Catastrophic bleaching risks to Mesoamerican coral reefs in recent climate change projections

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Abstract

The damaging effects of climate change and increased ocean temperatures are already visible in marine ecosystems worldwide. Degree heating weeks (DHW) provide a valuable metric for gauging excess sea surface temperature warming and coral bleaching risk. This study produces future DHW projections for the Mesoamerican reef (MAR) using a multi-model climate change ensemble. We show that current marine heat wave conditions linked to coral bleaching will be far exceeded in an average year by mid-century, creating an environment where MAR corals have no opportunity for normal year recovery between extreme years. The dramatic increase in DHW in the MAR indicates strong adaptation interventions need to be developed and implemented as soon as possible to support local communities in adjusting to the effects of a warming climate.

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Key Points:

- Projected increases in sea surface temperatures lead to high risk of permanent coral damage in the Mesoamerican reef
- Cumulative and consecutive marine heat stress events in the Mesoamerican reef allow low chance for coral recovery in climate projections

Abstract

The damaging effects of climate change and increased ocean temperatures are already visible in marine ecosystems worldwide. Degree heating weeks (DHW) provide a valuable metric for gauging excess sea surface temperature warming and coral bleaching risk. This study produces future DHW projections for the Mesoamerican reef (MAR) using a multi-model climate change ensemble. We show that current marine heat wave conditions linked to coral bleaching will be far exceeded in an average year by mid-century, creating an environment where MAR corals have no opportunity for normal year recovery between extreme years. The dramatic increase in DHW in the MAR indicates strong adaptation interventions need to be developed and implemented as soon as possible to support local communities in adjusting to the effects of a warming climate.

Plain Language Summary

Coral reefs are increasingly vulnerable to rising ocean temperatures, which can cause coral bleaching and mortality if sustained for long periods of time. Climate models can project the amount of marine warming and the risk to coral reefs using metrics that have been linked to historical bleaching events. We use the Degree Heating Week (DHW) indicator to show the potential for coral bleaching in the Mesoamerican reef under future climate change scenarios. An ensemble of 10 climate models shows that environmental conditions which are currently linked to severe bleaching will be exceeded in the average year by mid-century, creating a situation where corals have no opportunity for recovery between years with extremely high ocean temperatures. These results indicate that strong climate change adaptation interventions need to be developed and implemented as soon as possible to support local communities in the Mesoamerican reef.

1 Introduction

The Mesoamerican reef system (MAR), spanning more than 1,000 kilometers along the coastlines of Mexico, Belize, Honduras, and Guatemala, is the largest such expanse in the Northern Hemisphere and includes the world's second longest barrier reef (Gress et al., 2019; McField et al., 2008). The MAR is widely considered to be a region of global importance for biodiversity, containing more than 60 species of coral and 500 species of fish (De Mel et al., 2021), as well as a large network of habitats such as seagrasses, lagoons, and mangroves (Wilkinson & Souter, 2008). These coastal systems are critical for many of the region's economic activities, such as fisheries, tourism, and recreation, sustaining the livelihoods of more than two million people (De Mel et al., 2021; Green et al., 2017).

The MAR protects the coastal regions from erosion and damage from extreme weather events by reducing the intensity of waves and flooding, which additionally enables the formation of critical marine wildlife habitats and the protection of local economies (Hoegh-Guldberg, 1999). While the MAR helps support coastal communities against the negative impacts of climate change, the reef ecosystems are vulnerable to its escalating effects. These impacts include coral bleaching from warmer ocean temperatures (Baker et al., 2008; Brown, 1997; De Mel et al., 2021; Donner, 2011; Eakin et al., 2010; Eddy et al., 2021; Frieler et al., 2013; Goreau et al., 1992; Glynn & D'Croz, 1990; Hoegh-Guldberg, 1999; Langlais et al., 2017; McField et al., 2008; McWilliams et al., 2005; Nielsen et al., 2018; Sully et al., 2019; Teneva et al., 2012; Wilkinson & Souter, 2008), erosion and flooding of coastal areas due to extreme storms and sea level rise (Beck et al., 2018; Cuttler et al., 2018; Reguero et al., 2021), and other changing ocean parameters such as acidification (Anthony et al., 2008). The MAR also underwent amongst the largest coral bleaching events globally over the last twenty years (Sully et al., 2019). Figure 1 shows historical sea surface temperature (SST) anomalies across the broader Caribbean region for four recorded bleaching events in 1995, 1998, 2005 and 2015 using satellite data from the National Oceanic and Atmospheric Administration (NOAA) Coral Reef Watch (CRW), a global early-warning system that tracks conditions linked to coral bleaching (Liu et al., 2006).

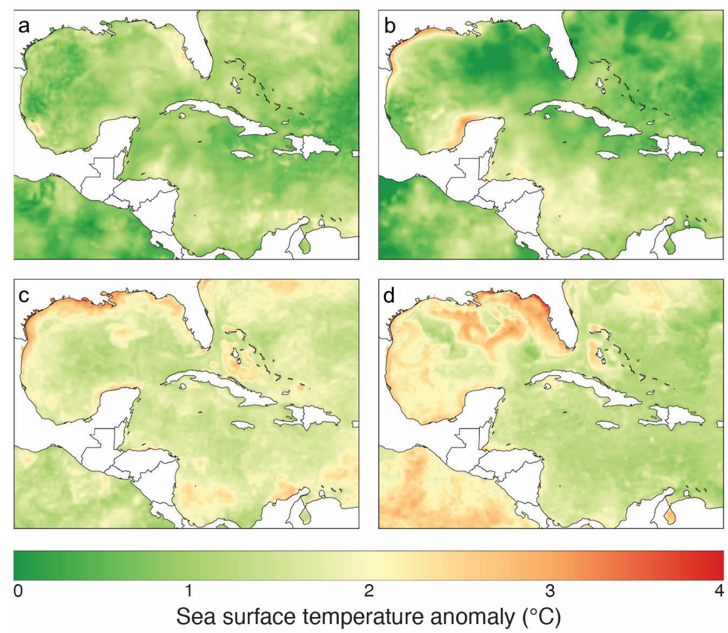

Figure 1. Sea surface temperature anomalies in the MAR during historical bleaching episodes. NOAA mean SST anomalies during recorded bleaching events in the MAR for (**a**) October 1 – November 30, 1995, (**b**) September 18 – October 1, 1998, (**c**) July 15 – November 15, 2005, and (**d**) October 1 – November 30, 2015.

This work was motivated by Climate-Smarting Marine Protected Areas and Coastal Management in the Mesoamerican Reef Region, an initiative to accelerate the implementation of climate-smart tools in coastal communities and local governments (De Mel et al., 2021). The project is a collaboration between the World Wildlife Fund, Stanford University and Columbia University in partnership with government agencies and implementing partners from all four countries. Climate risk information on mean and extreme temperatures, precipitation levels, sea level rise and sea surface temperatures were developed in collaboration with input from local stakeholders with the purpose of integration into decision-making practices to guide shoreline management (De Mel et al., 2021). The results presented here are meant to further inform not only these objectives but also future climate impacts and adaptation applications.

While global projections of the climate-change-induced threats to corals already exist, little is known about the future of the reefs specifically in the MAR (Beyer et al., 2018). The purpose of this research is to provide a large ensemble of multi-model, multi-scenario, and multi-generational experiments to show how SST warming in the MAR will impact the risk of coral bleaching and mortality in the coming decades.

2 Climate and Coral Bleaching

2.1 Bleaching Thresholds

Coral reefs are economically valuable and rich in species diversity but are vulnerable to detrimental impacts from human activities such as pollution, overfishing and the broad effects of climate change (Anthony et al., 2008; Baker et al., 2008; Beck et al., 2018; Brown, 1997; Cramer et al., 2021; Cuttler et al. 2018; De Mel et al., 2021; Donner, 2011; Eakin et al., 2010; Eddy et al., 2021; Frieler et al., 2013; Goreau et al., 1992; Glynn & D'Croz, 1990; Hoegh-Guldberg, 1999; Knowlton & Jackson, 2008; Langlais et al., 2017; McField et al., 2008; McWilliams et al., 2005; Nielsen et al., 2018; Sully et al., 2019; Teneva et al., 2012; Wilkinson & Souter, 2008). Frequent bleaching events are already threatening the existence of coral reefs on a global scale, as reef systems have begun to show the long-term effects of their exposure to marine heat waves (Fox-Kemper et al., 2021; Frieler et al., 2013; Lough et al., 2018). Biodiversity in coral reefs is estimated to have declined by more than 60% since the 1950s as the extent of living coral has declined by half worldwide (Eddy et al., 2021). Even under the United Nations Framework Convention on Climate Change Paris Agreement target of 1.5°C warming above pre-industrial conditions, climate model projections of thermal stress on sea surface temperatures indicate a high likelihood of more frequent mass bleaching events (Lough et al., 2018). This intensifying ocean warming is likely to affect the survival of many coastal ecosystems and their protection of shoreline economies (Fox-Kemper et al., 2021).

Coral bleaching occurs when the relationship between coral and endosymbiotic algae is stressed by external factors, resulting in the coral discarding their algae (Brown, 1997; Nielsen et al., 2018). If this occurs over a prolonged period without the re-establishment of coral-algal symbiosis, the result is coral mortality (Brown, 1997). Figure 2 shows an example photograph of coral after experiencing bleaching conditions.

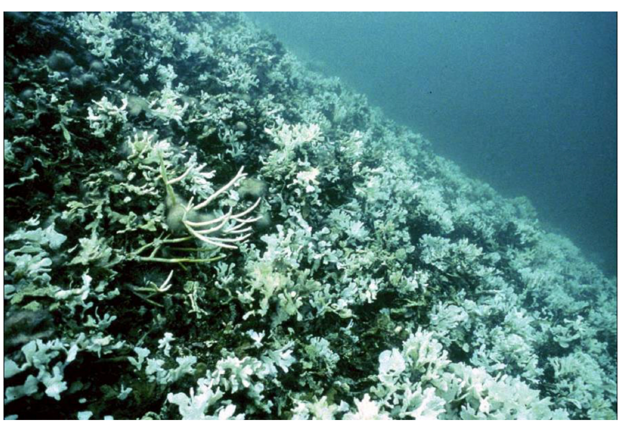

Figure 2. Example photograph of bleached coral. Bleached coral becomes white in appearance due to the loss of endosymbiotic algae. Photo provided by

Dr. Rich Aronson.

Although coral bleaching has been primarily linked to warmer ocean temperatures, coral health can be impacted by many other factors, including ocean currents, salinity, wind speed, hurricanes, sedimentation, and disease (Anthony et al., 2008; Baumann et al., 2019; Cuttler et al., 2018; Grimsditch & Salm, 2006; Hoegh-Guldberg, 1999; Knowlton & Jackson, 2008; McField et al., 2008; Nielsen et al., 2018; Wilkinson & Souter, 2008). Mass coral bleaching, however, is generally associated with higher-than-average ocean temperatures and solar radiation conditions (Eakin et al., 2010), with concurrent or compounding events contributing to vulnerable bleaching conditions and amplifying their effects (Dzwonkowski et al., 2020). Over time, repeated and chronic contributing factors can diminish reef resilience and have long-term effects on reef system health (Carilli et al., 2009; Grimsditch & Salm, 2006; Hughes et al., 2010). However, temperature-induced mass coral bleaching is only one of many threats facing the MAR (Ranasinghe et al., 2021). Increasing atmospheric CO_2 and declining ocean pH levels may result in lower levels of coral calcification and subsequent loss (Anthony et al., 2008); anthropogenic nutrient pollution conditions such as high inorganic nitrogen combined with low phosphate levels might expedite bleaching (Wiedenmann et al., 2013), and sea level rise will provide additional challenges for local communities of people in the fishing and tourism industries who rely on the reefs for their livelihoods (Perry et al., 2018). Coral bleaching can serve as an indicator for overall reef health, which provides critical information on the outlook for biodiversity and coastal economies over the coming decades.

The concept of a static temperature-based "bleaching threshold" varies, as different coral species are vulnerable at ocean temperatures that are anomalously higher than their species-specific baseline (Glynn & D'Croz, 1990; Teneva et al., 2012). Thus, it is important to assess past bleaching events to understand some of the underlying environmental conditions and compounding factors that lead to coral damage as well as management interventions that can help to avoid the worst mortality effects. Although smaller-scale bleaching events due to local stresses, extreme storms or increased temperatures were observed in the MAR before 1980, many of these events were followed by near-complete recovery (Glynn, 1984; Goreau et al., 1992; Wilkinson, 1999). Since that time, mass mortality events due to large-scale global temperature rise and concurrent weather extremes are becoming both more frequent and more severe as ocean temperatures increase (Glynn, 1984; Wilkinson, 1999).

2.2 Historical Bleaching Events in the MAR

2.2.1 1995 Bleaching Event

A widespread bleaching event occurred in the MAR in October and November of 1995 (Guzman & Guevara, 1998). Records indicate that ocean temperatures and solar radiation levels were anomalously high and wind speeds somewhat low (McField, 1999). Effects of bleaching varied widely by coral species, with one survey estimating the highest single-species mortality rate at 74% (Guzman & Guevara, 1998). Reefs across the Yucatán Peninsula as well as Belize and Honduras were severely impacted, although corals in the Western Caribbean escaped the worst effects (Hughes et al., 2018). The 1995 event also illustrates the connectivity between bleaching and longer-term effects on reef health, as it may have been associated with the subsequent outbreak of Black Band Disease (Guzman & Guevara, 1998).

2.2.2 1998 Bleaching Event

More significant damage was recorded after the 1998 bleaching event that occurred between September and October, which was followed by Hurricane Mitch in October-November 1998. Higher-than-average SSTs were recorded in the Yucatán Peninsula in Mexico in August 1998, spreading to Belize and Honduras in September (Kramer & Kramer, 2000). Category 5 Hurricane Mitch occurred in late October of that year, causing additional damage from severe winds and flooding (Kramer & Kramer, 2000). At the time of the hurricane, bleaching mortality had already occurred across much of the region, resulting in most of the storm damage impacting reef structures through physical devastation from storm waves and excessive sediment (Kramer & Kramer, 2000). Live coral cover mortality rates reached 50% through a combination of temperature and storm effects (McField et al., 2008).

2.2.3 2005 Bleaching Event

Another bleaching event in 2005 caused considerable damage, although there had been little regrowth between 1999 and 2005 (McField et al., 2008). Between June and November of 2005, satellite data showed SSTs at anomalously high levels compared to long-term averages not only in the MAR, but across the tropical Atlantic Ocean, with regional average SSTs at their warmest levels in the preceding 150 years (Eakin et al., 2010). Although widespread bleaching was recorded after the 2005 event, particularly in the Western Caribbean, coral mortality rates in the MAR were lower than those from the 1995 and 1998 events (Wilkinson & Souter, 2008). This was partially due to reduced coral cover of vulnerable species after the destruction of the 1998 event, as well as improved management decisions between 1998 and 2005 involving the reduction of local stressors such as pollution, overfishing, and overuse in tourism and recreational activities (McField et al., 2008; Schuttenberg & Marshall, 2008).

2.2.4 More Recent Bleaching Episodes

Moderate bleaching was reported near Belize in 2015, with more severe coral damage towards Cuba, the Cayman Islands, and the northern Caribbean region (Hughes et al., 2018). Coral core analysis of several sites on the coast of Belize indicated high thermal stress in near-shore reefs (Baumann et al., 2019). However, some studies indicate coral bleaching in 2015 was less severe than in previous events (Muñiz-Castillo & Arias-González, 2021). More frequent high-temperature events may have led to some reef resilience as the species survivors are becoming more tolerant to thermal stress, although at the cost of reef biodiversity as heat-intolerant species are unable to recover and may be permanently lost under continually warming conditions (Muñiz-Castillo & Arias-González, 2021).

3 Data and Methods

3.1 Degree Heating Weeks (DHW)

Recently, studies have shown the value of degree heating weeks (DHW) as a metric to indicate the severity of heat stress and potential for coral bleaching (Kayanne, 2017; Kayanne et al., 2017, Leggat et al., 2022). Although approaches have defined marine heat waves in slightly different ways (Hobday et al., 2016), the DHW approach used here is consistent with the NOAA CRW (Liu et al., 2006) and is among frequently used metrics in marine heat wave studies (Hobday et al., 2016; Kayanne, 2017; Kayanne et al., 2017, Leggat et al., 2022). Unlike static ocean temperature thresholds, the DHW indicator identifies cumulative heat stress measured by "HotSpots" of higher-than-average SST anomalies over a 12-week period (Liu et al., 2006), which have been linked to the timing and severity of coral bleaching and mortality not only in the MAR but across the globe (Eakin et al., 2010; Muñiz-Castillo & Arias-González, 2021). Significant coral bleaching generally happens when DHW exceed 4°C-weeks, with severe bleaching and likely significant mortality occurring at 8°C-weeks (Eakin et al., 2010; Liu et al., 2006).

During the 2005 bleaching event in the MAR, satellite and field data confirmed the accuracy of NOAA's DHW indicator in predicting the intensity of coral bleaching (see Figure S3a), with DHW reaching up to 16°C-weeks in some areas (Eakin et al., 2010). Additional studies across sites in the northwestern Pacific Ocean connect mass bleaching events to periods when the maximum DHW exceeded 8°C-weeks (Kayanne, 2017). Although the definition of DHW is not region- or species-specific and relies only on sea surface temperature inputs, it consistently correlates well with spatial and temporal patterns of bleaching worldwide (Donner, 2011; Heron et al., 2016; Langlais et al., 2017).

Previous studies have focused on correlating extreme or cumulative SST anomalies with recorded bleaching in reef systems across the globe (Eakin et al., 2010; Glynn & D'Croz, 1990; McWilliams et al., 2005). Several studies have used climate models to highlight the importance of concurrent stressors in region-specific settings, or the contribution of seasonal variability in the level of vulnerability (Langlais et al., 2017; Melbourne-Thomas et al., 2011). Here we focus on the magnitude of DHW in future scenarios relative to an observational baseline for the MAR, the frequency of weekly SST anomalies that contribute to high-value DHW, and the maximum consecutive duration of those anomalies, all of which can be considered as different indicators of the likelihood, severity, and length of marine heat waves.

DHW are calculated using SST anomalies from the climatological maximum mean month in a 7-year period from 1985-1993, excluding the years 1991 and 1992 due to the Mt. Pinatubo eruption (Liu et al., 2006). Monthly mean SST values are calculated over this 7-year period, with the maximum mean month (MMM_SST_CLIM) from this period as the baseline from which SST anomalies are calculated. Fig. 3a shows the value of MMM_SST_CLIM across the region using observational data from MERRA-2 reanalysis (described below). Regional averages in this study apply only to the area of interest outlined in black in Fig. 3. Although coral reefs are generally close to the coast, we use a larger area to avoid mixed coastal effects in the climate models and to capture broader warming effects.

As DHW are calculated twice-weekly, HotSpots are determined for each half-week in the historical period by subtracting the MMM_SST_CLIM from mean SSTs in that half-week and removing negative values. DHW are calculated for each half-week using a sum of HotSpots over the 12 preceding weeks, only for those HotSpots greater than 1 degree (Equation 1).

$$DHW \;=\; 0.5 \;*\; \sum_{i=1}^{i=24} [\mathrm{HotSpots}_i > 1C]_{\mathrm{halfweekly}}$$

(Eqn 1)

The resulting DHW can be produced for each half-week for a given location. To facilitate the communication of DHW results, we refer to "annual DHW" throughout this study as the multi-year average across annual maximum DHW values over any specified period.

3.2 Historical and future data sources

This analysis uses the Modern-era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) as a historical baseline (Gelaro et al., 2017). MERRA-2 is an assimilated dataset utilizing the Goddard Earth Observing System (GEOS) model along with satellite and in-situ observations and provided by NASA's Global Modeling and Assimilation Office (GMAO). For climate simulations, we analyze 10 Global Climate Models (GCMs) spanning two generations of Coupled Model Intercomparison Projects (CMIP5 and CMIP6), with three models from CMIP5 (Taylor et al., 2012) and seven from the newer-generation CMIP6 (Eyring et al., 2016), listed in Table 1. As an example within our ensemble of GCMs, we highlight the GISS E2.1-G model, a state-of-the-art ocean model that is fully coupled to the atmosphere, land, and sea-ice components (Kelley et al., 2020). The ocean component has 1x1.25-degree horizontal resolution with 40 vertical layers, with higher resolution near the surface of about 5-10m, and natural surface boundary conditions for heat and freshwater fluxes (Kelley et al., 2020; Miller et al., 2021; Nazarenko et al., 2022). Table 1 also includes global warming levels (GWLs) for each GCM and scenario for a mid-century period, calculated from a pre-industrial reference period (1850-1900). Common global warming levels have become increasingly useful indicators for comparing GCMs, as the level of warming is suggestive of associated earth system effects and global impacts (Ranasinghe et al., 2021). Global warming levels are calculated using area-weighted global mean temperatures to identify the temporal "crossing point" of a common set of global temperature anomalies from the reference period (Hauser et al., 2019). To calculate DHW in future scenarios, we use a "delta" approach by applying monthly SST warming amounts from GCMs for each future scenario to observational SSTs from MERRA-2 (see Supplementary Information for detailed materials and methods, including other bias-adjustment methods).

We analyze data from nine future decades of generated SST data using two different anthropogenic emission scenarios that are more comparable between CMIP5 and CMIP6. These scenarios are obtained from the Representative Concentration Scenarios (RCPs) or Shared Socioeconomic Pathways (SSPs) from CMIP5 or CMIP6 respectively. We include RCP4.5/SSP2-4.5 and RCP8.5/SSP5-8.5, which represent a "middle of the road" socioeconomic pathway with a nominal 4.5W/m^2 radiative forcing level by 2100, and a very high emissions pathway with a forcing of 8.5W/m^2, respectively (IPCC, 2021; Meinshausen et al., 2019; O'Neill et al., 2016). We focus on a mid-century period of 2050-2059, centered on the year 2054. GWLs for 2054 are interpolated from a list of 20-year windows associated with the available GWLs from each GCM. In addition to these GWLs derived from Hauser et al. (2019), we provide the area-averaged SST warming for each GCM across the rectangular region outlined in Figs. 3 and 5, calculated using SST data with a 1980-2009 reference period.

Table 1. GCMs included in multi-model ensemble. GCMs from CMIP5 and CMIP6 included in this study, with global warming level (GWL) from 1850-1900 and regional SST warming in the MAR from 1980-2009 for two emissions scenarios for the 2050s (both in °C). GWLs for GCMs, ensemble members and scenarios are derived from Hauser et al. (2019). Each GCM's ensemble member is also included as an "ripf" identifier, which categorizes the model's realization, initialization, physics and forcing indices (Taylor et al., 2018).

GCM	**SSP2-4.5**	**SSP5-8.5**
	GWL at 2054 (°C), 1850-1900 reference	MAR SST change for 2050s (°C), 1980-2009 r
ACCESS1-0	>2‡	1.29
ACCESS-CM2	2.45	1.73
CanESM5	3.15	1.76
GFDL-CM4	>2	1.48
GISS-E2-R	>1.5	0.92
GISS E2.1-G	1.98	1.37
IPSL-CM6A-LR	2.66	1.31
MRI-ESM2-0	>2	1.36
NorESM1-M	1.72	0.9
NorESM2-LM	1.48	1.33

† *Ensemble member from each model as denoted in the PCMIDI-AR6 database.*

‡ > *symbols indicate limited GWL data availability; see Table S1.*

4 Results

4.1 Projected Changes in DHW

For this analysis we select a mid-21st century period (2050-2059) to show the effects of warming over the next 30 years. Figs. 3b and 3c show the ensemble mean change in annual DHW between baseline and future for the 2050-2059 period in both emissions scenarios. Broad increases in DHW are visible across the outlined MAR region, well above the known bleaching and mortality thresholds of 4°C-weeks and 8°C-weeks. Increases in DHW in the MAR are slightly lower than in the southwest Atlantic in both scenarios, but are still dramatic, indicating that most future years will include significantly anomalously high SST values with weeks above dangerous DHW thresholds, even by mid-century.

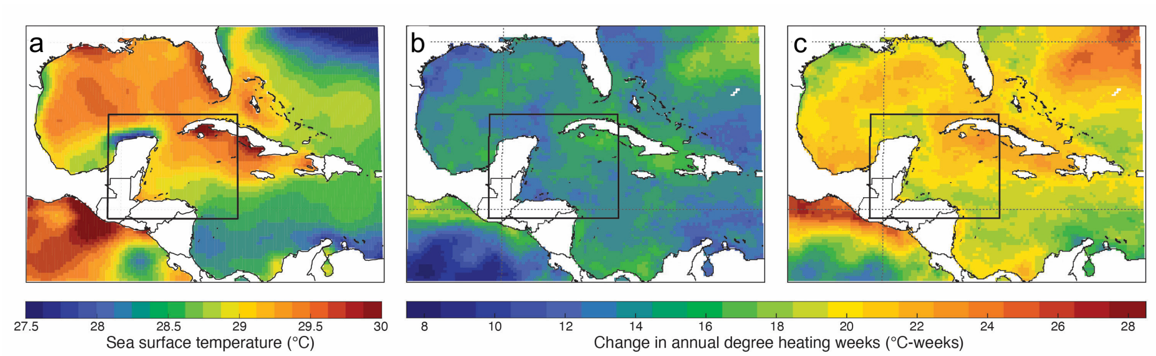

Figure 3. Climatological maximum mean month and ensemble mean changes in annual DHW. (**a**) MERRA-2 climatological maximum mean monthly SST (MMM_SST_CLIM) from 1985-1993, excluding 1991-2; this represents the baseline from which HotSpots are calculated. Ensemble mean changes in annual DHW across ensemble of GCMs for 2050-2059 period, calculated from 1980-2009 baseline, are shown for (**b**) SSP2-4.5 scenario and (**c**) SSP5-8.5 scenario.

Figure 4 shows the change in annual DHW as a regional average across the boxed area outlined in Figure 3. We show mean decadal DHW for the ensemble of 10 GCMs as well as the MERRA-2 baseline. Shaded areas represent the range between lowest and highest projected mean annual DHW for each decade, with the mean across models shown as a bold line. We extend the model “envelope” to the last decadal mean in MERRA-2, although model decadal points are centered on the middle-year (e.g., 2014 for the 2010-2019 decade).

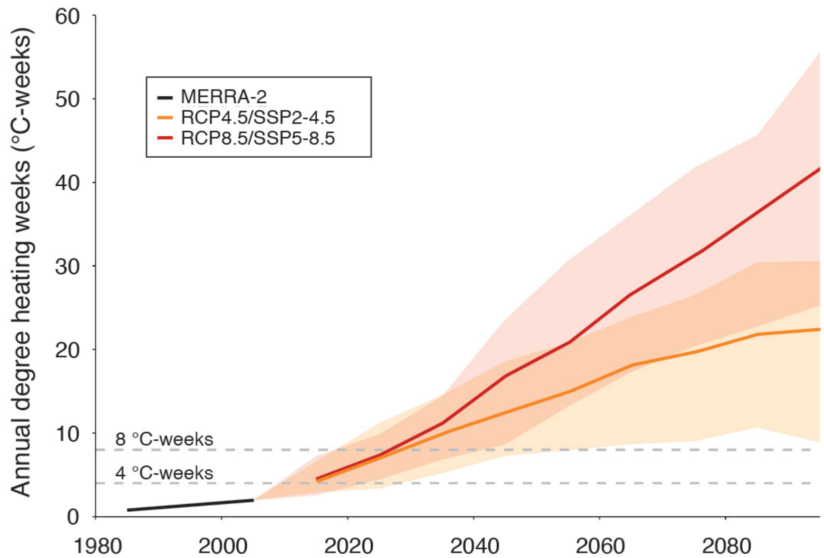

Figure 4. Regional decadal DHW from baseline to 2100. Time series of decadal DHW for MERRA-2 and future generated SST data using all GCMs and both scenarios. Shaded areas represent the range of lowest and highest projected mean annual DHW for each scenario and decade with ensemble means shown as bold lines.

The dramatic rise in annual DHW in Fig. 3 is again visible, with much more drastic impacts in the high-emissions scenario (SSP5-8.5). As these smoothed time series show only decadal averages, these do not include projections of extreme DHW correlating to marine heat wave events. The coastal ecosystem, biodiversity, and socioeconomic impacts of high-value DHW may therefore be even more dire than the values seen here, with current bleaching conditions becoming near-constant by mid-century. Even with smoothed data, the ensemble projects annual DHW in the region to increase by 7.9°C-weeks – 20.8°C-weeks under the lower-emissions scenario by the 2050s, with that range expanding to 13.2°C-weeks – 30.6°C-weeks under SSP5-8.5. By the 2090s, the upward trend in SSP2-4.5 projections has slowed due to the stabilization of greenhouse gas emissions in RCP4.5, but the range in projected increases is wider (8.9°C-weeks on the low end and 30.6°C-weeks on the high end). In the worst-case scenario, by the end of the century under SSP5-8.5, annual DHW may increase by 25.3°C-weeks – 55.6°C-weeks.

We additionally analyze metrics on the frequency and duration of HotSpots (SST anomalies greater than 1°C), values that are accumulated in each half-weekly DHW. As DHW are calculated using a rolling 12-week window, single half-weekly HotSpots may appear in multiple DHW. This approach is critical in defining DHW as enduring heat stress, but when assessing length and duration of heat spells, it is important to use non-recurring SST anomalies. For presentation, we apply a factor of 0.5 to half-weekly results to show the frequency and duration metrics in weeks per year. Fig. 5 shows the change in mean annual frequency of weekly HotSpots for the 2050-2059 period under both emissions scenarios, as well as the change in the maximum length of consecutive weekly HotSpots for the same period.

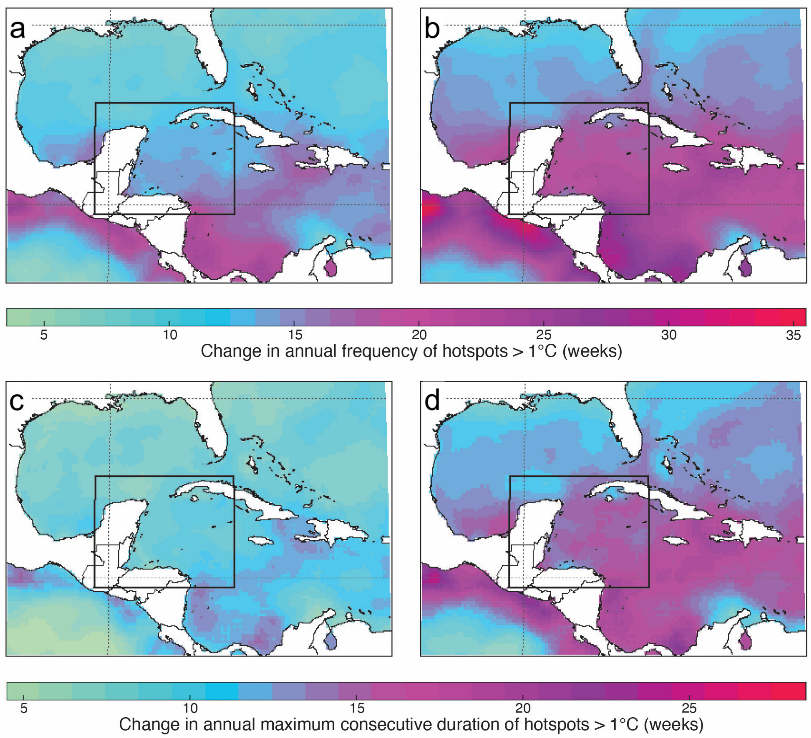

Figure 5. Ensemble mean changes in annual frequency and maximum consecutive duration of weekly HotSpots. Ensemble mean changes in annual frequency of weekly HotSpots for 2050-2059 period, calculated from 1980-2009 baseline, for (**a**) SSP2-4.5 scenario and (**b**) SSP5-8.5 scenario, and ensemble mean changes in annual maximum duration of consecutive weekly HotSpots for 2050-2059 period, calculated from 1980-2009 baseline, for (**c**) SSP2-4.5 scenario and (**d**) SSP5-8.5 scenario.

Without the cumulative effect of DHW calculation, spatial variability is more noticeable in both frequency and duration changes across the broader Caribbean region than in annual DHW changes (Fig. 3). Given significantly larger annual DHW in the future, the frequency of HotSpots is projected to increase substantially due to high levels of warming in regional SSTs. Relative spatial patterns in the changes of the maximum duration of warm spells (Figs. 5c, 5d) roughly match those seen in changes in frequency (Figs. 5a, 5b), with the highest values further south near Panama and along the southern coast of Guatemala and El Salvador. This indicates that the highest increases in the frequency of extreme events may correspond to much longer consecutive periods with SST anomalies above 1°C. The length of these warm spells, and the resulting extreme increases in DHW in both scenarios, imply severe consequences for the health of the MAR. Longer-length marine heat waves will likely be connected to higher incidences of coral bleaching and mortality, and increases in frequency suggest that the MAR may not have time to recover from consistently high SSTs in between events.

These changes in annual DHW may mask variability in the seasonal cycle of the average year in both baseline and future scenarios; therefore, it is useful to analyze the seasonal occurrence of high DHW values in comparison to present conditions. An average year of half-weekly DHW from the MERRA-2 baseline (1980-2009) is shown in black in Fig. 6 along with the spread of GCM projections of seasonal DHW in the 2050s under both scenarios, as in Fig. 4.

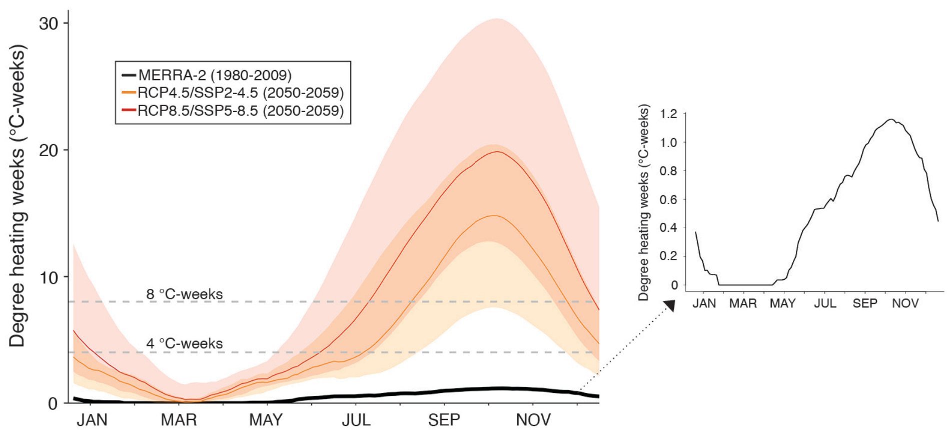

Figure 6. Average seasonal cycle of half-weekly DHW in baseline and future conditions. Average seasonal cycle of half-weekly DHW for baseline MERRA-2 (black) and range of GCMs under SSP2-4.5 (orange) and SSP5-8.5 (red). Shaded areas represent the full range of lowest and highest projected mean annual DHW for each scenario with ensemble means shown as bold lines. MERRA-2 seasonal cycle of DHW is shown in higher detail as an inset on the right.

The seasonal pattern of DHW visible in MERRA-2, with the lowest DHW in March and April after the cold months, is preserved in future scenarios, although this may be largely influenced by the delta method of bias-adjustment. The annual cycle of DHW peaks in October and November in both baseline and future scenarios, but the magnitude of future DHW greatly exceeds those seen in MERRA-2 in every month of the year. The highest DHW values in the MERRA-2 average are exceeded by nearly all GCM projections in all months of the year, except for the lowest estimates in the coolest months.

4.2 Data limitations and dimensions of uncertainty

This analysis uses SST data from combined GCM sources, providing a unique multi-model, multi-scenario perspective with a regional focus. However, additional factors could add new insights beyond the results presented here. First, we focus exclusively on the moderate (SSP2-4.5) and very high (SSP5-8.5) emission scenarios, with no results from the more optimistic SSP1-2.6. This adds a dimension of temporal uncertainty, with lower emissions and more mitigation measures in SSP1-2.6 allowing for more time before the crossing of critical warming thresholds. The range of GCM SST projections, even within this ensemble, provides another element of uncertainty; reducing inter-model spread would greatly benefit areas with strong adaptation needs such as the MAR. Additionally, these results use sea surface temperature data only, without the inclusion of vertical ocean profiles from individual GCMs. The incorporation of temperatures at different ocean depths can be important when studying the effects of warming on various marine species; however, we focus on SST data here due to the often shallow-water habitats of most coral species and the broad availability of observational and GCM SST outputs. Finally, at 0.25-degree spatial resolution, we interpolate GCM data to an extent where a much higher spatial variability is visible than in raw GCM ocean variables. Still higher-resolution SST products from global climate models with improved ocean processes and more complex model downscaling methods as well as advanced satellite data, such as that available from the NASA PACE Early Adopters Program (Cetinić et al., 2022), will contribute to improving projections for location-based planning and policymaking. Although the drastic warming results and the potential damages that we see from this ensemble are unlikely to be significantly altered with the addition of other temporal, vertical or spatial dimensions, these could provide new insights for those studying the effects of climate change with specific marine species, time horizons, emissions pathways, or mitigation scenarios.

5 Conclusions

Although specific to the MAR, this work provides insight into the link between climate change and the risk of significant coral bleaching. Despite spatial variability and GCM uncertainty in the magnitude of warming across the globe, warmer temperatures in many regions are all but guaranteed by mid-century under even more optimistic mitigation scenarios (Fox-Kemper et al., 2021; IPCC, 2021). As SSTs rise, the frequency, severity, duration, and spatial extent of marine heat waves also increases, a phenomenon which has already been observed in recent decades (Fox-Kemper et al., 2021; Pörtner et al., 2019). The level of warming during different parts of the seasonal cycle may vary, but even with moderate warming in cooler months, the traditionally "warm season" in the MAR will likely extend to include most of the year. When compared to current conditions, these changes indicate that the occurrence of consecutive weeks above critical DHW thresholds will be nearly inevitable. The definition of DHW as a metric that calculates SST anomalies relative to a region's climatological baseline gives it a portability that traditional thresholds lack, as the magnitude of difference between current and future climate conditions is a main contributor in calculating coral bleaching risk. This suggests that at a certain point, near-permanent warm season marine heat waves will make surface corals unviable in many regions, as the modes of variability in GCM projections likely present a larger source of uncertainty than regional disparities (Fox-Kemper et al., 2021; IPCC, 2021; Pörtner et al., 2019; Ranasinghe et al., 2021).

Despite rapid warming in the MAR, research indicates that coastal ecosystems can develop a level of natural resistance after exposure to warmer sea temperatures, although this often serves only as a temporary safeguard in the context of long-term warming (Munday et al., 2008). Studies that incorporate natural coral adaptation to higher SSTs show significantly reduced risk of bleaching across future scenarios (Frieler et al., 2013; Langlais et al., 2017; Logan et al., 2014; Teneva et al., 2012). However, compared to other regions, the MAR has historically seen less recovery after marine heat waves, due to a combination of factors such as the level and frequency of episodes, the affected species, and other concurrent extreme events (Baker et al., 2008). In research on the global consequences of warming on reef systems, the Caribbean is consistently classified among the most vulnerable, with thermal protection projected to decline significantly even under the ambitious target of 1.5°C above pre-industrial conditions (Dixon et al., 2022) and substantial declines in coral cover evident even in simulations of evolutionary adaptation responses (McManus et al., 2021).

Consequently, reef survival in the MAR depends on more than limiting emissions, although global mitigation of greenhouse gas emissions is still critical to delay the onset and reduce the severity of future marine heat waves to allow for the possibility of reef recovery. Reef restoration studies indicate moderate potential in adaptation methods such as coastal zone and fisheries management, structural restoration or physical reconstruction, and pollution reduction (Kleypas et al., 2021). More direct measures such as coral gardening through transplantation or micro-fragmentation, larval propagation, and artificial reef construction also show the capacity for coral regrowth in short-term research (Boström-Einarsson et al., 2020). Still, the success of adaptation measures depends strongly on the complexities of local governance, technological and financial limitations, and the genetic makeup of regional reef systems (Kleypas et al., 2021), as well as ongoing, long-term, and region-specific research on the efficacy of coral regrowth interventions (Boström-Einarsson et al., 2020).

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Open Research

Raw data and software: Raw data from NOAA are available from the NOAA Coral Reef Watch website (https://coralreefwatch.noaa.gov/index.php). Raw data from MERRA-2 are available from MDISC, managed by the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC; https://disc.gsfc.nasa.gov/datasets?project=MERRA-2). Raw GCM data from CMIP5 and CMIP6 are available from various nodes on ESGF (https://esgf.llnl.gov/). This research made use of MATLAB and R software for analysis (MATLAB, 2018; R Core Team, 2018).

Availability statement: To make all data and analysis behind this study publicly available, we provide the regridded (0.25-degree) daily SST data from each of 10 GCMs as well as MERRA-2 in an online Goddard Institute for Space Studies (GISS) Climate Impacts data portal maintained by the NASA Center for Climate Simulation (NCCS, 2022). All of the figures in this manuscript and supporting information, with the exception of Figures 1 and S3a, can be recreating using the data on the GISS Impacts portal. Figures 1 and S3a can be recreated using data directly available from the NOAA website above. Table 1 is derived from data on the GISS Impacts portal as well as data from the Hauser et al. (2019) dataset. Table S1 provides the relevant data directly from Hauser et al. (2019) which can be used to interpolate values in Table 1. We additionally provide scripts for processing and analyzing the daily SST data from GCMs and MERRA-2, which are available on GitHub (Phillips, 2022). These scripts use MATLAB version 9.5.0.1049112 (R2018b) Update 3, and R version 3.5.2 (MATLAB, 2018; R Core Team, 2018). Both the GISS Impacts data portal and the GitHub repository cited here are accessible to the public with no registration required.

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