Past the precipice? Projected coral habitability under global heating

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Key Points:

- We project over 85 percent of coral reefs will now experience severe-bleaching-level ocean heat recurring at least once per five years
- We project over 99 percent of reefs will experience severe-bleaching-level ocean heat at least once per ten years by 2032 under SSP3-7.0
- We find SSP1-2.6 to be the only scenario not consistent with near-complete global severe degradation or loss of coral reefs

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Abstract

Coral reefs are rapidly declining due to local environmental degradation and global climate change. In particular, corals are vulnerable to ocean heating. Anomalously hot sea surface temperatures (SSTs) create conditions for severe bleaching, the expulsion of photosynthetic algal symbionts leaving corals at risk of starvation and disease, or direct thermal death. We use SST observations and CMIP6 model SST to project thermal conditions at reef locations at a resolution of $1\,\mathrm{km}^2$, a 16-fold improvement over prior studies, under future emissions scenarios. For each location we present projections of thermal departure (TD, the date after which a location with steadily increasing heat exceeds a given thermal metric) for severe bleaching recurs every 5 years (TD5Y) and every 10 years (TD10Y), accounting for a range of post-bleaching reef recovery/degradation. As of 2021, we find that over 93% and 85% of $1\,\mathrm{km}^2$ reefs have exceeded TD10Y and TD5Y, respectively, suggesting that widespread long-term coral degradation may no longer be avoidable. We project 99% of $1\,\mathrm{km}^2$ reefs to exceed TD5Y by 2033, 2035, and 2041 under SSP5-8.5, SSP3-7.0, and SSP2-4.5 respectively, but this milestone would not be crossed under SSP1-2.6. We project that 2% of reef locations remain below TD5Y at 1.5°C of mean global heating, but 0% remain at 2.0°C. These results demonstrate the importance of further improving ecological projection capacity for climate-vulnerable marine and terrestrial species and ecosystems, including identifying refugia and guiding conservation efforts. Ultimately, saving coral reefs will require rapidly reducing and eliminating greenhouse gas emissions.

1 Plain Language Summary

Coral reefs face many challenges, but the most serious is climate change. Hotter oceans can kill corals via expulsion of their food-producing algae and eventual starvation, or by cooking them to death. We used satellite data and the latest global Earth system models to project when the world's coral reefs are expected to surpass a severe bleaching temperature threshold at 1-kilometer-square locations. To account for post-bleaching coral recovery times, we project the year after which each location will experience bleaching conditions at least once per 5 and 10 years.

As of 2021, we estimate that over 93% and 85% of reef locations will experience bleaching conditions at least once per 10 years and 5 years, respectively, suggesting that widespread long-term coral degradation is no longer avoidable. We estimate that 99% of reefs will experience bleaching conditions every 5 years by 2041, 2035, and 2033 under progressively higher future emissions scenarios, but that this milestone would never be crossed under an aggressive mitigation scenario. These results demonstrate the importance of improving ecological projection capacity for climate-vulnerable marine and terrestrial species and ecosystems, including identifying refuge locations and guiding conservation efforts, and rapidly reducing greenhouse gas (GHG) emissions.

2 Introduction

Coral reefs are among the most biodiverse ecosystems on the planet (Veron, 1995). However, over the last decade there has been a rapid global decline in coral health and coral cover due to both local environmental degradation (from destructive fishing practices, overfishing, coastal development, sedimentation, nutrient over-enrichment, and chemical pollutants, and other causes) and global climate change (increasing ocean heat, sea levels, and ocean acidification) (De'ath et al., 2012; Hughes et al., 2017).

Although regional bleaching events had been occasionally observed throughout the twentieth century (Yonge, 1930), the first *mass* event occurred during the 1982-83 El Niño and the first *global* event occurred during the 1997-98 El Niño (Hoegh-Guldberg et al., 2017). The next global bleaching event began in 2016 and lasted two years. Today, bleaching occurs even during La Niña years (Hughes et al., 2018). Over recent decades, 33-50% of coral reefs have been largely or completely degraded (The International Society for Reef Studies, 2015). Overall, there is great concern about the current state of reefs and for their future, as humans continue to heat the planet (Langlais et al., 2017).

Several prior studies have used SST outputs from global Earth system and climate models (hereafter global models or GMs) to assess future bleaching risk (Hoegh-Guldberg, 1999; Donner, 2009; Van Hooidonk et al., 2013; Frieler et al., 2013; Schleussner et al., 2016; Van Hooidonk et al., 2016). These studies most often report TD5Y, the year after which a thermal threshold is subsequently surpassed at least once per five years, at GM-like spatial resolution of $\sim$100 km^2. Severe bleaching projections could better inform local conservation decisions if they could capture spatial structure at $\sim$1 km (Van Hooidonk et al., 2016). Downscaling GM SST projections can therefore better inform decision-making, and statistical downscaling compares well to more computationally expensive dynamical downscaling(Van Hooidonk et al., 2015). Here, we provide the first projections of thermal severe bleaching from an ensemble of CMIP6 GMs, and the first at a spatial resolution of 1 km.

3 Data and Methods

3.1 Observational data

For performing statistical downscaling and for performing degree heating week estimates at 1 km scale, we use NASA/JPL Multiscale Ultrahigh Resolution (MUR) observational SST data from remote sensing, a 0.01°($\sim$1 km in the domain of our analysis) gridded daily satellite product, available from 2002 to the present, which increases feature resolution over existing SST analysis products with resolutions of 10-100 km. We average the daily MUR product into a monthly product.

The RMS difference between MUR and the quarter-degree-gridded GHRSST Multi-product Ensemble median SST analysis is 0.36°C in non-Arctic regions on a daily comparison basis (Chin et al., 2017). Assuming that both SST datasets are unbiased and have equal variance, we can then estimate a the error in MUR at one standard deviation to be 0.25°C on a daily basis, or roughly 0.05°C on a monthly basis. Biases from systematic errors would increase this, so it should be thought of as lower bound on the monthly observational SST uncertainty.

To determine the locations of coral reefs in the global ocean, we use a 4 km resolution reef mask from the NOAA Coral Reef Watch thermal history product, v1.0(Heron et al., 2016), which yields 989,936 1 km reef pixels with the caveat that some of these 1 km pixels may not contain reefs, as the 4 km reef pixels may not be fully covered by reefs. Any 1°coarse pixel that has fewer than 10 model output values (due e.g. to some models assuming a land pixel and assigning a null value) is excluded from the analysis. This leaves 828,639 1 km reef pixels remaining.

3.2 CMIP6 model data

We included in the analysis every CMIP6 model member available as of 2020/08/28 which had monthly SST output for the historical experiment and the four future emissions scenarios with the most available model runs, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 (where SSP is for "Shared Socioeconomic Pathway," O'Neill et al. (2014)). These four scenarios span a range of possible collective human futures in terms of GHG emissions, in order of increasing cumulative emissions, with SSP585 being the highest; the final two digits provide the estimated radiative forcing in 2100 in W/m^2. In what follows, we omit the punctuation in the emissions scenario labels. In all, the analysis included 127 model members from 27 model groups. (Not all model groups provided runs for all four emissions scenarios). The CMIP6 historical experiment begins in January 1870 and runs to December 2014, while the SSP experiments start in January 2014 and run until at least 2100. We regridded all models to be on the same 1° grid and homogenized all time dimensions to the same mid-month values. Any time series that ran beyond December 2099 were truncated to that month.

Global mean surface temperature anomalies (GMSTA) were estimated using 2 m surface temperatures from 33 GMs, one member (the one used for most runs and at least with runs for the four SSPs in this analysis) from each of 33 model groups, which were each regridded to the same uniform 1° grid. The area-weighted mean was taken for each model, and then the mean over every model per scenario was taken. GMSTA were calculated relative to an 1880-1900 baseline.

3.3 Degree heating week thresholds

DHW is a thermal stress index developed decades ago by Coral Reef Watch (CRW) (Liu et al., 2003, 2006). At a given location, the maximum monthly mean (MMM) is determined from a climatology (the climatologically hottest month of the year). Then for each day the MMM is subtracted from that day's SST, and if the result is >=1°C (i.e., a degree or more over the MMM) it is accumulated in a 12-week running sum. According to CRW, significant bleaching in corals is correlated to DHW values >4 DHW, and severe bleaching is likely and significant mortality can be expected above 8 DHW (CRW, n.d.). The original CRW DHW metric requires a 1°C excursion above MMM before it accumulates a daily value into DHW.

Following all prior monthly projection studies (see e.g., Van Hooidonk et al. (2016)), we deviate from the CRW definition by not requiring the >=1°C daily excursion above MMM, which cannot be implemented using monthly time series. To calculate an approximate DHW index, we first create a monthly MUR SST climatology from 2003 to 2014, inclusive, which determines a MMM value at each 1 km coral pixel. We subtract this MMM from the SST time series at that pixel, setting any negative values to zero, and multiply by 4.34 to convert from months to weeks. We then calculate a three month running sum, producing a monthly time series of DHW estimates.

The canonical CRW 8 DHW severe bleaching threshold is based on a climatology comprised of the seven-year period of 1985-1990 plus 1993 which excludes SST retrievals compromised by the Pinatubo eruption (Heron et al., 2014), the mean of which is 1988.3. However, as mentioned above, the MUR SST climatology central year is 2008.5. In the approximately two decades between these climatological references, SST in coral-reef-containing waters increased by approximately 0.25°C due to anthropogenic global heating, as estimated from the mean of all 1-degree-resolution HadISST (Rayner et al., 2003; National Center for Atmospheric Research Staff (Eds), n.d.) grid cells containing coral reef locations using a 10-year running mean to smooth the time series.

This anthropogenic increase in the climatological baseline has a large effect on the DHW thresholds. We empirically determined the linear relationship between the climatological central year and the DHW threshold required to keep departure year projection estimates constant (see supporting information). Using subscripts to denote the climatological central year, we found that, e.g.,

$$8.0\mathrm{DHW}_{1988} = 4.8\mathrm{DHW}_{2008}. \tag{1}$$

In other words, fully specifying a DHW threshold requires two numbers, the threshold and the climatological center year used to calculate it; and an 8.0 DHW thermal excursion calculated using a climatology centered in 1988 is thermally equivalent to a 4.8 DHW excursion calculated using a climatology centered in 2008. Similarly,

$$8.0\mathrm{DHW}_{2008} = 11.2\mathrm{DHW}_{1988}. \tag{2}$$

These equivalence relationships do not account for possible coral adaptation. Hypothetically, for example, if coral adaptation to rising heat was somehow perfect, the absolute temperature of the ocean heat event wouldn't matter; only the anomaly relative to very recent MMM would matter.

3.4 Statistical downscaling

We perform statistical downscaling at every 1 degree pixel with the mean GM SST projections. Let $y_t(s_n)$ denote the observational SST at MUR pixel s_n at month t. For each month, we downscale in two steps, first finding a mean component and then an error component, i.e.,

$$\underset{\sim}{y}_t = \underset{\sim}{\mu}_t + \underset{\sim}{\epsilon}_t, \tag{3}$$

where $\underset{\sim}{y}_t = \Big(y_t(s_1), \ldots, y_t(s_n)\Big)^T$ is the vector of observational SSTs at all the MUR pixels in the spatial domain. We begin by estimating the mean component. First, we remove the coarse-scale model climatology (calculated from 2002 to 2017, inclusive) from each GM ensemble time series and add the fine-scale MUR SST climatology (from the same period) aggregated to the coarse-scale model pixels; we call this the "bias correction" step. Then the bias-corrected coarse-scale model time series are interpolated (using bivariate interpolation) to the fine-scale spatial basis. We then model for residuals to account for remaining spatial dependencies using a framework called multivariate Basis Graphical Lasso (BGL).

BGL is a computationally efficient model proposed for highly-multivariate processes observed at a large number of observation locations with non-stationary data and intervariable dependencies (Krock et al., 2021). Let $w_t(s_n)$ denote the interpolated model output from coarse-resolution pixels to MUR pixel s_n. Then we assume that at each MUR location s_n, the residual $y_t(s_n) - \hat{\mu}_t(s_n)$ and $w_t(s_n) - \bar{w}(s_n)$ where $\bar{w}(s_n)$ is the average of interpolated model outputs over the observational years, follow a bivariate Gaussian process. This bivariate process is further expressed as a summation of a spatially correlated stochastic process and a white noise process. Then the BGL computationally benefits from the basis expansion of the spatially correlated stochastic process. In this framework, we combine months into seasons to generate pooled empirical orthogonal functions and use them as basis functions (Krock et al., 2021). BGL provides a sparse nonparametric estimate for the precision matrix of the stochastic coefficients. This estimated precision matrix is used to obtain conditional expectation of residuals given mean corrected $w_t(s_n)$ values for a future time point t and the conditional variance can be used as a metric for uncertainty. Finally, the predicted residuals are added to the estimated mean component to obtain the fine-scale SST estimate $\hat{\underset{\sim}{y}}_t$ for a future month t.

We have found that this downscaling methodology outperforms the standard deterministic method followed by e.g. Van Hooidonk et al. (2016), in terms of RMSE and spatial similarity comparisons between hindcast projections and MUR observations.

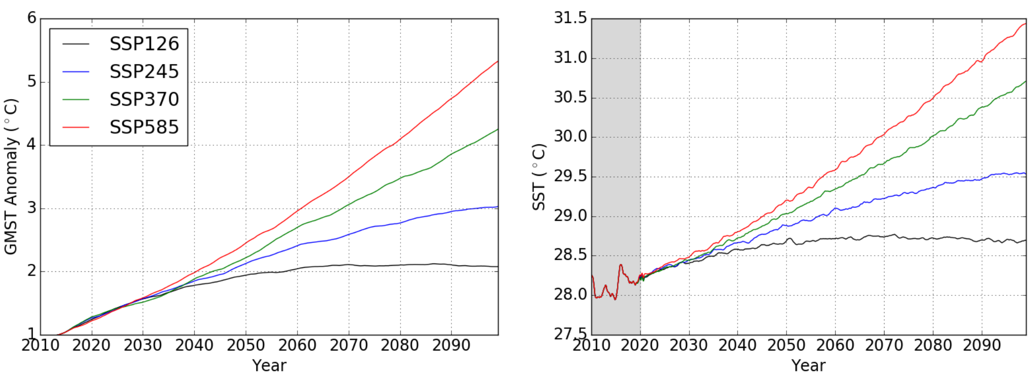
3.5 Thermal departure projections

We estimate projected times of TD using a specified DHW threshold and climatological baseline. The original CRW DHW was defined using a climatology centered on the fractional year 1988.3, while our climatology is centered in mid-2008 due to availability of MUR SST data. We therefore account for ocean heating during the intervening decades by using an adjusted DHW threshold of 4.8DHW_{2008}, which is equivalent to 8.0DHW_{1988} in an absolute sense. We also use the "traditional" threshold of 8.0DHW_{2008}, which is equivalent to 11.2DHW_{1988} in an absolute sense. The latter threshold follows most prior coral bleaching projection studies, and using it could account qualitatively for adaptation by the corals over time to hotter oceans, in effect measuring a fixed anomaly relative to very recent local mean maximum SSTs. However, such an accounting for adaptation would be speculative. In what follows, we include projections using the latter threshold as well as the former, to provide comparability with prior studies; and to show the sensitivity of bleaching projections to DHW threshold.

At each 1 km^2 pixel, we concatenate the MUR data from 2002 to 2020 to the mean downscaled projection time series for a particular emissions scenario to create a continuous SST time series from 2002 to 2100. We then calculate the DHW time series from this SST time series, and calculate the year after which every subsequent five year period and every subsequent ten year period (TD5Y, TD10Y) contains at least one heat event surpassing the DHW threshold, at least through 2100. Post-disturbance coral recovery through newly-settling recruits requires 7-13 years (Johns et al., 2014) or even >15 years (Baker et al., 2008) if it occurs at all. Thus TD5Y and TD10Y are representative of a range of post-bleaching coral recovery time scales from damaged but not completely destroyed ecosystems. We note that TD5Y might be overly optimistic given the observed coral recovery times, but that it is commonly used by prior studies. We also note that our construction allows for TD "projections" prior to 2022, and that all TD estimates, even those occurring in the past, depend on information to 2100.

4 Results

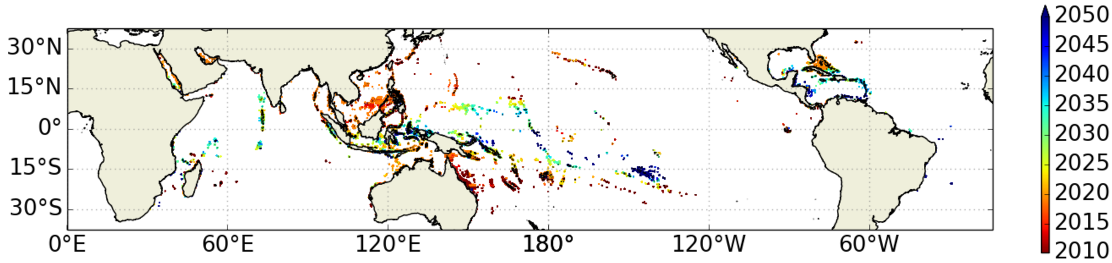
Figure 1a shows the CMIP6 ensemble mean of GMSTA over the entire globe in the four emissions scenarios, which begin running in 2014. Figure 1b shows the mean of the downscaled SST over all coral reef locations for the four scenarios, including observational MUR data before 2020. Note that the very strong 2015-2016 El Niño event is clearly apparent in the MUR SST data.



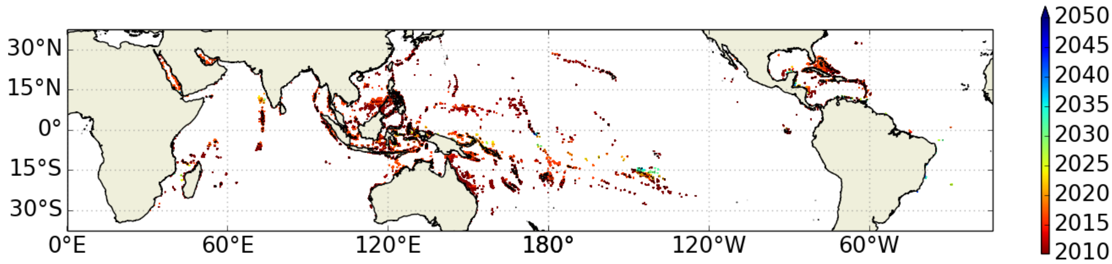
(a) (b)

Figure 1: (a) CMIP6 ensemble mean of GMSTA over the entire globe. (b) Mean SST over coral reef locations, with observational MUR data before 2020 shown within the shaded region and the downscaled CMIP6 model ensemble mean after 2020. Colors correspond to emissions scenarios as indicated in the legend.

Figure 2 shows global maps for two of the sixteen scenarios we explored, the most "optimistic" (TD5Y, 11.2 DHW$_1$988, and SSP126) and the most "pessimistic" (TD10Y, 8.0 DHW$_1$988, and SSP585). Full-resolution representations are available online. These low-resolution representations of our high-resolution results demonstrate general TD dependence on return year, DHW threshold, and cumulative GHG emissions. It is also apparent that some coral reef regions of the world are facing thermal stress earlier than others.



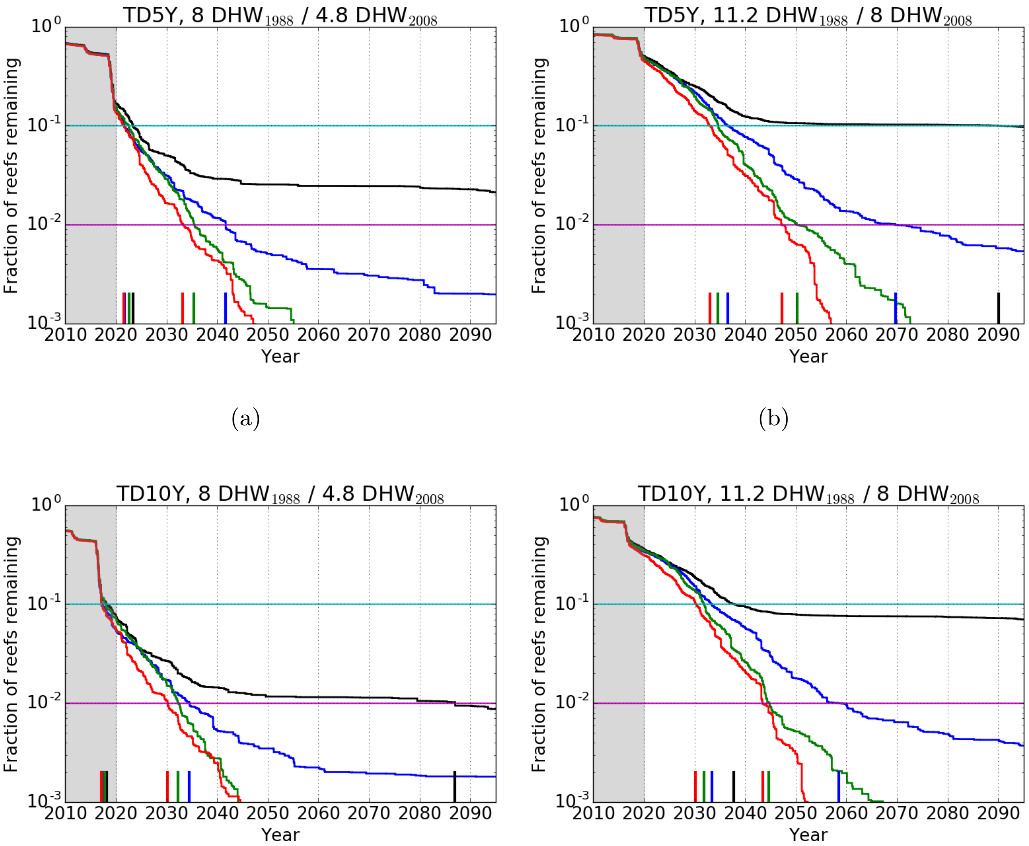
(a) TD5Y, 8 DHW_{2008}, SSP126



(b) TD10Y, 8 DHW_{1988}, SSP585

Figure 2: Global maps of thermal departure. (a) The most "optimistic" scenario we considered: TD5Y, 11.2 DHW_{1988} / 8 DHW_{2008} threshold, and SSP126. (b) The most "pessimistic" scenario we considered: TD10Y, 8 DHW_{1988} / 4.8 DHW_{2008} threshold, and SSP585. Maps of the other scenarios are shown in the supporting information.

Our main results are shown as cumulative histograms of 1 km^2 reef locations remaining under TD5Y and TD10Y (Figure 3) and "slices" through these cumulative histograms at the 30%, 10%, and 1% remaining levels (Table 1). Dashes in the table signify the indicated "milestone" is not crossed before 2100. Vertical gray shading denotes the period of MUR observational data. Note that the drop in reef locations remaining below TD that occurs in ~2015-2016 corresponds to warming of the reef locations due to the 2015-2016 El Niño visible in the SST data in Figure 1b.



(a) (b) (c) (d)

Figure 3: Cumulative histograms of thermal departure as a function of year, for SSP126 (black), SSP245 (blue), SSP370 (green), SSP585 (red), for a five year heat event return timescale (TD5Y, top row) and a ten year heat event return timescale (TD10Y, bottom row). Both DHW thresholds are shown. Cyan and magenta horizontal lines show the 10% and 1% fractional levels respectively; colored vertical ticks on the y-axis indicate crossings of these levels.

It is also useful to interpolate the departure year data using the GMSTA estimates displayed in Figure 1a; we perform the interpolation after applying a 10-year running mean to the GMSTA data. Plots of departure as a function of GMSTA are shown in the supporting information. Table 1 provides GMSTA points of departure beyond various thermal metrics for the four scenarios. Table 2 provides percentages and number of reefs remaining below the four combinations of recurrence time and DHW threshold for future GMSTA values.

99% of reef locations are projected to exceed a bleaching threshold of 4.8 DHW_{2008} (i.e., the CRW 8.0 DHW_{1988}) at least once every 10 years (TD10Y) by 2086, 2034, and 2032 under SSP126, SSP245, and SSP370. Under SSP585, this 99% milestone is projected to be crossed by 2030. In terms of GMSTA, once global heating surpasses 1.5°C or 1.6°C, we project that fewer than 1% of reefs will remain below TD10Y. As of 2021, fewer than 7% of 1 km^2 reef locations remained below TD10Y under all emissions scenarios.

TD5Y is a more stringent metric, as the severe bleaching threshold will be exceeded at least once every five years, so TD5Y projections are slightly further in the future than TD10Y projections. 99% of reef locations are projected to exceed TD5Y by 2041, 2035, and 2033 under SSP245, SSP370, and SSP585, corresponding to GMSTAs of 1.8°C, 1.7°C, and 1.6°C, respectively. The progressively lower GMSTA "milestones" for progressively higher emissions scenarios are due to the progressively steeper rates of global heating, as shown in Figure 1b.

As of 2021, fewer than 15% of 1 km^2 reef locations remained below TD5Y under all scenarios. Remarkably, however, under SSP126, 7% of the world's reef locations are projected never to exceed TD5Y, and the 99% exceedance "milestone" is never reached.

We project that at 1.5°C GMSTA, between 2% and 4% of reef locations will remain below TD5Y, and between 1% and 2% will remain below TD10Y. We project that at 2.0°C GMSTA, the number of reef locations remaining below TD5Y or TD10Y (fewer than 2000 and 1000 1 km^2 locations respectively) will be closer to 0% than to 1%.

Table 1: Projected years and GMSTAs after which fewer than the stated percentage of 1 km^2 reef locations remain below the thermal thresholds

	5Y 8 DHW_{2008}			10Y 8 DHW_{2008}			5Y 8 DHW_{1988}			10Y 8 DHW_{1988}		
SSP	30%	10%	1%	30%	10%	1%	30%	10%	1%	30%	10%	1%
Year in twenty-first century												
126	26	90	-	23	37	-	19	23	-	16	18	86
245	26	36	69	22	33	58	19	21	41	16	17	34
370	26	34	50	22	31	44	19	22	35	16	17	32
585	24	33	47	20	30	43	19	21	33	16	17	30
Global mean surface temperature (°C)												
245	1.4	1.7	2.0	1.3	1.6	2.0	1.2	1.3	1.8	1.1	1.1	1.6
370	1.4	1.7	2.0	1.3	1.6	1.9	1.2	1.3	1.7	1.1	1.2	1.6
585	1.4	1.6	2.0	1.3	1.5	2.0	1.2	1.3	1.6	1.1	1.1	1.5

Table 2: Percentages and numbers of reef locations remaining below the stated GMSTA value (in °C) for a given bleaching metric

	5Y 8 DHW_{2008}			10Y 8 DHW_{2008}			5Y 8 DHW_{1988}			10Y 8 DHW_{1988}		
SSP	1.5	1.7	2.0	1.5	1.7	2.0	1.5	1.7	2.0	1.5	1.7	2.0
Percent 1 km^2 reef locations remaining below GMSTA value												
245	26%	10%	1%	19%	7%	1%	4%	1%	0%	2%	1%	0%
370	24%	8%	1%	16%	6%	0%	3%	1%	0%	2%	1%	0%
585	15%	5%	1%	11%	3%	1%	2%	1%	0%	1%	0%	0%
Number of 1 km^2 reef locations remaining below GMSTA value, out of 829K												
245	213K	79K	10K	161K	59K	5350	30K	11K	1796	18K	5615	384
370	205K	74K	14K	139K	51K	6248	30K	10K	1983	19K	5090	717
585	136K	51K	16K	98K	29K	8005	16K	5117	1365	10K	3102	946

We validated our analysis by comparing the mean of the three annual maximum ocean heat events at each reef pixel from 2018-2020 in the downscaled SSP245 SST time series to the corresponding value in the MUR SST data. We found that the mean of a distribution of MUR values subtracted from corresponding downscaled model SST values was -1.7 DHW (with a standard deviation of 1.9 DHW), i.e., the downscaled model value underestimated the MUR data by 1.7 DHW. We found similar results for the other three SSPs (see Figure S6). This suggests that our projections are likely "conservative" or "optimistic" in the sense that they underestimate future coral bleaching.

5 Discussion and Conclusion

In 2020, global heating (GMSTA) was 1.2°C- 1.3°C above pre-industrial levels, and humanity will likely push Earth to 1.5°C GMSTA sometime in the 2030s, according to CMIP6 model projections (Figure 1a). Unless humanity accomplishes climate mitigation approximating the SSP126 scenario, Earth will likely surpass 2°C GMSTA around mid-century (e.g., Table 1). We have provided projections, with unprecedented spatial resolution, of coral severe bleaching conditions due to this anthropogenic global heating. Novel aspects of our analysis include using the CMIP6 model ensemble; attaining 1 km^2 resolution; downscaling with an improved method; performing an end-to-end validation against observational data; and providing projections under four combinations of two severe bleaching return timescales (5 years and 10 years) and two DHW thresholds.

Clarifying that DHW thresholds require not one, but two numbers to fully specify enables apples-to-apples comparisons with prior studies, and our results agree well. Schleussner et al. (2016) projected a 70–90% loss at 1.5°C and 99% loss at 2°C GMSTA, using CMIP3 GMs (without downscaling) and a thermal criteria of TD5Y and 8 DHW_{1990} (they use a 1980-2000 reference climatology). These results were adopted by the IPCC Special Report on Global Warming of 1.5°C ("Summary for Policymakers", 2018). Using nearly identical thermal criteria (TD5Y and 8 DHW_{1988}), we project a 74-85% loss at 1.5°C and 99% loss at 2°C GMSTA, a very similar result from an apples-to-apples comparison. A key difference between our results and those of Schleussner et al. (2016), however, is that TD5Y and 8 DHW_{1988} is our most optimistic, and possibly least realistic, scenario; under a scenario that more closely matches observed reef recovery times and adjusts for steadily rising ocean heat in its climatological baseline (i.e., TD10Y and 8 DHW_{2008}), we project a 98-99% loss at 1.5°C and a 99.5-99.95% loss at 2°C GMSTA.

Donner (2009) used one GM and a thermal metric of TD5Y and 8 DHW_{1988} (a 1985-2000 climatology) to project roughly 70% of coarse-scale (undownscaled) GM locations will depart (i.e, surpass the metric) in 2025, and 90% by 2040, under SRES B1 (similar to SSP245); our study projects 2026 and 2036. Again, this is good agreement, but the same note as above applies: under the TD10Y and 8 DHW_{2008} thermal scenario, the respective projected TD years decrease to 2016 and 2017.

Frieler et al. (2013), using 19 CMIP3 models and an 8 DHW_{1990} (1980-1999 climatology), found that 90% of coarse grid cells surpass TD5Y at 1.5°C, and that all grid cells surpass TD5Y before 2°C GMSTA; our study projects over 96% TD5Y at 8 DHW_{1988} and 1.5°C, and over 99.8% at 2°C.

Van Hooidonk et al. (2016) was the only prior study that applied statistical downscaling; they downscaled CMIP5 projections to 4 km resolution and found mean TD1Y values (annual recurrence) of ocean heat events surpassing 8 DHW_{1995} (1982-2008 climatology) of 2054 for RCP 4.5 and 2043 for RCP 8.5. Our study does not include comparable metrics, and we note that annual severe bleaching might be too "conservative" a metric to be useful, given observed post-bleaching recovery times of about a decade. We also note that our downscaled projections appeared to slightly underestimate ocean heat extremes when compared to the MUR data, which means that they could be optimistic.

There are three realms of uncertainty in our projections. The first is *scenario uncertainty*, the uncertainty over humanity's collective future emissions; this dimension is spanned over the four "SSP" emissions scenarios.

The second realm of uncertainty is *projection uncertainty*, part of which stems from uncertainties in the GMs (Lehner et al., 2020). Projection uncertainty, in the context of ecological projections, can also arise from uncertainties in observational datasets and from the downscaling methodology. The two prior studies that do estimate projection uncertainty do so from the spread of individual GMs within the model ensemble (Frieler et al., 2013; Schleussner et al., 2016). However, we cannot apply this method directly to our downscaled results. One key area for future work is to understand and reduce projection uncertainty. We are currently developing a statistical uncertainty quantification from the BGL downscaling method and the model ensemble (informed by comparative assessments between individual models and observations). In addition to uncertainty quantification, skill-weighting the ensemble could allow better use of information, potentially improving projection accuracy, which could be checked in hindcast experiments.

The third realm of uncertainty is *ecological uncertainty*, the uncertainty in the relationship between ocean heat events and the response of coral reefs. We have spanned a small part of this realm by providing projections under the two severe bleaching recovery timescales, and the two DHW thresholds.

As is the case with the prior studies, our study does not factor in additional ecologic factors which could potentially mitigate coral reef degradation and loss, or exacerbate it, adding to ecological uncertainty in our projections. On shorter timescales, clouds can block sunlight, potentially reducing algal production of reactive oxygen species (M. E. Baird et al., 2018; Skirving et al., 2018; Roth, 2014), and mitigating bleaching during marine heat events (Mumby et al., 2001). Reef depth could also affect bleaching by reducing sunlight and water temperatures (Muir et al., 2017; Frade et al., 2018; A. H. Baird et al., 2018; Smith et al., 2014). Relatively high SST variability correlates with lower bleaching risk (Safaie et al., 2018; Beyer et al., 2018), while relatively high nutrient levels correlates with higher bleaching risk (DeCarlo & Harrison, 2019).

On longer timescales, dispersal of coral larval could result in establishment of populations in cooler regions of the future ocean (Greenstein & Pandolfi, 2008). Adaptation of corals or symbionts (such as acclimatization, symbiont shuffling, or genetic change) might improve coral prospects, but might be insufficient (Baker et al., 2004; Donner et al., 2005; Parmesan, 2006; Hoegh-Guldberg, 2014; Chakravarti et al., 2017). Ocean acidification, sea-level-rise, sedimentation, and intensifying storms could further harm corals (Hoegh-Guldberg et al., 2007; Cohen et al., 2009; Field et al., 2011; Blanchon et al., 2009; Perry et al., 2018; Cheal et al., 2017).

Future work could attempt to understand and constrain ecological uncertainty. If rates of coral adaptation to higher ocean temperatures are sufficiently quantified, these quantified rates could be incorporated into projections. (We chose not to incorporate speculative adaptation rates, as some prior studies have done.) It might also be possible to constrain the coral response to ocean heat events through the use of empirical data, such as remotely sensed severe coral bleaching from satellite platforms. This could provide sufficient data to create models of the coral response that account for the coral's location, and could include additional predictor variables.

Our analysis does provide projected $1\,\mathrm{km}^2$ locations of global coral refugia, and they are available to explore online. However, given the high degree of uncertainty, and imminent data science innovations with the potential to constrain this uncertainty, we have chosen not to highlight the identification of refugia in the current study. We note that a small number of reef locations are projected to persist beyond 2°C GMSTA even under the most stringent metric (Table 2), but that we have low confidence in these projections. Indeed, we recognize an urgent need to further improve ecological projection in order to attain the capacity to robustly identify refugia, including understanding the physical basis for their projected persistence, for the sake of guiding conservation efforts.

Overall, we feel that it is no longer possible to overstate the importance of rapid cessation of human GHG emissions. In the absence of extremely rapid adaptation to increasing heat, which would need to occur in the simultaneous presence of the many additional and serious anthropogenic stressors listed earlier, our results suggest that 2°C of global heating could render Earth essentially uninhabitable to warm water coral reefs. Furthermore, if near-future emissions are equivalent or greater than SSP245, we project that by 2041 over 99% of the world's reefs will be subject to thermal severe bleaching conditions too recurrent for recovery (TD5Y), which will continue to worsen. On the other hand, if emissions approximated the SSP126 scenario and GMSTA were limited to 1.5°C, this level of severe bleaching is projected to never attain and global conditions would stabilize.

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6 Open Research

The datasets analysed during the current study are available in the following repositories and persistent web links.

Group for High Resolution Sea Surface Temperature (GHRSST) Level 4 NASA/JPL Multiscale Ultrahigh Resolution (MUR) MUR Global Foundation Sea Surface Temperature Analysis (v4.1), `https://doi.org/10.5067/GHGMR-4FJ04` (JPL MUR MEaSUREs Project, 2015).

Reef mask from the NOAA Coral Reef Watch thermal history product, v1.0, `ftp://ftp.star.nesdis.noaa.gov/pub/sod/mecb/crw/data/thermal_history/v1.0/` (Heron et al., 2016).

Projections of monthly variables 'tos' and 'tas' were obtained using the Intake-esm framework, `https://intake-esm.readthedocs.io/en/latest/`. 'tos' was obtained from the following models: ACCESS-CM2 r1i1p1f1, ACCESS-CM2 r2i1p1f1, ACCESS-CM2 r3i1p1f1, ACCESS-ESM1-5 r1i1p1f1, ACCESS-ESM1-5 r2i1p1f1, ACCESS-ESM1-5 r3i1p1f1, BCC-CSM2-MR r1i1p1f1, CAMS-CSM1-0 r1i1p1f1, CAMS-CSM1-0 r2i1p1f1, CESM2 r10i1p1f1, CESM2 r11i1p1f1, CESM2 r4i1p1f1, CESM2-WACCM r1i1p1f1, CMCC-CM2-SR5 r1i1p1f1, CNRM-CM6-1 r1i1p1f2, CNRM-CM6-1 r2i1p1f2, CNRM-CM6-1 r3i1p1f2, CNRM-CM6-1 r4i1p1f2, CNRM-CM6-1 r5i1p1f2, CNRM-CM6-1 r6i1p1f2, CNRM-CM6-1-HR r1i1p1f2, CNRM-ESM2-1 r1i1p1f2, CNRM-ESM2-1 r2i1p1f2, CNRM-ESM2-1 r3i1p1f2, CNRM-ESM2-1 r5i1p1f2, CanESM5 r10i1p1f1, CanESM5 r10i1p2f1, CanESM5 r11i1p1f1, CanESM5 r11i1p2f1, CanESM5 r12i1p1f1, CanESM5 r12i1p2f1, CanESM5 r13i1p1f1, CanESM5 r13i1p2f1, CanESM5 r14i1p1f1, CanESM5 r14i1p2f1, CanESM5 r15i1p1f1, CanESM5 r15i1p2f1, CanESM5 r16i1p1f1, CanESM5 r16i1p2f1, CanESM5 r17i1p1f1, CanESM5 r17i1p2f1, CanESM5 r18i1p1f1, CanESM5 r18i1p2f1, CanESM5 r19i1p1f1, CanESM5 r19i1p2f1, CanESM5 r1i1p1f1, CanESM5 r1i1p2f1, CanESM5 r20i1p1f1, CanESM5 r20i1p2f1, CanESM5 r21i1p1f1, CanESM5 r21i1p2f1, CanESM5 r22i1p1f1, CanESM5 r22i1p2f1, CanESM5 r23i1p1f1, CanESM5 r23i1p2f1, CanESM5 r24i1p1f1, CanESM5 r24i1p2f1, CanESM5 r25i1p1f1, CanESM5 r25i1p2f1, CanESM5 r2i1p1f1, CanESM5 r2i1p2f1, CanESM5 r3i1p1f1, CanESM5 r3i1p2f1, CanESM5 r4i1p1f1, CanESM5 r4i1p2f1, CanESM5 r5i1p1f1, CanESM5 r5i1p2f1, CanESM5 r6i1p1f1, CanESM5 r6i1p2f1, CanESM5 r7i1p1f1, CanESM5 r7i1p2f1, CanESM5 r8i1p1f1, CanESM5 r8i1p2f1, CanESM5 r9i1p1f1, CanESM5 r9i1p2f1, CanESM5-CanOE r1i1p2f1, CanESM5-CanOE r2i1p2f1, CanESM5-CanOE r3i1p2f1, EC-Earth3 r11i1p1f1, EC-Earth3 r15i1p1f1, EC-Earth3 r1i1p1f1, EC-Earth3 r4i1p1f1, EC-Earth3-Veg r1i1p1f1, EC-Earth3-Veg r2i1p1f1, EC-Earth3-Veg r3i1p1f1, EC-Earth3-Veg r4i1p1f1, FGOALS-f3-L r1i1p1f1, FGOALS-f3-L r2i1p1f1, FGOALS-f3-L r3i1p1f1, FGOALS-g3 r1i1p1f1, FGOALS-g3 r2i1p1f1, FGOALS-g3 r3i1p1f1, FGOALS-g3 r4i1p1f1, GFDL-ESM4 r1i1p1f1, GISS-E2-1-G r1i1p3f1, IPSL-CM6A-LR r14i1p1f1, IPSL-CM6A-LR r1i1p1f1, IPSL-CM6A-LR r2i1p1f1, IPSL-CM6A-LR r3i1p1f1, IPSL-CM6A-LR r4i1p1f1, IPSL-CM6A-LR r6i1p1f1, MCM-UA-1-0 r1i1p1f2, MIROC-ES2L r1i1p1f2, MIROC6 r1i1p1f1, MIROC6 r2i1p1f1, MIROC6 r3i1p1f1, MPI-ESM1-2-HR r1i1p1f1, MPI-ESM1-2-HR r2i1p1f1, MPI-ESM1-2-LR r10i1p1f1, MPI-ESM1-2-LR r1i1p1f1, MPI-ESM1-2-LR r2i1p1f1, MPI-ESM1-2-LR r3i1p1f1, MPI-ESM1-2-LR r4i1p1f1, MPI-ESM1-2-LR r5i1p1f1, MPI-ESM1-2-LR r6i1p1f1, MPI-ESM1-2-LR r7i1p1f1, MPI-ESM1-2-LR r8i1p1f1, MPI-ESM1-2-LR r9i1p1f1, NorESM2-LM r1i1p1f1, NorESM2-MM r1i1p1f1, UKESM1-0-LL r1i1p1f2, UKESM1-0-LL r2i1p1f2, UKESM1-0-LL r3i1p1f2, UKESM1-0-LL r4i1p1f2, UKESM1-0-LL r8i1p1f2, INM-CM4-8 r1i1p1f1, INM-CM5-0 r1i1p1f1.

'tas' was obtained from the following models: ACCESS-CM2 r1i1p1f1, ACCESS-ESM1-5 r10i1p1f1, BCC-CSM2-MR r1i1p1f1, CAMS-CSM1-0 r1i1p1f1, CanESM5CanOE r1i1p2f1, CanESM5 r10i1p1f1, CESM2 r10i1p1f1, CESM2-WACCM r1i1p1f1, CMCC-CM2-SR5 r1i1p1f1, CNRM-CM6-1-HR r1i1p1f2, CNRM-CM6-1 r1i1p1f2, CNRM-ESM2-1 r1i1p1f2, EC-Earth3 r11i1p1f1, EC-Earth3-Veg-LR r1i1p1f1, EC-Earth3-Veg r1i1p1f1, FGOALS-f3-L r1i1p1f1, FGOALS-g3 r1i1p1f1, GFDL-ESM4 r1i1p1f1, GISS-E2-1-G r1i1p3f1, IITM-ESM r1i1p1f1, INM-CM4-8 r1i1p1f1, INM-CM5-0 r1i1p1f1, IPSL-CM6A-LR r14i1p1f1, KACE-1-0-G r1i1p1f1, MCM-UA-1-0 r1i1p1f2, MIROC6 r1i1p1f1, MIROC-ES2L r1i1p1f2, MPI-ESM1-2-HR r1i1p1f1, MPI-ESM1-2-LR r10i1p1f1, NorESM2-LM r1i1p1f1, NorESM2-MM r1i1p1f1, TaiESM1 r1i1p1f1, UKESM1-0-LL r1i1p1f2.

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