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Key Points:

- Sea-surface temperatures (SSTs) surpass critical coral bleaching thresholds by mid-century in the Gulf of Mexico (GoM) and Caribbean Sea
- The rate and magnitude of SST changes in the GoM/Caribbean more strongly influence future coral reef vulnerability than ocean acidification
- Future climate projections with high greenhouse gas forcing underscore the need for mitigation to ensure long-term coral reef preservation

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Rates of Future Climate Change in the Gulf of Mexico and the Caribbean Sea: Implications for Coral Reef Ecosystems

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Abstract Rising temperatures and ocean acidification due to anthropogenic climate change pose ominous threats to coral reef ecosystems in the Gulf of Mexico (GoM) and the western Caribbean Sea. Unfortunately, the once structurally complex coral reefs in the GoM and Caribbean have dramatically declined since the 1970s; relatively few coral reefs still exhibit a mean live coral cover of >10%. Additional work is needed to characterize future climate stressors on coral reefs in the GoM and the Caribbean Sea. Here, we use climate model simulations spanning the period of 2015–2100 to partition and assess the individual impacts of climate stressors on corals in the GoM and the western Caribbean Sea. We use a top-down modeling framework to diagnose future projected changes in thermal stress and ocean acidification and discuss its implications for coral reef ecosystems. We find that ocean temperatures increase by 2°C–3°C over the 21st century, and surpass reported regional bleaching thresholds by mid-century. Whereas ocean acidification occurs, the rate and magnitude of temperature changes outpace and outweigh the impacts of changes in aragonite saturation state. A framework for quantifying and communicating future risks in the GoM and Caribbean using reef risk projection maps is discussed. Without substantial mitigation efforts, the combined impact of increasing ocean temperatures and acidification are likely to stress most existing corals in the GoM and the Caribbean, with widespread economic and ecological consequences.

Plain Language Summary Coral reefs are among the most diverse and valuable ecosystems on Earth, and the coral reefs in the Gulf of Mexico (GoM) and the Caribbean Sea are no exception. In this region, coral reefs support vibrant recreation, tourism, and fishing industries. However, climate change, including rising temperatures and ocean acidification, threaten the future health of corals. To asses climate change-related risks to coral reefs in the GoM and the Caribbean Sea, this study uses climate model simulations spanning 2015–2100 to understand future changes in temperature and ocean acidification. Although many regions of the GoM and the western Caribbean Sea will cross the critical coral reef bleaching thresholds by mid-century, we hope that this work will inform and streamline mitigation efforts to protect vulnerable coral reef ecosystems and the valuable benefits and resources they provide to local communities.

1. Introduction

Coral reefs are some of the most diverse ecosystems on Earth (Fisher et al., 2015), and foster ecologically diverse habitats, nurture vibrant tourism industries (Spalding et al., 2017), protect shorelines from tropical storms and erosion (Barbier et al., 2011), and provide ecosystem goods and services (Costanza et al., 2014). That said, shallow water coral reef ecosystems are rapidly declining due to anthropogenic activities (Cornwall et al., 2021; Eddy et al., 2021; Hoegh-Guldberg et al., 2017). On a global scale, thermal stress and ocean acidification are the leading climate-related stressors on coral reef ecosystems (Hoegh-Guldberg et al., 2017; Hughes et al., 2017). Worldwide, coral reef cover has declined by approximately 50% since the 1950s due to the combined impact of climate change and local stressors (Eddy et al., 2021).

Scleractinian (stony) corals that provide the foundation for coral reefs typically prefer a narrow range of warm water temperatures and carbonate saturation states, as well as clear, nutrient-poor waters to form their calcium carbonate (aragonite) skeletons. Episodes of thermal stress—typically four or more degree heating weeks (DHWs; van Hooidonk & Huber, 2009)—can cause stony corals to lose their dinoflagellate endosymbionts (family Symbiodiniaceae), resulting in coral bleaching (Anthony et al., 2008; Baird et al., 2009; Frieler et al., 2013). Whether coral bleaching occurs is influenced by the magnitude and duration of the thermal stress episode. For example, a total of 27.5 days or more above 30°C will result in bleaching in the East Flower Garden Banks (northwestern Gulf of Mexico [GoM]) (Johnston, Hickerson, et al., 2019). However, bleaching can also occur at this location when there are more than 57.5 days above 29.6°C or more than 79 days above 29°C (Johnston, Hickerson, et al., 2019). Furthermore, different coral species have varying thermal tolerances, and local adaptation can occur, so the threshold for coral bleaching will vary with species and locality. When bleached, corals receive little to no photosynthesized sugars from Symbiodiniaceae and are in a weakened state. This can make them more susceptible to competitors (e.g., macroalgae) and disease, and lead to partial or total mortality of a colony (Baker et al., 2008; Frieler et al., 2013; Hughes et al., 2017).

Ocean acidification due to the surface ocean uptake of CO_2 (Sabine, 2004) is the second leading climate-related stressor on coral reefs. Ocean acidification reduces the rate of coral calcification (Kleypas & Langdon, 2006) by decreasing skeletal density, leaving corals more vulnerable to physical breakage (Mollica et al., 2018). As pH declines, the concentration of carbonate ions ($[CO_3^{2-}]$) in seawater decreases, which in turn lowers the aragonite saturation state ($\Omega_{aragonite} = [CO_3^{2-}][Ca^{2+}]/K_{sp}$). This makes the precipitation of calcium carbonate less favorable (Kleypas & Langdon, 2006), directly hindering coral skeleton growth.

Coral reefs in the GoM and the Caribbean Sea are among those that have degraded over the last four decades (Dee et al., 2019; Gil-Agudelo et al., 2020; Muñiz-Castillo et al., 2019; Toth et al., 2019) due to climate-related stressors in conjunction with other local disturbances such as over-fishing, pollution (chemical and physical), agricultural runoff, disease, invasive species, sedimentation, and unrestricted tourism (Carricart-Ganivet et al., 2011; Gil-Agudelo et al., 2020; Holbrook et al., 2019; Horta-Puga et al., 2015; Jordán-Dahlgren & Rodríguez-Martínez, 2003; Precht, 2021; Precht et al., 2016; Schutte et al., 2010; Smale et al., 2019; Spadafore et al., 2021; Tunnell et al., 2007). For example, researchers using nautical charts have documented a 52% decline in coral cover over the past 240 years in the Florida Keys (McClenachan et al., 2017). Additionally, the recent increase in hurricane intensity has also devastated some Caribbean coral reef communities over the past 20 years (e.g. Gochfeld et al., 2020; Rogers, 2019). At present, few coral reefs in the GoM and the Caribbean exhibit mean live coral cover exceeding >10% (Waddell & Clarke, 2008; Wilkinson & Souter, 2008); this is lower than, for example, estimates of an average of 15% live coral cover in the Hawaiian Island archipelago (Asner et al., 2020), and 27% in the Great Barrier Reef (AIMS, 2021). The Flower Garden Banks (FGB) National Marine Sanctuary offshore of Texas and Louisiana, and Dry Tortugas National Park in western Florida are exceptions within the GoM and Caribbean, as these locations have live coral cover >50% (Gil-Agudelo et al., 2020; Johnston et al., 2017; Waddell & Clarke, 2008; Wilkinson & Souter, 2008). However, even corals in these protected regions are not immune to the impact of climate change, disease, and other local stressors.

Over the past several decades, one of the largest documented changes in GoM and Caribbean coral reefs is the loss of prevalent branching acroporid corals, whose populations have declined more than 90% since the 1960s due to thermal stress, local anthropogenic stressors, and disease (Cramer et al., 2020, 2021). Two species, *Acropora palmata* and *Acropora cervicornis*, are listed as threatened under the United States Endangered Species Act of 2006 (Hogarth, 2006), and five more coral Caribbean species were added as threatened in 2014 (NMFS, 2014). At least six major bleaching events have occurred in the Florida Keys since 1987, impacting >40% of coral colonies (Manzello, 2015; van Woesik & McCaffrey, 2017). Recent bleaching events occurred throughout the GoM and Caribbean in the last three decades (Muñiz-Castillo et al., 2019), including during the severe global bleaching events of 1998, 2005, and 2014–2017 (Claar et al., 2018; Eakin et al., 2010, 2019; Johnston, Hickerson, et al., 2019). Prompt mitigation to reduce fossil fuel emissions and resulting climate change-related stressors are needed to protect vulnerable coral reef ecosystems in these areas.

In contrast to the Florida Keys and other parts of the GoM and Caribbean Sea, deeper-water, geographically isolated mesotrophic corals have historically experienced less thermal stress (Gil-Agudelo et al., 2020). For example, coral bleaching in 2005 was reduced below 29 m depth at the Flower Garden Banks in the northern GoM. More recently, over 60% of corals at monitored sites on East Flower Garden Bank were impacted during the 2016 bleaching event, but the majority of coral colonies recovered once sea water temperatures cooled, and overall coral mortality from this bleaching event was low (Johnston, Hickerson, et al., 2019). The FGB continues to contain some of the highest coral cover in the region. Yet, an increase in the frequency of extreme bleaching events in the future (Dee et al., 2019; Manzello et al., 2021) will test the thermal tolerance of coral species within the FGB.

As the climate continues to warm from rising greenhouse gas emissions, massive global coral bleaching events like the recent one from 2014 to 2017 (Eakin et al., 2019) are likely to become more frequent. Climate models are powerful tools that provide a means to simulate and investigate the climate system's response to a set of future carbon emissions scenarios. Model simulations for the future project an increase in coral bleaching risk and a decrease in coral reef calcium carbonate production (Cornwall et al., 2021; Dee et al., 2019; Frieler et al., 2013; van Hooidonk et al., 2015), coral metapopulation decline (Holstein et al., 2022), and reduced coral reef habitat suitability (Couce et al., 2013). Work by Sully et al. (2019) suggests that coral bleaching may be more probable at higher latitudes (15°–20° N) compared to equatorial regions where corals are subjected to similar temperatures regularly, further motivating our focus on the GoM and the western Caribbean Sea.

To provide a framework for diagnosing the impact of future climate change on coral reefs in the GoM and the western Caribbean Sea, this study quantifies the rates and magnitudes of temperature and ocean acidification changes using state-of-the-art global climate model simulations for the 21st century. We provide a suite of projections of environmental stressors that impact coral reefs in this region, and diagnose the leading risks for coral reefs under future climate scenarios with varying greenhouse gas forcing. We partition how individual environmental threats (e.g., rising temperature and ocean acidification) independently and jointly contribute to future coral reef demise in the GoM and Caribbean. Such information is needed to inform mitigation efforts to protect vulnerable coral reef ecosystems.

2. Materials and Methods

2.1. Climate Model Simulations

Our study evaluates the leading climate risks to coral reef ecosystems in the GoM and the western Caribbean Sea under high radiative forcing and increased pCO_2. We evaluate future climate model simulations from versions 1 and 2 of the Community Earth System Model (CESM) (Kay et al., 2015; Rodgers et al., 2021) to investigate the leading climate drivers of coral reef vulnerability under high greenhouse gas forcing.

CESM is a state-of-the-art global climate model (GCM) developed by the National Center for Atmospheric Research. CESM versions 1 and 2, respectively, participated in Phase 5 and Phase 6 of the Coupled Model Intercomparison Project (CMIP5/CMIP6). The CESM1 Large Ensemble includes 40 climate model simulations (40 ensemble members) for 2006–2100 that follow the representative concentration pathway 8.5 (RCP8.5) scenario (Kay et al., 2015). RCP8.5 corresponds to 8.5 W/m^2 of radiative forcing by the year 2100 due to anthropogenic emissions, and assumes minimal greenhouse gas mitigation (IPCC, 2013).

Building from the RCPs used in CMIP5 (Taylor et al., 2012), CMIP6 includes Shared Socioeconomic Pathways (SSPs) that include elements of socioeconomic change (O'Neill et al., 2016). The CESM2 Large Ensemble uses the high greenhouse gas forcing SSP3-7.0 scenario, which also assumes a fossil fuel-based economy. The SSP3-7.0 scenario has approximately 7.0 W/m^2 of radiative forcing by the year 2100. The CESM2 large ensemble contains 100 members, but here we focus on the 50 ensemble members that use the original CMIP6 biomass burning protocol. Model horizontal resolution is approximately 1° latitude × 1° longitude for the ocean model.

Climate variables that impact coral reef ecosystems are readily available in model simulations, including changes in temperature, pH, and salinity. For both large ensembles, we extracted output for the GoM and Caribbean domain and calculated the ensemble mean at every grid point for sea-surface temperature (SST), salinity (SALT), pH, alkalinity (ALK), and dissolved inorganic carbon (DIC) for the upper-most surface layer of the ocean model POP2. For each climate variable, we subset both the CESM1 and CESM2 ensemble mean to their common 2015–2100 interval of overlap. Finally, to investigate regional patterns in the simulated changes at locations pertinent to coral reefs, we subdivide the GoM domain into four key regions based on the modern distribution of shallow-water stony corals in the western Caribbean Sea, northern Gulf Coast, Florida, and the Atlantic shelf (Figure 1a).

2.2. CO2SYS: Program for CO_2 System Calculations

The saturation state of seawater with respect to the carbonate mineral aragonite ($\Omega_{aragonite}$) is not part CESM's standard output. We compute the saturation states using the Python implementation of the CO2SYS software (Humphreys et al., 2022; Lewis & Wallace, 1998). Monthly temperature, salinity, alkalinity, DIC, and water

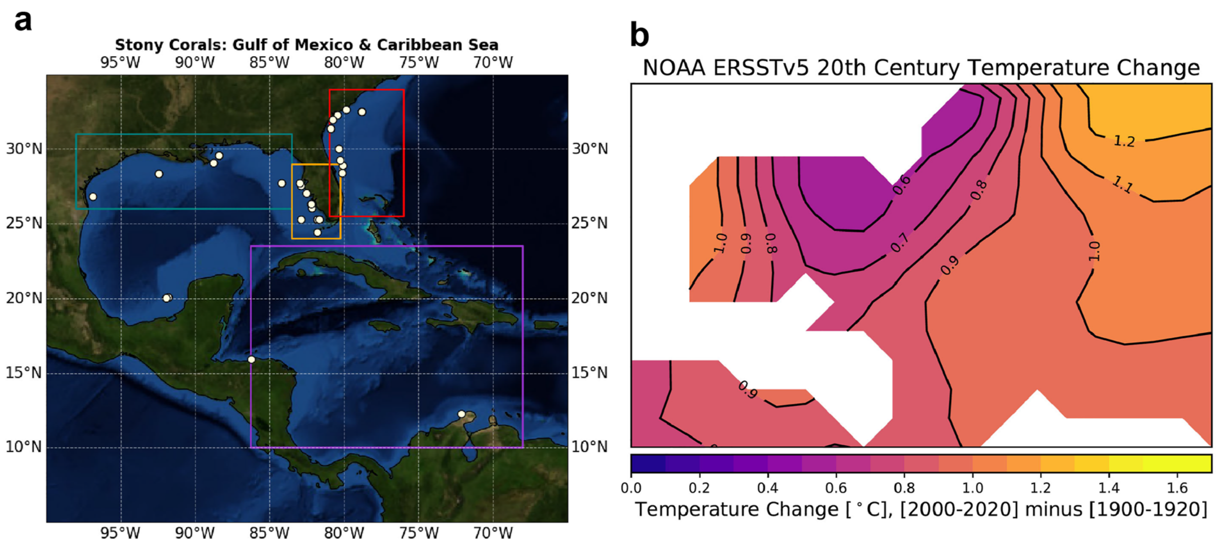

Figure 1. (a) Gulf of Mexico and Caribbean Sea stony coral sites in the upper 50 m as reported in NOAA deep sea coral database https://deepseacoraldata.noaa.gov/. Outlined areas indicate the regions of interest discussed in this study. Northern Gulf Coast (teal), Florida (orange), Atlantic shelf (red), and the Caribbean Sea (purple). (b) Historical SST change [2000–2020] to [1900–1920] for the GoM and western Caribbean Sea. Data from NOAA ERSSTv5 (Huang et al., 2017).

depth (pressure) output from the CESM1 and CESM2 are used as inputs to CO2SYS. Due to the proximity of the Mississippi River outflow, phosphate and silicate loads are likely elevated and may impact GoM corals (Aulenbach et al., 2007). For simplicity, however, here we assume that the phosphate and silicate concentrations are 0 μM, and use documented dissociation constants of carbonic acid, bicarbonate, and sulfuric acid (Dickson & Riley, 1979; Dickson & Millero, 1987; Dickson, 1990; Mehrbach et al., 1973).

2.3. Defining Coral Reef Ecosystem Stressors

Warmer ocean temperatures and ocean acidification are two leading climate-related threats to coral reef ecosystems as further discussed in the following subsections:

2.3.1. Temperature

We evaluate projected changes in ensemble mean annual SST, seasonal SST, and degree heating months (DHMs). Our approach characterizes thermal stress using diagnostics similar to those used by the NOAA Coral Reef Watch (https://coralreefwatch.noaa.gov/), here adapted for future climate scenarios.

Work by Wilkinson and Souter (2008) reports that corals had bleached in the Caribbean when SST reached and sustained 31°C during July and August. More recent in situ studies from the Flower Garden Banks and the Florida Keys found a lower bleaching threshold ranging from 29.5 to 31°C (Johnston, Hickerson, et al., 2019; Johnston, Nuttall, et al., 2019). We thus consider mean annual SSTs approaching 29.5°C as high risk for coral bleaching in the model time series data.

A DHW is a commonly used predictor for coral bleaching that captures both the intensity and duration of heat stress (Gleeson & Strong, 1995; G. Liu et al., 2003). DHWs are expressed in the unit of °C-weeks and reflect the amount of heat stress that has accumulated in an area. A DHW value of 4°C-weeks has been shown to cause significant coral bleaching; values over 8°C-weeks have caused severe bleaching and significant mortality (Skirving et al., 2020). A DHM (Donner, 2009; Frieler et al., 2013) is a similar metric used as a predictor for coral bleaching that is a more suitable target for climate models since model output is typically archived at a monthly time step. A DHM is defined when the monthly SST at a given location exceeds 1°C of the warmest monthly SST during a climatological base period (Donner, 2009; Frieler et al., 2013). At this temperature, bleaching would be predicted to occur. To evaluate how the number of DHMs change over the 21st century, we extract monthly SSTs and compute departures based on the SST climatology for 2015–2034. We note that the DHM calculation used herein does not assume a change in the threshold through time, as may occur with coral adaptation.

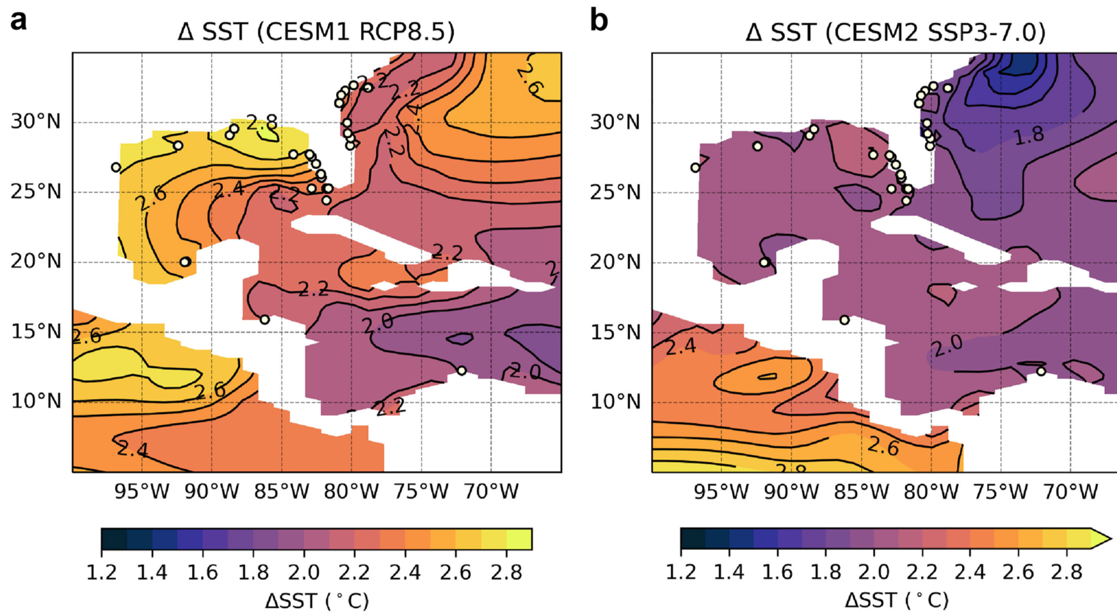

Figure 2. Projected changes in sea-surface temperature (SST) for the Gulf of Mexico (GoM) and the western Caribbean Sea. Absolute difference in SST between [2080–2099] and [2015–2034] for (a) the CESM1 RCP8.5 and (b) the CESM2 SSP3-7.0 ensemble means. Continental regions in this and subsequent figures are shown in white. Stony coral sites in the upper 50 m are indicated by yellow circles as in Figure 1a.

2.3.2. Ocean Acidification

As ocean pH decreases due to the uptake of carbon dioxide, the concentration of carbonate ions ($[CO_3^{2-}]$) in seawater decreases and lowers the aragonite saturation state of seawater ($\Omega_{aragonite} = [CO_3^{2-}][Ca^{2+}]/K_{sp}$). This makes the precipitation of calcium carbonate less favorable (Kleypas & Langdon, 2006) and thus may either inhibit coral skeleton growth and/or make skeletons less dense and more brittle (e.g. Guo et al., 2020; Mollica et al., 2018). To evaluate future changes in ocean acidification, we jointly investigate changes in ocean pH and $\Omega_{aragonite}$ as simulated by CESM1 and CESM2. The majority of shallow-water scleractinian corals in the modern ocean are found within $\Omega_{aragonite} > 3$ conditions (Hoegh-Guldberg et al., 2007; Kleypas et al., 1999). Here we use an experimentally determined calcification threshold of $\Omega_{aragonite} > 2$ (Albright et al., 2008; Langdon et al., 2000), and the thermodynamic limit for aragonite precipitation of $\Omega_{aragonite} = 1$ as thresholds. Although this study focuses on scleractinian corals, we note that other coral reefs organisms may have calcite or high-magnesium calcite skeletons with differing saturation states. High-magnesium calcite skeletons (e.g., coralline algae, serpulid worms, foraminifera, echinoderms, and a subset of bryozoans) have saturation states that make them more susceptible to acidification than organisms with aragonite skeletons (Morse et al., 2006; Ries, 2011).

3. Results

3.1. Temperature

We first evaluate projected changes in thermal stress over time using regional maps, regional time series analysis, and calculations of DHMs to investigate how changes in mean temperature (monthly, seasonal, and annual) arise under high radiative forcing. These changes are compared to observed SST changes since 1900.

3.1.1. Mean SST Changes

Observed SSTs in the GoM and the western Caribbean Sea have increased 0.6–1.1°C since 1900 (Figure 1b). These changes contextualize the projected changes in SST as simulated by CESM1/CESM2. Annual SSTs in the GoM and western Caribbean Sea are projected to increase by 2.2–2.8°C by the end of the century under RCP8.5 forcing (Figure 2a), with the largest heating along the northern Gulf coast in CESM1 RCP8.5. Unfortunately, this zone of high heating intersects many of the coral reefs lining the coastlines of the U.S. and Mexico (Figure 2a, yellow markers). In the lower forcing scenario (Figure 2b.), temperatures increase more modestly,

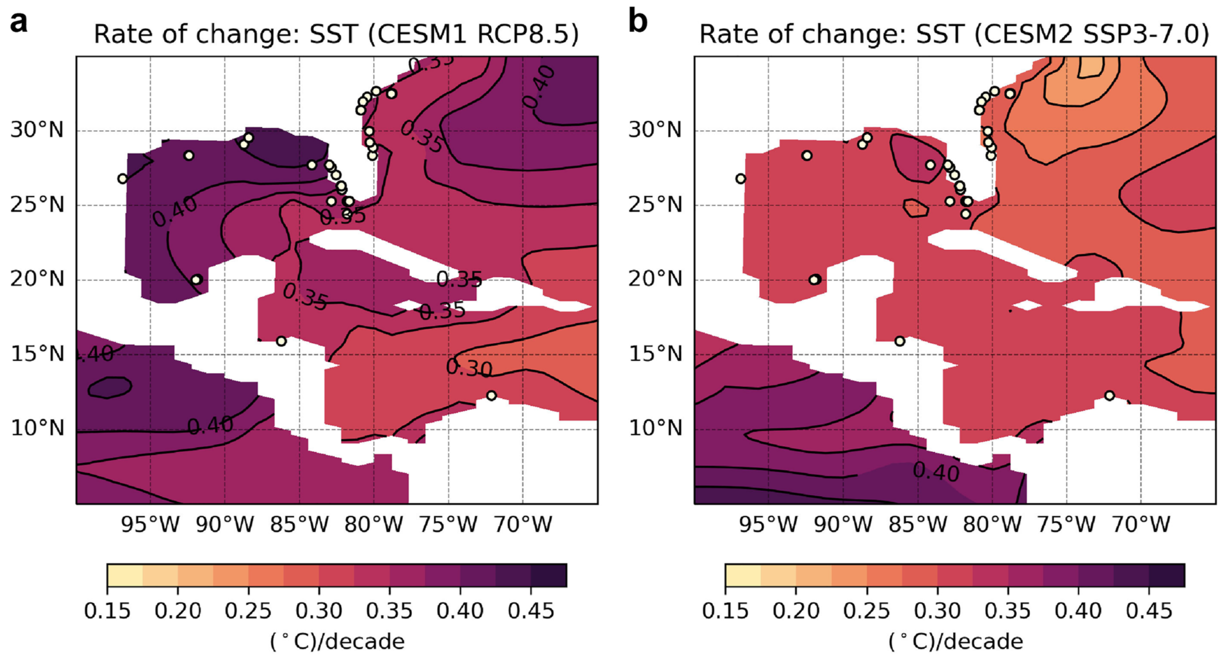

Figure 3. Projected rate of SST change for the GoM and the Caribbean Sea. Rate of SST change per decade (°C/decade) for 2015–2100 for (a) the CESM1 RCP8.5 and (b) CESM2 SSP3-7.0 ensemble means. The rate of change is determined by linear regression. Stony coral sites in the upper 50 m are indicated by yellow circles as in Figure 1a.

with a maximum of 2.0–2.2°C. The maximum simulated difference between RCP8.5 and SSP3-7.0 of approximately 0.8°C is large, and suggests the value of carbon mitigation may be substantial in this region.

Similarly, Figure 3 provides the projected rate of SST change per decade for the GoM and western Caribbean Sea for RCP8.5 (a) and SSP3-7.0 (b), calculated using linear regression of the temperature trend at each model grid cell. For the RCP 8.5 scenario, the fastest rates of SST change occur along the northern and western coastlines at a rate of 0.4–0.5°C/decade (Figure 3a). The rates of SST change in the GoM and the western Caribbean are approximately 0.3°C/decade in the SSP3-7.0 lower emission scenario (Figure 3b). The simulated warming rates exceed the rate of ~0.15°C of warming per decade seen in coral reconstructions in the GoM from the Little Ice Age to the twentieth century (DeLong et al., 2014), the Caribbean (Kilbourne et al., 2008), and the late 1800s to the 21st century in the central Caribbean (von Reumont et al., 2016), and is approaching the rapid late twentieth century increase in the eastern Caribbean (Hetzinger et al., 2010). These warming patterns differ from the patterns observed by satellites since the 1980s that show a 0.4–0.5°C increase in the eastern Caribbean (Chollett et al., 2012). Corals in the Caribbean are already suffering from thermal stress due to warming, and similar stress may propagate into the GoM and western Caribbean when warming rates increase.

While annual mean changes are informative, temperatures across the GoM and Caribbean are generally highest during the summer (June-July-August, JJA) and fall (September-October-November, SON) seasons. Thus, it is important to separately examine the seasonal changes in SST to check the representativeness of the annual mean projections. The spatial pattern of JJA and SON temperature changes (Figure 4) are similar to the annual mean (Figure 2), and range from 2.0°C in the Caribbean to 2.8°C in the northern GoM (Figures 4a and 4c) in the RCP8.5 forcing scenario. In the lower forcing scenario, JJA and SON SST changes are more modest, with maximum changes of ~2.2–2.3°C (Figures 4b and 4d). A coral reconstruction in the GoM reveals summer maxima are increasing over the past 274 years whereas winter minima are not (DeLong et al., 2014). The GoM generally cools in the winter months due to winter storms and cold outbreaks. Continued summer warming would increase the thermal stress of GoM corals. Conversely, a downscaled regional ocean model study finds a reduction in the Loop Current in the 21st century would help reduce the warming in the GoM (Y. Liu et al., 2012).

3.1.2. Degree Heating Months

Coral mortality following a bleaching event is likely to increase if a coral experiences prolonged exposure to SSTs in excess of their thermal tolerance, preventing post-bleaching recovery. As mentioned in Section 2.3.1,

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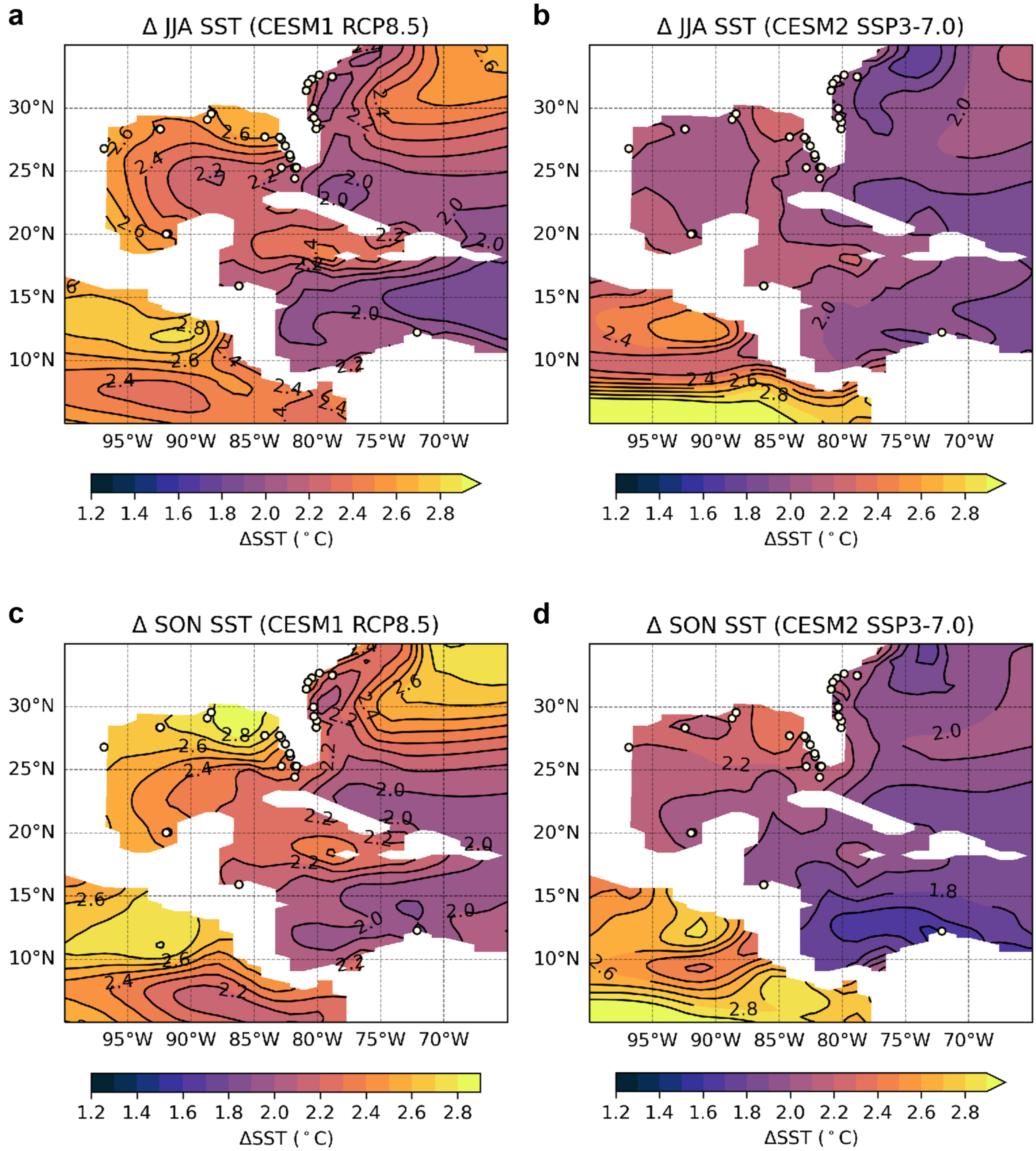

Figure 4. Projected absolute changes in sea-surface temperature for (a, b) June-July-August (JJA) and (c, d) September-October-November (SON) as simulated by the (a, c) CESM1 and (b, d) CESM2 ensemble means. Differences are for [2080–2099] to [2015–2034] under RCP8.5 and SSP3-7.0 forcing.

DHMs are commonly employed as a predictor for coral bleaching (Gleeson & Strong, 1995; G. Liu et al., 2003), and provide a way to account for the cumulative temporal heat stress on the reefs. The DHM calculation is based on the climatology (i.e., the seasonal/monthly averages) of a given time period; a DHM occurs if temperatures exceed the average temperature for the hottest month at that site. For example, if the hottest month for a given location occurs in August (on average), a DHM is defined (or labeled) for any month SSTs exceed the August SST average. If the August climatological average temperature is 29°C, a DHM would be classified any time temperatures are equal to or exceed 30°C. In essence, DHMs provide a way to quantify the total number of months above

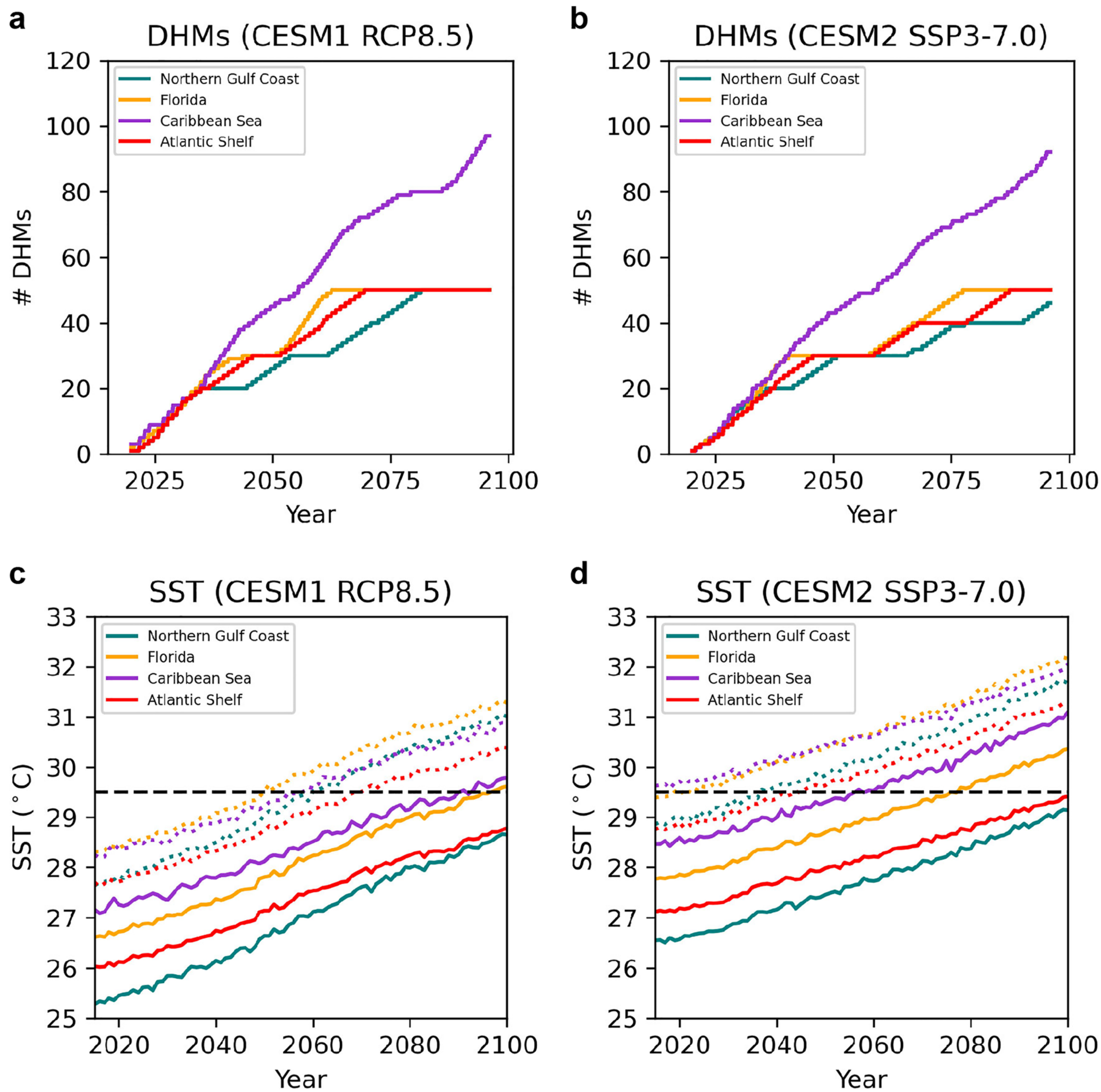

Figure 5. Projected regional changes in Degree Heating Months (DHMs) and annual SST under (a, c) RCP8.5 and (b, d) SSP3-7.0 forcing as simulated by CESM for 2015–2100. (a, b) Time series for the total number of DHMs in a running 10-year window. (c, d) Time series of mean annual (solid) and September-October-November (dashed) SST from 2015 to 2100. In all panels, each line corresponds to a different region: Northern Gulf Coast (teal), Florida (orange), Atlantic Shelf (red), and Caribbean Sea (purple) as outlined in Figure 1. The dashed horizontal black line in (c, d) indicate the 29.5°C threshold of Johnston, Hickerson, et al. (2019) and Johnston, Nuttall, et al. (2019) considered high risk for coral bleaching. This threshold does not assume local adaptation to increasing temperatures over time.

a coral reef's normal thermal range. If the number of DHMs increases, the number of months in which coral bleaching likely occurs is increasing.

The number of DHMs in the Northern Gulf Coast, Florida coastline, western Caribbean Sea, and Atlantic Shelf regions (Figure 1a) all increase by the end of the 21st century regardless of forcing scenario (Figures 5a and 5b). The total number of additional DHMs by the end of the century ranges from 40 to 50 for the Gulf Coast, Florida coastline, and Atlantic shelf to almost 100 for the Caribbean Sea (Figures 5a and 5b).

The changes in DHMs, unlike the changes in mean temperatures, are relatively consistent between the two forcing scenarios given that a DHM is calculated based on each simulation's underlying climatology. Broadly, these data suggest a large increase in the number of DHMs in the late 21st century relative to the early 21st century. Notably,

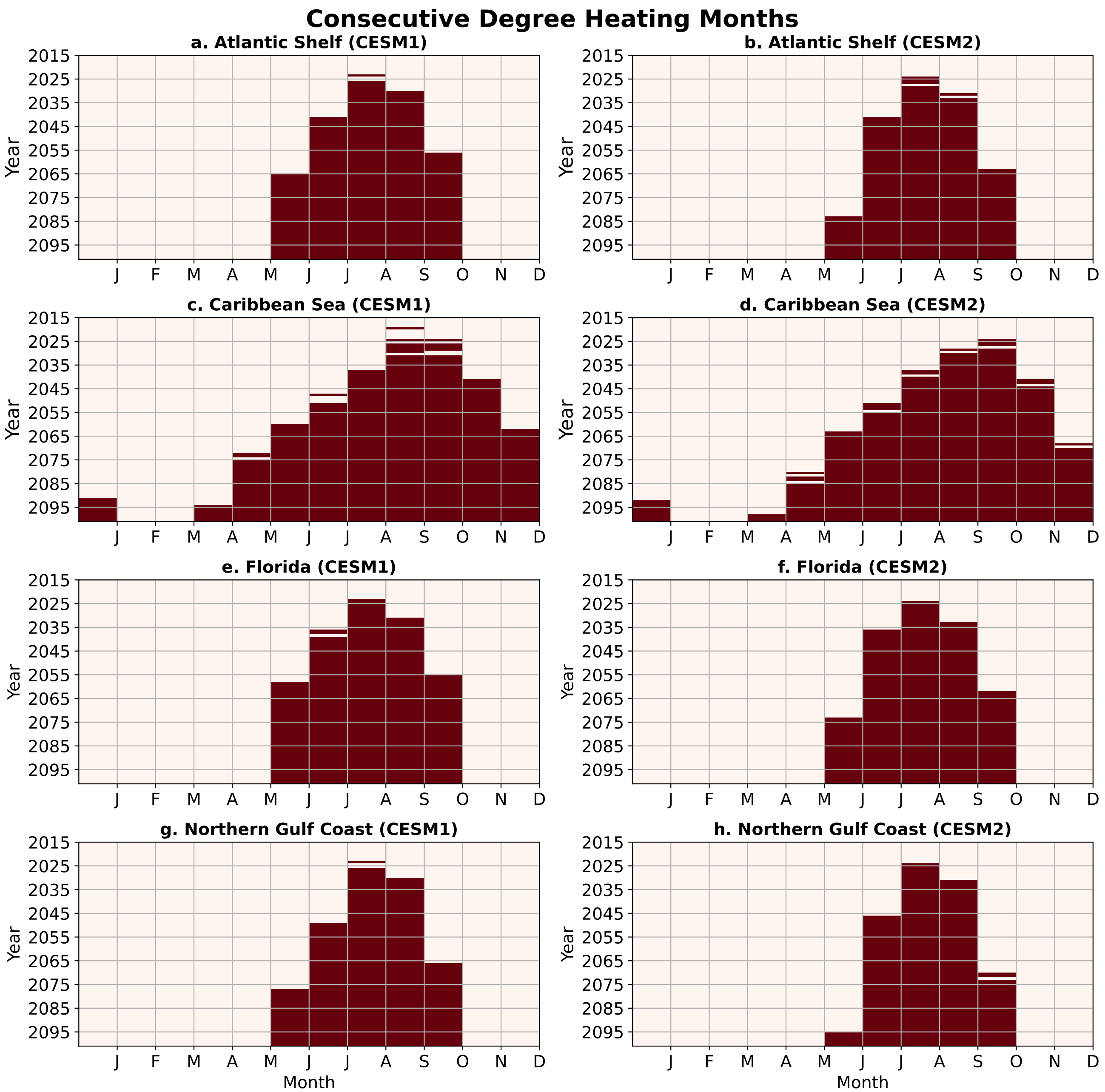

Figure 6. Simulated changes in consecutive degree heating months for CESM1 RCP8.5 (left column) and CESM2 SSP3-7.0 (right column) for the four key regions in Figure 1. Horizontal red bars indicate months that surpass the regional SST threshold for a degree heating month. (a, b) Atlantic Shelf, (c, d) Caribbean Sea, (e, f) Florida, and (g, h) the northern Gulf Coast. Months along the *x*-axis span January (J) through December (D) for each year 2015–2100 indicated along the *y*-axis.

Figure 6 shows increasing likelihood of successive DHMs within a single year, as well as the consecutive years with DHMs for both forcing scenarios. By the end of the century, SSTs during the months of June–October consistently surpass the DHM threshold in all four regions and in both forcing scenarios (Figure 6). All regions have on average 1–2 successive DHMs during the months of July and August until around 2035 (Figure 6). The number of successive DHMs then increases to around 5 total DHMs per year (typically during the months of June–October) by the end of the century, with the relative timing of this transition varying for each region. The Caribbean Sea is a notable exception (Figures 6c and 6d). The Caribbean Sea has the overall largest number of DHMs (Figure 5), and unlike the other three regions, DHMs occur outside of the summer and fall seasons, particularly during the second half of the century. For example, June-December consistently crosses the DHM threshold by 2065 in the RCP8.5 simulation (Figure 6c).

Table 1
Regional Changes in SST for CESM1 RCP8.5 and CESM2 SSP3-7.0

Region	Model	[2015–2034] (°C)	[2080–2099] (°C)	ΔSST (°C)
Atlantic Shelf	CESM1 RCP8.5	26.2	28.5	2.2
	CESM2 SSP3-7.0	27.3	29.1	1.8
Caribbean Sea	CESM1 RCP8.5	27.4	29.5	2.1
	CESM2 SSP3-7.0	28.6	30.6	2.0
Florida	CESM1 RCP8.5	26.9	29.3	2.4
	CESM2 SSP3-7.0	27.9	30.0	2.0
Northern Gulf Coast	CESM1 RCP8.5	25.6	28.3	2.7
	CESM2 SSP3-7.0	26.7	28.8	2.1

Note. Mean SST for [2015–2034] and [2080–2099] and the difference between these intervals for the four regions in Figure 1a.

3.1.3. SST Time Series

Finally, we characterize temporal changes in projected mean annual SST and mean SON SST. As mentioned above, the warm, subtropical waters of the GoM and Caribbean are projected to increase in temperature, with coastal regions projected to warm the most (Figure 2).

To evaluate the likelihood of crossing coral bleaching threshold under different radiative forcing scenarios in CESM, Figures 5c and 5d show time series of simulated changes in mean annual SST for four GoM and Caribbean regions (solid lines). Also shown are the SON fall temperatures (dotted lines), the season when SSTs are typically highest. Although all four regions will warm under RCP8.5 forcing, the Caribbean and the Florida coast are projected to surpass the mean-annual bleaching threshold by 2100 (Figure 5c, solid purple and yellow lines). The overall changes in regional SST are further summarized in Table 1. In all regions and in both forcing scenarios, SON temperatures surpass the 29.5°C threshold around mid-century. In CESM1 (Figure 5c.), SON temperatures exceed 29.5°C by ~2060; simulated temperatures SON start hotter, 27–28°C, in the SSP3-7.0 CESM2 simulation (Figure 5), and exceed 29.5°C by 2040. These differences in absolute SST may be attributable to differences in CESM2's initial conditions and starting temperatures, as discussed in Section 4.

3.2. Acidification

Future projections of pH and $\Omega_{aragonite}$ are used to assess the potential for ocean acidification to inhibit coral calcification in the GoM and Caribbean. The GoM and the western Caribbean Sea both experience a decrease in pH under high greenhouse gas forcing (Figures 7c and 7f). The pH change from [2080–2099] to [2015–2034] is larger for the CESM1 RCP8.5 large ensemble compared to CESM2 SSP3-7.0, likely due to the stronger radiative forcing. Substantial pH changes occur along the northern Gulf coast and Florida (approx. −0.235 to −0.245) for both CESM1 and 2. Regionally, the projected change in pH is relatively linear after 2040, with an ~0.2 pH unit change by the end of the 21st century.

The decrease in pH occurs in conjunction with a change in the aragonite saturation state of seawater (Figures 8 and 9). The majority of shallow-water scleractinian corals in the modern ocean are found within a relatively narrow range of $\Omega_{aragonite} > 3$ conditions (Hoegh-Guldberg et al., 2007; Kleypas et al., 1999) (Section 2.3.2). Previous work by Dee et al. (2019) compared simulated changes in $\Omega_{aragonite}$ with field observations. The offset between surface ocean (0–50 m depth) $\Omega_{aragonite}$ for CESM is relatively small. At 100 m, the offset is larger due to a higher model-predicted DIC at depth, but both the model and observations indicate a decreasing trend in $\Omega_{aragonite}$ with depth. Due to the data-model offset >100 m depth, we focused on the surface waters, where the majority of reef-building stony corals live.

Regionally, $\Omega_{aragonite} > 3$ conditions persist until around 2065 for CESM1 and 2085–2090 for CESM2. $\Omega_{aragonite}$ exceeds a value of 4 during 2015 for all key regions in CESM2 SSP3-7.0. This 20-year offset has important implications for coral reef vulnerability in the coming decades, highlighting the sensitivity of major ocean acidification changes to the underlying forcing scenario. Although no region falls below the experimentally determined calcification threshold of $\Omega_{aragonite} = 2$ (Albright et al., 2008; Langdon et al., 2000), all regions fall below $\Omega_{aragonite}$ values of 3 by the end of the century (Figure 8). The relative timing of crossing this threshold varies by region and forcing scenario. Under RCP8.5 forcing, the northern Gulf coast, Florida, the western Caribbean Sea, and the Atlantic shelf cross the $\Omega_{aragonite} = 2$ threshold by 2065, 2068, 2068, and 2067, respectively. In contrast, this threshold is surpassed approximately 20 years later for the SSP3-7.0 scenario. The northern Gulf coast, Florida, the western Caribbean Sea, and the Atlantic Shelf each respectively crossing the $\Omega_{aragonite} = 2$ threshold in 2084, 2091, 2091, and 2087.

4. Discussion

This study synthesizes future climate projections to characterize temperature and ocean acidification changes in the GoM and the western Caribbean Sea. Our synthesis includes regional projections of temperature changes,

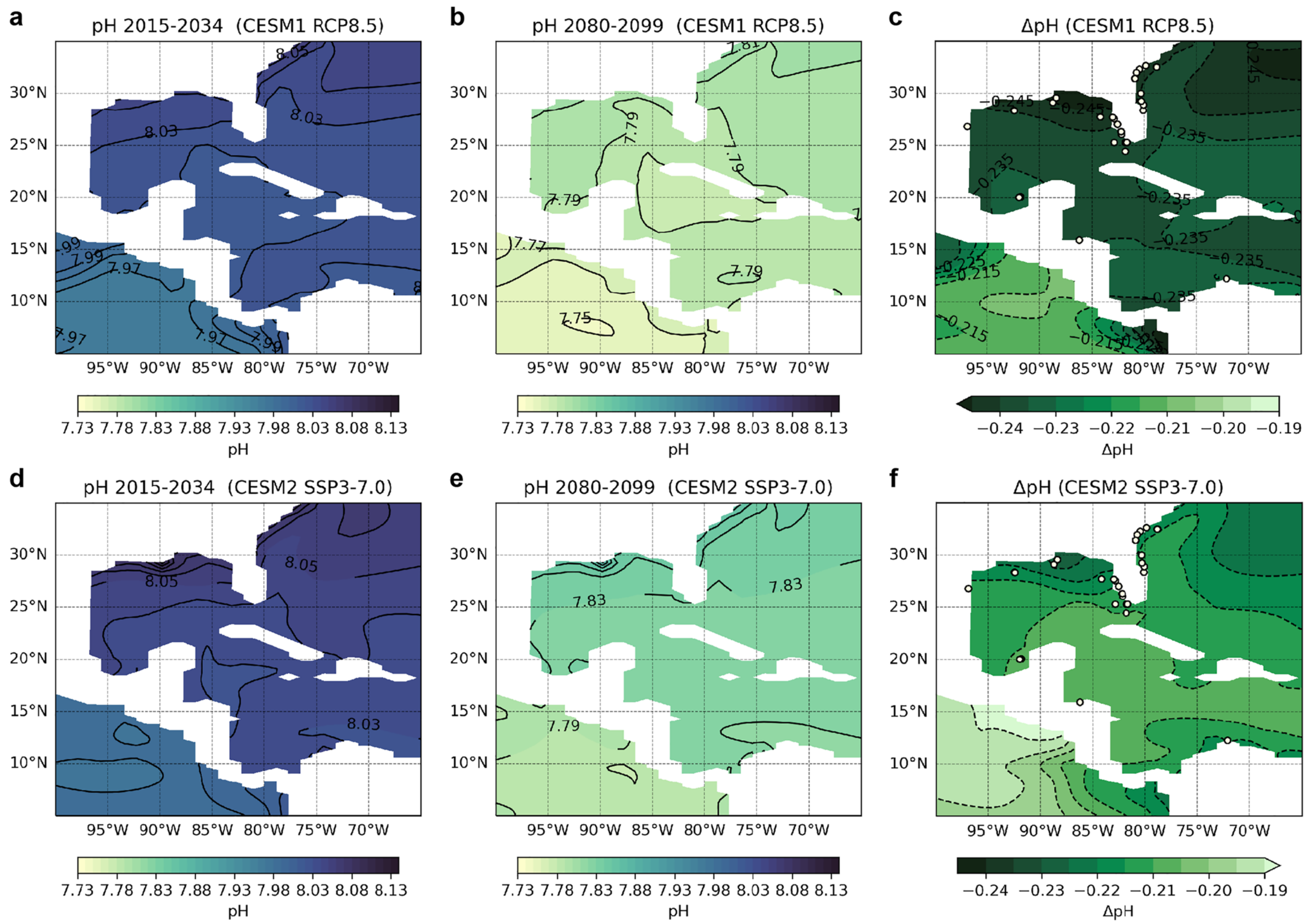

Figure 7. Projected changes in pH for the GoM and the Caribbean Sea. Average pH for (a, d) [2015–2034], (b, e) [2080–2099], and (c, f) the difference between these intervals for (a)–(c) the CESM1 RCP8.5 and (d)–(f) the CESM2 SSP3-7.0 ensemble means. Stony coral sites in the upper 50 m are indicated by yellow circles in (c, f) as in Figure 1a.

DHMs, and changes in the ocean carbon cycle under high greenhouse gas forcing. We evaluate these changes within the context of CESM's simulation of future GoM and Caribbean Sea climate. To guide intervention strategies, our research presents a modeling framework to partition the leading climate risks for coral reefs, and indicate how these risks vary as a function of greenhouse gas forcing.

Under high greenhouse gas forcing, SSTs in the GoM and the western Caribbean Sea are projected to increase at a rate of approximately 0.3–0.4°C/decade between 2015 and 2100, although the precise magnitude varies based on region, the underlying forcing scenario (RCP8.5 vs. SSP3-7.0) and model version (CESM1 vs. CESM2). Regional controls on temperature and acidification yield heterogeneous results in the GoM and Caribbean. The rate of change is larger under RCP8.5 forcing. This corresponds with a >2°C projected increase in boreal summer (JJA) and fall (SON) SSTs in the GoM that contribute to the projected increase in DHMs across the northern Gulf coast, Florida, and the Atlantic shelf (Figures 5 and 6). These results suggest that coral bleaching events, including bleaching events that happen in consecutive years, are likely to become more frequent with future warming. Although coral reefs can recover after some episodes of bleaching, if these events occur in consecutive years, this may result in widespread mortality and slow or halt reef recovery. Although the absolute seasonal SST changes in the Caribbean Sea are smaller in both CESM1 and CESM2, overall mean SSTs are higher and thus more prone to crossing the DHM threshold. The Caribbean Sea experiences the largest change in DHMs by the end of the 21st century. While ocean acidification also occurs, our threshold analysis suggests that the rate and magnitude of temperature changes outpace and outweigh the impacts of changes in aragonite saturation state.

The climate modeling-based approach presented in this work can be leveraged by researchers, managers, and restoration practitioners to mitigate coral reef degradation and intervene for the resilience of reef organisms

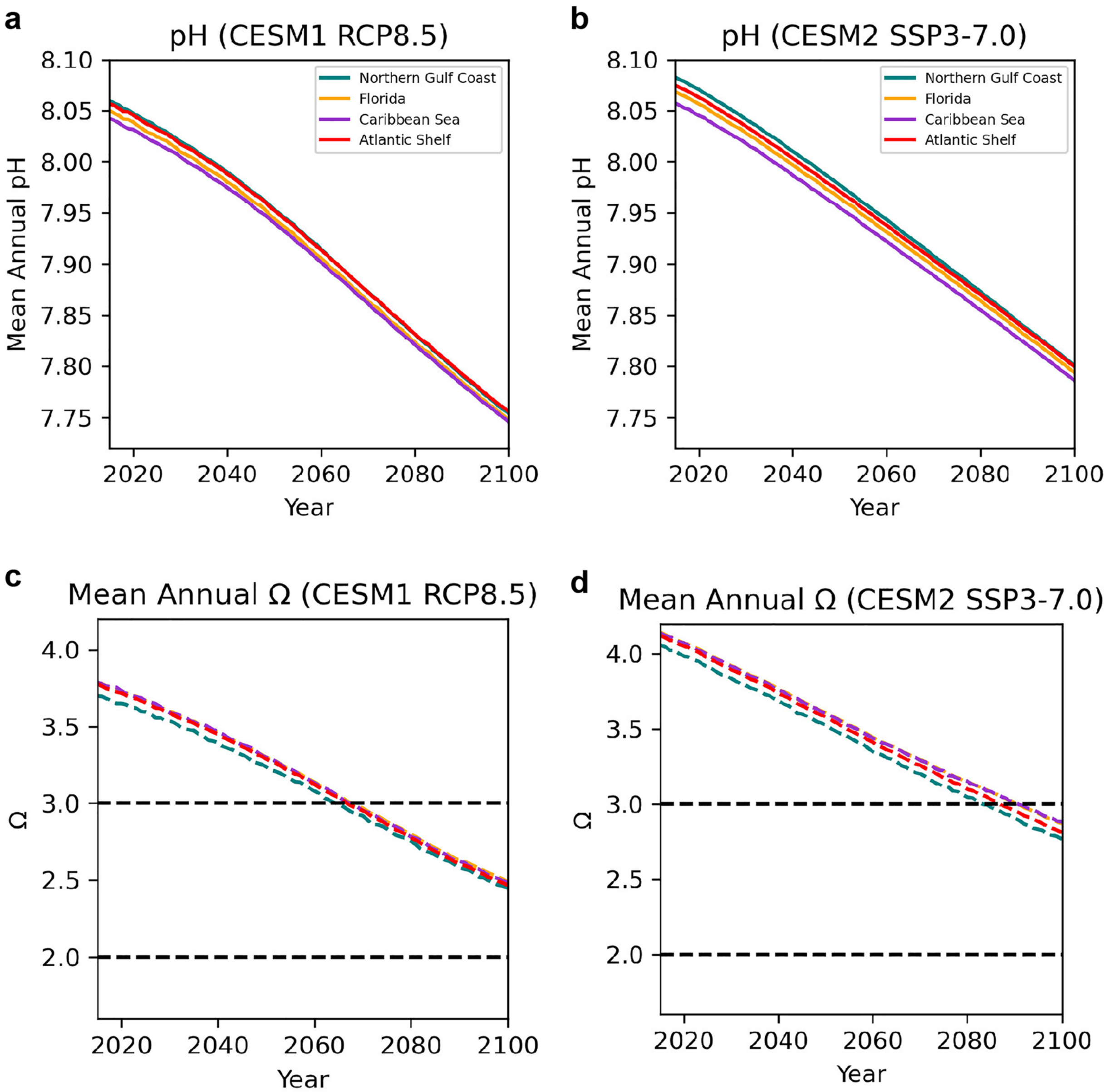

Figure 8. Projected regional changes in pH and $\Omega_{aragonite}$ (a, c) RCP8.5 and (b, d) SSP3-7.0 forcing as simulated by CESM for 2015–2100. (a, b) Time series for mean annual pH. (c, d) Time series of mean annual $\Omega_{aragonite}$ for 2015–2100. In all panels, each line corresponds to a different region: Northern Gulf Coast (teal), Florida (orange), Atlantic Shelf (red), and Caribbean Sea (purple) as outlined in Figure 1a.

(Anthony et al., 2020; National Academies of Sciences Engineering & Medicine, 2019). For example, regions identified here as having slower rates of change could be prioritized for protection as refugia by resource managers. To foster resilience, it would be beneficial to increase focus on this region within existing global conservation programs (Beyer et al., 2018; Gil-Agudelo et al., 2020), as well as to engage with local stakeholders and regional ocean management programs. Fortunately, many corals within the GoM and the Caribbean Sea are within managed and protected areas, including the Dry Tortugas, Biscayne Bay, and Virgin Islands National Parks, the Flower Garden Banks and Florida Keys Marine Sanctuaries, Veracruzano Coral Reef System National Park in Mexico, and the John Pennekamp Florida State Park, thus providing an opportunity for coordinated conservation efforts at local, state, federal, and at the international levels via Caribbean Community (CARICOM). The research presented in this work details the regional and temporal evolution of future risks to facilitate targeted conservation and management efforts from a climate change perspective. Such work will also inform

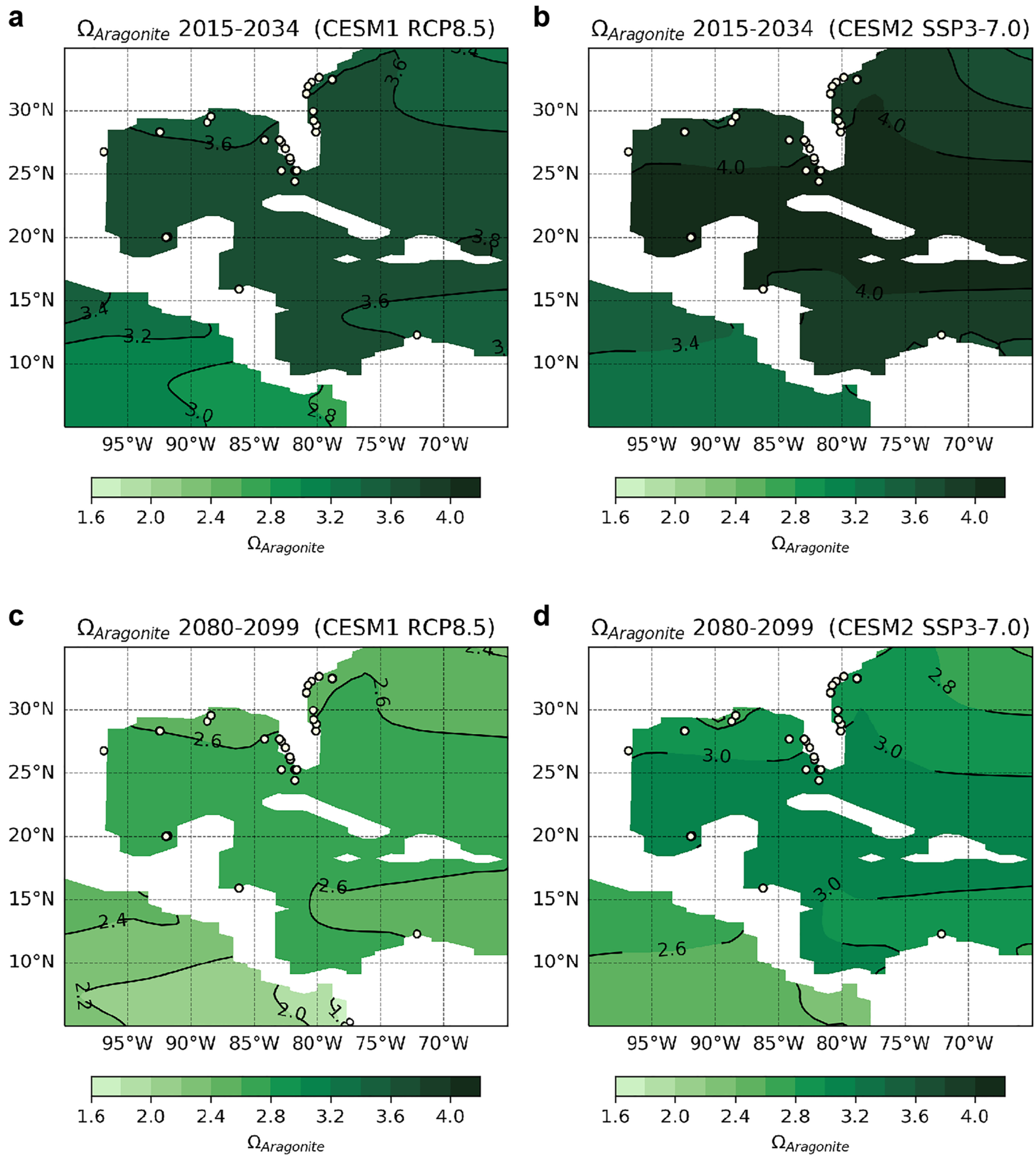

Figure 9. Simulated values of $\Omega_{aragonite}$ for the GoM and the Caribbean Sea in the CESM1 RCP8.5 and CESM2 SSP3-7.0 large ensembles in the surface ocean (0–10 m). Stony coral locations in the upper 50 m overlain (yellow markers) as in Figure 1a. (a, b) 2015–2034, (c, d) 2080–2099 mean.

future studies that downscale future projections to facilitate coral reef conservation efforts at a local scale (e.g., van Hooidonk et al., 2015).

One climate model is used in this study; future work should compare these findings with other CMIP6-era climate model projections for the region. The CESM simulations employed here use two different emissions scenarios, RCP8.5 and SSP3-7.0. While it is informative to check the simulated temperature differences between the two forcing scenarios, it is also important to acknowledge the differences between CESM1 used to run the RCP8.5 scenario and CESM2 used to run the SSP3-7.0 scenario in terms of both model physics and initial conditions.

For example, the CESM2 SSP3-7.0 ensemble mean has higher starting SST values in the GoM and the Caribbean Sea than the CESM1 RCP8.5 ensemble mean (Figure 5). The different boundary conditions and different model physics are difficult to tease apart. Additionally, CESM2 has a higher equilibrium climate sensitivity of 5.5°C compared to 4.1°C in CESM1 based on 2xCO2 experiments with each respective model, whereas the transient response to a 1% annual CO_2 increase is similar (Bacmeister et al., 2020). Future work could consider inter-model comparisons with different external forcing (e.g., SSP1-SSP5) using CESM2; at present, however, large ensemble runs are only available for RCP8.5 and SSP3. Thus, we are inherently limited by the choice of forcings employed for both CESM1 and CESM2 large ensembles.

Another potential caveat is that many GCMs contain cold temperature biases in the GoM and the Caribbean Sea when compared to observed temperatures (Exarchou et al., 2018; L. Liu et al., 2012; Martin & Schumacher, 2012; McGregor et al., 2018; Ryu & Hayhoe, 2015; Wang et al., 2014). Such model biases have important implications for the coral bleaching thresholds (Figure 5), and the simulated temperature changes by the end of the 21st century may be underestimated. Furthermore, the approximately 1°C spatial resolution is too coarse to resolve sub-grid scale upwelling dynamics and the eddy shedding characteristics of the Loop Current (Y. Liu et al., 2012) that impact the spatial SST pattern in the GoM and how it may change in response to radiative forcing.

We emphasize that the timing of crossing critical coral reef bleaching thresholds presented in this work is likely conservative given that our results are solely based on SST and ocean acidification changes. In addition to temperature and pH changes, multiple secondary impacts will accompany climate change in the GoM and the Caribbean; among these are sea level rise and inundation, extreme storms (specifically tropical cyclones/hurricanes), and coral disease which are not considered here. For example, coral growth rates must keep up with the current and future rates of sea-level rise to survive; today, sea level rise threatens the Florida Keys and other GoM coral reefs (Shinn, 1976; Toth et al., 2015). As corals become more stressed, reef accretion rates may decline compared to a healthy reef, and thus be unable to keep up with projected sea-level rise. Perry et al. (2018) find that although many tropical Atlantic coral reefs have retained accretion rates close to recent sea-level rise trends, few will have the capacity to track sea-level rise projections under moderate and high greenhouse gas forcing.

Furthermore, major hurricanes have wiped out coral reefs (e.g., Hurricane Mitch in Belize and Dorian in the Bahamas), and other hurricanes have caused significant damage to reefs (e.g., Hurricane Irma in the Florida Keys). Floodwaters generated by extreme storms have recently been shown to impact not only nearshore reefs, but even those ~185 km offshore in the FGB (Doyle et al., 2022; Johnston, Nuttall, et al., 2019; Shore et al., 2021; Wright et al., 2019). Recovery timescales for physical disturbance are on the order of multiple years to decades in a healthy coral reef, but are longer in degraded reefs (Dollar & Tribble, 1993; Edmunds & Gray, 2014). In 2017, the US Virgin Islands were impacted by two category 5 hurricanes, but because the reefs were already so degraded, the damage was not statistically discernible (Edmunds, 2019).

We note that future projections of hurricanes and tropical cyclones in the Atlantic Ocean suggest storm intensity (wind speeds) will increase, rainfall will increase, and that sea level rise coupled with increased rainfall will lead to stronger storm surges and inundation (Balaguru et al., 2018; Klotzbach et al., 2018; Knutson et al., 2020; Ting et al., 2019; Trenberth et al., 2018). High storm surges, wave impacts, and associated floodwaters will further degrade GoM and Caribbean reefs and increase shoreline erosion and the import of sediments. Such storms also destabilize mangrove and sea grass populations. Unfortunately, these impacts would compound the temperature and acidification risks documented here.

Future work could expand upon the reef resiliency model of Anthony et al. (2011) that considers the impacts of not only temperature and acidification, but also nutrients, and the over-fishing of herbivores that help control algal populations. This can expand our ability to forward-model community regime shifts under different nutrient and herbivory levels. Furthermore, in the future, findings from efforts to model the impacts of coral diseases and tropical cyclones can be incorporated into coral resilience models. This comprehensive, integrated approach can reveal whether certain regions are likely to be more resilient, and thus better targets for local mitigation efforts to curb pollution and improve water quality. Thermal stress has been linked to observed disease outbreaks (Brandt & McManus, 2009; Randall & van Woesik, 2015) and this association may intensify under future warming (Hoegh-Guldberg & Bruno, 2010). The intersection between climate change and disease will be an important feature to include in future risk assessment. Additionally, statistical downscaling tropical cyclone models (Emanuel et al., 2006; Lee et al., 2018) can be used to simulate synthetic storm tracks and intensities for a given region, using climate model output (e.g., CESM2) as a boundary condition (Camargo & Wing, 2016). While

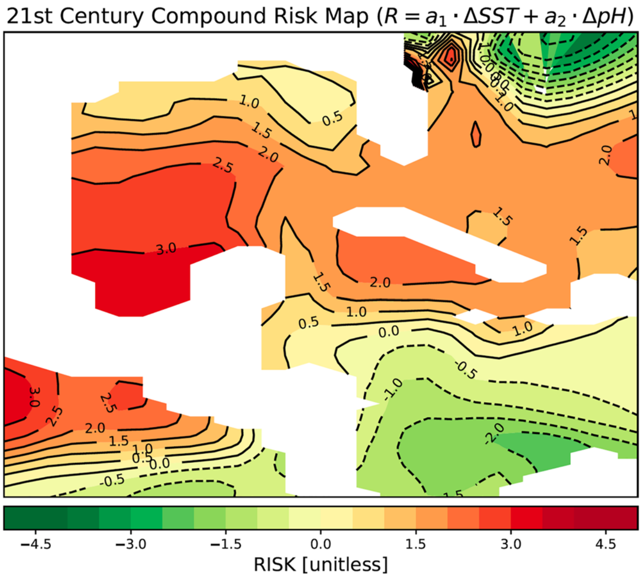

Figure 10. Proof-of-concept coral risk map. GoM and western Caribbean Sea risk calculated for CESM2 SSP3-7.0. Please see Section 4 for a description of the methods and an interpretation guide.

such modeling is outside the scope of work presented here, studies using such approaches to evaluate tropical cyclone response to climate change are ongoing (Garner et al., 2021; Wallace et al., 2021), and simulated storms forced with future SSTs could lend insight into future coral reef degradation.

To further characterize feedbacks between oceanic ecosystems and anthropogenic forcing, a natural next step for this research could incorporate laboratory and field-based derived calcification parameters (Cornwall et al., 2021) to create weighted regional risk maps for coral reef ecosystems that jointly consider multiple risk factors at once. As a preliminary, proof-of-concept, Figure 10 shows the regional risk (R) projected for the 21st century in CESM2-SSP3 as a function of SST and pH:

$$R = a_1 \cdot \Delta SST + -a_2 \cdot \Delta pH$$
$$R = (R - mean(R)) \cdot 100 \qquad (1)$$

In this simple risk calculation (Figure 10), total risk (R) is calculated as follows (and could readily be adapted):

- Standardize SST and pH from the climate model (Z-score)
- Compute the change in SST and pH, Δ SST and Δ pH, which are defined as the difference between the late (2091–2100) and early (2015–2024) 21st century (standardized units).
- Assign weights for Equation 1: In this case, we chose to ensure weights added up to 1, and more heavily weighted SST (0.7) compared to pH (0.3). The coefficient a_2 is negative since decreasing pH negatively impacts corals, whereas increasing SST negatively impacts corals. For simplicity, as a proof-of-concept, here we respectively use arbitrary weights of 0.7 and 0.3 for a_1 and a_2, but note that the coefficients a_1, and a_2 must be further refined and ultimately derived from in situ measurements (e.g., Cornwall et al., 2021).
- Risk (R) is calculated per Equation 1.
- To facilitate interpretation, we centered the data by removing the mean of R and multiplying by 100.

Thus, in Figure 10, higher numbers suggest a larger positive SST change (hotter) and a larger decrease in pH (more acidic). Red colors indicate higher risk, and green colors indicate less positive numbers and lower risk. The ability to combine additional stressors into such risk maps would enhance regional coral reef resilience planning globally, enabling a ranking system by severity to inform targeted mitigation. Such weighted coral reef risk maps that jointly consider temperature and acidification are sorely needed: reef organism responses are likely not stationary in time, since corals respond to thresholds and not trends. Unfortunately, at present, the data availability and in situ monitoring required to determine the weighting coefficients are extremely limited. Future work will require experimental tests to define these parameters and enable quantitative risk predictions.

Finally, this work underscores the need for past climate reconstructions from corals to contextualize modern and future warming in the GoM and the Caribbean Sea (see Tierney et al., 2015 for a review). These reconstructions of past coral responses to temperature changes provide critical retrospective views before the industrial revolution. Past warming trends allow us to test the sensitivity of existing corals to SST change. Existing and future work generating such SST reconstructions from corals could highlight past intervals of thermal stress during which corals survived to provide more robust statistics on SST bleaching thresholds and targets for assisted evolution.

5. Conclusions

This work synthesizes projections of coral reef risk factors, including temperature and ocean acidification in the GoM and the western Caribbean Sea, characterizing how each contributes to the decline of coral reefs. By ranking these stressors by region, we hope that this work will inform and streamline mitigation efforts to protect vulnerable coral reef ecosystems and the valuable benefits and resources they provide to local communities.

Collaborations between climate modelers, coral reef ecologists, and local stakeholders are rare in practice; we hope that our approach will engender a seamless integration of climate projections with GoM and Caribbean coral reef risk analysis. The results presented here constitute predictive regional risk assessments that rank stressors by severity to inform targeted mitigation for the coming decades.

Indeed, our results underscore existing and future climatic risks to GoM and western Caribbean Sea coral reefs which necessitate mitigation with profound economic consequences: coral reef-related expenditures generate more than $4.4 billion annually in southeast Florida alone, and coral reef recreation supports more than 70,000 jobs. Over-fishing, chemical pollution (e.g., oil spills and oil production by-products, pesticides), agricultural runoff, disease, invasive species, sedimentation, and unrestricted tourism have caused the once structurally complex coral reefs in the GoM and the Caribbean Sea to decline since the 1970s (Carricart-Ganivet et al., 2011; Gil-Agudelo et al., 2020; Holbrook et al., 2019; Horta-Puga et al., 2015; Jordán-Dahlgren & Rodríguez-Martínez, 2003; Schutte et al., 2010; Smale et al., 2019; Tunnell et al., 2007; Weerabaddana et al., 2021). We underscore that this work is a conservative approach in that it explores the impacts of temperature and acidification—two of various compounding risk factors—affecting reefs. Large and coordinated interdisciplinary efforts incorporating the impacts of hurricanes, disease, and pollution are needed to comprehensively delineate risks. We assert that, without substantial mitigation efforts, increasing ocean temperatures and acidification are likely to stress corals and increase bleaching events that will subsequently kill most existing corals in the GoM and the Caribbean by the end of the 21st century (Dee et al., 2019). Coral reef vulnerability and hazard assessments such as those presented here are a step toward *guiding intervention strategies* for coastal communities and ecosystems.

Data Availability Statement

The CESM1 and CESM2 climate model simulations used in this study are publicly available via the National Center for Atmospheric Research Earth System Grid: www.earthsystemgrid.org/. The stony coral sites are from the NOAA deep sea coral database: https://www.ncei.noaa.gov/maps/deep-sea-corals/mapSites.htm. The PyCO2SYS Python toolbox (Humphreys et al., 2022) for solving the marine carbonate system is available via Zenodo, https://doi.org/10.5281/zenodo.6560756.

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