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# Downscaled projections of Caribbean coral bleaching that can inform conservation planning

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## Abstract

Projections of climate change impacts on coral reefs produced at the coarse resolution (~1°) of Global Climate Models (GCMs) have informed debate but have not helped target local management actions. Here, projections of the onset of annual coral bleaching conditions in the Caribbean under Representative Concentration Pathway (RCP) 8.5 are produced using an ensemble of 33 Coupled Model Intercomparison Project phase-5 models and via dynamical and statistical downscaling. A high-resolution (~11 km) regional ocean model (MOM4.1) is used for the dynamical downscaling. For statistical downscaling, sea surface temperature (SST) means and annual cycles in all the GCMs are replaced with observed data from the ~4-km NOAA Pathfinder SST dataset. Spatial patterns in all three projections are broadly similar; the average year for the onset of annual severe bleaching is 2040–2043 for all projections. However, downscaled projections show many locations where the onset of annual severe bleaching (ASB) varies 10 or more years within a single GCM grid cell. Managers in locations where this applies (e.g., Florida, Turks and Caicos, Puerto Rico, and the Dominican Republic, among others) can identify locations that represent relative albeit temporary refugia. Both downscaled projections are different for the Bahamas compared to the GCM projections. The dynamically downscaled projections suggest an earlier onset of ASB linked to projected changes in regional currents, a feature not resolved in GCMs. This result demonstrates the value of dynamical downscaling for this application and means statistically downscaled projections have to be interpreted with caution. However, aside from west of Andros Island, the projections for the two types of downscaling are mostly aligned; projected onset of ASB is within ±10 years for 72% of the reef locations.

*Keywords:* climate change, climate model, coral reefs, dynamical downscaling, refugia, statistical downscaling

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## Introduction

The ocean components of the Coupled Model Intercomparison Project phase-5 (CMIP5) Global Climate Models (GCMs or 'climate models') used by the Intergovernmental Panel on Climate Change (IPCC) to publish their fifth assessment report have a coarse resolution (on the scale of 1°) (Frieler *et al.*, 2012; Taylor *et al.*, 2012). This is due to climate models being extremely computationally intensive and costly to run. This coarse resolution prevents climate models from resolving local-scale features that influence climate (Oey *et al.*, 2005; Karnauskas & Cohen, 2012). Climate model projections at ~1° resolution have informed discussions among policymakers at regional and global scales (Lemos & Rood, 2010) and have been used to lobby for legislation that would curb emissions (Stern, 2008). Projections at ~1° resolution are also effective education and outreach tools, raising awareness among stakeholders and the public of future regional-scale climate variability (Jylhä *et al.*, 2010). However, the on-ground management of land, coast, and ocean ecosystems always requires managers make decisions at the local scale (a few km or 10s of kms) (Palumbi, 2004; McLeod *et al.*, 2009). These decisions shape or restrict human–environment interactions to avoid user conflict and are increasingly made in the hope of mitigating impacts associated with climate change (Hughes *et al.*, 2003; Hoegh-Guldberg *et al.*, 2007). Informing decisions related to increasingly urgent local-scale actions means there is often value in producing downscaled climate model projections (Oreskes *et al.*, 2010). This study describes and compares projections of coral bleaching events for the Gulf of Mexico, Florida, and Caribbean using both statistical and dynamical downscaling.

Coral bleaching events are expected to increase in frequency and severity as the climate changes

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(Hoegh-Guldberg, 1999; Donner *et al.*, 2005; Hoegh-Guldberg *et al.*, 2007; Donner, 2009; van Hooidonk *et al.*, 2013, 2014). Stony corals bleach when warm sea temperatures disrupt their mutualistic relationship with algal symbionts, called zooxanthellae, which reside within coral tissue (Douglas, 2003). With the colorful algae expelled, the limestone coral skeleton can be seen through transparent tissue. Corals can either regain their zooxanthellae and survive (Baker, 2001) or die if temperature stress persists. The most severe bleaching event ever recorded in the Caribbean occurred in 2005 due to high ocean temperatures in the tropical Atlantic and Caribbean Sea. During this event, 80% of corals by area were affected by bleaching and 40% died at many locations across 22 countries (Eakin *et al.*, 2010). Coral reefs provide numerous goods and services such as coastal protection and can be critically important to livelihoods. As an example, in 2010, the tourism industry supplied 12.8% or US$39.4 billion of the Caribbean's gross domestic product (World Travel & Tourism Council (WTTC), 2010). Further loss of corals on Caribbean reefs due to bleaching can directly impact both food security and island economies (Trotman *et al.*, 2009).

Spatial variation in the extent and severity of coral bleaching can be predicted in near real time by determining whether empirically derived temperature stress thresholds strongly correlated to bleaching have been exceeded (van Hooidonk & Huber, 2009). The common metric used for predicting spatial variation in coral bleaching severity due to temperature stress is degree heating weeks (DHWs) (Gleeson & Strong, 1995). DHW represent the accumulation of temperature stress above long-term averages for the warmest month; 1 degree above the long-term average for the warmest month in a climatology for 1 week equals 1 DHW. 6.1 DHW is the global optimum predictor of bleaching presence (van Hooidonk & Huber, 2009), and eight DHW is known to cause severe bleaching and mortality (Donner *et al.*, 2005; Eakin *et al.*, 2010; Frieler *et al.*, 2012). These uniform thresholds have practical application but do not account for species-specific thresholds or any possible adaptation or acclimatization of the corals (Logan *et al.*, 2014).

Global projections of bleaching conditions and ocean acidification (OA) using the CMIP5 models were made publicly accessible in an interactive format in late 2013 for all four Representative Concentration Pathways (RCP, see Moss *et al.*, 2010; van Hooidonk *et al.*, 2014). However, at the resolution of the GCMs, there is great spatial variation (30+ years) across the globe in the projected timing of the onset of annual bleaching conditions. This suggests that resolving this variation at higher resolution through downscaling will enable managers to identify relative refugia and undertake more informed conservation planning. Climate model projections can be downscaled either dynamically or statistically. With dynamical downscaling, outputs from various GCMs are used to drive a regional numerical model in higher spatial resolution, enabling local conditions to be simulated in greater detail (Liu *et al.*, 2012; Sun *et al.*, 2012). Dynamical downscaling is frequently used to produce projections of local-scale variation in variables such as temperature and precipitation (Maraun *et al.*, 2010; Paeth *et al.*, 2011). We use the GFDL Modular Ocean Model version 4.1 (MOM4.1) here. MOM4.1 is available for the Gulf of Mexico and wider Caribbean following multiple years of investment of effort in bias correction and to establish initial and boundary conditions (Liu *et al.*, 2015). The downscaled projection is of sea surface temperature (SST), which we assess with respect to the likelihood of severe bleaching events by calculating accumulated DHW for each year through 2100.

For the statistical downscaling presented here, high-resolution (4 km) observations of SST are used to adjust the CMIP5 model baseline to present-day values before the projections are run. Most previous projections (pre-2013) of the timing of the onset of annual severe bleaching have not adjusted the annual cycle of the GCMs to observed values (Sheppard, 2003; Sheppard & Rioja-Nieto, 2005), which can severely over- or underestimate the onset of annual bleaching (van Hooidonk & Huber, 2012). Although the spatial patterns of monthly climatological sea surface temperatures (SST) are well represented by the current generation of GCMs at coarser scales; the skill is often reduced during the warmest months (Kwiatkowski *et al.*, 2014). Overall, at reef locations in the Caribbean, the current CMIP5 models show a cold bias (Wang *et al.*, 2014). To account for these biases, the annual cycle was corrected in the most up-to-date climate projections of coral bleaching conditions (van Hooidonk *et al.*, 2013, 2014). For those projections (van Hooidonk *et al.*, 2014), the model mean and annual cycles for SST were replaced with observed data, but the observed SST data used have the same coarse resolution as the GCMs (dataset: OISST V2, see also Oey *et al.*, 2005; Liu *et al.*, 2012; Lauer *et al.*, 2013). This reduces computational intensiveness but means known high local-scale variation in SST is smoothed and hidden. For the statistical downscaling approach used here, the observed baseline mean present-day SST and the annual cycles are used from the high-resolution (4 km) Pathfinder SST climatology.

We present projections as maps and histograms for the GCMs at model resolution and for both the dynamical and statistical downscaling approaches. Spatial patterns in the relative timing of the projected onset of annual severe bleaching are compared among all three types of projections (i.e., CMIP5, and dynamical and statistical downscaling approaches). The primary study objective was to inform a discussion about the merits of both dynamical and statistical downscaling for this application and demonstrate the need for downscaled projections of climate change impacts for other reef regions. The secondary objective was to assess whether and for which locations there is sufficient local-scale spatial variation in the downscaled projections to inform conservation planning.

## Materials and methods

SST data from GCMs were obtained from the CMIP5 (http://pcmdi9.llnl.gov/esgf-web-fe/) for the RCP8.5 experiment (Moss *et al*., 2010; Riahi *et al*., 2011). Currently, and as in all of the past generations of scenarios used in IPCC reports, emission concentrations are tracking above the projected concentrations of the worst-case scenario (Peters *et al*., 2012). RCP8.5 is used here as this scenario has the highest emission concentrations and growth rates and best characterizes current conditions. Model outputs from 33 GCMs (see Table S1) were adjusted by substituting the 2006–2011 model mean with the observed mean from 1982 to 2008 from the Pathfinder v5.0 climatology (Casey *et al*., 2010) (see Table S1 for list of models). The 1982–2008 Pathfinder climatology is used for four reasons: (1) 2006–2011 is too short a period to calculate a climatology, (2) it has been found to have low bias and standard deviation in comparison with other observational datasets (Kara *et al*., 2008), (3) it includes a sophisticated harmonic analysis of the AVHRR Pathfinder versions 5.0 and 5.1 day time and night-time SST, and (4) another possible option for a climatology, the NOAA CRW 1985–1993 climatology (excludes 1990 and 1991), has too coarse a resolution (0.5°). The 1982–2008 period is slightly cooler than the 2006–2011 period. This makes our projections slightly conservative or 'optimistic'; the bleaching conditions we project could occur slightly earlier than the projected date.

For the GCM-resolution (1°) projections ($n$ = 176 cells), the annual cycle was replaced with the annual cycle from the Pathfinder climatology following bilinear interpolation of the Pathfinder to the GCM grid. To produce a statistically downscaled output, the model annual cycle was replaced with the observed annual cycle from the Pathfinder data (Sheppard, 2003; Sheppard & Rioja-Nieto, 2005), after interpolating both the Pathfinder and GCM data to the grid for the model used for dynamical downscaling using bilinear interpolation (see next section). Where model outputs were missing due to a land mask, SSTs were interpolated in the zonal direction. Degree heating months were calculated in the projections as anomalies above the warmest monthly temperature (the maximum monthly mean or MMM) from the Pathfinder climatology (Casey *et al*., 2010) and were summed for each 3-month period. An alternative to MMM is the mean of the maximum monthly SST from each year in the time period of the climatology (MMMmax), a metric that represents the maximum climatological temperature better in locations where the warmest month changes from year to year (Donner, 2011). Here, the MMM is used instead of the MMMmax for three reasons. (1) DHW calculated from the MMM baseline outperform DHW calculated from MMMmax in a global analysis presented in Donner (2011). (2) MMM and MMMmax differ most for areas within 5–8° from the equator where low seasonal variability results in higher differences between MMM and MMMmax (our study area is >10°N). (3) Using MMM ensures the downscaled projections presented here are compared to the GCM-resolution projections for coral reef areas made publicly accessible with van Hooidonk *et al.* (2014). The sigma-based variability method of Donner (2011) is not used because this results in alert levels (bleaching thresholds) of 2.5 DHWs for bleaching and ~5 DHWs for severe bleaching. 2.5 DHWs are occurring annually everywhere now, which we know to be false so cannot be used to project future bleaching conditions. Degree heating months are converted into DHW by multiplying by 4.35 (see also Donner 2005 and van Hooidonk *et al*., 2013, 2014). The onset of annual severe coral bleaching (referred to from here as ASB) is defined as the annual exceedance of >8 DHW accumulating during any 3-month period (as in van Hooidonk *et al*., 2014). The onset of annual bleaching conditions is defined as the annual exceedance of >6 DHW accumulating during any 3-month period. Thresholds are used here that are higher than the mean optimum predictor of 5.1 DHW for the Caribbean (van Hooidonk & Huber, 2009) because at 6 and 8 DHW species-specific differences in susceptibility and adaptive capacity will matter less and we can have confidence thermal stress is sufficiently great for bleaching to occur.

The Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model version 4.1 (MOM4.1; Griffies *et al*., 2004) is used for the dynamical downscaling presented in this study. The high-resolution, fully eddy-resolving MOM4.1 has a horizontal resolution of 0.13 × 0.1 (~11 km, 3781 model cells with coral reefs) in the study region and was forced with an ensemble of 18 weighted GCMs (see Table S1). Biases in the surface forcing fields were corrected by computing the difference between the observed surface forcing climatology and the climatology from the weighted ensemble of CMIP5 models. The difference (the bias-correction term) is added to the CMIP5 surface forcing fields for the period of 1900–2098. The initial and boundary conditions for the temperature and salinity are also bias-corrected following the same methodology used for the surface forcing fields. For more details on surface forcing, bias correction, and initial condition setting for MOM4.1, see the electronic supplementary material and Liu *et al.* (2015). MOM4.1 was run in hindcast mode for 1900–2005 and produced SST anomalies that very closely track the HadISST dataset (see Liu *et al*., 2015, and Fig. S1). The MOM4.1 outputs were adjusted by changing the 2006–2011 model mean to observed values from the 1982–2008 Pathfinder v5.0 climatology, after interpolating Pathfinder to the MOM4.1 grid using bilinear interpolation. A pseudo-ensemble of the MOM4.1 was made because the 33-member GCM ensemble mean has less interannual variability than any one model member used in

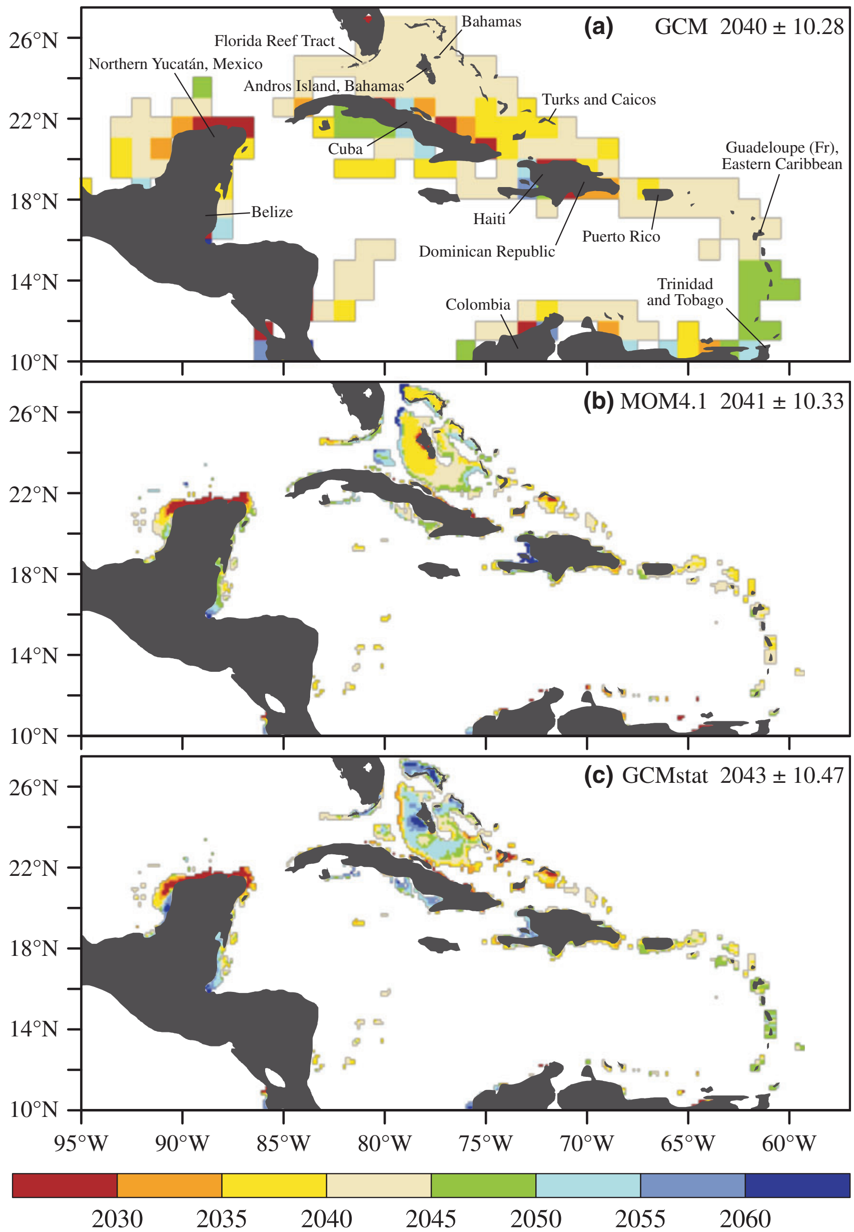


**Fig. 1** Projected timing in the onset of annual severe bleaching (>8 DHW) in years for: (a) the ensemble of Global Climate Models (GCMs, see Table S1 for list) at model resolution (1° × 1°), (b) dynamical downscaling through using GCM outputs to force the GFDL Modular Ocean Model (MOM4.1, ~0.1° resolution), and (c) statistically downscaling GCM outputs by replacing the model mean and annual cycle for SST with observed data from 1982 to 2008 re-gridded to the scale of MOM4.1. For each plot, mean year is shown ±1 standard deviation.

the 18-member ensemble used to force MOM4.1, or the single output of MOM4.1. To create pseudo-ensemble members, the quadratic trend and annual cycle of the mean-corrected MOM4.1 output were removed and all remaining monthly anomalies were randomized 33 times. The observed seasonal cycle from Pathfinder v5.0 data was then added to these 33 time series and the quadratic trend was re-inserted. To identify the onset of ASB, ensemble mean DHW values were calculated for each year by averaging the DHW value from all ensemble members. The mean, trend, and variation in projected DHW counts for each year were plotted for the GCM and MOM4.1 ensembles to ensure projections can be meaningfully compared (see Fig. S2).

All model outputs were reduced to a subset of only reef locations obtained from the coral reef distribution layer from UNEP-WCMC (http://www.unep-wcmc.org), generated using the validated Millennium Coral reef Mapping Project (MCRMP) data (Andréfouët *et al.*, 2006). The three types of

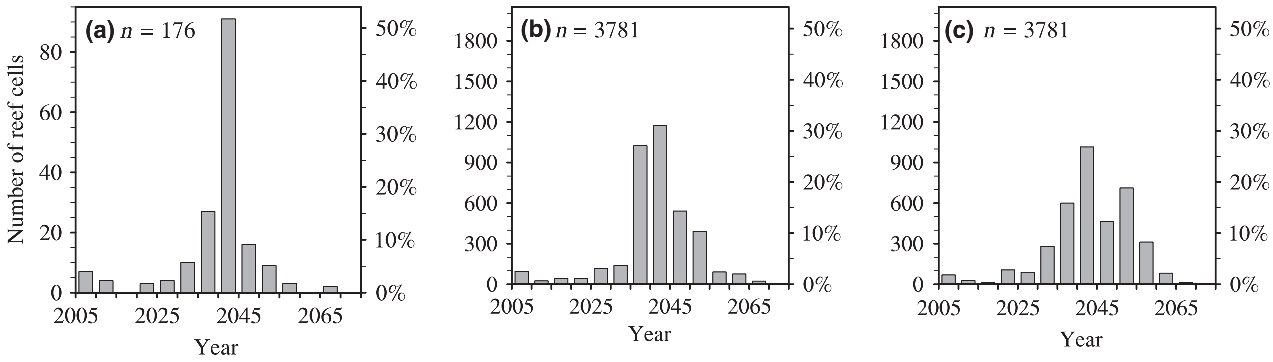


**Fig. 2** Histograms showing the distribution of the data presented within Fig. 1 (labels here and in Fig. 1 match, (a) GCM, (b) MOM4.1, and (c) GCMstat); values for number and percent of reef locations (grid cells) are shown in Table S2.

projections (GCM ensemble, and dynamical and statistical downscaling) are shown as maps of the year of onset of 6 and 8 DHW conditions and are presented with complementary histograms. Differences in the timing of the onset of annual severe bleaching (8 DHW) are expressed in years and calculated for each grid cell by: (1) subtracting the dynamical downscaling output year from the output year from the GCMs, (2) subtracting the statistical downscaling output year from the projected year from the GCMs, and (3) subtracting the dynamical downscaling output year from the statistical downscaling output year. Differences in the projected timing of annual bleaching (6 DHW) and severe bleaching (8 DHW) conditions are compared using scatter plots and linear regression. The average difference in the projected timing for the two bleaching conditions and the standard deviation are calculated for each projection type. GCM cells are identified within which the dynamical or statistical downscaling results for the timing of ASB have a range of 10–15, or >15 years. These thresholds, 10 and 15 years, are suggested to aid in identifying where the range of model projections is sufficiently great to inform conservation planning. These thresholds are greater than the region-wide standard deviation of the GCM runs for statistical downscaling (10.47 years).

All interpolation was performed using Climate Data Operators, a software package available from: https://code.zmaw.de/projects/cdo/. All model output adjustment, projections, data visualization, and analysis were conducted using the NCAR Command Language (NCL; http://www.ncl.ucar.edu/).

## Results

For the projections produced using the GCM ensemble (Fig. 1a), the onset of ASB occurs before 2030 for 7.95% of reef locations (Fig. 2a). These locations are in the northern Yucatan, northeastern Cuba, parts of the northern and southern Dominican Republic, and northern Colombia (Fig. 1a). Annual severe bleaching is projected to occur after 2050 for another 7.95% of reef locations. These locations are in Belize, Haiti, Trinidad, and Tobago and parts of northern and southern Cuba. The average year for the onset of ASB projected using the GCM ensemble mean is 2040 $\pm$ 10.28 (Fig. 1a). Greater than 75% (76.14) of reef locations have a projected timing for the onset of ASB between 2035 and 2050 (Fig. 2a).

The average year for the onset of ASB projected using dynamical downscaling is 2041 $\pm$ 10.33 (Fig. 1b). As is the case for the GCM ensemble, >70% (72.41) of reef locations have a projected timing for the onset of ASB between 2035 and 2050 (Fig. 2b). Just over 15% (15.39) of reef locations are projected to experience ASB after 2050 for the dynamical downscaling, roughly twice that seen for the GCM ensemble projections (7.95%, Fig. 2a). The projected timing in the onset of ASB from dynamical downscaling is within 5 years of the projection from the GCM ensemble for 50.54% of reef locations ($n$ = 3781). 21.21% of reef locations are projected to experience ASB >5 years earlier in the dynamically downscaled projections and 28.25% >5 years later (Fig. 4a).

The projections produced using dynamical downscaling (via MOM4.1), shown in Fig. 1b, have many similar spatial patterns at the regional scale as those produced with the GCM ensemble (Fig. 1a, b). Differences in the projected timing of the onset of ASB between the dynamical downscaling and the GCM ensemble are shown in numbers of years in Fig. 3a. Negative and positive values mean that the downscaled projection of ASB occurs sooner and later in the dynamical downscaling, respectively. Differences in the projected timing of the onset of ASB averaged over the entire region are <1 year (0.52 $\pm$ 9.52; Fig. 3a) for the 3781 reef locations in the study region (at MOM4.1 resolution of ~11 km). Timing in the onset of ASB is projected for the northern Yucatan before 2030, for Haiti after 2055, and between 2040 and 2050 for the eastern Caribbean in both the GCM and dynamically downscaled projections (Fig. 1b). However, there is also major local-scale variation (>20 years in some

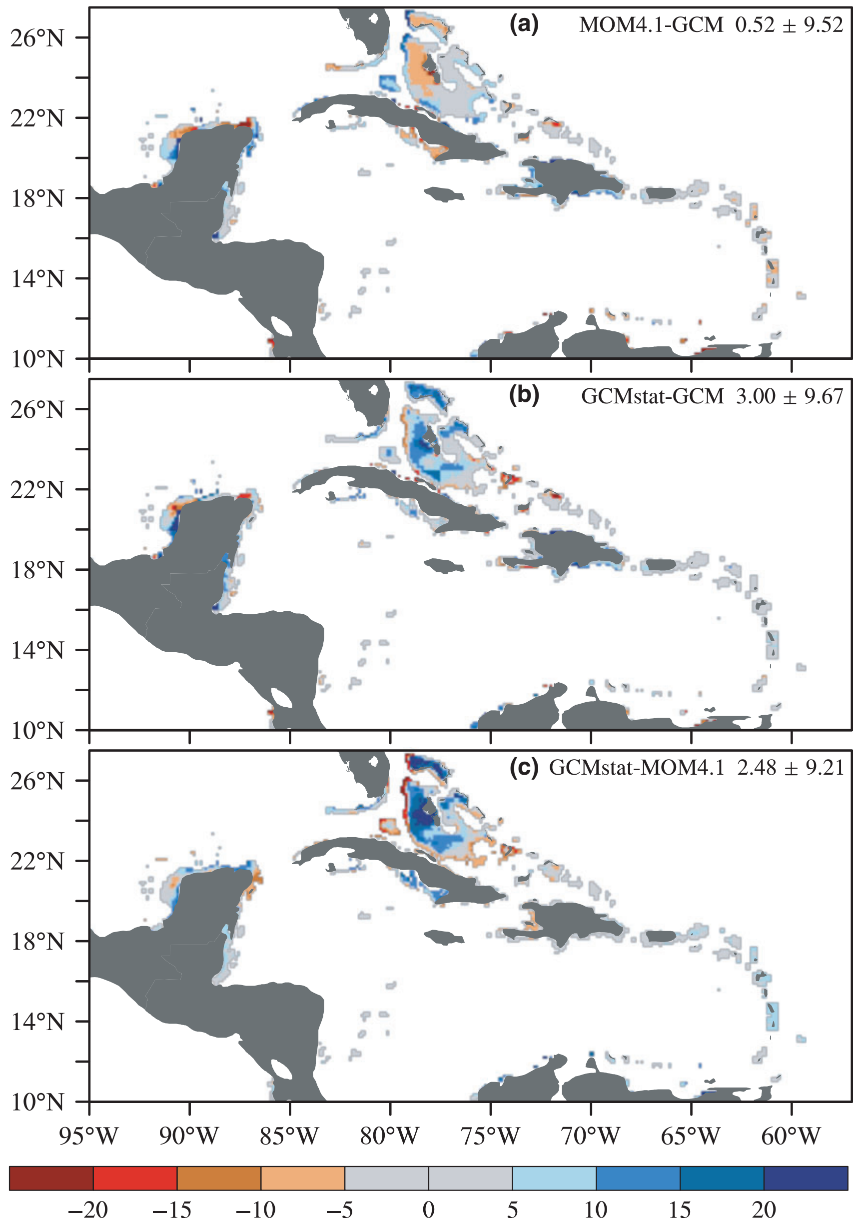


**Fig. 3** Differences in the projected timing in years of the onset of annual severe bleaching between (a) the dynamical downscaling using GFDL's Modular Ocean Model (MOM4.1) and the year projected by the ensemble of GCMs, (b) the statistical downscaling of the GCM outputs and the year projected by the ensemble of GCMs, and (c) the statistical downscaling of the GCM outputs and dynamical downscaling using MOM4.1. For each plot, the mean difference is shown ±1 standard deviation.

cases) in the projected timing of the onset of ASB (Fig. 1b) within what are single grid cells (1° × 1°) in the GCM ensemble projections. The differences are >5 years for parts of the west Yucatan, the Dominican Republic, southern Cuba, Turks and Caicos, Andros Island and for the greater Bahamas and Florida Reef Tract (Fig. 3a).

There is 25+ years variation in the projected timing of the onset of ASB for reefs near Andros Island and in the greater Bahamas area in the dynamical downscaling (Fig. 5b). Specifically, reefs near the west coast of Andros Island are projected to experience ASB before 2030 and reefs far offshore of west Andros after 2055. The projected timing for the onset of ASB from the GCM ensemble is 2040 for this entire area (Fig. 1a; Fig. 5a). There is also 20+ years of variation within the Florida Reef Tract (FRT) in projected timing for the onset of ASB (Fig. 5b). Reef locations in the western FRT are projected to experience ASB ~20 years sooner (late 2020s in the dynamical downscaling vs. early 2040s in

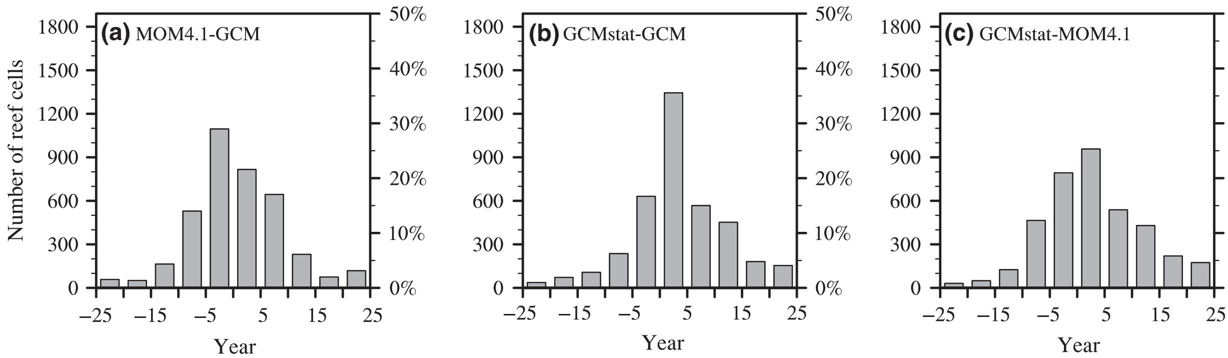


**Fig. 4** Histograms showing the distribution of the data presented within Fig. 3 (labels here and in Fig. 3 match, (a) MOM4.1-GCM, (b) GCMstat-GCM, (c) GCMstat-MOM4.1); values for number and percent of reef locations (grid cells) are shown in Table S3.

the GCM ensemble projections). In contrast, reefs in the eastern FRT are projected to experience ASB 10+ years later (early 2050s vs. early 2040s in the GCM ensemble projections).

The spatial patterns in the projected timing of ASB produced using statistical downscaling of the GCM ensemble output nearly exactly match those produced using dynamical downscaling (Fig. 1b, c; Fig. 3c); the only exceptions being the FRT and Bahamas (Fig. 2b, c). The statistically downscaled projections do not suggest that the western FRT will experience ASB 10+ years sooner than the GCM ensemble projects, as is the case for the dynamical downscaling (Fig. 3b, c). However, both the statistically and dynamically downscaled projections suggest the eastern FRT will experience ASB 10+ years later than the GCM ensemble projects. The dynamical and statistical downscaling produced contrasting results for the large reef area off the west coast of Andros Island in the Bahamas. The statistically downscaled projections suggest that reefs along the coast will experience ASB in the late 2040s and early 2050s (dynamical downscaling – late 2020s and early 2030s) and that the offshore areas to the west will experience ASB 20+ years earlier than those near the coast in the 2030s (dynamical downscaling – late 2040s and early 2050s, see Fig. 5b, c). The average year for the onset of ASB projected using statistical downscaling is 2043 $\pm$ 10.47. The projected timing in the onset of ASB from statistical downscaling is within 5 years of the projection from the GCM ensemble for 52.23% of reef locations ($n = 3781$) and is within 10 years of the projection using dynamical downscaling for (72% of reef locations, Figs. 3c, 4c). Statistical downscaling projects ASB >10 years earlier than dynamical downscaling for 5% of reef locations and >10 years later for 21% of locations, nearly all of which are west of Andros Island (Fig. 3c).

There are almost no differences in the spatial variation in projections for annual bleaching (6 DHW, Figs S3, S4) and severe bleaching (8 DHW, Fig. 1). Plots comparing the projected timing of bleaching vs. severe bleaching conditions are shown in Fig. S5 with $R^2$ values equal to or exceeding 0.95 in all three cases. Projected spatial variation does not differ between the thresholds for any of the projection types, but the timing does shift. The average difference in the projected timing for annual bleaching conditions is 6 years earlier than annual severe bleaching conditions for all three projection types (SD values, GCM – 2.15, MOM4.1 – 1.58, GCMstat – 2.13).

The range for projections of the onset of annual severe bleaching conditions within GCM cells is <10 years for ~50% of the GCM cells for both downscaling approaches (Fig. 6). For the dynamical downscaling, 15% of the GCM cells have a range for the downscaled output for ASB of 10–15 years, and 29% have a range of >15 years. Similarly, for the statistical downscaling, 13% of the GCM cells have a range for the downscaled output for ASB of 10–15 years, and 38% have a range of >15 years. Locations where the projected range exceeds 15 years for both downscaling approaches (western Bahamas excluded) include the Yucatan Peninsula, Belize, Cuba, Puerto Rico, and northern Brazil (Fig. 6).

## Discussion

Looking region-wide, the downscaled projections describe a future for Caribbean coral reefs with respect to exposure to bleaching conditions that is broadly similar to what is projected by the GCM ensembles. As examples of this, there are similarities in the spatial variation in the timing of the onset of ASB among the three types of projections, and there are similarities in the mean year for the onset of ASB, which is within 2 years of 2041. Further, the standard deviation around all three means is very nearly the same, ranging from 10.28 to 10.47 years. For all projection types, all reef

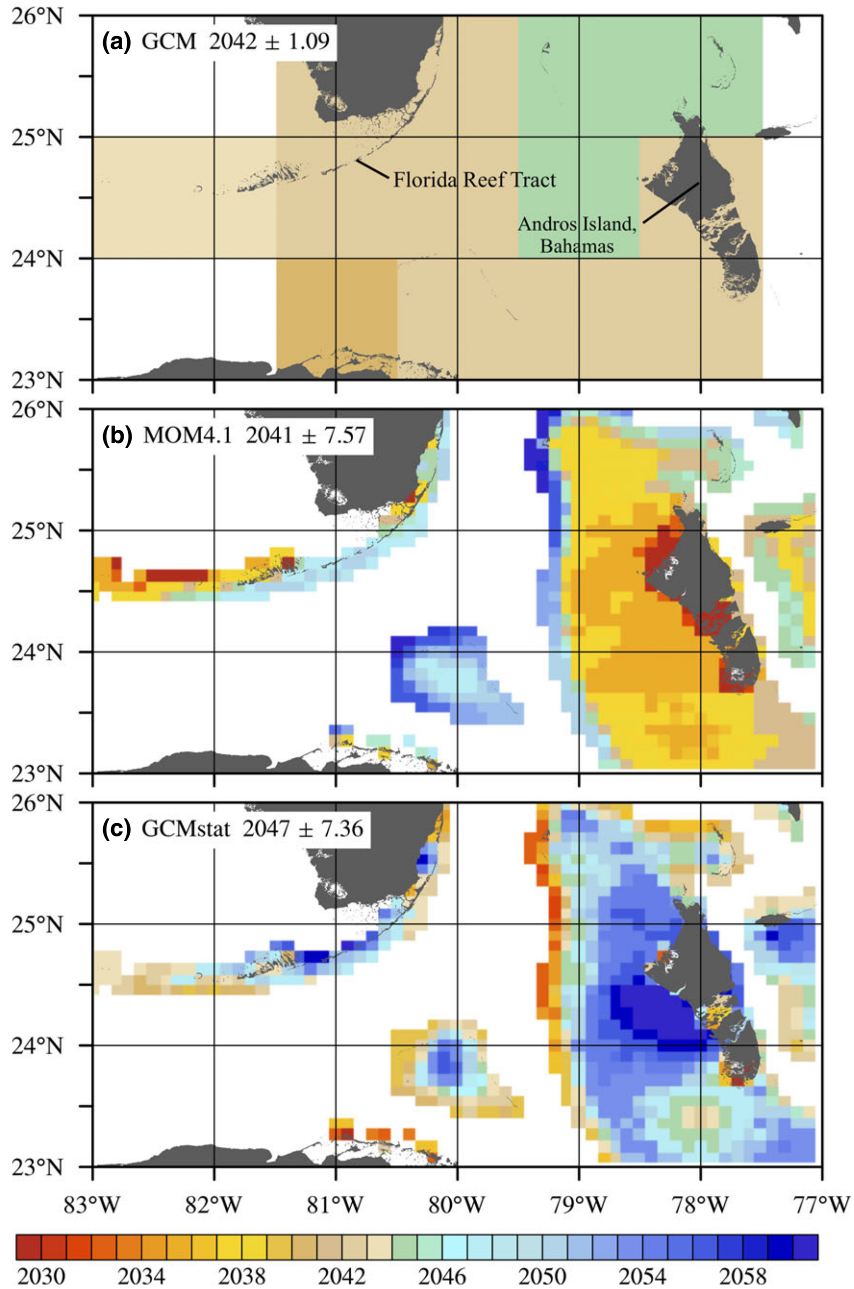


**Fig. 5** Projected timing in years of the onset of annual severe bleaching (>8 DHW) for the Florida Reef Tract and the Bahamas for: (a) the ensemble of Global Climate Models (GCMs, see Table S1 for list) at GCM-resolution (~1°), (b) dynamical downscaling through using GCM outputs to force the GFDL Modular Ocean Model (MOM4.1, ~0.1° or ~11 km resolution), and (c) statistically downscaling GCM outputs by replacing the model mean and annual cycle for SST with observed data from 1982 to 2008. For each plot, mean year is shown ±1 standard deviation.

locations are projected to experience ASB by the early 2070s and half or more of the locations are projected to experience ASB by the mid-2050s. Such general similarities are expected given GCM model outputs are the inputs for both approaches to downscaling. Nevertheless, the general similarities among the three projection types increase confidence that the projections can be meaningfully compared. Broad similarities aside, the downscaled projections show high local-scale variation in the timing of the onset of ASB within what are single GCM grid cells. There is also a high level of agreement between the projections produced with dynamical and statistical downscaling for the great majority of the study region.

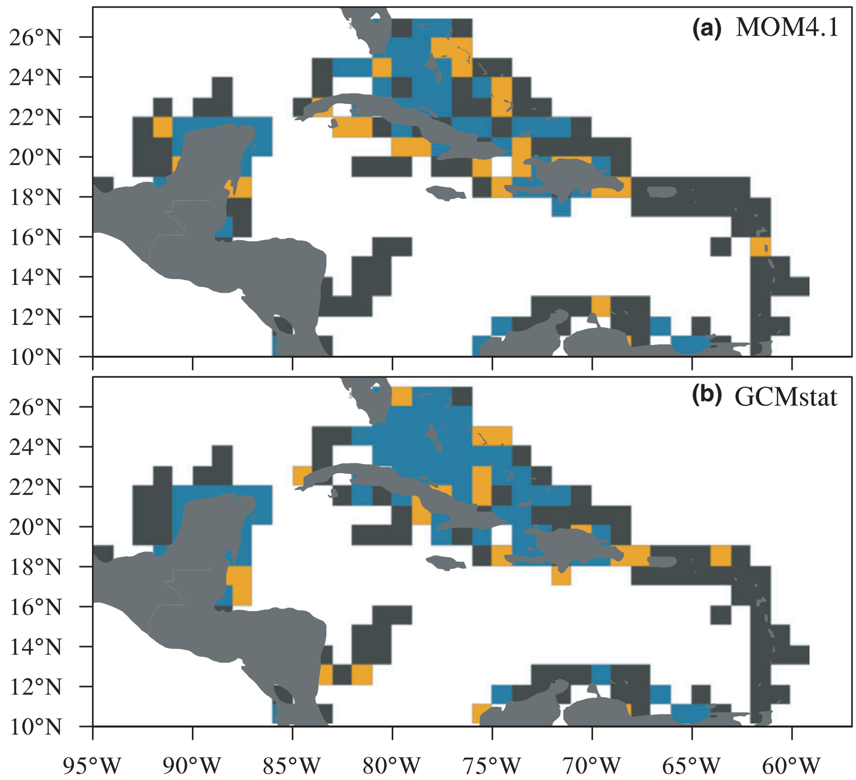


**Fig. 6** Projected range in the onset of annual severe bleaching (>8 DHW) conditions within GCM cells for both downscaling approaches. Dark gray, orange, and blue correspond to a range <10, 10–15, and >15 years, respectively. Percentages are as follows: MOM4.1 (0–10 years – 56%, 10–15 years – 15%, >15 – 29%); GCMstat (0–10 years – 49%, 10–15 – 13%, >15 years – 38%).

When the shallow lagoon west of Andros Island is excluded, the projected year for the onset of ASB from statistical downscaling is within ±10 years of the projected year from dynamical downscaling for 90% of reef locations. The benefit of dynamical downscaling using a regional ocean model (e.g., Karnauskas & Cohen, 2012; Liu *et al.*, 2012, 2015) is that we can better resolve features that greatly influence the warming that leads to thermal coral bleaching. Examples of these features that relate to local-scale hydrodynamics include horizontal transport and entrainment, upwelling, wind-driven mixing, eddies, and the influence of shallow bathymetry on any of the listed variables (Skirving *et al.*, 2006). Several of these features apply in the large (~30 000+ km$^2$) shallow area west of Andros Island where the spatial patterns in the projected timing of the onset of ASB are very different (see Fig. 5b, c) for the two types of downscaled projections. The dynamical downscaling projects an earlier onset of ASB for the shallow region west of Andros Island than the statistically downscaled projections. The projected enhanced warming in this shallow region in the dynamically downscaled projections is directly affected by the projected changes in the regional current systems. MOM4.1 projects a weakening of the Loop Current, which brings warm water from along the eastern part of the Yucatan Peninsula up into the Gulf of Mexico and then south and east through the Florida Straights (between Florida and Cuba, Liu *et al.*, 2015). MOM4.1 projects the Loop Current will slow just west of Andros Island, which will probably result in warm water pooling during summer months. An additional explanation for the early onset of ASB west of Andros in the dynamical but not statistical downscaling is that the shallow bathymetry in the area prevents vertical mixing, which may not be resolved in all GCMs (see Liu *et al.*, 2015).

The statistical downscaling of the GCM ensemble outputs does not resolve local-scale features such as the eddies required to properly represent the Loop Current (Oey *et al.*, 2005). Therefore, the statistically downscaled projection of ASB for west Andros is 15+ years later than is seen in the dynamically downscaled projections. However, if we combine all local-scale decision-making capacity across the study region, we can use the level of agreement between the dynamical and statistical downscaling as a proxy for the value of dynamical downscaling region-wide for projecting bleaching conditions. Viewed this way, dynamical downscaling would be seen as critical for Andros

 

Island but low value region-wide, given 90% of the cells (excluding Andros Island) in the dynamical and statistical downscaling projections vary by <10 years. This point is critically important in establishing the merit and utility of applying statistical downscaling globally to the projection of bleaching conditions. Dynamical downscaling requires highly specialized expertise and is extremely time-intensive and expensive. For these reasons, dynamical downscaling is unlikely to be feasible within the coming few years for most reef regions. The benefit of statistical downscaling in contrast is that it is inexpensive, is possible now for all reef locations, and can be undertaken at an even higher resolution than shown in Fig. 1c and 3c. We interpolated the Pathfinder SST climatology used to replace the mean and annual cycle in the GCMs from 4 km to the MOM4.1 grid (0.13° × 0.1°, ~11-km). Future statistical downscaling of GCM ensemble outputs to project bleaching conditions could be produced at 4 km resolution with the same approach used here.

Using the downscaled projections, we identified GCM cells within which the dynamical and statistical downscaling projections for timing of the onset of ASB are >10 years. At all of these locations, local managers can use the downscaled projections to identify relative refugia (orange and blue in Fig. 6). These refugia are reefs projected to experience severe thermal stress annually later than other locations within the same management area. Knowing projected local-scale variation in exposure to bleaching conditions can inform management decision-making in two interrelated ways. Firstly, managers may choose to target actions to reefs likely to have earlier exposure to bleaching conditions to help mitigate impacts and support recovery. Such actions include reducing anthropogenic stressors such as land-based sources of pollution, herbivore fishing, and other extractive practices and anchoring. Managers may also target actions to sites likely to have later exposure to bleaching conditions (the relative refugia) as these reefs may be able to provide ecosystem goods and services longer than the locations with earlier exposure to bleaching conditions and may be optimal coral nursery locations. Managers can also target actions to both kinds of sites (see Salm *et al.*, 2006; McLeod *et al.*, 2009). Secondly, managers can use downscaled projections as education and outreach tools. Increased awareness of projected local-scale variation in exposure to bleaching conditions may galvanize people into action. Increased awareness may also increase environmental stewardship, raising support for and compliance with the actions described above that shape or restrict resource use.

At the time of publication, only one other published study has employed dynamical downscaling to produce projections of climate change impacts or ocean acidification in coral reef areas. Karnauskas & Cohen (2012) use an eddy-resolving regional ocean circulation model to show that warming declines around some Pacific islands due to enhanced upwelling associated with a strengthening of the equatorial undercurrent. This result is analogous to that shown here for Andros Island but is the opposite finding. Karnauskas & Cohen (2012) provide an example of dynamical downscaling revealing locations likely to experience less thermal stress than the GCM ensembles suggest. Our example from Andros Island identified a location likely to experience more thermal stress than the GCM ensembles suggest.

Statistical downscaling has been used to refine previous generations of GCMs to project coral bleaching at select sites, but the resolutions of the downscaled projections were 36 km or in the range of 1–2° (Sheppard, 2003; Donner *et al.*, 2005; Sheppard & Rioja-Nieto, 2005; Hoeke *et al.*, 2011). Donner *et al.* (2005) undertake statistical downscaling to produce projections of bleaching using the UK Meteorological Office HadCM3 model and National Center for Atmospheric Research PCM1 model. These authors project biennial bleaching (~4.35 DHW threshold) for 95–98% of reefs by 2050–2059 under the SRES A2 scenario. In contrast, this and related previous studies (van Hooidonk *et al.*, 2013, 2014) use the current generation of models (CMIP5) and the new RCP emission scenarios and project annual severe bleaching conditions (8 DHW) under RCP8.5 for >90% of reef locations by 2060 (van Hooidonk *et al.*, 2014). There are a number of reasons why the current projections vary so markedly from those presented by Donner *et al.* (2005). PCM1 is among the models with lowest sensitivity; for a doubling of CO2, the projected temperature increase is only 1.5 °C. The CMIP5 models resolve climate processes in greater detail and with greater accuracy than previous generations of climate models, and a model ensemble is used here to develop summary projections rather than individual models. Lastly, RCP8.5 is a more emission-intensive scenario than SRES A2.

This study is the first to use statistical downscaling to produce projections of climate-related threats to coral reefs from a model ensemble and on a scale of <20 km. We make the case that statistical downscaling of GCM ensemble projections of coral bleaching conditions is critical future work for all of the world's coral reef locations. Statistically downscaled SST projections can also potentially be used to produce high-resolution projections of shifts in aragonite saturation state due to ocean acidification. However, the results from dynamical downscaling presented by Karnauskas & Cohen (2012) and presented here for Andros Island indicate why statistically downscaled projections would need to be interpreted with caution in some regions. Statistically downscaled projections will have higher uncertainty in locations where climate change is expected to affect dynamically changing properties of currents and/or affect other features that influence warming.

There are a number of caveats and assumptions that relate to the use of climate models to produce projections of environmental conditions (see review in van Hooidonk *et al.*, 2013). These are characteristic of all studies using climate models and ensembles of models to project future conditions in coral reef areas or elsewhere and cannot be completely overcome. However, some sources of uncertainty in GCM ensemble projections at average global model resolution ($1° \times 1°$) can be reduced. A key concern with the coarse resolution projections is that models describe surface and deep waters only and thus do not resolve near-reef and near-coastal processes that can influence sea temperatures. Here, we reduce the uncertainty this causes in different ways for each of the downscaling approaches used. In the dynamical downscaling, MOM4.1 resolves processes such as eddies and eddy shedding needed to describe the western boundary currents in the region. At the resolution of the GCM ensemble members, eddies or the Loop Current cannot be resolved (Liu *et al.*, 2012, 2015). These processes influence transport of heat throughout the region and thus are important in projecting bleaching conditions. Here, we use the ensemble mean from the CMIP5 models to drive the downscaled MOM4.1 simulations, which may reduce the internal variability within the individual models. Therefore, this work can also benefit from performing more downscaled MOM4.1 simulations forced by one (or more) of the individual models, especially by choosing the model or models with the greatest weights (see Table S1) to estimate the range of temperature variability within the 21st century. In the statistical downscaling, the high-resolution (4-km) SST observations from 1982 to 2008 replace the SST means and annual cycles in the GCMs, grounding them in the reality of past conditions at the local scale. An implication of using the 1982–2008 climatology, rather than a climatology inclusive of even more recent years, is that the projections presented here are slightly optimistic. Substituting SST means and annual cycles in the GCMs with slightly higher values (for some locations) would result in an even earlier onset of the bleaching and severe bleaching conditions than is shown here. Knutti & Sedláček (2013) review robustness and uncertainties in the new CMIP5 climate model projections (used here). These authors explain that the climate models are improving and representing more climate processes in greater detail and that the *'uncertainties should not stop decisions being made'*.

A 2004 survey revealed that two-thirds of scientists and managers (survey included 286 people) believe that local anthropogenic stress poses a greater threat to coral reefs than global climate change (Kleypas & Eakin, 2007). Even so, climate change impacts on coral reefs have been so well publicized that climate change is popularly described as the single greatest threat to coral reef ecosystems and the goods and services they provide. The reality is that climate change impacts compound those caused by local human activities and natural resource managers have far greater influence over local anthropogenic stressors than the root cause of global climate change. For this reason, managers need downscaled projections that increase understanding of what spatial variation in exposure to climate-related stressors like bleaching conditions may be. Managers also need to know whether variation in model projections is sufficiently great to warrant inclusion in decision-making processes (see Fig. 6). In the framework used by the IPCC to assess vulnerability, exposure and sensitivity combine to produce potential impact. Whether the impacts manifest determines vulnerability and this vulnerability is moderated by adaptive capacity (Schröter *et al.*, 2004; IPCC, 2007). Spatial variation in sensitivity and adaptive capacity is not included in the projections presented here. Future local-scale variation in reef-scale vulnerability to climate change is likely to be driven as much by variation in sensitivity and adaptive capacity as by exposure to thermal stress. Our knowledge of spatial variation in sensitivity and adaptive capacity and our confidence in that knowledge varies at all spatial scales. Where and when available, managers can combine that knowledge with information on spatial variation in projected exposure to thermal stress made available from downscaled projections. Vulnerability assessments can be developed and refined as a result and then used in management and conservation planning.

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## Supporting Information

Additional Supporting Information may be found in the online version of this article:

**Appendix S1.** Methods related to the MOM4.1 model run.
**Figure S1.** MOM4.1 in hindcast mode compared to HadISST.
**Figure S2.** Comparison of mean DHW count variability and trend.
**Figure S3.** Projections of annual bleaching conditions (6 DHW).
**Figure S4.** Histograms for projections of annual bleaching conditions (6 DHW).
**Figure S5.** Scatter plot comparing projected timing of annual 6 and 8 DHW.
**Table S1.** List of models used in GCM ensemble and to force MOM4.1.
**Table S2.** Data distribution for Fig. 2 in paper.
**Table S3.** Data distribution for Fig. 4 in paper.
**Table S4.** Data distribution for Fig. S3.