carvalho, & Berumen, 2022). However, benthic surveys conducted as part of this study show that the back reef of Cement Wreck is characterized by high rock cover and greater macroalgal cover than hard coral cover, whereas the fore reef has greater hard coral and CCA cover. Full details of the benthic community composition analysis are presented in the Results section.

2.2. Autonomous Sensor Mooring

Two fixed-point sensor moorings were deployed on Cement Wreck reef. The primary mooring was deployed on the back reef from 19 October–12 December 2023, and the secondary mooring was deployed on the fore reef slope of Cement Wreck from 26 October–30 November 2023 (Figure 2).

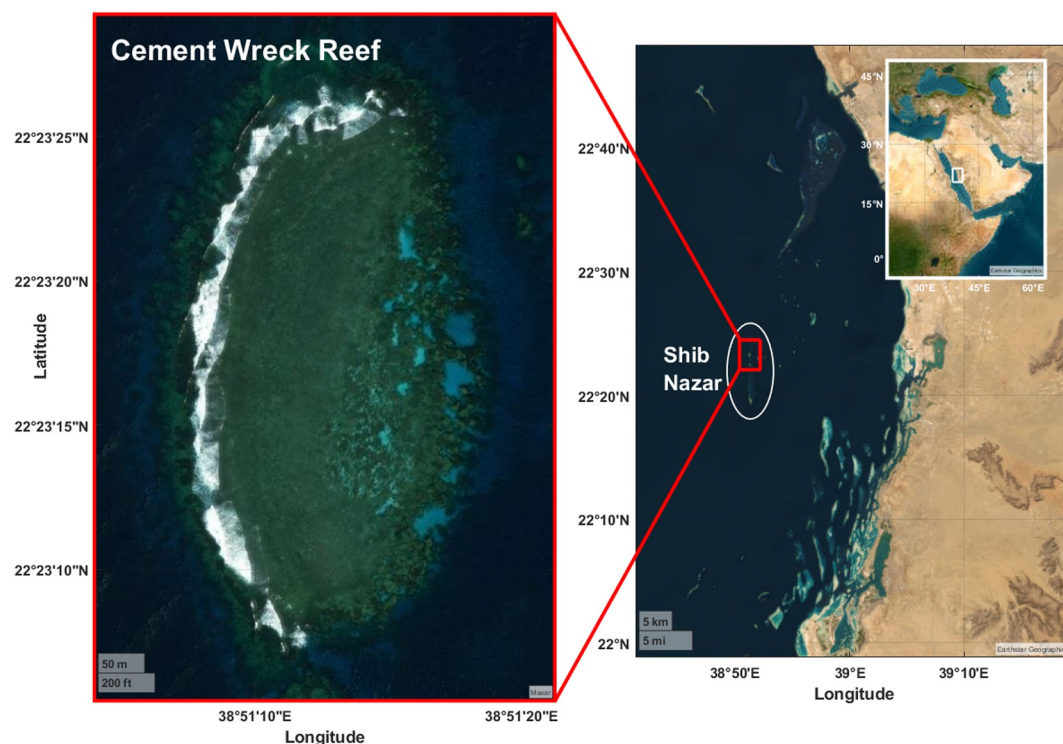


Figure 1. Location of Cement Wreck Reef (left) in the central Red Sea (right), part of the Shib Nazar reef system (circled in white, right).

The primary sensor mooring was a custom-built steel frame fixed-point observing platform originally developed by the National Oceanography Centre (NOC) for the Commonwealth Marine Economies Program (<https://cmeprogramme.org/>). Without instrumentation, the frame weighs 20 kg, is 0.75 m in height, and has a base footprint spanning 0.5 m in width. The frame was fitted with several oceanographic sensors including a Lab-On-Chip (LOC) pH sensor (NOC), a LOC TA sensor (NOC), SAMI-CO₂ sensor (<http://www.sunburstsensors.com>), a SBE 37 SMP-ODO MicroCAT Conductivity-Temperature-Depth/dissolved oxygen (DO) sensor (CTD-DO; SeaBird Scientific), and an ECO Triplet-w chlorophyll sensor (SeaBird Scientific) and deployed at a depth of

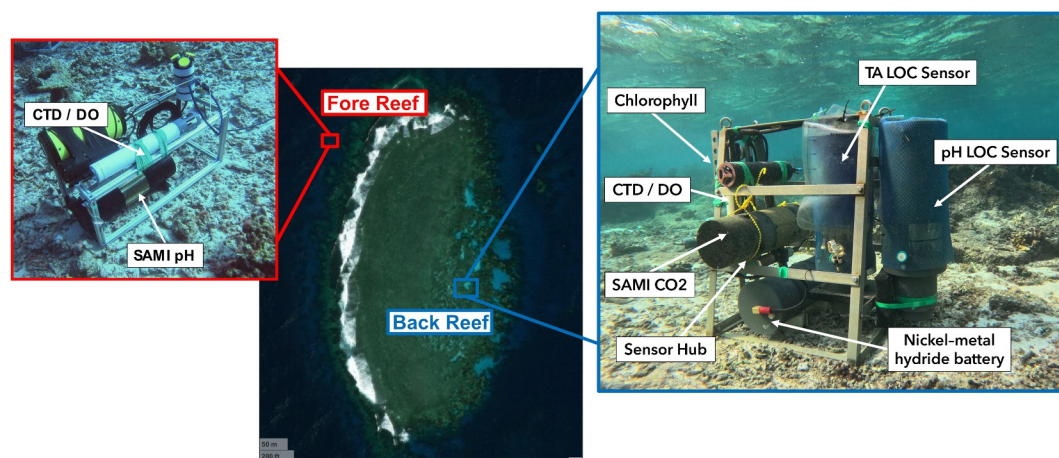


Figure 2. Sensor mooring frames deployed at Cement Wreck Reef. The primary sensor mooring (zoomed inset image right, outlined in blue) is situated in a particularly shallow region on the back reef at ~1.5 m depth, and secondary sensor mooring (zoomed inset image left, outlined in red) on the fore reef slope at ~15 m depth, both with labeled oceanographic sensors integrated.

Table 1
Overview of Sensor Deployments at Cement Wreck Reef Back Reef and Fore Reef Slope

Location	Sensor	Start date	End date	Duration (days)	Frequency f
Back Reef	Lab-On-Chip pH (National Oceanography Center)	19/10/2023	12/12/2023	54	1 hr
	Lab-On-Chip TA (National Oceanography Center)	02/11/2023	04/12/2023	32	1 hr/30 min
	CTD-DO (SeaBird Scientific)	19/10/2023	12/12/2023	54	2 min/5 min
	chlorophyll (SeaBird Scientific)	26/10/2023	02/11/2023	39	2 min
	Sami-CO2 (Sunburst Sensors LLC)	02/11/2023	09/11/2023	27	30 min
Fore Reef	CTD-DO (Idronaut)	26/10/2023	30/11/2023	35	5 min
	Sami-pH (Sunburst Sensors LLC)	26/10/2023	30/11/2023	35	1 hr

Note. Listed are sensor type, manufacturer, deployment start and end dates, duration, and measurement frequency.

~1.5 m (Figure 2). Only one TA sensor was available for this deployment, and because the LOC pH and TA sensors required weekly servicing, the TA sensor was placed on the shallow, more accessible back reef. Additionally, the back reef was the priority site for resolving TA–DIC dynamics due to its expected stronger diel carbonate-system variability and greater metabolic modification of resident water.

The LOC pH sensor measures pH on the total proton scale (pH_T) with a precision of 0.001 pH units using photometric determination with the purified indicator dye meta-Cresol Purple. Relative to validation seawater samples, the LOC pH sensor has 0.003 ± 0.022 accuracy and a combined standard measurement uncertainty of ± 0.010 pH units (Yin et al., 2021). The LOC TA sensor methodology is based on single-point acid titration to a photometrically determined endpoint $\text{pH} = 3.0\text{--}3.5$. The titration is done using hydrochloric acid (HCl) titrant containing unpurified Bromophenol Blue (BPB) indicator dye. The titrant consisted of 0.03 M HCl and 0.00015 M BPB in 0.6 M NaCl, formulated to a salinity of 41.52 psu, aligning with the high-salinity conditions of the Red Sea. During deployment, the TA sensor periodically measured “CO2-in-seawater Reference Materials” (RMs; Scripps Institution of Oceanography, USA) which are stored onboard the sensor. These measurements were used to determine sensor-specific calibration coefficients that enable in situ recalibration of the sensor as described in Schaap et al. (2025). Two RMs were plumbed on board the TA sensor for this purpose, Batch 206 (certified $[\text{TA}] = 2193.88 \mu\text{mol kg}^{-1}$) coupled with either Batch 162 (certified $[\text{TA}] = 2403.72 \mu\text{mol kg}^{-1}$) or Batch 164 (certified $[\text{TA}] = 2309.32 \mu\text{mol kg}^{-1}$). These RMs were analyzed after every sixth seawater measurement. The TA sensor has a precision and accuracy better than $5 \mu\text{mol kg}^{-1}$ in ideal conditions (Schaap et al., 2025). Here, we present the first deployment of the LOC TA sensor in a high-salinity (>38 psu) and high-temperature ($>30^\circ\text{C}$) environment. The LOC pH and TA sensors sampled every hour, except for the period 30 November–04 December 2023, when the TA sensor made measurements every 30 min (Table 1). All waste produced by both LOC sensors was collected and stored onboard each sensor and safely disposed of back onshore.

The CTD-DO on the primary sensor mooring measured in situ temperature (T), salinity (S), and DO every two minutes (Table 1), and was independently powered by 12 lithium AA batteries. Corresponding in situ T and S data from the CTD-DO were made available to the LOC pH and TA sensors when they made a measurement via a 1 Hz stream facilitated by the Sensor Hub. The Sensor Hub was developed by NOC specifically to simplify the integration of multiple sensors on autonomous platforms, and is fully programmable, allowing it to poll for samples from the CTD-DO. Power was provided to the LOC pH sensor, LOC TA sensor, and Sensor Hub by a custom-made rechargeable nickel-metal hydride battery pack enclosed within polyvinyl chloride (PVC) housing rated to 100 m depth.

The SAMI-CO2 is a commercially available sensor that measures the partial pressure of CO_2 (pCO_2) using the colorimetric reagent method (DeGrandpre et al., 1995), and made measurements every 30 min. The SAMI-CO2 was powered from a self-contained 8 alkaline D-cell battery pack and has an accuracy and precision of $\pm 2 \mu\text{atm}$

and $<1 \mu\text{atm}$ respectively (DeGrandpre et al., 1995; Lai et al., 2018). The ECO Triplet-w recorded measurements every 2 minutes as the average from a burst of five 1 Hz optical fluorescence signals. Chlorophyll concentration was then derived using the calibrated coefficients and scale factor specific to the instrument provided by the manufacturer.

The secondary sensor mooring was comprised of a SAMI-pH Sensor and a CTD-DO situated at ~ 15 m water depth (Figure 2). The SAMI-pH sensor is a commercially available sensor that measures pH_T based on the spectrophotometric method in which a diprotic sulfonephthalein pH indicator is used (Lai et al., 2018). The SAMI-pH sensor has a reported accuracy and precision of ± 0.003 and <0.001 pH units respectively (Sunburst Sensors, LLC, Shangguan et al., 2022; Seidel et al., 2008) and for this work, made measurements every hour on the fore reef. The Idronaut CTD-DO sensor in the forereef took measurements of T, S, DO (polarographic), and pressure (P) every 5 minutes. An overview of each sensor's reef location, deployment duration, and frequency can be found in Table 1.

2.3. Data Processing

On the back reef, corresponding in situ T and S measurements from the CTD-DO polled by the sensor hub were used by the LOC pH and TA sensors to determine pH_T and TA as described by Yin et al. (2021) and Schaap et al. (2025), respectively.

The operation and data processing for the remaining sensors (SBE CTD-DO, ECO Triplet-w, SAMI-CO₂, Idronaut CTD-DO, and SAMI-pH) were in accordance with the standard operating procedures and software provided by the manufacturers. Using the Hampel Filter method, data within a 1-hr rolling window that differed by more than three standard deviations from the local median were detected as outliers and removed (Hampel, 1974; The Mathworks Inc, 2024). The Hampel Filter was chosen based on timeseries nature of the data set and the high diel cycles seen throughout (Liu et al., 2004; Roos-Hoefgeest Toribio et al., 2025).

2.3.1. Carbonate System Calculations

The speciation of the marine carbonate system on the Cement Wreck back reef was constrained using MATLAB (version v3.1.1) CO2SYS package (Lewis & Wallace, 1998; Orr et al., 2018; Sharp & Byrne, 2021; The Mathworks Inc, 2024), with sensor obtained in situ TA, pH_T , S, T, and set $P = 1.5$ dbar as input parameters. Nutrient (phosphate, silicate, and ammonia) concentrations were not measured during this deployment and were therefore set to 0 for CO2SYS computations. This assumption is reasonable for the Red Sea, which is oligotrophic and generally characterized by nutrient deficiencies (Acker et al., 2008; Raitso et al., 2013). A sensitivity analysis using mean nutrient concentrations from central Red Sea reefs reported by Roik et al. (2016) changed derived DIC by $\leq 0.1 \mu\text{mol kg}^{-1}$, pCO_2 by $\leq 0.03 \mu\text{atm}$, and Ω_{arag} by ≤ 0.0003 , confirmed this assumption.

In accordance with the recommendations from A. Dickson et al. (2007), CO2SYS computations used the dissociation constants of carbonic acid (K_1 and K_2) from Lueker et al. (2000), KSO₄ from A. G. Dickson (1990), KF from Perez and Fraga (1987), and total boron concentration from Lee et al. (2010) to derive DIC, aragonite saturation state (Ω_{arag}), and partial pressure of CO₂ (pCO_2) on the back reef of Cement Wreck.

2.3.2. Sensor Validation Efforts

During the final week of the deployment, two supplementary RMs were plumbed on the TA sensor, in addition to the two certified RMs assigned for the determination of the sensor calibration coefficients throughout the deployment. The supplementary RMs were a high TA RM (Scripps, Batch 206 with 20 mg NaHCO₃ added) and a certified RM with lower TA (Scripps, Batch 186). The supplementary RMs were used to verify the range of the sensor. The sensor TA determination in the additional RMs was programmed to occur in sequence with the measurements in the ambient seawater and in the certified RMs assigned for sensor calibration. The sensor TA determined in the supplementary RMs was in good agreement with the expected values. We consider this to validate the observed diel TA trend on the back reef and the TA versus DIC slopes. Both the LOC pH sensor (deployed on the back reef) and the SAMI-pH sensor (deployed in the fore reef) were simultaneously verified against the same certified TRIS buffer post-deployment. Each instrument reported pH values that matched the known TRIS value within stated uncertainty and no systematic bias relative to one another. The remaining sensors (e.g., CTD, DO) are community-accepted as routine mooring instrumentation without regular co-samples

validation. Each of these sensors were factory-calibrated (or calibrated to manufacturer specifications) prior to deployment.

2.4. Metabolic Analysis

To evaluate the role of metabolic processes in the study sites, the relationship between measured pH_T and DO was plotted and compared to a reference Photosynthesis:Respiration (P:R) model, as first used by Frieder et al. (2012) and applied to coral reefs in Cryer et al. (2023). The P:R model uses the Redfield Ratio (Equation 1; Anderson, 1995) to convert a given change in DO (ΔO_2) to ΔDIC through net photosynthetic uptake or release of CO_2 (ΔCO_2). The associated change in TA (ΔTA) resulting from proton production or removal during nutrient uptake and release associated with respiration and photosynthesis is then calculated from Redfield nutrient stoichiometry using Equation 2 (Frieder et al., 2012; Stumm & Morgan, 1996). Finally, the resulting (ΔpH) was computed from ΔTA and ΔDIC using CO2SYS. This method yielded the reference pH–DO relationship in the system assigned by the P:R Redfield Stoichiometry. Deviation of measured data from this P:R model reference line is indicative of additional processes occurring.

$$\Delta\text{CO}_2 = \frac{\Delta\text{O}_2}{-150/106} \quad (1)$$

$$\Delta\text{TA} = \frac{\Delta\text{CO}_2}{-18/106} \quad (2)$$

The P:R model assumes that (a) any contributions to the DIC and TA budget from calcification or carbonate dissolution will be evident in ΔpH without effect on ΔDO , and (b) the contribution to the DIC budget from CO_2 air-sea fluxes is comparatively small. Back reef median TA and DIC values (alongside in situ T,S,P, and density) were input to the P:R model to initialize the pH–DO reference line. The fore reef site, which did not have TA measurements, used back reef median TA and DIC derived from fore reef pH and back reef TA as model inputs. This use of back reef median TA was limited to initializing the model comparison and was not used to interpret carbonate chemistry or NCP/NCC in the fore reef. Initial carbonate-system conditions do not affect the slope of the P:R model reference line, rather it only changes its placement (y-intercept) on the graph (Cryer et al., 2023). For comparison with observed pH and DO relationships at each site, a subset of the P:R model based on the site-specific range of variables was fitted to a curve using linear least squares regression.

Derived DIC and observed TA measurements on the back reef over the course of the deployment were analyzed using linear least squares regression. The relative % influence of NCP on changes in DIC was calculated according to Equation 3 (Cyronak et al., 2018):

$$\%\text{NCP} = \left(1 - \frac{m_{\text{TA-DIC}}}{2}\right) \times 100 \quad (3)$$

where $m_{\text{TA-DIC}}$ is the slope of the TA–DIC regressions. For all calculations, TA and DIC data were not normalized to salinity because our site was an offshore reef with minimal salinity variability in a region without major river (freshwater) input or heavy precipitation. In addition, the absence of a well-defined region-specific oceanic or freshwater end-member and linear TA–S relationship could introduce data artifacts or unnecessary error into our results (Courtney et al., 2022; Jiang et al., 2014).

2.5. Benthos Characterization

On the back reef, benthic cover was quantified from an averaged quadrat image analysis (0.5×0.5 m, $n = 5$) collected from randomly placed quadrats within 5 m of the sensor frame and photographed using a GoPro HERO12 Black (<https://gopro.com/>). Each image was analyzed using CoralNet (<https://coralnet.ucsd.edu/>), where 25 stratified random points per image were manually classified according to sub-functional groups: Hard coral, soft coral, sponge, other invertebrates, calcifying algae, CCA, macroalgae, dead coral, rubble, rock, and sand. Benthos characterization on the fore reef used randomly selected still image frames taken from video surveys within 5 m of the sensor site (using a GoPro HERO12 Black). Using the known sensor frame size for scale reference, the images were adjusted to represent an estimated 0.5×0.5 m quadrat, and analyzed using

Table 2

Summary of Physical, Biogeochemical, and Carbonate Chemistry Observations at Cement Wreck Reef From the Back Reef and Fore Reef Sensor Moorings

Location	Variable	Min–Max (range)	Mean $\pm$ SD	<i>n</i>
Back Reef	Temperature ($^{\circ}\text{C}$)	28.71–33.37 (4.66)	30.60 ± 0.73	38,559
	Salinity (psu)	38.67–39.76 (1.09)	39.37 ± 0.10	38,495
	DO ($\mu\text{mol/kg}$)	55–288 (408.51)	173.13 ± 53.46	38,556
	[O ₂] %	13–243 (230)	94 ± 30	38,572
	Chlorophyll ($\mu\text{g/L}$)	0.01–0.44 (0.43)	0.13 ± 0.06	16,897
	pH	7.80–8.30 (0.50)	7.98 ± 0.07	1,183
	TA ($\mu\text{mol/kg}$)	2406–2565 (159)	2522.60 ± 26	871
	pCO ₂ (μatm)	214–1743 (1529)	537 ± 148	1,479
	Derived pCO ₂ (μatm)	228–825 (598)	516 ± 103	755
	Derived DIC ($\mu\text{mol/kg}$)	1871–2297 (426)	2156 ± 66	755
	Derived Ω_{Ar}	2.90–6.15 (3.24)	4.07 ± 0.53	755
Fore Reef	Temperature ($^{\circ}\text{C}$)	29.89–31.58 (1.68)	30.91 ± 0.31	8,007
	Salinity (psu)	39.1–39.52 (0.40)	39.38 ± 0.04	7,933
	DO ($\mu\text{mol/kg}$)	81–370 (290)	172 ± 25	7,844
	[O ₂] %	44–203 (159)	94 ± 14	8,025
	pH	7.91–8.11 (0.20)	8.05 ± 0.02	899

Note. For each parameter, minimum–maximum (range), mean $\pm$ standard deviation (SD), and number of observations (*n*) are reported.

CoralNet with the same routine used for the back reef analysis ($n = 5$). These benthic surveys were designed to provide representative benthic cover estimates around each sensor deployment rather than a comprehensive ecological assessment. Therefore, the resulting benthic compositions are used here to support interpretation of the sensor-observed biogeochemical differences between sites.

3. Results

The two sensor moorings captured high-resolution biogeochemical and carbonate observations across the back reef and fore reef zones of Cement Wreck Reef (Figures 1 and 2). These data reveal distinct environmental processes, diel variability, and spatial contrasts linked to benthic compositions. A complete summary of the physical, biogeochemical, and carbonate properties recorded at both sites is provided in Table 2.

3.1. Physical Setting and Biogeochemical Conditions

On the back reef, temperatures ranged from 28.71 to 33.37 $^{\circ}\text{C}$ (mean $30.60 \pm 0.73^{\circ}\text{C}$), with clear short-term, diurnal variability and a broader seasonal decrease in temperature over the deployment (Figure 3a). Salinity varied between 38.90 and 39.64 psu (mean 39.37 ± 0.10 psu) with short-term decreases likely coinciding with heavy rainfall events (Figure 3b). Fore reef temperatures experienced a smaller diel cycle than the back reef, ranging 29.80–31.58 $^{\circ}\text{C}$ (mean $30.91 \pm 0.31^{\circ}\text{C}$; $n = 8,007$; Figure 3a) and exhibited a narrower salinity range of 39.10–39.52 psu (mean 39.38 ± 0.04 ; Figure 3b). Salinity was the only parameter observed that did not have any diel signal. DO concentrations differed in both range and variability between the Cement Wreck mooring sites. Back reef DO spanned 24–432 $\mu\text{mol kg}^{-1}$ (mean $173 \pm 53 \mu\text{mol kg}^{-1}$), corresponding to oxygen saturation of 13%–243% (mean $94\% \pm 30$; Figure 3c and Table 1). The fore reef exhibited a similar mean DO ($172 \pm 25 \mu\text{mol kg}^{-1}$), but had a narrower range of 81–370 $\mu\text{mol kg}^{-1}$, with saturation levels ranging 44%–203% (mean $94\% \pm 14$; Figure 3c and Table 2). At both sites, DO experienced daily peaks, with their highest values during daylight, and did not exhibit clear seasonal trends over the course of the deployment (as with temperature). On the back reef, chlorophyll concentrations were low, ranging from 0.01 to 0.44 $\mu\text{g L}^{-1}$ (mean $0.13 \pm 0.06 \mu\text{g L}^{-1}$), but experienced daily fluctuation (Figure 3d).

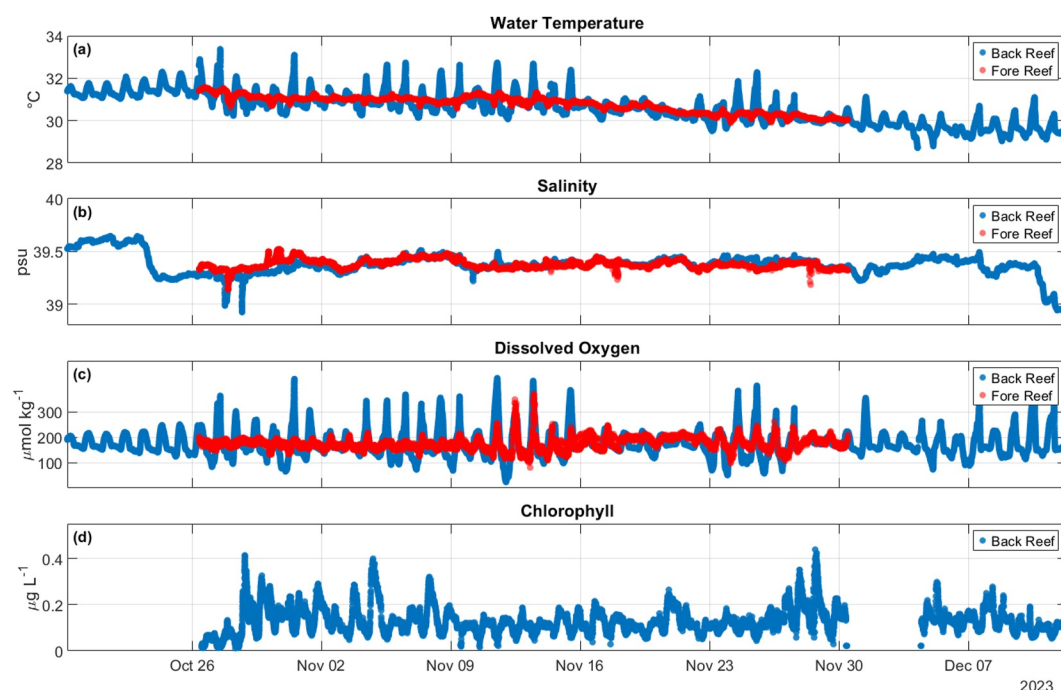


Figure 3. Time series of physical and biogeochemical parameters at Cement Wreck back reef (blue) and fore reef (red) sites. (a) Temperature in $^{\circ}\text{C}$, (b) salinity in psu, (c) dissolved oxygen concentration in $\mu\text{mol kg}^{-1}$, and (d) chlorophyll concentration in $\mu\text{g L}^{-1}$ (back reef only) are plotted from 19 October–12 December 2023.

3.1.1. pH Across the Reef

Throughout the deployment, pH_T on the back reef ($\text{pH}_{T\text{-BR}}$) was observed to be more variable than in the fore reef ($\text{pH}_{T\text{-FR}}$), but both sites displayed strong diel cycles. Ranging from 7.80 to 8.30, $\text{pH}_{T\text{-BR}}$ not only had a wider range, but a lower mean (7.98 ± 0.07) than that of $\text{pH}_{T\text{-FR}}$ which ranged from 7.91 to 8.11 and averaged 8.05 ± 0.02 (Figure 4). The pH discrepancy between sites ($\text{pH}_{T\text{-FR}} - \text{pH}_{T\text{-BR}}$) ranged from -0.27 to 0.28 (mean = 0.08 ± 0.07) and persisted for the extent of the deployment. Although different pH sensor models were deployed at each site, both instruments were tested against certified TRIS buffer solutions post-deployment and performed well within their stated accuracy specifications, indicating that the measured differences reflect real in situ variability rather than sensor bias.

3.1.2. Back Reef Carbonate Observations

Carbonate chemistry measurements on the back reef further demonstrated the observed back reef pH variability described above. TA ranged from 2,414 to 2,570 $\mu\text{mol kg}^{-1}$ with a mean of $2,523 \pm 24 \mu\text{mol kg}^{-1}$ (Figure 5a). Measured pCO_2 exhibited wide fluctuations ranging from 213 to 1,743 μatm with mean $537 \pm 148 \mu\text{atm}$, and derived pCO_2 (from TA/pH LOC sensor measurements) closely tracked sensor pCO_2 , with a milder range of 228–825 μatm and mean $516 \pm 103 \mu\text{atm}$ (Figure 5b). The mean and median difference between (time-matched) measured and derived pCO_2 on the back reef was 18 μatm , and 6 μatm respectively ($1\sigma = 64 \mu\text{atm}$, $n = 748$). The only significant disagreement between measured and derived pCO_2 can be seen the week of November 23 (Figure 5), when the SAMI-CO2 sensor measured pCO_2 up to 1,743 μatm (November 24 at 02:00 Arabian Standard Time (AST)) while the derived pCO_2 peaked at 817 μatm (November 23 at 23:00 AST). The median difference between the two is much lower than the mean difference because of this event.

DIC, which was calculated from sensor-measured TA and pH_T , ranged from 1,868 to 2,298 $\mu\text{mol kg}^{-1}$ with mean $2,157 \pm 67 \mu\text{mol kg}^{-1}$ (Figure 5c), and often tracked pCO_2 changes in relative magnitude and timing. Unlike pH_T , the TA and pCO_2 sensors were deployed for a shorter duration beginning 26 October 2023 and ending on 30 November 2023 with non-operational performance gaps spanning 9–14 November 2023 for TA and pCO_2 sensors and 18–22 November 2023 for only the TA sensor. Subsequently, there are gaps in the DIC timeseries during

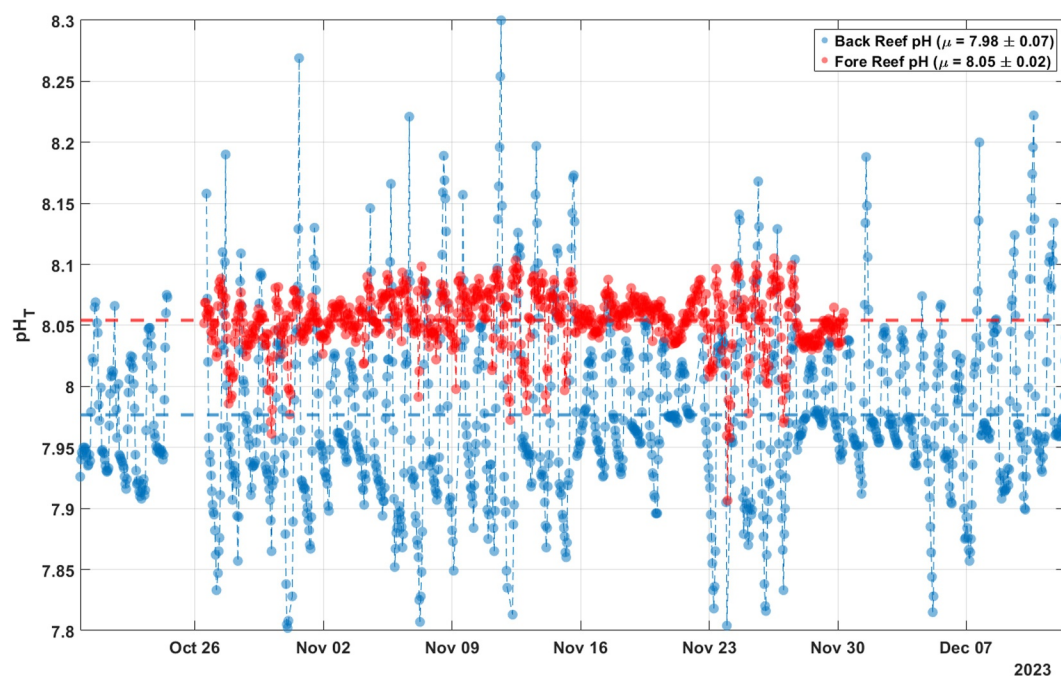


Figure 4. Time series of pH_T on the Cement Wreck back reef (blue) and fore reef (red) sites. Dashed blue line ($pH_T = 7.976$) and dashed red line ($pH_T = 8.054$) represent the mean pH_T on the back reef from 19 October–12 December 2023 and on the fore reef from 26 October–30 November 2023 respectively.



Figure 5. Time series of carbonate system observations on the Cement Wreck back reef. (a) total alkalinity (TA) in $\mu\text{mol kg}^{-1}$, (b) $p\text{CO}_2$ (in μatm) measured by the SAMI-CO2 sensor (blue) and $p\text{CO}_2$ derived from pH and TA LOC sensor measurements (pink) (c) derived dissolved inorganic carbon (DIC) in $\mu\text{mol kg}^{-1}$ are plotted from 02 November–12 December 2023. Gaps in timeseries reflect sensor downtime (a–b) and therefore corresponding missing derived DIC (c) and derived $p\text{CO}_2$ (b).

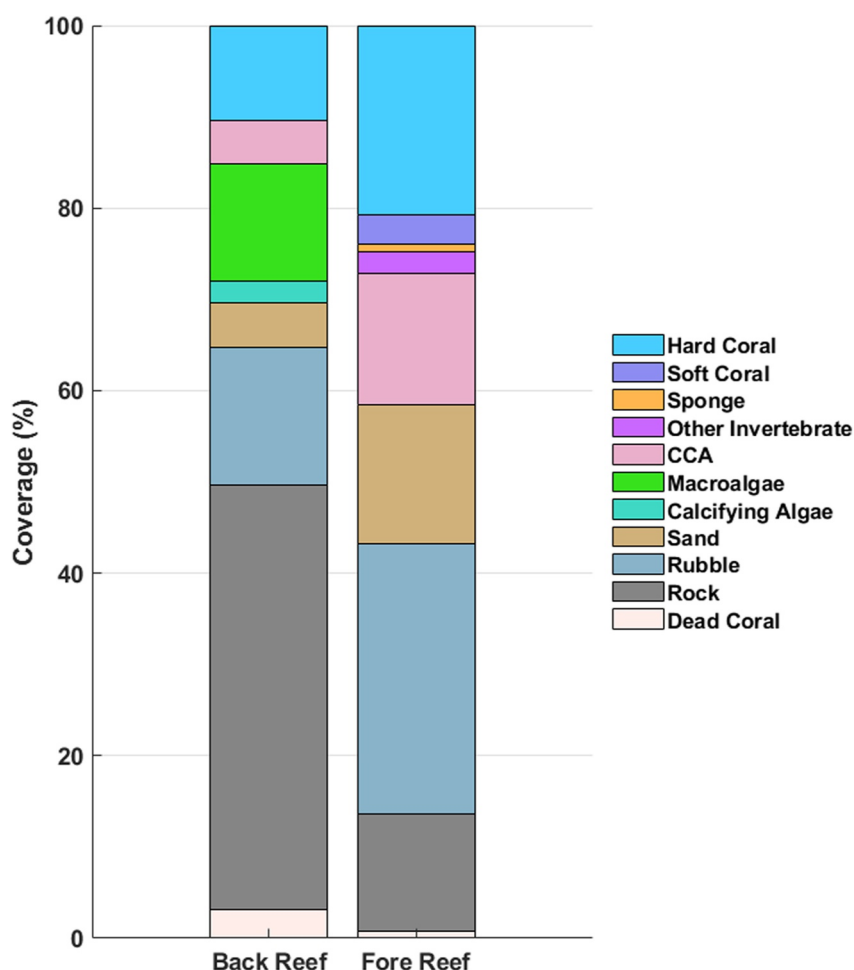


Figure 6. Back Reef (left) and Fore Reef (right) benthic habitat composition based on quadrat analysis, showing proportions of major functional groups.

these dates because of its reliance on TA for derivation (Figure 5). The aragonite saturation state (Ω_{arag}) ranged from 2.90 to 6.15 with mean 4.07 ± 0.53 .

3.2. Benthic Habitat

From benthic habitat quadrat surveys at the back reef site, the substrate was dominated by rock (46%), followed by rubble (15%), macroalgae (13%), and hard coral cover (10%) (Figure 6). Smaller contributions included sand (5%), CCA (5%), dead coral (3%), and calcifying macroalgae (2%). On the fore reef, estimated quadrat surveys revealed higher coverage of hard coral (21%) and rubble (30%), followed by sand (15%), CCA (14%), and rock (13%). While not found on the back reef, soft coral (3%), other invertebrates (2%), and sponges (1%), were found on the fore reef in low abundances. There was less dead coral at the fore reef (1%) than the back reef (3%). Unlike the back reef, macroalgae and calcifying algae were not found in the fore reef benthic survey.

3.3. Metabolic Signals

Pronounced diel cycles were observed in several parameters at both sites, with greater amplitudes on the back reef than on the fore reef (Figure 7). On the back reef, water temperatures increased during daylight hours (daylight hours defined as between 06:00 and 18:00 AST), producing daily ranges over 1.5°C , with the highest temperatures between 13:00 and 14:00 AST and the lowest temperatures between 05:00 and 06:00 AST (Figure 7a). The fore reef experienced daily high and low temperatures at the same time as the back reef, but exhibited more minor daily temperature changes, generally less than 0.25°C (Figure 7a). Salinity experienced minimal to no diel

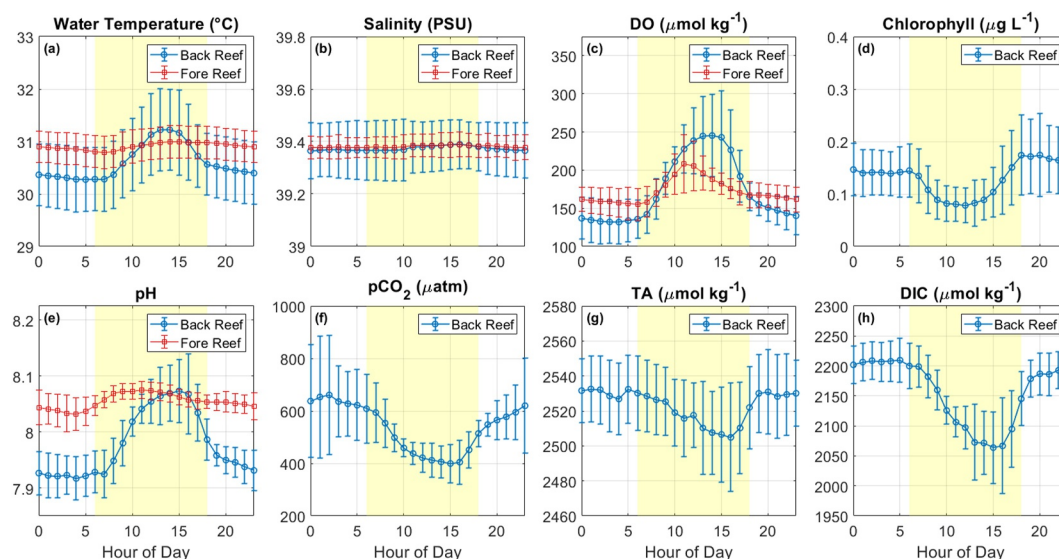


Figure 7. Diel cycles of environmental and carbonate parameters on the back reef (blue) and fore reef (red) sites of Cement Wreck Reef. (a) Temperature in $^{\circ}\text{C}$ from both sites, (b) salinity in psu from both sites, (c) dissolved oxygen in $\mu\text{mol kg}^{-1}$ from both sites, (d) chlorophyll in $\mu\text{g L}^{-1}$ from the back reef, (e) pH_T from both sites (f) pCO_2 in μatm from the back reef, (g) total alkalinity in $\mu\text{mol kg}^{-1}$ from the back reef, and (h) derived dissolved inorganic carbon in $\mu\text{mol kg}^{-1}$ from the back reef are all plotted representing the average value of each parameter per hour of day over the duration of the deployment, with error bars representing ± 1 standard deviation. Yellow highlighted areas (a–h) depict daytime hours from 06:00–18:00 Arabian Standard Time.

variability at both sites with daily ranges less than 0.02 psu (Figure 7b). DO concentrations on the back reef peaked during late afternoon (14:00–15:00 AST) and reached minima in the early hours of each morning (02:00–04:00 AST), with daily amplitudes frequently exceeding $120 \mu\text{mol kg}^{-1}$ (Figure 7c). Unlike the back reef, the fore reef DO reached minima later in the morning (around 05:00–06:00 AST) and consistently peaked earlier in the afternoon (11:00–12:00 AST), with much smaller daily changes than the back reef, typically less than $60 \mu\text{mol kg}^{-1}$ (Figure 7c). Observed pH_T mirrored DO in its diel cycle. $\text{pH}_{T-\text{BR}}$ values peaked around 15:00 AST and nighttime minima between 04:00 and 06:00 AST, with average daily ranges of 0.14 (Figure 7d). Like DO in the fore reef, $\text{pH}_{T-\text{FR}}$ peaked earlier in the day (11:00–12:00 AST) but reached minima an hour before DO, between 03:00 and 04:00 AST. Diel amplitudes of $\text{pH}_{T-\text{FR}}$ were comparatively much smaller than $\text{pH}_{T-\text{BR}}$, averaging 0.04 pH units (Figure 7d). Overall, $\text{pH}_{T-\text{FR}}$ values were much less variable than $\text{pH}_{T-\text{BR}}$, and were consistently higher, except for during the $\text{pH}_{T-\text{BR}}$ daily maxima when the upper ± 1 standard deviation reaches up to 8.12 at 16:00 AST.

Chlorophyll, pCO_2 , TA, and derived DIC exhibited inverse diel cycling. These parameters were only observed on the back reef, and they reveal a daily nighttime maxima and daytime minima. Chlorophyll concentrations on the back reef show a clear dip in the middle of the day around 12:00–13:00 AST, followed by a sharp increase still during daylight, but peaking just after sunset around 18:00–20:00 AST. The daily change in chlorophyll averaged $0.1 \mu\text{g L}^{-1}$. On the back reef, highest pCO_2 values occur at 02:00 AST and lowest values later in the day between 15:00 and 16:00 AST (Figure 7f). Daily pCO_2 maxima commonly exceeded $600 \mu\text{atm}$, with minima at $400 \mu\text{atm}$ (atmospheric equilibrium), and typical daily changes averaging $300 \mu\text{atm}$. TA on the back reef exhibited a shallower diel curve due to its higher variability throughout the deployment. TA was relatively steady during the nighttime, averaging $2,529 \mu\text{mol kg}^{-1}$ from the hours of 19:00–06:00 AST. However, TA would decrease daily at around 15:00–16:00 AST and often drop below $2,500 \mu\text{mol kg}^{-1}$ (Figure 7g). The amplitude of change in TA during the day ranged from 4 to $108 \mu\text{mol kg}^{-1}$ (Figures 4a and 5g), meaning that during some 24-hr periods, there was very limited change in TA (e.g., November 28–29). DIC followed a similar pattern to pCO_2 , with afternoon minima (between 15:00–16:00 AST) ranging from $1,987$ to $2,124 \mu\text{mol kg}^{-1}$, and nighttime maxima (between 04:00 and 05:00 AST) ranging from $2,174$ to $2,246 \mu\text{mol kg}^{-1}$, resulting in average diel cycle of $146 \mu\text{mol kg}^{-1}$.

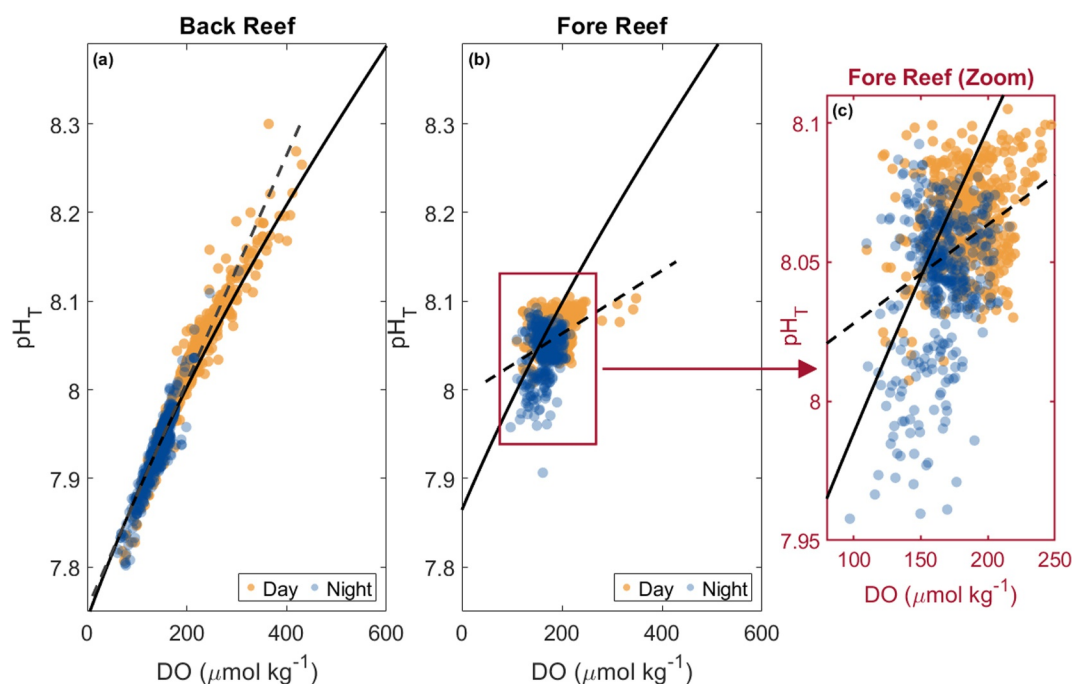


Figure 8. Relationship between dissolved oxygen (DO) and pH_T at (a) back reef and (b) fore reef sites of Cement Wreck Reef. A zoomed view of the fore reef pH–DO relationship is shown in (c). Both relationships are compared with theoretical Redfield-based Photosynthesis:Respiration (P:R) model shown as a solid black line in (a), (b), and (c). Best fit line between pH and DO as determined by the linear least squares regression (dashed black line) in (a), (b), and (c).

The relationship between measured pH_T and DO were compared to the theoretical relationship (pH–DO) based on Redfield Ratio (Figure 8). pH and DO correlated positively at both sites, however, the relationship between pH and DO varied.

On the back reef, the pH–DO relationship was highly correlated ($R^2 = 0.943$) and the slope of its best-fit line closely followed that of the theoretical relationship subset of 0.0013 and 0.0011 respectively (Table 3, Figure 8a). In the fore reef, the pH_T values are lower than expected based on DO range, and the pH–DO relationship is weak ($R^2 = 0.145$). When fit to a linear regression, the fore reef observed pH–DO relationship has a slope of 0.0004, which differs from the P:R model subset slope of 0.0011 (Table 3, Figures 8b and 8c). On both sites, we observe a pH–DO nighttime slope 0.0002 higher than the respective daytime slope (Table 3).

Table 3

Linear Regression Equations Describing the Relationship Between Dissolved Oxygen and pH_T at Back Reef and Fore Reef Sites of Cement Wreck Reef, Separated by Diel Periods (All, Day, Night)

Location	Diel cycle	pH–DO best fit line eq.	R^2	n
Back Reef	All	$y = 0.0013x + 7.7535$	0.943	1280
	Day	$y = 0.0012x + 7.7723$	0.934	629
	Night	$y = 0.0014x + 7.7266$	0.886	651
	P:R Model	$y = 0.0011x + 7.7812$	0.996	n/a
Fore Reef	All	$y = 0.0004x + 7.9923$	0.145	854
	Day	$y = 0.0002x + 8.0347$	0.070	440
	Night	$y = 0.0004x + 7.9844$	0.074	414
	P:R Model	$y = 0.0011x + 7.8823$	0.998	n/a

Note. The P:R Model subset for each site is included (red). Best-fit equations, coefficient of determination (R^2), and number of observations (n) are reported for each.

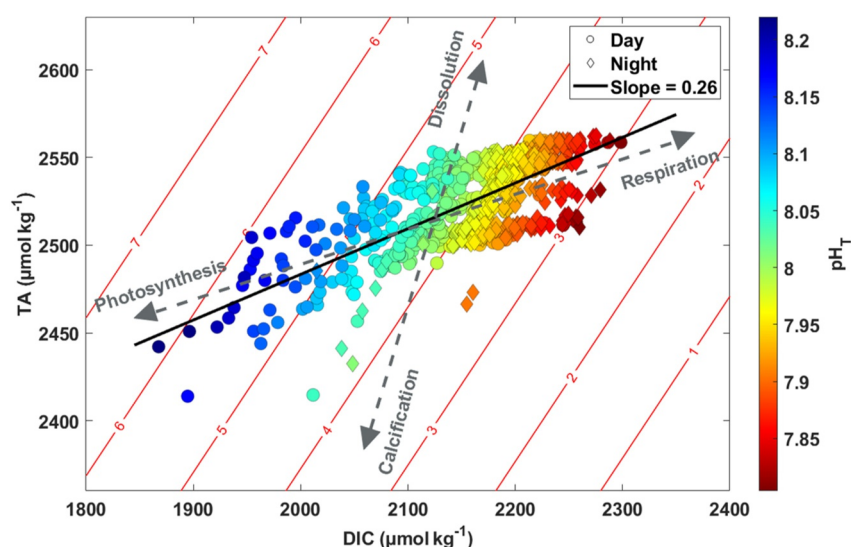


Figure 9. Relationship between dissolved inorganic carbon (DIC) and total alkalinity (TA) on the back reef. Color represents pH_T with circle markers at daytime and diamond markers at nighttime. Aragonite saturation state (Ω_{arag}) levels are drawn in red diagonal contour lines. The DIC to TA known ratios for calcification/dissolution ($-2/2$) and photosynthesis/respiration ($-0.2/0.2$) are depicted by gray dashed lines. The best fit line between DIC and TA as determined by the linear least squares regression (slope = 0.26) is the solid black line. The intersection of the known ratios (gray dashed lines) have been centered on the scattered data distribution and are not intended to imply where each process begins and ends, but rather illustrate the expected trajectories of these processes in DIC-TA space.

4. Discussion

Globally, coral reefs are shifting toward NCP dominance and declining NCC (K. L. Davis et al., 2021; Cyronak et al., 2018). This transition has major implications for reef health because NCC maintains the CaCO_3 framework that supports reef structure, while NCP regulates short-term organic carbon cycling, oxygen dynamics, and much of the diel variability in seawater pH, pCO_2 , DIC, and Ω_{arag} . Quantifying this metabolic balance remains challenging as reef metabolism varies strongly over diel, seasonal, and annual timescales, with many existing carbonate system observations based on short-term or discrete sampling. High-resolution observations are therefore required to resolve how reefs move between production, respiration, calcification, and dissolution, and thus predictors of reef health. To predict coral reefs may change under future warming, acidification, and deoxygenation, we need to understand the current status of reefs, and their biogeochemical diel cycles provide valuable information on their metabolic baselines and potential vulnerability (Calvin et al., 2023; Chan et al., 2025; Doney et al., 2009). For example, coral reefs that experience greater diel variability in pCO_2 have been found to exhibit greater resilience to extreme conditions (Brown et al., 2022). Within this context, the central Red Sea is a particularly important region because it is naturally warm, saline, oligotrophic, and characterized by high-alkalinity waters, while also being considered a potential analogue for future warmer-ocean conditions and a reservoir of thermally tolerant corals (Fine et al., 2013, 2019). The autonomous observations from Cement Wreck therefore provide not only a novel high-resolution regional data set, but also a benchmark for evaluating whether NCP-dominated carbonate system dynamics in the Red Sea reflect a recent shift consistent with global reef trajectories, or a longer-standing metabolic state exemplary of future conditions.

4.1. Cement Wreck Reef Metabolic Balance in a Global Context

The TA–DIC relationship observed on the Cement Wreck back reef indicates that carbonate system variability was strongly dominated by organic processes like photosynthesis and respiration. The overall TA–DIC slope ($\Delta\text{TA}:\Delta\text{DIC} = 0.26$, $R^2 = 0.510$, $p < 0.001$; Figure 9, Table 4) falls much closer to the ratio for photosynthesis/respiration (slope = 0.2), than the calcification dissolution ratio (slope = 2) line (Cyronak et al., 2018; Ho & Schanze, 2020; Yeakel et al., 2015). Because photosynthesis and respiration primarily alter DIC with comparatively small nutrient-linked changes in TA, low TA–DIC slopes are expected when NCP is the dominant metabolic driver (Deffeyes, 1965; Suzuki & Kawahata, 2003; Watanabe et al., 2006). Reefs with a large NCP

Table 4

Linear Regression Results for the Relationship Between Dissolved Inorganic Carbon and Total Alkalinity on the Back Reef at Cement Wreck in 2023, Separated by Diel Period (All, Day, Night), With Historical Red Sea TA–DIC Relationships Included for Comparison

Location	Year	Diel cycle	TA–DIC slope	R^2	n
Back Reef (This Study)	2023	All	0.2602	0.510	755
		Day	0.2654	0.533	369
		Night	0.4011	0.473	368
Red Sea (Historical)	1997	All	0.29	0.344	39
	1998	All	0.26	0.344	30
	2013	All	0.25	0.954	16

Note. TA–DIC slope, coefficient of determination (R^2), and number of observations (n) are reported.

contribution are particularly effective at driving pH, because organic metabolism produces stronger proton fluxes per unit change in DIC compared to calcification/dissolution. This can be visualized in TA–DIC space where pH isolines typically have a slope close to 1. When the TA–DIC relationship yields a slope <1 (as seen with dominant NCP), it crosses more isolines of pH, resulting in larger pH variability (Cyronak et al., 2018). This can be clearly seen in Figure 9 as our data points cover a relatively large pH and DIC range (pH represented by color, crossing Ω_{arag} contours depicted by red contour lines) within the TA versus DIC space. At Cement Wreck, this TA–DIC slope corresponds to an estimated NCP contribution of approximately 87%, indicating that NCP was the dominant control on back reef carbonate variability. This interpretation is consistent with the large diel range and strong co-variation of pH and DO on the back reef, which closely followed the theoretical P:R model (Figure 8a). The benthic community composition of the back reef, characterized by greater turf and macroalgal cover than hard coral or CCA (Figure 6), further supports our interpretation, as algae and turf-rich communities tend to exhibit greater NCP relative to NCC than coral-dominated benthos (Roth et al., 2020, 2021).

In contrast, the fore reef exhibited weaker pH–DO correlation that did not align as well with the theoretical P:R model (Figure 8b; Table 3). This suggests that photosynthesis and respiration alone did not explain carbonate-system variability as clearly at that site. Because TA was not measured on the fore reef, we do not calculate fore reef TA–DIC slopes or infer fore reef NCP/NCC contribution quantitatively. The agreement between TA–DIC and pH–DO interpretation on the back reef provides important context: the back reef was dominated by primary production and had a strong agreement with the theoretical P:R model, while in the fore reef other biogeochemical processes must be occurring to cause divergence. The divergence from the P:R model is consistent with the fore reef benthic community composition, which had greater hard coral and CCA cover and no observed macroalgae compared with the back reef (Figure 6). This greater calcifier abundance would be expected to modify pH without a corresponding oxygen signal, shifting pH–DO relationships away from a purely photosynthesis–respiration trajectory. At the same time, the deeper and more exposed fore reef likely experienced stronger mixing and shorter residence of metabolically modified water, which would dampen diel pH–DO variability and weaken local metabolic signals. Thus, the contrast between our sites suggests that Cement Wreck contains distinct reef-zone metabolic dynamics: a shallow back reef dominated by organic carbon cycling, and a fore reef where calcification, dissolution, and hydrodynamic exchange likely exert greater relative influence. The absence of fore reef TA measurements is a recognized limitation of our ability to further resolve the controlling processes at that site, and future paired pH–DO–TA observations across both reef zones would strengthen these interpretations. Nevertheless, the back reef measurements provide observed carbonate system signals and metrics that can be compared to global reefs.

When placed in a global context, the NCP-dominated signal observed at Cement Wreck is not atypical, especially when considering the broader trajectory of reefs shifting toward greater organic control and declining relative calcification (K. L. Davis et al., 2021). Across ocean basins, reefs span a broad range of TA–DIC slopes and estimated % NCP contributions, reflecting differences in benthic composition, climate impact, geomorphology, hydrodynamic setting, residence time, spatial scale, and sampling approach (Takeshita et al., 2018). Contribution of NCP (87%) and the TA–DIC slope (0.26) at Cement Wreck falls near the high end of % NCP and the lower end of TA–DIC slope of a global compilation range (27%–95%, 1.45–0.1, respectively), synthesized from Cyronak

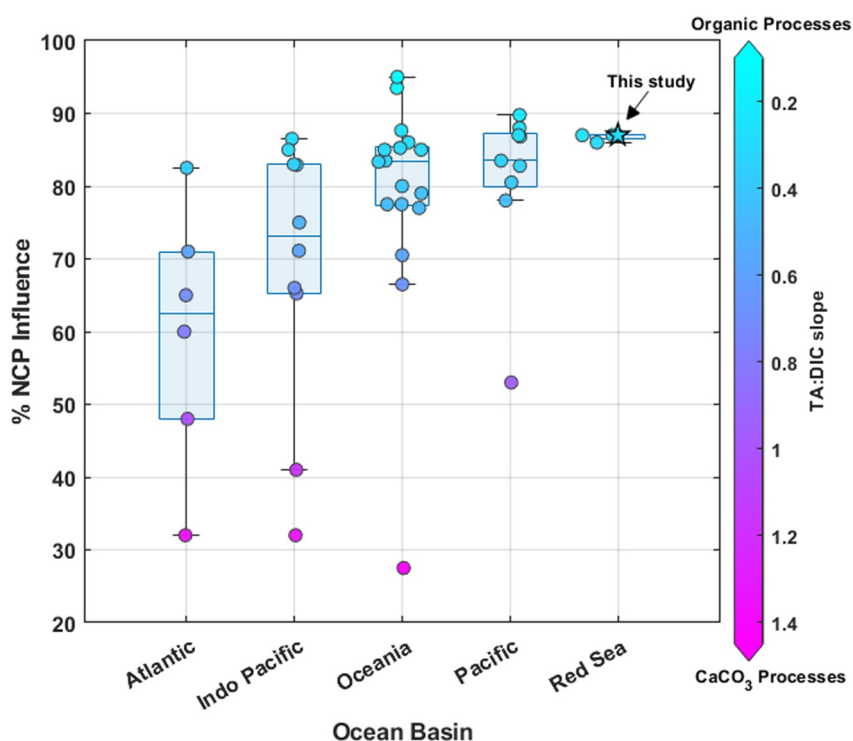


Figure 10. Global comparison of reef metabolic balance from TA–DIC relationships. Boxplots show the distribution of estimated % net community production (NCP) influence by ocean basin, with individual reef study observations shown as points and colored by TA–DIC slope. Lower TA–DIC slopes indicate stronger organic carbon control on dissolved inorganic carbon variability, whereas higher slopes indicate greater relative influence of CaCO_3 production and dissolution. Cement Wreck Reef, marked by the arrow, falls within the high % NCP end of the global compilation and closely overlaps previous Red Sea observations. Sample sizes by ocean basin are Atlantic ($n = 6$), Indo Pacific ($n = 10$), Oceania ($n = 17$), Pacific ($n = 9$), and Red Sea ($n = 4$).

et al. (2013) and K. L. Davis et al. (2021), and plotted in Figure 10. What is notable, however, is Cement Wreck's consistency with previous Red Sea Observations. Regional comparisons from the northern Red Sea reported near-identical TA–DIC slopes of 0.29, 0.26, and 0.25, corresponding to NCP contributions of approximately 85%, 87%, and 87% in 1997, 1998, and 2013, respectively (Table 4; Figure 10; Silverman et al., 2007; Cyronak et al., 2018). The near-identical metrics observed at Cement Wreck in 2023 suggests that strong NCP control has been a recurring characteristic of the available Red Sea reef observations over the last 25 years, rather than solely representing a recent site-specific shift toward organic dominance.

The consistency of Red Sea TA–DIC slopes can also be compared with historical observations from One Tree Island on the Great Barrier Reef. K. L. Davis et al. (2019) found that net calcification in 2017 was comparable to estimates from the 1970s, despite substantially lower rates reported during intervening observations in 2014. This fluctuation was associated in part with changes in live coral cover and highlights the influence of local ecological conditions on reef metabolisms. In contrast, the (also sporadic) Red Sea observations from 1997 to 2023 show similar TA–DIC slopes and NCP dominance. This does not imply that absolute NCP, NCC, or reef condition have remained unchanged, but suggests that the relative contribution of organic versus inorganic metabolism has remained remarkably consistent across the observations available.

Rather than representing only a recent phase shift, Red Sea reefs may already occupy a metabolic end-member characterized by strong organic carbon control under warm, saline, oligotrophic, and high alkaline conditions. Several non-exclusive mechanisms could contribute to this pattern, including high irradiance, strong diel metabolic forcing in shallow reef habitats, low nutrient availability, high background TA, and reef communities that have evolved to inhabit extreme environments. However, unlike the One Tree Island record (K. L. Davis et al., 2019), where repeated benthic surveys provided evidence linking changes in coral cover to changes in calcification and TA–DIC slope, the historical Red Sea data sets do not provide sufficient consistent ecological

information to attribute the observed similarity to a single mechanism. Comparisons among reef systems must be interpreted cautiously because the compiled studies differ in spatial scale, residence time, sampling duration, methodology, and available data. Nevertheless, the recurrence of strongly NCP-dominated TA–DIC relationships across the available Red Sea observations compared to the variability of the remaining ocean basins, suggests that the Red Sea may provide a valuable natural analogue for understanding how reef carbonate-system variability may function in warmer future oceans.

4.2. Drivers of Temporal Variability

While Cement Wreck is placed globally within a high-NCP metabolic state, we can more closely examine how this metabolic balance is expressed over diel cycles from high-resolution sensor observations. On Cement Wreck Reef, pronounced diel variability in temperature, pH_T, and DO were apparent. At both sites, daily cycles followed the expected pattern of oxygen production and CO₂ uptake, driven by photosynthesis during the day (0600–1,800 AST) and respiration, with oxygen drawdown and CO₂ release, at night (18:00–06:00 AST). Reef depth is a key driver of magnitude with diel variability of temperature and pH found to diminish significantly at depths greater than ~6 m (Cyronak et al., 2020). As expected, the shallower back reef site experienced greater diel magnitude in all parameters compared to the fore reef (Figures 7a, 7c, and 7e). While residence times, are not reported for Cement Wreck Reef, it is important to note that longer residence times are often expected to amplify diel ranges by allowing greater seawater modification (Lowe et al., 2016; Zhang et al., 2013). However, rapid diel oscillations in parameters like those measured in this study (temperature, DO, pH) dominate short-term variability from biological forcing, whereas residence time will play a greater role in determining mean reef conditions over longer time periods (Cyronak et al., 2020; Falter et al., 2013; Takeshita et al., 2018; Zhang et al., 2013).

Separating the TA–DIC relationship by diel period give further insight into how the relative influence of organic and inorganic reef dynamics changed over the daily cycle, and provides an important nuance to our interpretations. The daytime TA–DIC slope remained strongly NCP-dominated (0.265), while the nighttime slope steepened to 0.401 (Table 4). Although the nighttime slope is still closer to the photosynthesis–respiration trajectory than to the calcification–dissolution trajectory, its steepening suggests a greater relative contribution of CaCO₃-related processes at night.

This finding is consistent with enhanced CaCO₃ dissolution seen by reef frameworks under low pH and low Ω_{arag} nighttime conditions—an effect shown to intensify under OA (Cyronak & Eyre, 2016; Kwiatkowski et al., 2016; Stoltenberg et al., 2021). Long-term observations from the Eilat Nature Reserve (Red Sea) documented substantially higher nighttime CaCO₃ dissolution in 2015–2016 compared to 2000–2002 (Moav-Barzel et al., 2023). Our pH-colored data plotted across Ω_{arag} contours in Figure 9 align with this archetype of lower pH, lower Ω_{arag} at night (denoted by diamond markers), with modest TA depletion, likely by dissolution. Taken together, these results highlight how the balance between organic and inorganic metabolism varies not only across global reef settings, but also within single reef systems over a diel periods. Although the overlying seawater remained supersaturated with respect to aragonite ($\Omega_{\text{arag}} > 2.90$; Figure 9), this does not prevent CaCO₃ dissolution within reef sediments. Eyre et al. (2018) found that reef sediments transitioned from net precipitation to net dissolution with overlying seawater Ω_{arag} of ~2.92. This transition was attributed to organic matter respiration increasing DIC and driving down Ω_{arag} in the sediment porewaters. At Cement Wreck, nighttime decreases in pH and Ω_{arag} together with substantial rock, rubble, and sand cover on the back reef (Figure 6), suggest that respiration-driven dissolution within permeable sediments or other microenvironments could contribute to the steeper nighttime TA–DIC slope of 0.401 (Cyronak et al., 2013; Moav-Barzel et al., 2023; Precht & Huettel, 2003; Rao et al., 2012; Romanó de Orte et al., 2021). However, porewater chemistry was not measured during this deployment, so this remains to be investigated further.

Diel cycling also emphasizes that reef metabolic processes do not respond instantaneously to changing carbonate chemistry. Diel hysteresis between calcification and Ω_{arag} has been observed on other reefs, where metabolic rates follow different trajectories during the morning and afternoon despite similar carbonate chemistry conditions (McMahon et al., 2013, 2018). Similarly, late-day and nighttime shifts toward greater dissolution have been interpreted as indicators of reefs approaching net-dissolving conditions under OA (Stoltenberg et al., 2021). We do not directly calculate NEC or dissolution rates here, but the day/night separation in TA–DIC slopes suggests that high-resolution TA observations can resolve diel metabolic transitions that would likely be missed by lower-frequency sampling. Mean diel patterns in our study further show that carbonate system parameters were not

perfectly synchronized over the day. On the back reef, DO and pH increased rapidly through the morning and reached afternoon maxima, while TA declined throughout the day and reached its lowest values later in the afternoon. This staggered timing indicates that alkalinity removal lagged behind the initial daytime increase in pH and DO, suggesting that organic production, carbonate chemistry, and alkalinity-modifying processes were coupled over the diel cycle, but not instantaneous. Such offsets are consistent with reef diel structure, where photosynthesis, respiration, calcification, dissolution, and physical exchange do not necessarily reach maximum influence at the same time, making it difficult to disentangle multiple metabolic drivers from any single carbonate system variable (McMahon et al., 2013, 2018). The strong daytime pH–DO co-variation is consistent with light-driven metabolic control (Cryer et al., 2023), while the delayed TA minimum suggests that calcification and/or other alkalinity-removing processes continued after the initial morning increase in organic production (Andersson & Gledhill, 2013).

The observed diel phase lags in our data may also be linked to irradiance-driven biological responses. Seawater chlorophyll concentrations on the back reef exhibited unique diel variability, with minima measured at midday followed by an increase toward late afternoon and evening (Figure 7d). Similar chlorophyll concentration dynamics in the Red Sea have been previously reported by Y. Wang et al. (2025), who found this diel phenomenon to be predominately controlled by irradiance rather than nutrient availability. High midday irradiance, as found in the Red Sea (Overmans & Agustí, 2019), can induce photoinhibition in phytoplankton, reducing chlorophyll fluorescence and limiting primary production (X. J. Wang et al., 2009). Although we measured seawater chlorophyll concentration rather than coral-tissue symbiont chlorophyll, the observed diel pattern is broadly consistent with photoacclimation responses reported for the dominant coral at Cement Wreck, *S. pistillata*. The success of hermatypic corals such as *S. pistillata* in oligotrophic waters is underpinned by their symbiosis with photosynthesizing microalgae, zooxanthellae (Rowan, 1998). To sustain this relationship, *S. pistillata* is known to adjust chlorophyll concentration and other symbiont traits dynamically in response to irradiance levels in the Red Sea (Mass et al., 2007; Titlyanov et al., 2001; Winters et al., 2009). Therefore, the delayed afternoon peaks in back reef DO and pH may reflect a lagged metabolic response following midday irradiance stress and subsequent recovery.

5. Conclusion and Broader Implications

The central novelty of this work was the use of co-located, autonomous, high-resolution sensors, including in situ TA, for multi-month observations on a coral reef. Autonomous sensors transform reef biogeochemistry from occasional snapshots into a high-frequency observing system. Critically, this deployment demonstrated the feasibility and scientific value of continuous in situ TA measurements alongside pH and DO, on a reef. The inclusion of high-resolution autonomous TA observations provided an ideal input parameter pairing to constrain the carbonate system, highlighted direct alkalinity short-term trends, and corroborated interpretations of reef metabolic control based on pH/DO observations. By sustaining sub-hourly measurements, our sensor moorings detected synoptic variability that drives reef metabolic processes, and captured short-lived transitions between net production and net dissolution that conventional sampling surveys may miss. Furthermore, the large quantity of observations tightens regressions and reaffirms processes seen across diel cycles.

By characterizing diel variability and quantifying the dominance of NCP over NCC at Cement Wreck Reef, this study contributes to baseline understanding of Red Sea reef metabolism while placing these observations in a broader global context. Importantly, we found that present Red Sea TA–DIC slopes closely matches previous reported over the last 25 years. These observations demonstrated that, despite the environmental extremes unique to the Red Sea, Cement Wreck metabolically behaves in ways that are consistent with reef carbonate system processes observed globally, while also providing evidence that the Red Sea may represent a stable high-NCP end-member for understanding future reef conditions.

As reefs continue to face global and local stressors, the ability to monitor reef health is imperative. We demonstrate how by deploying pH, DO, and TA sensors, we are able to fully constrain (and over-determine) the carbonate chemistry of the reefs and identify metabolic processes more efficiently than traditional discrete measurements alone. Scaling up autonomous deployments like this one, and integrating them into comprehensive observing networks, could more effectively predict how future ocean conditions will alter coral reef carbonate budgets and metabolic balances globally.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

All sensor data and benthic community imagery are archived in The University of Southampton Data Repository: <https://doi.org/10.5258/SOTON/D3691>.

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