nature climate change

Analysis

https://doi.org/10.1038/s41558-023-01619-2

Increasing hypoxia on global coral reefs under ocean warming

In the format provided by the authors and unedited

Table of Contents

Extended Methods

Please note, any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Detailed Site and Deployment Information

A summary of the deployment information can be found in Table S1. Detailed descriptions of each site and deployment are described below.

Heron Island, Australia

Heron Island (23.443 °S, 151.915 °E) is a small coral cay (~0.16 km^2) located on the Heron Reef platform (~28 km^2) in the Capricorn Group of the Southern Great Barrier Reef (*14, 73*). The Heron Reef platform is characterized by reef flat and lagoon habitats dominated by calcium carbonate sands, some algae, and live coral, predominantly *Acropora* spp. (*74-75*). SeapHOx (*76*) sensors were deployed on the benthos at three sites along the Heron Reef platform along an east-west transect: close to Heron Island (Heron 1), in the middle of the lagoon (Heron 2), and on the reef flat (Heron 3) (*47*). All instruments were deployed starting on October 8, 2015, and recorded temperature, salinity, dissolved oxygen, and pH every 30 minutes. Heron 1 was deployed for 14 days at ~0.7 m depth, Heron 2 was deployed for 7 days at ~2.1 m, and Heron 3 was deployed for 7 days at ~1.2 m depth (*47*; Table S1).

Bocas del Toro, Panama

Bocas del Toro (9.358 °N, 82.244 °W) is an archipelago on the northwest coast of Panama, separated from the Caribbean Sea by the estuarine Almirante Bay (*48*). Almirante Bay is influenced by intense terrestrial runoff, freshwater discharge, and sedimentation from upstream rivers, streams, and plantations (*77*). Punta Caracol (9.377 °N, 82.300 °W) is a shallow reef site on the west coast of Isla Colón in Almirante Bay of Bocas del Toro, mostly protected from open ocean water flow and surrounded by dense mangroves (*48*). Punta Caracol is mainly composed of sandy sediments and large colonies of *Porites*, *Orbicella*, *Diploria*, *Montastraea* and *Colpophyllia* at 2 to 4 m depth and a mixed community with muddy sediments from 4 to 12 m depth (*48*). Punta Vieja (9.259 °N, 82.108 °W) is a reef site at the southern tip of Isla Bastimentos, exposed to the Caribbean Sea and subject to much less terrestrial runoff and fewer anthropogenic inputs (*48*). The reef at Punta Vieja is dominated mainly by *Acropora cervicornis* and *Acropora palmata* from 2 to 5 m and drops off to a muddy bottom at 12 m depth (*48*).

Four SeapHOx (*76*) sensors were deployed on the benthos at Punta Caracol on November 3–4, 2015, at depths of 1 m, 3 m, 8 m, and 12 m depth (Bocas 1a, 1b, 1c, and 1d, respectively) and recorded temperature, salinity, dissolved oxygen, and pH every 30 minutes (Table S1). The sensors at 3 m and 8 m remained in place for 16 days and were recovered on November 19. On November 9, the sensors at 1 m and 12 m were moved to Punta Vieja and deployed at 2.6 m and 7.6 m (Bocas 2a and Bocas 2b, respectively). The sensors at Punta Vieja were recovered on November 20 after 11-day deployments (*48*).

Kāneʻohe Bay, Oʻahu, Hawaiʻi, USA

Kāneʻohe Bay (21.463 °N, 157.810 °W) is a large bay on the northeastern (windward) coast of Oʻahu, home to a large barrier reef extending 13 km (alongshore) by 4 km (cross shore) (*49*). The reef area has a reef crest, reef and sand flats, and lagoon with many patch reefs (*78-79*). The reef flat is shallow and has a mixed benthic community, with some areas dominated by reef, rubble (coral skeletons with encrusting or turf algae), or sand (*78-79*). A SeapHOx sensor (*76*) was deployed on the benthos (~2.8 m, as determined by current sensors deployed at the site) between June 17–30, 2016, at a reef site near the NOAA CRIMP2 buoy (https://www.pmel.noaa.gov/co2/story/CRIMP2), measuring temperature, salinity, pH, and dissolved oxygen every 30 minutes for the 13-day deployment (Kāneʻohe 1a). Two SeapHOx sensors were also later deployed on the benthos in the fall at the same CRIMP2 reef site (Kāneʻohe 1b) and at a rubble site (Kāneʻohe 2, at ~3.1 m) for 7 days from November 10 to 17, 2016, recording temperature, salinity, pH, and dissolved oxygen every 30 minutes (*49*; Table S1).

Hog Reef, Bermuda

Hog Reef (32.457 ºN, 64.835 ºW) is a rim-reef on the northern side of the Bermuda carbonate platform dominated by macroalgae (35 ± 3 %), hard coral (27 ± 5 %), turf algae (20 ± 4 %), soft coral (16 ± 2 %), and some areas of sand, rock, rubble, and coralline algae (<5 %; mean ± 1 SD benthic cover) (*50, 80-81*). The depth at Hog Reef ranges from 4 to 25 m, with a mean (± 1 SD) of 10.3 ± 3.3 m, generally increasing offshore but with variable structure and complexity (*50, 81-82*). A suite of autonomous sensors was deployed at Hog Reef in September of 2017, including Aanderaa oxygen optodes measuring dissolved oxygen and a CTD (Microcat, Sea-Bird Scientific) measuring temperature and salinity (*50*; Table S1). Instruments were deployed either attached to (surface, Hog 1a) or on the reef benthos below (7 m; Hog 1b) the NOAA PMEL MAPCO2 buoy on Hog Reef (https://www.pmel.noaa.gov/co2/story/Hog+Reef) for 21 days from September 1-22, 2017, recording every 15 minutes. Note that the buoy is deployed over a sand hole that measures 11 m deep and is surrounded by sloping reef (~7 m where instrument was deployed on the bottom). Salinity values for the Hog 1a sensors were taken from the MAPCO2 buoy and linearly interpolated to match the recording frequency of the sensors (every 15 minutes) (*50*).

Dongsha Atoll, Taiwan

Dongsha Atoll (20.682 ºN, 116.808 ºE) is a large (~23 km wide), circular atoll in the South China Sea (also known as one of the Pratas Islands) southwest of Taiwan, with a wide reef flat and large lagoon containing thousands of patch reefs of varying size. Dongsha Island on the western side of the atoll has a large seagrass bed on its north shore, extending up to 1 km offshore with scattered patches of *Porites spp*. coral colonies. The lagoon patch reefs are dominated mainly by massive *Porites*, foliaceous *Echinopora*, *Pavona*, and *Turbinaria* corals (*83*). An Idronaut CTD was deployed on the bottom in the shallow seagrass (Dongsha 1) at 0.9 m depth during July 1–8, 2018, recording temperature, salinity, pH, and dissolved oxygen every 15 minutes for 7 days. Another Idronaut CTD was deployed on the benthos of a large patch reef (Dongsha 2) near the center of the lagoon from July 1–8, 2018, at ~2 m for 7 days, also recording temperature, salinity, pH, and dissolved oxygen every 15 minutes. A Sea-Bird CTD sensor and Aanderaa oxygen optode were deployed on the benthos at a smaller patch reef on the eastern side of the lagoon at ~2 m depth for 7 days from July 1–8, 2018, measuring temperature, salinity, and dissolved oxygen every 10 minutes (Table S1).

Taiping Island, Taiwan

Taiping Island (10.376 ºN, 114.365 ºE) or Itu Aba Island is the largest of the naturally occurring Spratly Islands in the South China Sea (0.57 km^2), ~500 km due west of Palawan Island, Philippines and ~1180 km southwest of Dongsha Atoll, Taiwan (*84*). The east-west oriented coral island is surrounded by shallow seagrass beds that transition into a reef flat (1–4 m in depth) extending ~50 m offshore before a steep reef drop off with low to no coral cover below 18 m depth (*85*). Previous work employing remote sensing data estimates that Taiping is home to 1.27 km^2 of reef flat and 2.46 km^2 of sub-tidal reef area (*84*). The reef areas surrounding Taiping are high in coral cover, with less than 5 % cover of algae, most of which is crustose coralline algae (*86*). Surveys in 1994 identified 120 species of corals on the south side of the island, dominated mainly by *Pocillopora* and *Acropora* species (*85*). A Sea-Bird CTD and PME MiniDOT were deployed in the shallow seagrass (~1 m) and a SeapHOx (*76*) sensor was deployed on the benthos of the reef flat (~2.5 m) on the south side of the island for 3 days from March 28–31, 2019. The Sea-Bird and MiniDOT measured temperature, salinity, and dissolved oxygen every 10 minutes and the SeapHOx sensor measured temperature, salinity, dissolved oxygen, and pH every 10 minutes (Table S1).

Okinawa, Japan

Okinawa Island is the largest of the Ryuku Islands of southern Japan's Kyushu region. Onna Reef (26.449 ºN, 127.796 ºE), located in Onna Village near Nakadomari, is a fringing coral reef along Okinawa's central western side, extending 2.8 km alongshore with a 150 km wide reef flat. The reef flat has a mean depth of ~1.3 m and is composed mainly of carbonate rock, crustose coralline algae, sand, rubble, turf algae, and some small coral colonies (*53*). The lagoon (3–4 m depth) inshore from the reef flat is mainly sand, with scattered patch reefs, coral farms (*87*), seaweed farms, and has several deeper channels in the south and north. A SeapHOx (*76*) sensor was deployed on the benthos on the reef flat (Okinawa 1) and two Sea-Bird CTDs equipped with

Aanderaa oxygen optodes were deployed in the lagoon near a coral farm (Okinawa 2) and in the southern boat channel (Okinawa 3) next to a group of artificially placed large *Porites* colonies (*53*). The sensors were deployed at ~1.3 m, 2.8 m, and 6.6 m, respectively from October 10–29, 2019; however, biofouling on the Sea-Bird and Aanderaa sensors led to unusable dissolved oxygen data after October 21 (*53*). Thus, the SeapHOx sensor recorded temperature, salinity, dissolved oxygen, and pH for 19 days every 30 minutes, and the other instruments recorded temperature, salinity, and dissolved oxygen every 10 minutes for ~10 (Okinawa 3) and 11 days (Okinawa 2) (*53*; Table S1).

Crocker Reef, Florida, USA

Crocker Reef (24.908 ºN, 80.525 ºW), located on the outer reef tract of the Florida Keys, is a "senile or dead reef" dominated mainly by rubble, sand, and scattered coral colonies (*88*). An autonomous sensor package including a SeapHOx (*76, 89*) sensor was deployed on the benthos (3.7 m) in a sandy patch next to hardbottom to capture temperature, salinity, dissolved oxygen, and pH every hour for 47 days during late summer (July 19–September 3, 2013; Crocker 1a), 46 days in winter (December 4, 2013–January 19, 2014; Crocker 1b), and 126 days from summer to fall (June 24, 2014–October 27, 2014; Crocker 1c) (*46*; Table S1).

Baker Island, Phoenix Islands

Baker Island (0.194 ºN, 176.478 ºW) is a small (2.1 km^2), uninhabited atoll in the Central Pacific and part of the Baker Island National Wildlife Refuge and the Pacific Remote Island Marine National Monument. The low-lying island is surrounded by a narrow fringing reef extending mainly east to west, and deeper reef slopes and terraces that drop off precipitously (*90*), with a total reef area of about 4 km^2 (*91*). Benthic community composition on the southern reef slopes at Baker is dominated by *Acropora* corals (28.9 % cover), turf algae (22.3 %), macroalgae (15.6 %), and crustose coralline algae (24.2 %) (*91-92*). A Sea-Bird SBE43 dissolved oxygen sensor and Sea-Bird SBE19 plus CTD were deployed on the forereef benthos at 14.3 m for 3 days between June 12 and 15, 2018, recording temperature, salinity, and dissolved oxygen every 10 seconds (*52*; Table S1).

Jarvis Island, Line Islands

Jarvis Island (0.372 ºS, 159.997 ºW) is a small (4.5 km^2), barren island in the Central Pacific surrounded by narrow fringing reefs and steep forereefs that drop off to depths of more than 3,000 m (*91, 93*). Total reef area at Jarvis is approximately 3 km^2, with less than 1 % live coral cover following mass bleaching in 2015 (*93*). A Sea-Bird SBE43 dissolved oxygen sensor and Sea-Bird SBE19 plus CTD were deployed on the forereef benthos at 17.1 m for 3 days between July 28 and 31, 2018, recording temperature, salinity, and dissolved oxygen every 10 seconds (*52*; Table S1).

Tutuila, American Samoa

Tutuila (14.319 ºS, 170.751 ºW) is the main and largest island of American Samoa at 142.3 km^2. The island is surrounded by narrow fringing reefs, with highly variable coral and macroalgal cover (*91*). The benthic community of the reefs on the northwest side of the island is dominated by turf algae (~40 % cover), hard coral (~25 %), crustose coralline algae (<20 %), and some macroalgae (<4 %), with similar composition at shallow (0–6 m), mid (>6–18 m), and deeper depths (18–30 m; *91*). A Sea-Bird SBE43 dissolved oxygen sensor and Sea-Bird SBE19 plus CTD were deployed on the forereef benthos at 15.2 m for 24 days between June 23 and July 17, 2018, recording temperature, salinity, and dissolved oxygen every 5 minutes (*51*; Table S1).

Palmyra Atoll, Line Islands

Palmyra Atoll (~2 km^2) of the northern Line Islands is a coral atoll in the South Pacific (5.882 ºN, 162.081 ºW) approximately due south of the Hawaiian Islands. Palmyra is a National Fish and Wildlife Refuge and part of the Pacific Remote Island Areas National Marine Monument, and thus not exposed to recent anthropogenic influences such as fishing or pollution (*94-95*). The atoll runs east to west, with two large lagoons and shallow reef terraces on either side (*96*) and a total reef area of about 42 km^2 (*91*). The benthic community at Palmyra is dominated by live stony corals (28.5 %), crustose coralline algae (18.9 %), turf algae (24.3 %), and macroalgae

(12.8 %) (*91, 97*). The forereef of Palmyra has been noted to contain a more diverse coral community, with higher cover of faster growing species like *Acropora* and *Pocillopora* (*98*).

SeapHOx (*76*) sensors were deployed at a site on the reef terrace in 2016–2017 and 2018–2019 and on the back reef in 2016–2017. A SeapHOx sensor was deployed on the benthos of the reef terrace at approximately 5 m depth to record temperature, salinity, pH, and dissolved oxygen every 30 minutes from July 7, 2016–April 8, 2017 (275 days; Palmyra 1a) and October 30, 2018–May 14, 2019 (196 days; Palmyra 1b). The SeapHOx placed on the benthos of the back reef was deployed from July 7, 2016, to May 12, 2017 (309 days; Palmyra 2) at ~4 m depth, also recording temperature, salinity, pH, and dissolved oxygen every 30 minutes. An SBE43 dissolved oxygen sensor and Sea-Bird SBE19 plus CTD were also deployed at a site on the forereef benthos from August 3–6, 2018 (3 days; Palmyra 3) at 12.8 m depth, recording temperature, salinity, and dissolved oxygen every 10 seconds (*52*; Table S1).

<u>Potential Errors and Uncertainty</u>

The accuracy of autonomous oxygen measurements depends on a number of factors including quality of the initial sensor calibration, subsequent sensor drift (during storage, transport, and/or deployment), and biofouling (*99*). We note the oxygen data in the present study were collated from multiple sources including both published (i.e., Crocker Reef, Heron Island, Bocas del Toro, Kāne‘ohe Bay, Jarvis, Baker, Tutuila, Palmyra 3, Okinawa, and Bermuda; *46-53*) and unpublished (i.e., Dongsha Atoll, Taiping Island, Palmyra, 1a, 1b, 2) datasets as well as different oxygen sensors, calibration protocols, deployment durations, and users. However, because of the dynamic nature of oxygen in coral reef benthic environments spanning the full range from anoxia (e.g., *9, 100-101*) to extensive super saturation (e.g., *102*), it is not straightforward to identify suboptimal measurements that remain within reasonable bounds. We have done our best to assess the validity of each dataset both technically (i.e., following calibration protocols, etc.) and holistically (i.e., if a range of observations from a given environment makes sense based on the local benthic community, geomorphology, hydrodynamics, and history), and have found no direct evidence of any outstanding problems with the datasets that would negate our main conclusions. If we consider a hypothetical mean bias of -5 % of our oxygen measurements (*103*), this alters the percentage of observations below the different thresholds at present by at most -32 % (153 μmol O_2 kg^{-1}), -31 % (122 μmol O_2 kg^{-1}), -21 % (92 μmol O_2 kg^{-1}), and -6 % (61 μmol O_2 kg^{-1}) with mostly similar or smaller reductions under future warming projections (Table S9). This would lessen the observed and projected hypoxia intensity and severity with respect to the defined thresholds, but it does not affect the ranges of oxygen variability and the projected decreases in dissolved oxygen under different warming scenarios. The same would be true for a positive measurement bias, although this would worsen the observed and projected intensity and severity for the different reefs. In either case, under projected future warming, there will be an increase in the frequency, intensity, duration, and severity of hypoxia for all reefs in this study compared to present, which emphasize the concerns raised here and elsewhere (*7-9*). It also highlights the need to further solidify relevant physiological oxygen thresholds and their implications, and to continue developing methodological and technological improvements for making high quality, autonomous oxygen measurements in shallow, near-shore environments.

Box Model of DO Changes as a Result of Temperature Rise

A simple box model was used to validate the methodology and calculations performed as described in the Methods. The objective of the model was not to create a full-fledged biogeochemical coral reef model, but simply to create a model that could be used to conceptually validate the computational approximation of DO changes owing to the combined effect of decreasing gas solubility and increasing respiration rates resulting from ocean warming. The observations of DO from each reef location reflected the net effect of primary production, respiration, and physical transport processes, but without quantitative knowledge of these individual processes, we could only approximate the net effect of future warming on DO concentrations (see Methods). In the model, individual fluxes were prescribed and assessed independently, which allowed us to model the effect of warming on these processes and compare the net effect to the computational approximation applied to the global coral reef oxygen dataset.

The model calculations were assessed for a 1 m^3 seawater reservoir (1 m x 1 m x 1m) with dissolved oxygen concentration influenced by inflow ($F_{sw\text{-}i}$) and outflow ($F_{sw\text{-}o}$) of seawater as well as gross primary production (F_{PP}) and respiration (F_R). Gas exchange was negligible relative to these other fluxes and therefore not included in the model. The mass balance of oxygen was described by:

$$\frac{dDO}{dt} = F_{sw-i} - F_{sw-o} + F_{PP} - F_R \quad \text{(Equation 14)}$$

All calculations were conducted at constant salinity, with the base scenario having a salinity of 35 g kg^{-1} and temperature of 25 ºC. At initial conditions, seawater was assumed to be at 100 % oxygen saturation. Seawater inflow was assumed constant from an open ocean end member at 100 % oxygen saturation throughout the simulation. Gross primary production was defined according to Falter et al. (*104*):

$$F_{PP} = P * \sin\left(\frac{\pi(t-t_{sr})}{(t_{ss}-t_{sr})}\right)^{1.2} \text{ for } t_{sr} \leq t \leq t_{ss} \quad \text{(Equation 15)}$$

$$F_{PP} = 0 \qquad \text{in all other cases}$$

where P is the maximum rate of gross primary production, t is time, and t_{sr} and t_{ss} represent the time of sunrise and sunset. For this model, we used a 12-hour day night cycle, with sunrise and sunset being at 6:00 h and 18:00 h, respectively. Respiration was assumed to be constant. Primary production and respiration rates were prescribed according to typical coral reef rates (*104* and references therein) and tuned to reproduce a typical diel cycle of reef oxygen variability (194 μmol O_2 kg^{-1} to 233 μmol O_2 kg^{-1}). Thus, the maximum rate of gross primary production was prescribed at 40 mmol O_2 m^{-2} h^{-1} (P = 40 mmol m^{-2} h^{-1}) and respiration at 12 mmol O_2 m^{-2} h^{-1} resulting in a daily net productivity of 0 O_2 mmol m^{-2} day^{-1} in the base scenario. Numerical integration was conducted with MATLAB (*105*) using an ordinary differential equation solver (ode45) based on an explicit Runge-Kutta (4, 5) formula. The model was run for 7 days.

Sensitivity analyses were conducted with respect to different residence times (1 and 5 hours) and three temperature scenarios (25 ºC, 28 ºC, 31 ºC) to assess the influence on both the mean and the diel variability in DO concentrations. For each scenario, open ocean and initial seawater conditions were assumed to be at 100 % oxygen saturation calculated using the constant salinity and given temperature of the scenario. Gross primary production was assumed to be unaffected by warming whereas respiration rates changed according to the Q_{10} relationship described in the Methods (Eq. 9). The computational approximation approach employed by the global coral reef dataset was used for each model scenario and compared to the exact model results of DO concentrations (Extended Data Fig. 5). These comparisons showed that the approximation approach reproduced oxygen concentrations to within 0 to 0.5 μmol O_2 kg^{-1} of the actual results for a 1 hour residence time and within 0.1 to 5.6 μmol O_2 kg^{-1} for a 5 hour residence time, once the model reached a near quasi-steady state (Extended Data Fig. 5). This comparison provides confidence of the application of the calculations used to estimate the effect of warming on oxygen solubility and biological oxygen demand for the global coral reef dataset.

Table S1. Instrument deployment information. For each location, different instrument deployment sites are represented by numbers (e.g., Dongsha 1 and Dongsha 2), or a combination of letters and numbers where letters represent either different depths at the same site (e.g., Bocas 1a, 1b, 1c, and 1d) or different deployments at the same site over time (e.g., Crocker 1a, 1b, and 1c). The instrument column lists instrument package followed by specific oxygen optode model in parentheses if relevant. Reef type categorization is based on standard definitions (*58*).

Location	Site	Instrument	Deployment Dates	Duration (days)	Depth (m)	Latitude	Longitude	Reef Type	Dominant community	Ref
Bocas del Toro	Bocas 1a	SeapHOx (Aanderaa)	Nov. 4, 2015 – Nov. 9, 2015	5	1	9.377	-82.3	Inner Reef Flat	Sand, seagrass	*48*
Bocas del Toro	Bocas 1b	SeapHOx (Aanderaa)	Nov. 3, 2015 – Nov. 19, 2015	16	3	9.377	-82.3	Inner Reef Flat	Sand, coral	*48*
Bocas del Toro	Bocas 1c	SeapHOx (Aanderaa)	Nov. 3, 2015 – Nov. 19, 2015	16	8.4	9.377	-82.3	Inner Reef Flat	Mixed coral	*48*
Bocas del Toro	Bocas 1d	SeapHOx (Aanderaa)	Nov. 3, 2015 – Nov. 9, 2015	6	12	9.377	-82.3	Inner Reef Flat	Sand	*48*
Bocas del Toro	Bocas 2a	SeapHOx (Aanderaa)	Nov. 9, 2015 – Nov. 20, 2015	11	2.6	9.259	-82.108	Patch Reef	Mixed coral	*48*
Bocas del Toro	Bocas 2b	SeapHOx (Aanderaa)	Nov. 9, 2015 – Nov. 20, 2015	11	7.6	9.259	-82.108	Patch Reef	Mixed coral	*48*
Crocker Reef	Crocker 1a	SeapHOx (Aanderaa)	July 19, 2013 – Sept. 3, 2013	47	3.7	24.909	-80.526	Lagoon	Rubble, soft coral	*46*
Crocker Reef	Crocker 1b	SeapHOx (Aanderaa)	Dec. 4, 2013 – Jan. 19, 2014	46	3.7	24.909	-80.526	Lagoon	Rubble, soft coral	*46*
Crocker Reef	Crocker 1c	SeapHOx (Aanderaa)	June 24, 2014 – Oct. 27, 2014	126	3.7	24.909	-80.526	Lagoon	Rubble, soft coral	*46*
Hog Reef	Hog 1a	Sea-Bird (Aanderaa)	Sept. 1, 2017 – Sept. 22, 2017	21	1*	32.457	-64.834	Reef Front	Algae, coral	*50*
Hog Reef	Hog 1b	Sea-Bird (Aanderaa)	Sept. 1, 2017 – Sept. 22, 2017	21	7**	32.457	-64.834	Reef Front	Algae, coral	*50*
Heron Island	Heron 1	SeapHOx (Aanderaa)	Oct. 9, 2015 – Oct. 22, 2015	13	0.7	-23.444	151.913	Inner Reef Flat	Sand, coral	*47*
Heron Island	Heron 2	SeapHOx (Aanderaa)	Oct. 9, 2015 – Oct. 15, 2015	6	2.1	-23.451	151.958	Lagoon	Rubble, sand	*47*
Heron Island	Heron 3	SeapHOx (Aanderaa)	Oct. 9, 2015 – Oct. 15, 2015	6	1.2	-23.464	151.985	Outer Reef Flat	Rubble, sand	*47*
Kāne‘ohe Bay	Kāne‘ohe 1a	SeapHOx (Aanderaa)	June 17, 2016 – June 30, 2016	13	2.8	21.458	-157.798	Inner Reef Flat	Rubble, coral	*49*

Location	Site	Instrument	Deployment Dates	Duration (days)	Depth (m)	Latitude	Longitude	Reef Type	Dominant community	Ref
Kāne‘ohe Bay	Kāne‘ohe 1b	SeapHOx (Aanderaa)	Nov. 10, 2016 – Nov. 17, 2016	7	2.8	21.458	-157.798	Inner Reef Flat	Rubble, coral	*49*
Kāne‘ohe Bay	Kāne‘ohe 2	SeapHOx (Aanderaa)	Nov. 10, 2016 – Nov. 17, 2016	7	3	21.462	-157.792	Inner Reef Flat	Rubble	*49*
Dongsha	Dongsha 1	Idronaut CTD	July 1, 2018 – July 8, 2018	7	0.9	20.707	116.721	Shallow Lagoon	Seagrass	This Study
Dongsha	Dongsha 2	Idronaut CTD	July 1, 2018 – July 8, 2018	7	2	20.705	116.808	Patch Reef	Mixed coral	This Study
Dongsha	Dongsha 3	Sea-Bird (Aanderaa)	July 1, 2018 – July 8, 2018	7	2	20.702	116.89	Patch Reef	Mixed coral	This Study
Okinawa	Okinawa 1	SeapHOx (Aanderaa)	Oct. 10, 2019 – Oct. 29, 2019	19	1.3	26.452	127.795	Outer Reef Flat	Rubble	53
Okinawa	Okinawa 2	Sea-Bird (Aanderaa)	Oct. 10, 2019 – Oct. 21, 2019	11	2.8	26.447	127.796	Lagoon	Coral	53
Okinawa	Okinawa 3	Sea-Bird (Aanderaa)	Oct. 10, 2019 – Oct. 21, 2019	10	6.6	26.439	127.792	Lagoon	Sand, coral	53
Taiping	Taiping 1	Sea-Bird (MiniDOT)	Mar. 28, 2019 – Mar. 31, 2019	3	1	10.377	114.37	Shallow Lagoon	Seagrass	This Study
Taiping	Taiping 2	SeapHOx (Aanderaa)	Mar. 28, 2019 – Mar. 31, 2019	3	2.5	10.376	114.37	Outer Reef Flat	Mixed coral	This Study
Baker	Baker	Sea-Bird (SBE43)	June 12, 2018 – June 15, 2018	3	14.3	0.192	-176.489	Reef Front	Coral	*52*
Jarvis	Jarvis	Sea-Bird (SBE43)	July 28, 2018 – July 31, 2018	3	17.1	-0.369	-16082	Reef Front	Algae, coral	*52*
Palmyra	Palmyra 1a	SeapHOx (Aanderaa)	July 7, 2016 – April 8, 2017	275	5	5.889	-162.124	Reef Terrace	Coral, algae	This Study
Palmyra	Palmyra 1b	SeapHOx (Aanderaa)	Oct. 30, 2018 – May 14, 2019	196	5	5.889	-162.124	Reef Terrace	Coral, algae	This Study
Palmyra	Palmyra 2	SeapHOx (Aanderaa)	July 7, 2016 – May 12, 2017	309	4	5.869	-162.111	Back Reef Slope	Coral, algae	This Study
Palmyra	Palmyra 3	Sea-Bird (SBE43)	Aug. 3, 2018 – Aug. 6, 2018	3	12.8	5.866	-162.11	Reef Front	Coral, algae	*52*
Tutuila	Tutuila	Sea-Bird (SBE43)	June 23, 2018 – July 17, 2018	24	15.2	-14.295	-170.812	Reef Front	Algae, coral	*51*

* Instrument deployed just below surface, but depth of water column 11 m (reef depth 7 m)

** Instrument deployed on reef benthos (7 m), but depth of water column nearby above sand hole is 11 m

Table S2. Mean daily statistics of oxygen concentration, oxygen saturation, and temperature. Mean daily statistics (calculated using n days of N total observations) of dissolved oxygen concentration (μmol O_2 kg^{-1}), dissolved oxygen saturation (%), and temperature (ºC) at each reef site (mean ± standard deviation) using only complete days (i.e., full 24 hours).

Site	N	n	Dissolved Oxygen (μmol O_2 kg^{-1})			Dissolved Oxygen Saturation (%)			Temperature (ºC)		
			Mean Daily Range	**Mean Daily Min**	**Mean Daily Max**	**Mean Daily Range**	**Mean Daily Min**	**Mean Daily Max**	**Mean Daily Range**	**Mean Daily Min**	**Mean Daily Max**
Bocas 1a	231	4	28.2 ± 8.6	156.2 ± 8.5	184.4 ± 4.8	15.9 ± 5.5	80.9 ± 4.5	96.8 ± 2.8	1.3 ± 0.3	29.7 ± 0.2	31 ± 0.3
Bocas 1b	765	15	41.7 ± 9.8	145.1 ± 7.8	186.8 ± 5.4	22.5 ± 5.3	75.8 ± 4.2	98.2 ± 2.9	0.7 ± 0.2	29.9 ± 0.3	30.6 ± 0.2
Bocas 1c	767	15	37.3 ± 7.1	134.3 ± 7.8	171.6 ± 6.5	19.6 ± 3.6	70.6 ± 3.9	90.2 ± 3.2	0.4 ± 0.2	30.1 ± 0.3	30.5 ± 0.2
Bocas 1d	273	5	27.3 ± 4.4	136.4 ± 7.4	163.7 ± 5.9	14.4 ± 2.3	71.8 ± 3.8	86.2 ± 3	0.3 ± 0.1	30.2 ± 0.1	30.5 ± 0.1
Bocas 2a	524	10	45.7 ± 13	141.6 ± 9	187.3 ± 10.1	24.4 ± 6.9	74.2 ± 4.6	98.6 ± 5.2	0.5 ± 0.2	30.1 ± 0.2	30.6 ± 0.2
Bocas 2b	523	10	49 ± 15.1	133.4 ± 15.5	182.4 ± 4.8	25.8 ± 8.2	70.3 ± 8.1	96.1 ± 2.7	0.4 ± 0.2	30 ± 0.2	30.4 ± 0.1
Crocker 1a	1128	45	87.4 ± 38.5	141.8 ± 22.3	229.2 ± 25.2	46.1 ± 20.2	74.1 ± 11.6	120.2 ± 13.6	0.6 ± 0.3	29.2 ± 0.4	29.8 ± 0.4
Crocker 1b	1096	45	48.2 ± 50.8	189.9 ± 9.7	238.1 ± 43	23.9 ± 25.1	93.4 ± 4.6	117.2 ± 21.4	0.8 ± 0.5	25 ± 1.1	25.8 ± 0.7
Crocker 1c	3006	124	133.1 ± 88.3	131.9 ± 36.9	265 ± 66.5	70.3 ± 46.9	69.1 ± 19.3	139.3 ± 35.7	0.6 ± 0.3	29.7 ± 0.9	30.3 ± 0.9
Hog 1a	2018	20	78.3 ± 29.7	200.7 ± 7.6	279 ± 28.3	41.1 ± 15.4	103.5 ± 3.9	144.6 ± 14.4	0.5 ± 0.2	28.1 ± 0.4	28.6 ± 0.4
Hog 1b	2018	20	54 ± 16.3	196.8 ± 10.7	250.8 ± 13.6	28.4 ± 8.6	101.4 ± 5.3	129.9 ± 6.9	0.4 ± 0.1	28.2 ± 0.4	28.6 ± 0.4
Heron 1	610	12	125.4 ± 46.1	128.2 ± 25	253.6 ± 29.7	65.1 ± 23.1	58.6 ± 11.5	123.7 ± 15	4.8 ± 1.1	20.7 ± 0.5	25.5 ± 1.1
Heron 2	293	5	58.4 ± 17.4	187.9 ± 18.1	246.3 ± 4.5	29.9 ± 9.3	87.6 ± 7.5	117.5 ± 3.3	1.9 ± 0.4	22.1 ± 0.6	24 ± 0.8
Heron 3	291	5	111.4 ± 21.1	153.9 ± 18.5	265.3 ± 9.7	57.7 ± 10.7	71.1 ± 7.6	128.8 ± 5.7	3.1 ± 0.5	21.8 ± 0.7	24.9 ± 0.9
Kāneʻohe 1a	624	12	164 ± 15.7	105.3 ± 11	269.2 ± 11.5	83.8 ± 8.5	51.6 ± 5.1	135.4 ± 6.5	1.7 ± 0.3	25.7 ± 0.4	27.4 ± 0.4
Kāneʻohe 1b	320	6	73.6 ± 24.4	90.9 ± 7	164.6 ± 29.3	37.1 ± 12.4	44.5 ± 3.2	81.6 ± 14.6	1 ± 0.5	25.5 ± 0.6	26.5 ± 0.3
Kāneʻohe 2	321	6	69.6 ± 31.6	145.4 ± 33.3	215 ± 12.9	35 ± 15.5	71.5 ± 16.7	106.5 ± 7.1	0.7 ± 0.2	25.7 ± 0.4	26.4 ± 0.5
Dongsha 1	710	6	187.5 ± 14.2	20.7 ± 17.1	208.1 ± 8.2	100.3 ± 7	10.8 ± 8.9	111.1 ± 4.5	2.3 ± 0.2	29.4 ± 0.4	31.7 ± 0.3
Dongsha 2	671	6	99.9 ± 59.6	93.8 ± 17.2	193.6 ± 45	52.6 ± 31.5	48.9 ± 8.7	101.6 ± 24.1	0.7 ± 0.1	29.7 ± 0.3	30.5 ± 0.3
Dongsha 3	1003	6	120 ± 45.6	83.9 ± 10.5	203.9 ± 36.4	63.3 ± 24	43.9 ± 5.5	107.2 ± 19.2	0.8 ± 0.2	30.1 ± 0.1	30.9 ± 0.2
Okinawa 1	909	18	31.6 ± 18.6	171.4 ± 9.5	203 ± 11.1	16.1 ± 9.6	84.5 ± 4.8	100.6 ± 5.8	0.5 ± 0.3	26.1 ± 0.2	26.7 ± 0.2
Okinawa 2	506	10	67.6 ± 19.7	185.7 ± 8.2	253.3 ± 16	34.1 ± 9.9	91.5 ± 3.9	125.6 ± 8.2	0.6 ± 0.2	26 ± 0.2	26.6 ± 0.2
Okinawa 3	503	10	80.3 ± 14.6	174.1 ± 8	254.4 ± 14.4	41 ± 7.7	85.5 ± 3.9	126.5 ± 7.8	0.9 ± 0.3	25.9 ± 0.2	26.8 ± 0.3
Taiping 1	374	2	258.1 ± 11.5	48.1 ± 11.2	306.1 ± 0.3	138.6 ± 4.5	24.2 ± 5.4	162.7 ± 0.9	3.8 ± 0.6	27.6 ± 0.3	31.4 ± 0.3
Taiping 2	376	2	123.1 ± 17	90.4 ± 5.4	213.4 ± 11.6	64.1 ± 9.2	46.1 ± 3.1	110.2 ± 6.1	1.2 ± 0	28.3 ± 0.1	29.5 ± 0.1
Baker	25716	2	35.1 ± 4.9	144.6 ± 1.5	179.8 ± 3.3	17.9 ± 2.1	74 ± 0.6	92 ± 1.5	0.8 ± 0.1	27.8 ± 0	28.6 ± 0.1
Jarvis	26530	2	32 ± 2.8	134.2 ± 4.4	166.2 ± 1.6	16.5 ± 1.3	67.8 ± 2.1	84.4 ± 0.8	0.4 ± 0.1	27.5 ± 0.1	27.8 ± 0
Palmyra 1a	13185	274	95.9 ± 21.2	140.1 ± 11.8	235.9 ± 20.2	50.1 ± 11.2	71.4 ± 5.9	121.4 ± 10.4	0.9 ± 0.4	28.1 ± 0.6	29 ± 0.6
Palmyra 1b	4701	195	73.5 ± 20.3	124.4 ± 10.2	197.9 ± 18.8	38.5 ± 10.7	63.7 ± 5.3	102.2 ± 9.8	0.7 ± 0.4	28.3 ± 0.6	29 ± 0.5
Palmyra 2	14852	308	76.7 ± 27	151.7 ± 14.3	228.4 ± 16.5	40.7 ± 14.7	77 ± 8.7	117.8 ± 8.6	1 ± 0.4	28.1 ± 0.6	29.1 ± 0.5
Palmyra 3	26761	2	40.9 ± 15.2	142.3 ± 10.2	183.2 ± 5	21.2 ± 8	73.5 ± 5.3	94.7 ± 2.7	0.2 ± 0.1	29.2 ± 0.1	29.4 ± 0
Tutuila	6878	23	22.9 ± 3.8	141.1 ± 2.9	164 ± 4	11.7 ± 1.9	72.3 ± 1.2	84 ± 2	0.2 ± 0.1	28.4 ± 0.4	28.6 ± 0.4

Table S3. Mean current speed and depth for coral reef sites where current meters were deployed. Mean current speed (m s^{-1}; ± 1 standard deviation (SD)) and depth (m; ± 1 SD) based on depth-integrated data recorded by current meters co-deployed with oxygen sensors at select reef sites used in regression analysis (Extended Data Figure 2). N values for each calculated mean are listed in parentheses. Missing values are reported as N/A.

Site	Mean speed ± 1 SD (m s^{-1})	Mean depth ± 1 SD (m)
Bocas 1c	0.035 ± 0.023 (2291)	8.00 ± 0.10 (2291)
Bocas 2b	0.027 ± 0.020 (1567)	8.65 ± 0.11 (1567)
Dongsha 2	0.048 ± 0.018 (1007)	1.91 ± 0.31 (1007)
Heron 2	0.118 ± 0.053 (879)	2.22 ± 0.60 (879)
Hog 1b	0.079 ± 0.024 (868)	6.60 ± 0.28 (868)
Jarvis	0.058 ± 0.032 (4381)	N/A*
Kāne‘ohe 1a	0.062 ± 0.039 (1873)	2.83 ± 0.21 (1873)
Kāne‘ohe 2	0.124 ± 0.049 (961)	3.11 ± 0.25 (961)
Okinawa 2	0.26 ± 0.13 (5473)	2.85 ± 0.50 (5473)
Okinawa 3	0.20 ± 0.10 (1814)	6.62 ± 0.50 (1814)
Palmyra 3	0.073 ± 0.048 (937)	N/A*
Tutuila	0.110 ± 0.0633 (6878)	N/A*

* No pressure data was recorded for Jarvis, Palmyra 3, or Tutuila. Thus, no mean depth was calculated for either site.

Table S4. Statistics of regression fits for the depth, flow speed, and reef type analyses. All curves were fit using a power model (f(x) = a*x^b) in the MATLAB (*105*) Curve Fitting Tool. The R^2 and Root Mean Square Error (RMSE) are shown to demonstrate goodness of fit.

Figure	X	Y	a	b	R^2	RMSE
Extended Data Fig. 2A	Mean depth	Mean daily range in oxygen	127.7	-0.4088	0.3212	44.65
Extended Data Fig. 2B*	Mean flow speed	Mean daily range in oxygen	71.4	0.0398	0.0022	39.83
Extended Data Fig. 2C	Mean depth	Mean daily minimum oxygen	117.9	0.1006	0.0998	38.02
Extended Data Fig. 2D	Mean flow speed	Mean daily minimum oxygen	246.2	0.2065	0.4043	26.20

*This regression is not plotted in the figure due to poor fit of the model.

Table S5. **Temperature projections by location.** Predicted temperature rise (ºC) by 2100 for each location sourced from the Coupled Model Intercomparison Project 6 (CMIP6) ensemble member Community Earth System Model Whole Atmosphere Community Climate Model (CESM2-WACCM) model (*63-64*).

Location	**Predicted Temperature Rise (ºC)**			
	SSP1-2.6	**SSP2-4.5**	**SSP3-7.0**	**SSP5-8.5**
Bocas del Toro	0.85	1.53	2.39	3.18
Crocker Reef	0.92	1.54	2.45	3.09
Hog Reef	0.68	1.23	2.43	3.38
Heron Island	0.95	1.87	2.72	3.76
Kāne‘ohe Bay	0.36	1.90	2.22	3.47
Dongsha	0.97	1.11	2.34	3.03
Okinawa	1.07	1.06	2.32	2.94
Taiping	0.98	1.16	2.55	3.49
Baker	0.60	2.14	2.93	3.89
Jarvis	0.72	2.37	3.30	4.05
Palmyra	0.29	1.55	2.30	3.38
Tutuila	0.64	1.14	1.83	2.79

Table S6. Changes in percent of observations below each hypoxia threshold under warming. Percent of total observations (N) that are hypoxic at present, under each temperature projection, and under a 6 ºC heatwave scenario for each site for four thresholds: ≤153, ≤122, ≤92, or ≤61 μmol O_2 kg^{-1} using the datasets standardized to 30-minute sampling intervals.

		Threshold = 153 μmol O_2 kg^{-1}						Threshold = 122 μmol O_2 kg^{-1}					
Site	**N**	**Present**	**SSP 1-2.6**	**SSP 2-4.5**	**SSP 3-7.0**	**SSP 5-8.5**	**Heatwave**	**Present**	**SSP 1-2.6**	**SSP 2-4.5**	**SSP 3-7.0**	**SSP 5-8.5**	**Heatwave**
Bocas 1a	231	0.3	1.1	1.9	3	4.2	11.6	0	0	0	0	0	0
Bocas 1b	765	2.7	3.8	4.6	5.9	7.7	13.7	0	0.1	0.1	0.1	0.2	1.9
Bocas 1c	767	6.3	8.7	10	12	13.5	16.5	0	0.1	0.3	0.5	1	4.6
Bocas 1d	273	9.2	11	12.5	14.5	15.9	16.7	0	0	0.1	0.3	0.9	5.5
Bocas 2a	524	2.4	4.1	6.1	8.3	9.8	15.3	0	0	0	0.2	0.3	1.8
Bocas 2b	523	6.9	8.1	9.6	11.1	12.3	15.5	0.7	1	1.2	1.8	2.3	5.7
Crocker 1a	2255	3.9	4.9	5.6	6.9	7.8	11.3	0.1	0.1	0.2	0.3	0.9	4.6
Crocker 1b	2191	0	0	0	0	0.1	0.5	0	0	0	0	0	0
Crocker 1c	6027	4.6	5.4	6.3	7.6	8.5	11.4	1.3	1.8	2.2	2.8	3.3	6.6
Hog 1a	1009	0	0	0	0	0	0	0	0	0	0	0	0
Hog 1b	1009	0	0	0	0	0.1	0.2	0	0	0	0	0	0
Heron 1	610	3.1	5.7	6.9	7.6	8.3	9.9	0.9	1.3	1.5	1.9	3.1	7.2
Heron 2	293	0	0	0	0	0.4	1.9	0	0	0	0	0	0
Heron 3	291	0.2	0.4	0.7	1.4	2.9	7.4	0	0	0.1	0.1	0.2	1
Kāne‘ohe 1a	624	6.5	6.7	8.1	8.3	9.3	11.2	2.5	3	4.9	5.2	6.5	8.7
Kāne‘ohe 1b	320	13.3	13.4	14.1	14.2	14.8	15.9	10.3	10.7	11.9	12	12.6	13.6
Kāne‘ohe 2	321	2.2	2.3	3.6	3.9	5.7	11.2	0.7	0.8	1.1	1.3	1.7	2.6
Dongsha 1	355	10.9	11.7	11.9	12.8	13.4	16.5	8.6	9.4	9.4	10.4	11	14.1
Dongsha 2	336	12	13	13.2	14.4	15.3	16	6.3	7.7	7.8	9.4	10.1	13.2
Dongsha 3	335	11.3	11.9	12	12.7	12.9	14.7	8.7	9.2	9.3	9.7	10.1	12.5
Okinawa 1	909	0.2	0.3	0.3	0.7	0.8	4.2	0	0	0	0	0	0.1
Okinawa 2	169	0	0	0	0	0	1	0	0	0	0	0	0
Okinawa 3	168	0	0	0	0.4	0.7	5.3	0	0	0	0	0	0
Taiping 1	125	9.1	9.5	9.6	10.7	10.9	14.3	5.6	7.6	7.6	8.9	9.5	11.3
Taiping 2	126	7.5	9.5	9.5	11	12.4	16	3.2	3.7	4.1	6.5	7.3	10.7
Baker	143	1.4	2.7	8.7	11	13.4	16.3	0	0	0	0	0	0
Jarvis	148	11.1	12.5	16.7	16.7	16.7	16.7	0	0	0.1	0.5	1.7	6.2
Palmyra 1a	13185	3.1	3.5	5.3	6.3	7.7	10.2	0.1	0.1	0.4	0.8	1.5	5.1
Palmyra 1b	9401	8.6	9	10.2	10.8	11.7	13.7	0.8	1	2.5	3.5	5.3	9.3
Palmyra 2	14852	1.4	1.6	2.7	3.6	5.5	9.8	0.1	0.1	0.2	0.3	0.5	1.9
Palmyra 3	149	4.4	4.7	7.9	10.3	14.3	16.6	0	0	0	0.1	0.2	2.3
Tutuila	1147	9.7	12.5	14.1	15.6	16.5	16.7	0	0	0	0	0	1.3

Site	Threshold = 92 μmol O_2 kg^{-1}						Threshold = 61 μmol O_2 kg^{-1}					
	Present	SSP 1-2.6	SSP 2-4.5	SSP 3-7.0	SSP 5-8.5	Heatwave	Present	SSP 1-2.6	SSP 2-4.5	SSP 3-7.0	SSP 5-8.5	Heatwave
Bocas 1a	0	0	0	0	0	0	0	0	0	0	0	0
Bocas 1b	0	0	0	0	0	0	0	0	0	0	0	0
Bocas 1c	0	0	0	0	0	0	0	0	0	0	0	0
Bocas 1d	0	0	0	0	0	0	0	0	0	0	0	0
Bocas 2a	0	0	0	0	0	0	0	0	0	0	0	0
Bocas 2b	0	0	0	0	0	0.6	0	0	0	0	0	0
Crocker 1a	0	0	0	0	0	0.1	0	0	0	0	0	0
Crocker 1b	0	0	0	0	0	0	0	0	0	0	0	0
Crocker 1c	0.4	0.5	0.6	0.7	0.9	2.5	0.1	0.2	0.2	0.2	0.3	0.6
Hog 1a	0	0	0	0	0	0	0	0	0	0	0	0
Hog 1b	0	0	0	0	0	0	0	0	0	0	0	0
Heron 1	0.2	0.2	0.3	0.5	1	1.8	0	0.1	0.1	0.1	0.2	0.4
Heron 2	0	0	0	0	0	0	0	0	0	0	0	0
Heron 3	0	0	0	0	0	0.1	0	0	0	0	0	0
Kāne‘ohe 1a	0.1	0.1	1.1	1.3	2.7	6.1	0	0	0	0	0.1	2
Kāne‘ohe 1b	1.4	2.2	6.4	7	8.8	11	0	0	0	0	0	3.1
Kāne‘ohe 2	0.1	0.1	0.3	0.3	0.5	0.9	0	0	0	0	0.1	0.1
Dongsha 1	6	6.9	6.9	8.2	8.7	11.4	2.5	3.6	3.8	5.4	6.1	9.1
Dongsha 2	1.3	2.1	2.3	3.5	4.4	8.1	0	0	0	0.1	0.1	2.2
Dongsha 3	0.9	2.4	2.6	5.5	6.6	9.5	0	0.1	0.1	0.2	0.2	4.2
Okinawa 1	0	0	0	0	0	0	0	0	0	0	0	0
Okinawa 2	0	0	0	0	0	0	0	0	0	0	0	0
Okinawa 3	0	0	0	0	0	0	0	0	0	0	0	0
Taiping 1	2.1	2.9	3.2	5.3	7.6	9.6	0.9	1.2	1.3	2	2.8	7.6
Taiping 2	0.4	1.3	1.3	2.4	3	6.5	0	0	0	0	0.1	2.4
Baker	0	0	0	0	0	0	0	0	0	0	0	0
Jarvis	0	0	0	0	0	0	0	0	0	0	0	0
Palmyra 1a	0	0	0	0	0	0.4	0	0	0	0	0	0
Palmyra 1b	0	0	0	0	0.1	1.5	0	0	0	0	0	0
Palmyra 2	0	0	0	0	0	0.1	0	0	0	0	0	0
Palmyra 3	0	0	0	0	0	0	0	0	0	0	0	0
Tutuila	0	0	0	0	0	0	0	0	0	0	0	0

Table S7. Percent of sites experiencing hypoxic events of various durations under warming. Percent of sites (N = 32) experiencing hypoxia of various durations (≤1 hour, >1 to ≤6 hours, >6 to ≤12 hours, >12 hours to ≤24 hours, or >24 hours) at present, under each temperature projection, and under a 6 ºC heatwave scenario for each site for four thresholds: ≤153, ≤122, ≤92, or ≤61 μmol O_2 kg^{-1} using the datasets standardized to 30-minute sampling intervals.

		Percent of Sites				
Threshold	**Projection**	**<1 hr**	**1 to 6 hr**	**6 to 12 hr**	**12 to 24 hr**	**>24 hr**
Weak: 153 µmol O_2 kg^{-1}	Present	68.8	59.4	53.1	43.8	12.5
	SSP1-2.6	71.9	62.5	53.1	53.1	15.6
	SSP2-4.5	65.6	62.5	56.3	56.3	21.9
	SSP3-7.0	65.6	68.8	56.3	62.5	31.3
	SSP5-8.5	68.8	68.8	53.1	68.8	31.3
	Heatwave	62.5	53.1	43.8	65.6	53.1
Mild: 122 µmol O_2 kg^{-1}	Present	43.8	37.5	31.3	15.6	0
	SSP1-2.6	43.8	31.3	34.4	15.6	0
	SSP2-4.5	56.3	37.5	37.5	18.8	6.3
	SSP3-7.0	56.3	43.8	37.5	21.9	6.3
	SSP5-8.5	56.3	50.0	34.4	28.1	9.4
	Heatwave	62.5	59.4	40.6	50.0	15.6
Moderate: 92 µmol O_2 kg^{-1}	Present	25.0	25.0	6.3	0	0
	SSP1-2.6	31.3	28.1	12.5	0	0
	SSP2-4.5	40.6	28.1	12.5	3.1	0
	SSP3-7.0	34.4	25.0	21.9	6.3	0
	SSP5-8.5	37.5	34.4	28.1	12.5	0
	Heatwave	43.8	34.4	31.3	18.8	0
Severe: 61 µmol O_2 kg^{-1}	Present	12.5	9.4	3.1	0	0
	SSP1-2.6	18.8	9.4	6.3	0	0
	SSP2-4.5	18.8	9.4	6.3	0	0
	SSP3-7.0	12.5	12.5	6.3	0	0
	SSP5-8.5	21.9	18.8	6.3	0	0
	Heatwave	25.0	25.0	18.8	3.1	0

Table S8. Literature review of tropical coral low oxygen aquarium experiments. Summary of published, peer-reviewed studies from the literature that test the effects of reduced oxygen concentration on tropical scleractinian corals in the laboratory either alone or in combination with other parameters. Information summarized includes the study citation, species tested, where the corals were collected or sourced from, duration of experiment (for multi-day experiments), duration of low oxygen exposure for the corals tested, concentrations of oxygen used (names of levels provided if used in study), other stressors tested in experiment(s), if mortality or bleaching was recorded, other responses measured, and if the pH was controlled (as most studies used addition of N_2 gas to purge O_2). A value of N/A means that the information was either not measured or not reported in the study. Studies testing multiple species are listed separately.

Study	Species	Corals From	Duration of experiment	Duration of low oxygen exposure	Levels of dissolved oxygen	Other stressors	Mortality	Bleaching	Other responses	pH
7	*Agaricia lamarcki*	Bocas del Toro, Panama	7 days	Constant?	0.5 mg O_2 L^{-1} (hypoxic), >5 mg O_2 L^{-1} (normoxic)	28 ºC (cool), 32 ºC (warm)	100% in both hypoxia treatments	N/A	N/A	No
7	*Stephanocoenia intersepta*	Bocas del Toro, Panama	7 days	Constant?	0.5 mg O_2 L^{-1} (hypoxic), >5 mg O_2 L^{-1} (normoxic)	28 ºC (cool), 32 ºC (warm)	None across any treatment	N/A	N/A	No
18	*Acropora yongeii*	Birch Aquarium	10 days	12 hours (nightly)	2-4 mg O_2 L^{-1} (low), 4-6 mg O_2 L^{-1} (decreased), 6-8 mg O_2 L^{-1} (ambient)	N/A	All after Day 3 (low)	All by Day 3 (low)	Decrease in photosynthetic performance, oxygen production rates, green fluorescence; increase in red fluorescence (low treatment)	No
19	*Acropora cervicornis*	Mote Marine Lab, Florida	5 days	Constant	1 mg O_2 L^{-1}, 2.25 mg O_2 L^{-1}, 4.25 mg O_2 L^{-1}, 6.25 mg O_2 L^{-1}	N/A	Half within 5 days	Starting Day 2 in lowest treatment	Increasing tissue loss over time, decline in F_v/F_m after 2 days, reduction in symbiont density (lowest treatment)	No
19	*Orbicella faveolata*	Mote Marine Lab, Florida	11 days	Constant	1 mg O_2 L^{-1}, 2.25 mg O_2 L^{-1}, 4.25 mg O_2 L^{-1}, 6.25 mg O_2 L^{-1}	N/A	None	None	Decline in F_v/F_m in lowest treatment after 7 days	No

20	*Orbicella faveolate*	Big Pine Key, Florida	1 day?	2-hour O_2 ramp down, 6-hour incubation	~<2 mg O_2 L^{-1} (hypoxic), ~6 mg O_2 L^{-1} (ambient) but varied by tank/treatment	28 ºC (ambient), 31.5 ºC (elevated) [All in dark]	None (and none 2 months after)	Paling observed but not measured	Decreased O_2 consumption under hypoxia for both temperature treatments	No
29	*Montipora capitata*	Kāneʻohe Bay, Hawaiʻi	7 days	12 hours (nightly)	0 ppm	N/A	Most by Day 5	Starting on Night 2, all by Night 5	Increase in strombine and alanopine dehydrogenase (SDH and ADH) activity	No*
30	*Acropora tenuis*	Great Barrier Reef, Australia	1 day	12 hours (overnight)	1.09–2.8 mg O_2 L^{-1} (hypoxia), ~5.5 mg O_2 L^{-1} (control)	N/A	None	None	Changes in gene expression after nighttime hypoxia exposure	Yes
30	*Acropora selago*	Great Barrier Reef, Australia	1 day	12 hours (overnight)	0.64–3.42 mg O_2 L^{-1} (hypoxia), ~5.5 mg O_2 L^{-1} (control)	N/A	None	After 24 hours (following reoxygenation)	Decrease in Symbiodiniaceae cell density and chlorophyll concentration after nighttime hypoxia, changes in gene expression after reoxygenation only	Yes
31	*Galaxea fascicularis*	Gulf of Aqaba, Jordan	30 minutes?	30 minutes?	?	Light and dark (feeding tested in separate experiment)	N/A	N/A	No effect of O_2 on light calcification rates; Dark calcification reduced under lower O_2	No
32	*Galaxea fascicularis*	Burgers' Zoo, Netherlands	6 hours	6 hours	0.87 mg O_2 L^{-1}, 3.33 mg O_2 L^{-1}, 5.33 mg O_2 L^{-1}, 7.33 mg O_2 L^{-1}, 10.00 mg O_2 L^{-1}, 18.67 mg O_2 L^{-1}	Light, Dark; Fed, Unfed	N/A	N/A	Decreased calcification rates under both low and high O_2, light enhanced calcification (especially when fed), but calcification was reduced in darkness (further when fed)	No?
33	*Acropora millepora*	Commercial supplier	5 hours	5 hours	Light: 6.36 mg O_2 L^{-1}, 10.81 mg O_2 L^{-1} Dark:	Light: 8.1 pH, 8.4 pH Dark:	N/A	N/A	Light: hyperoxia negated positive effect of high pH on calcification	Yes

					1.91 mg O_2 L^{-1}, 6.36 mg O_2 L^{-1}	7.8 pH, 8.1 pH			Dark: hypoxia inhibited calcification, no effect of pH	
34	*Acropora spp.*	Commercial supplier	8 days	12 hours (nightly)	1.75 mg O_2 L^{-1} (hypoxia) 6.73 mg O_2 L^{-1} (control)	N/A	None	None	Impairment of electron transport and increase in DNA damage under hypoxia, no changes in pigment composition, lipid peroxidation, or catalase activity	No
35	*Acropora selago* (larvae)	Great Barrier Reef, Australia	1 day	12 hours (overnight)	2.2–2.5 mg O_2 L^{-1} (hypoxia), ~6.8 mg O_2 L^{-1} (control)	N/A	None	None	Changes in gene expression after reoxygenation	Yes
37	*Acropora cytherea*	Mo‘orea, French Polynesia	1 day	2 hours (vertical swimming experiment), 1 day (settlement experiment)	1.44–1.92 mg O_2 L^{-1} (low), 4.16–4.80 mg O_2 L^{-1} (intermediate), 6.08–6.40 mg O_2 L^{-1} (ambient)	N/A	N/A	N/A	Reduction in bottom exploration time under decreasing O_2, decreased settlement under lower O_2	No
37	*Acropora pulchra*	Mo‘orea, French Polynesia	1 day	2 hours (swimming experiment), 1 day (settlement experiment)	1.44–1.92 mg O_2 L^{-1} (low), 4.16–4.80 mg O_2 L^{-1} (intermediate), 6.08–6.40 mg O_2 L^{-1} (ambient)	N/A	N/A	N/A	Reduction in bottom exploration time under decreasing O_2, decreased settlement under lower O_2	No
106	*Acropora nobilis*	Sanya Bay, China	1 night?	Overnight	0.11 mg O_2 L^{-1}, 1.02 mg O_2 L^{-1}, 2.95 mg O_2 L^{-1}†	Temp, ammonia in separate experiments	N/A	More with lower O_2 except in one low treatment†	N/A	No
106	*Palythoa sp.*	Sanya Bay, China	1 night?	Overnight	0.11 mg O_2 L^{-1}, 1.02 mg O_2 L^{-1}, 2.95 mg O_2 L^{-1}†	Temp, ammonia in separate experiments	N/A	More with lower O_2, less sensitive than *Acropora*	N/A	No
106	*Alveopora verrilliana*	Sanya Bay, China	1 night?	Overnight	0.11 mg O_2 L^{-1}, 1.02 mg O_2 L^{-1}, 2.95 mg O_2 L^{-1}†	Temp, ammonia in separate experiments	N/A	Only under lowest O_2	N/A	No

107	*Galaxea fascicularis*	Burgers' Zoo, Netherlands	80 minutes	80 minutes	20 %, 100 %, 150 % O_2 saturation (100 % and 280 % O_2 saturation in additional experiment)	1–1.6 cm s^{-1} (low flow), 4–13 cm s^{-1} (high flow); 7.84 (low pH), 8.1 (ambient pH)	N/A	N/A	No changes in photosynthetic rate under different O_2, interactive effect of hypoxia and flow speed on respiration (lower respiration under lower O_2 and flow)	Yes
108	*Pocillopora damicornis*	Heron Island, Australia	30 minutes?	30 minutes?	100 % O_2 saturation + 4 cm s^{-1} flow (control), 40 ± 5 % O_2 saturation + 2 cm s^{-1} flow, 0–2 % O_2 saturation + 2 cm s^{-1} flow, 0 % O_2 saturation + no flow	see flow rates (not fully crossed)	N/A	N/A	Decreases in effective quantum yield and changes in chlorophyll fluorescence under low oxygen and reduced flow	No
109	*Montipora peltiformis*	Hannah Island, Australia	96 hours (48h exposure, 48h recovery) or 144 hours (96h exposure, 48h recovery)	48 hours or 96 hours, depending on experiment	0 µM (anoxia) in dark, 207 µM (normoxia) in light	7.1, 8.2 pH 0, 10, 20 µM H_2S	Recovery failed under anoxia + low pH alone and if exposed to H_2S under anoxia + low pH	N/A	No change in photosynthetic yield under anoxia with high pH, but decreased over time under anoxia + low pH or anoxia + low pH + H_2S	Yes

* pH not controlled, but did not differ significantly between treatments
N/A = not assessed or reported
† Hypoxia treatments achieved by additions of 0, 2.0, 4.0, and 5.0 g sodium sulfite to seawater (instead of N_2 bubbling). Additions of 4.0 g and 5.0 g both achieved 0.11 mg O_2 L^{-1} but yielded different responses in terms of bleaching.

Table S9. Assessment of dissolved oxygen measurement bias. Percent (%) of observations below each threshold (153 μmol O_2 kg^{-1}, 122 μmol O_2 kg^{-1}, 92 μmol O_2 kg^{-1}, 61 μmol O_2 kg^{-1}) for observed oxygen data (Obs.; left) and oxygen data corrected for a -5% bias (Bias; right) for each projection (Present, Shared Socioeconomic Pathway (SSP)1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5, and a 6 °C Heatwave).

	153 μmol O_2 kg^{-1}		**122 μmol O_2 kg^{-1}**		**92 μmol O_2 kg^{-1}**		**61 μmol O_2 kg^{-1}**	
Projection	**Obs.**	**Bias**	**Obs.**	**Bias**	**Obs.**	**Bias**	**Obs.**	**Bias**
Present	3.91	2.67	0.55	0.38	0.10	0.08	0.03	0.03
SSP1-2.6	4.41	3.07	0.68	0.47	0.14	0.11	0.04	0.04
SSP2-4.5	5.54	4.08	1.09	0.69	0.19	0.14	0.05	0.04
SSP3-7.0	6.46	4.91	1.48	0.98	0.25	0.21	0.06	0.06
SSP5-8.5	7.68	6.03	2.12	1.47	0.33	0.27	0.08	0.07
Heatwave	10.50	9.31	4.68	3.58	0.96	0.69	0.22	0.18

References for Supplementary Information

73. C. Roelfsema, E. M. Kovacs, K. Markey, J. Vercelloni, A. Rodriguez-Ramirez, S. Lopez-Marcano, M. Gonzalez-Rivero, O. Hoegh-Guldberg, S. R. Phinn, Benthic and coral reef community field data for Heron Reef, Southern Great Barrier Reef, Australia, 2002–2018. *Sci. Data* **8**, 1–7 (2021).
74. W. Ahmad, D. T. Neil, An evaluation of Landsat Thematic Mapper (TM) digital data for discriminating coral reef zonation: Heron Reef (GBR). *Int. J. Remote Sens.* **15**, 2583–2597 (1994).
75. I. R. Santos, R. N. Glud, D. Maher, D. Erler, B. D. Eyre, Diel coral reef acidification driven by porewater advection in permeable carbonate sands, Heron Island, Great Barrier Reef. *Geophys. Res. Lett.* **38**, L03604 (2011).
76. P. J. Bresnahan, T. R. Martz, Y. Takeshita, K. S. Johnson, M. LaShomb, Best practices for autonomous measurement of seawater pH with the Honeywell Durafet. *Methods Oceanog.* **9**, 44–60 (2014).
77. L. D'Croz, J. B. Del Rosario, P. Góndola, The effect of fresh water runoff on the distribution of dissolved inorganic nutrients and plankton in the Bocas Del Toro Archipelago, Caribbean Panama. *Car. J. Sci.* **14**, 414–429 (2005).
78. S. V. Smith, W. J. Kimmerer, E. J. Laws, R. E. Brock, T. W. Walsh, Kaneohe Bay sewage diversion experiment: perspectives on ecosystem responses to nutritional perturbation. *Pac. Sci.* **35**, 279–395 (1981).
79. P. Jokiel, "Jokiel's Illustrated Scientific Guide to Kane'ohe Bay, O'ahu" (Hawai'i Institute of Marine Biology, 1991).
80. Marine Environmental Program, "Marine Environmental Program Annual Report, 2006-2007." (Bermuda Institute of Ocean Sciences, 2007).
81. T. A. Courtney, A. J. Andersson, N. R. Bates, A. Collins, T. Cyronak, S. J. de Putron, B. D. Eyre, R. Garley, E. J. Hochberg, R. Johnson, S. Musielewicz, T. J. Noyes, C. L. Sabine, A. J. Sutton, J. Toncin, A. Tribollet, Comparing chemistry and census-based estimates of net ecosystem calcification on a rim reef in Bermuda. *Front. Mar. Sci.* **3**, 1–15 (2016).
82. Y. Takeshita, T. Cyronak, T. R. Martz, T. Kindeberg, A. J. Andersson, Coral reef carbonate chemistry variability at different functional scales. *Front. Mar. Sci.* **5**, 1–12 (2018).

83. K. S. Tkachenko, K. Soong, Dongsha Atoll: a potential thermal refuge for reef-building corals in the South China Sea. *Mar. Environ. Res.* **127**, 112–125 (2017).
84. Y. Duan, Y. Liu, M. Li, M. Zhou, Y. Yang, Survey of reefs based on Landsat 8 Operational Land Imager (OLI) images in the Nansha Islands, South China Sea. *Acta Oceanol. Sinica* **35**, 11–19 (2016).
85. C. -F. Dai, T. Y. Fan, "Coral fauna of Taiping Island (Itu Aba Island) in the Spratlys of the South China Sea" (Atoll Research Bulletin, Smithsonian Institution, 436, 1996).
86. P. -C. Chen, S. -L. Liu, DNA-assisted barcoding of seaweed community in Taiping Island in South China Sea. *Phycologia* **56**, 31 (2017).
87. M. Omori, Y. Higa, C. Shinzato, Y. Zayasu, T. Nagata, R. Nakamura, A. Yokokura, S. Janadou, "Development of active restoration methodologies for coral reefs using asexual reproduction in Okinawa, Japan", paper presented at the 13th International Coral Reef Symposium, Honolulu, Hawai'i, 1 December 2016.
88. C. A. Kellogg, K. K. Yates, S. N. Lawler, C. S. Moore, N. A. Smiley, "Seasonal microbial and environmental parameters at Crocker Reef, Florida Keys, 2014–2015" (U.S. Geological Survey Open-File Report 1203, 2015, http://dx.doi.org/10.3133/ofr20151203).
89. K. K. Yates, C. S. Moore, N. H. Goldstein, E. T. Sherwood, "Tampa bay ocean and coastal acidification monitoring quality assurance project plan" (U.S. Geological Survey Open-File Report 1003, 2019, https://doi.org/10.3133/ofr20191003).
90. J. Maragos, J. Miller, J. Gove, E. De Martini, A. M. Friedlander, S. Godwin, C. Musburger, M. Timmers, R. Tsuda, P. Vroom, E. Flint, E. Lundblad, J. Weiss, P. Ayotte, E. Sala, S. Sandin, S. McTee, T. Wass, D. Siciliano, R. Brainard, D. Obura, S. Ferguson, B. Mundy, "US coral reefs in the Line and Phoenix Islands, central Pacific Ocean: history, geology, oceanography, and biology." in *Coral Reefs of the USA*, B. M. Riegl, R. E. Dodge, Eds. (Springer Netherlands, 2008) pp. 595–641.
91. S. Boyle, V. De Anda, K. Koenig, E. O'Reilly, M. Schafer, T. Acoba, A. Dillon, A. Heenan, T. Oliver, D. Swanson, B. Vargas-Ángel, M. Weijerman, L. Wegley Kelly, R. Brainard, I. Williams. "Coral reef ecosystems of the Pacific Remote Islands Marine National Monument: a 2000-2016 overview" (NOAA Pacific Islands Fisheries Science Center, PIFSC Special Publication, SP-17-003, 2017).

92. P. S. Vroom, C. A. Musburger, S. W. Cooper, J. E. Maragos, K. N. Page-Albins, M. A. V. Timmers, Marine biological community baselines in unimpacted tropical ecosystems: spatial and temporal analysis of reefs at Howland and Baker Islands. *Biodiv. Conserv.* **19**, 797–812 (2010).
93. B. Vargas-Ángel, B. Huntington, R. E. Brainard, R. Venegas, T. Oliver, H. Barkley, A. Cohen, El Niño-associated catastrophic coral mortality at Jarvis Island, Central Equatorial Pacific. *Coral Reefs* **38**, 731–741 (2019).
94. J. E. Smith, R. Brainard, A. Carter, S. Grillo, C. Edwards, J. Harris, L. Lewis, D. Obura, F. Rohwer, E. Sala, P. S. Vroom, S. Sandin, Re-evaluating the health of coral reef communities: baselines and evidence for human impacts across the Central Pacific. *Proc. Royal Soc. B: Biol. Sci.* **283**, p20151985 (2016).
95. Y. Takeshita, W. McGillis, E. M. Briggs, A. L. Carter, E. M. Donham, T. R. Martz, N. N. Price, J. E. Smith, Assessment of net community production and calcification of a coral reef using a boundary layer approach. *J. Geophys. Res.: Oceans* **121**, 5655–5671 (2016).
96. J. D. Collen, D. W. Garton, J. P. A. Gardner, Shoreline changes and sediment redistribution at Palmyra Atoll (Equatorial Pacific Ocean): 1874–present. *J. Coastal Res.* **25**, 711–722 (2009).
97. S. A. Sandin, J. E. Smith, E. E. DeMartini, E. A. Dinsdale, S. D. Donner, A. M. Friedlander, T. Konotchick, M Malay, J. E. Maragos, D. Obura, O. Pantos, G. Paulay, M. Richie, F. Rohwer, R. E. Schroeder, S. Walsh, J. B. C. Jackson, N. Knowlton, E. Sala, Baselines and degradation of coral reefs in the Northern Line Islands. *PLoS ONE* **3**, e1548 (2008).
98. G. J. Williams, J. E. Smith, E. J. Conklin, J. M. Gove, E. Sala, S. A. Sandin, Benthic communities at two remote pacific coral reefs: effects of reef habitat, depth, and wave energy gradients on spatial patterns. *PeerJ* **1**, e81 (2013).
99. H. C. Bittig, A. Körtzinger, C. Neill, E. van Ooijen, J. N. Plant, J. Hahn, K. S. Johnson, B. Yang, S. R. Emerson. Oxygen optode sensors: principle, characterization, calibration, and application in the ocean. *Front. Mar. Sci.* **4**, 1–25 (2018).
100. A. J. Andersson, N. R. Bates, F. T. Mackenzie, Dissolution of carbonate sediments under rising $p\mathrm{CO_2}$ and ocean acidification: observations from Devil's Hole, Bermuda. *Aq. Geochem.* **13**, 237–264 (2007).

101. E. F. Camp, M. R. Nitschke, R. Rodolfo-Metalpa, F. Houlbreque, S. G. Gardner, D. J. Smith, M. Zampighi, D. J. Suggett, Reef-building corals thrive within hot-acidified and deoxygenated waters. *Sci. Rep*. **7**, 1–9 (2017).

102. F. Giomi, A. Barausse, C. M. Duarte, J. Booth, S. Agusti, V. Saderne, A. Anton, D. Daffonchio, M. Fusi, Oxygen supersaturation protects coastal marine fauna from ocean warming. *Sci. Adv.* **5**, eaax1814 (2019).

103. Y. Takeshita, T. R. Martz, K. S. Johnson, J. N. Plant, D. Gilbert, S. C. Riser, C. Neill, B. Tilbrook, A climatology-based quality control procedure for profiling float oxygen data. *J. Geophys. Res.: Oceans* **118**, 5640–5650 (2013).

104. J. L. Falter, R. J. Lowe, Z. Zhang, M. McCulloch, Physical and biological controls on the carbonate chemistry of coral reef waters: effects of metabolism, wave forcing, sea level, and geomorphology. *PloS ONE* **8**, e53303 (2013).

105. MATLAB R2022b, Natick, Massachusetts: The MathWorks Inc (2022).

106. B. Zhu, , G. Wang, B. Huang, C. K. Tseng, Effects of temperature, hypoxia, ammonia and nitrate on the bleaching among three coral species. *Chinese Sci. Bull.* **49**, 1923–28 (2004).

107. R. Osinga, M. Derksen-Hooijberg, T. Wijgerde, J. A. J. Verreth, Interactive effects of oxygen, carbon dioxide and flow on photosynthesis and respiration in the scleractinian coral *Galaxea fascicularis*. *J. Exp. Biol.* **220**, 2236–2242 (2017).

108. K. E. Ulstrup, R. Hill, P. J. Ralph, Photosynthetic impact of hypoxia on in hospite zooxanthellae in the scleractinian coral *Pocillopora damicornis*. *Mar. Ecol. Prog. Ser.* **286**, 125–132 (2005).

109. M. Weber, D. de Beer, C. Lott, L. Polerecky, K. Kohls, R. M. M. Abed, T. G. Ferdelman, K. E. Fabricius, Mechanisms of damage to corals exposed to sedimentation. *Proc. Nat. Acad. Sci.* **109**, E1558–1567 (2012).