Opposite latitudinal gradients in projected ocean acidification and bleaching impacts on coral reefs

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Abstract

Coral reefs and the services they provide are seriously threatened by ocean acidification and climate change impacts like coral bleaching. Here, we present updated global projections for these key threats to coral reefs based on ensembles of IPCC AR5 climate models using the new Representative Concentration Pathway (RCP) experiments. For all tropical reef locations, we project absolute and percentage changes in aragonite saturation state (Ωarag) for the period between 2006 and the onset of annual severe bleaching (thermal stress >8 degree heating weeks); a point at which it is difficult to believe reefs can persist as we know them. Severe annual bleaching is projected to start 10–15 years later at high-latitude reefs than for reefs in low latitudes under RCP8.5. In these 10–15 years, Ωarag keeps declining and thus any benefits for high-latitude reefs of later onset of annual bleaching may be negated by the effects of acidification. There are no long-term refugia from the effects of both acidification and bleaching. Of all reef locations, 90% are projected to experience severe bleaching annually by 2055. Furthermore, 5% declines in calcification are projected for all reef locations by 2034 under RCP8.5, assuming a 15% decline in calcification per unit of Ωarag. Drastic emissions cuts, such as those represented by RCP6.0, result in an average year for the onset of annual severe bleaching that is ~20 years later (2062 vs. 2044). However, global emissions are tracking above the current worst-case scenario devised by the scientific community, as has happened in previous generations of emission scenarios. The projections here for conditions on coral reefs are dire, but provide the most up-to-date assessment of what the changing climate and ocean acidification mean for the persistence of coral reefs.

Keywords: climate change, climate models, coral bleaching, coral reefs, ocean acidification, projections

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Introduction

Approximately 30% of the CO_2 released into the atmosphere since the industrial revolution has been absorbed by the world's oceans (Sabine *et al.*, 2004). This uptake of CO_2 is causing an ongoing decline in seawater pH that is commonly referred to as ocean acidification (OA) (Caldeira & Wickett, 2003). OA is causing a decline in the saturation state of calcium carbonate ($CaCO_3$) minerals such as aragonite (Ωarag) (Orr *et al.*, 2005). Aragonite is the building block of stony corals that are the primary framework and habitat builders of coral reef ecosystems. Declines in Ωarag result in declines in calcification rates of corals (Langdon *et al.*, 2000; Schneider & Erez, 2006). Declines in the calcification rate of corals on reefs are a grave concern because coral reefs are highly

dynamic ecosystems where rates of $CaCO_3$ production on healthy reefs only slightly outpace the loss of $CaCO_3$ due to physical and biological erosion (Glynn, 1997). Small reductions in calcification can tip reefs from net accretion into a state of net erosion.

Ocean acidification is a ramp-type disturbance. The stress on corals keeps increasing and keeps slowing calcification and growth rates (Kleypas, 1999). This ongoing process on reefs is punctuated by episodic pulse-type disturbances such as coral bleaching events caused by anomalously warm sea water. Bleaching events can and have killed many corals (Wilkinson, 1999). While calcification rates are decreasing due to declining Ωarag caused by OA (Chan & Connolly, 2013), coral bleaching events are expected to become more frequent and severe (Hoegh-Guldberg, 1999; van Hooidonk *et al.*, 2013). Bleaching events are projected to occur annually on 90% of coral reefs by 2060 under fossil fuel aggressive emissions scenarios such as

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Representative Concentration Pathway 8.5 (RCP8.5, van Hooidonk *et al.*, 2013). The ramp- and pulse-type disturbances of acidification and coral bleaching are inextricably linked in both their cause (rising CO_2 concentrations) and the influence (negative) of their trajectory on coral reef decline (Anthony & Maynard, 2011; Anthony *et al.*, 2011).

Coral reefs are clearly sensitive to OA and thermal stress which raises concerns that they can persist even beyond the first half of the 21st century (Hoegh-Guldberg *et al.*, 2007). However, the manifestation of these effects will not occur uniformly in space and time across the world's reef regions and reef habitat types (Pandolfi *et al.*, 2011; Albright *et al.*, 2013). There are multiple reasons why both changes in temperatures and Ωarag will not be uniform across the globe. For example, tropical easterly trade winds in the Pacific are expected to weaken causing decreased upwelling, a flattening of the thermocline, and high SST warming rates near the equator (Collins *et al.*, 2010). This will result in spatial variability in the frequency and severity of future bleaching events and the timing of the onset of the annual exceedance of coral bleaching thresholds (van Hooidonk *et al.*, 2013).

When severe bleaching starts occurring annually, many of the goods and services that coral reefs provide will already be lost or detrimentally impacted (Moberg & Folke, 1999). Declines at that point in Ωarag will be far less meaningful because there will be far less corals calcifying. Projections in the timing of the onset of annual bleaching from van Hooidonk *et al.* (2013) are readdressed here with a higher bleaching threshold of 8 degree heating weeks (rather than 6 DHWs). At 6 DHWs, some coral reefs might be in a state of rapid decline but others may not, as there is variability at multiple scales in the sensitivity of corals to thermal stress (Marshall & Baird, 2000; Berkelmans & Van Oppen, 2006; Ulstrup *et al.*, 2006). Bleaching is likely to occur at the 6-DHW threshold used in van Hooidonk *et al.* (2013), but at the higher threshold of 8 DHWs interspecies or regional differences in sensitivity matter less and most corals are highly likely to bleach (Yee & Barron, 2010). At this point systems will have shifted into a different state that may or may not be dominated by algae depending on local processes, but will certainly have fewer corals (Donner, 2009). Here, projections are presented of absolute changes in Ωarag up until the year in which thermal stress levels of 8 DHWs are projected to start occurring annually.

From the projected absolute changes in Ωarag we project changes in calcification by using relationships between the decline in Ωarag and reductions in calcification from a meta-analysis by Chan & Connolly (2013). Chan and Connolly used 25 published studies that reported on the effect of changes in Ωarag on coral calcification to estimate the overall mean response of coral calcification to a decrease in Ωarag. Our projections are the first showing spatial variability in declines in calcification based on the meta-analysis these authors present.

Global projections of the effects of OA on Ωarag and calcification in coral reef areas have been produced before (Cao & Caldeira, 2008; Silverman *et al.*, 2009). However, most previous studies use one or a few models but not an ensemble, or present projections for some but not all current emissions scenarios, or present projections for coral bleaching or acidification but not both (only acidification Kleypas, 1999; one model: Cao & Caldeira, 2008; one emission scenario and only for Japan: Yara *et al.*, 2012). All models show biases and errors and some of these are time dependent. Averaging over multiple models can reduce these errors and generally increases the accuracy, skill, and consistency of model forecasts (Tebaldi & Knutti, 2007). Some previous studies also approximate or simplify the calculation of Ωarag. For example, in Frieler *et al.* (2012) a linear rational function is used to estimate tropical Ωarag from atmospheric CO_2 concentrations. In that study the synergistic effect of OA decreasing a bleaching threshold was modeled, not the effect of OA on calcification. To accurately calculate Ωarag and solve the complete carbonate system sea surface temperature (SST), salinity and two of these five variables are required: total alkalinity, total carbon dioxide, pH, and partial pressure of carbon dioxide or fugacity of carbon dioxide (see: Zeebe & Wolf-Gladrow, 2001). Our acidification projections are the first for coral reef areas based on ensembles of IPCC AR5 climate models forced with all four of the RCP experiments and using all four critical input variables to calculate Ωarag. This is also the first time such projections have been compiled for the scientific and management community into a freely available file that can be viewed through Google Earth™. These projections address the spatial patterns in projected bleaching and OA impacts and the projected effects of OA on previously identified temporary bleaching refugia.

Materials and methods

Ensembles of climate models were used to generate projections of the year when severe coral bleaching events start to occur annually, and of changes in Ωarag. To produce the projections, monthly data for the following variables were obtained from fully coupled models in the Coupled Model Intercomparison Project 5 (CMIP5; http://pcmdi9.llnl.gov/esgf-web-fe/) for all four RCP experiments (Moss *et al.*, 2010): SST, surface pressure of CO_2, pH, and salinity. All modeled data were remapped to a $1 \times 1°$ resolution grid. Model outputs were reduced to a subset of only reef locations. These

were obtained from the UNEP-WCMC's Millennium Coral Reef Mapping Project Seascape (http://imars.usf.edu/MC/). A cell was counted as a reef cell if it contained any tropical coral reefs according to the original Seascape database. We have added in all the main Hawaiian islands.

To calculate DHWs all available models (at the time of writing) that archived SST were used (see Table S1); totaling 25, 35, 17, and 33 models for RCPs 2.5, 4.5, 6.0, and 8.5, respectively. To calculate Ωarag only the models that produce all the following variables were used: SST, surface pressure of CO_2, pH, and salinity (Table S2). This ensures that input variables for calculating Ωarag are not sourced from different models, rather an Ωarag projection is produced for a single model prior to model outputs being combined into our ensembles. Total model counts for Ωarag are 7, 8, 4, and 9 for RCP experiments 2.5, 4.5, 6.0, and 8.5, respectively (Tables S1 and S2). Model outputs were adjusted to the mean and annual cycle of observations of SST based on the OISST V2 1982-2005 climatology (as in van Hooidonk & Huber, 2012; van Hooidonk et al., 2013).

Degree heating months were calculated by summing the positive anomalies above the warmest monthly temperature from the OISST V2 1982–2005 climatology (Reynolds et al., 2002) for each 3-month period. Degree heating months are then converted into DHWs by multiplying by 4.35 (see also Donner et al., 2005; van Hooidonk et al., 2013). The output for the projections we present is the year when DHWs exceed 8 every single year in the next 10 years; referred to here as the onset of annual severe coral bleaching.

Aragonite saturation state was computed by adopting the routines in the Matlab program CO2SYS (http://cdiac.ornl.gov/oceans/CO2rprt.html) with K1 and K2 constants used from Mehrbach et al. (1973), refit by Dickson & Millero (1987).

Several outputs were generated for the acidification projections including: (a) the value for Ωarag when 8 DHWs start to occur annually (see above), (b) the decline in Ωarag from 2006 to the year when 8 DHWs start to occur annually, and (c) the decline in Ωarag expressed as a percentage of the 2006 values. From these data we calculate declines in calcification (as percentages) compared to 2006 rates by using the mean reduction per unit of Ωarag from the meta-analysis presented in Chan & Connolly (2013) of 15%. We also show the extreme ends of the meta-analysis outcomes in that study, the mean ± 1SD; 7% and 23% per unit reduction in Ωarag.

Previously, a latitudinal gradient was found in the projected onset of annual bleaching (van Hooidonk et al., 2013); therefore, we group reef locations here in latitudinal ranges. Reef locations are grouped in the following six latitudinal ranges; from −4 to 4°, and on both sides of the equator from 4 to 8°, 8 to 12°, 12 to 16°, 16 to 20°, and for all latitudes higher than 20°. For these latitudinal 'reef areas' we graph the mean ± 1SD of the year when 8 DHWs start to occur annually and the percentage change in Ωarag between 2006 and that year. We also track temperature stress and acidification through time and the spread between the models (as SD of the mean of all models at each time step) for the latitudinal reef areas from 2010 to 2100 for RCP8.5.

Results

All results presented relate to the RCP8.5 scenario. Results for the other RCPs are presented in the supplementary information. Among 95% of all reef locations there is a ~30-year range in the projected year in which severe coral bleaching (thermal stress >8 DHWs) starts to occur annually. Coral reefs in the Gilbert Islands (Republic of Kiribati) and Nauru are projected to experience these conditions earliest (2023). Coral reefs in the southern Great Barrier Reef, southern Austral Islands, and in the Persian Gulf and Red Sea are projected to experience these conditions latest (some only in 2082). A total of 90% of reef locations are projected to experience annual severe bleaching prior to 2055; less than 5% are projected to experience these conditions after 2060 (Figs 1a and 2a). There is both high spatial variability in the projected year of annual severe coral bleaching (Fig. 1a) and a strong latitudinal gradient. Reefs at higher latitudes are generally projected to experience annual severe bleaching later than locations close to the equator. The zonal patterns can be seen clearly when viewing the mean projected year for severe bleaching for groups of reef locations along the five 8° zonal bands from the equator to 20°, and then for all locations with latitudes higher than 20° (Fig. 3). For the zonal reef areas, the mean projected year for severe bleaching increases linearly with latitude from 2038 for −4 to 4°, to 2054 for reef locations with latitudes higher than 20° (Fig. 3).

Given the pattern seen for bleaching, higher latitude reefs are likely to persist longer and are thus projected to experience the greatest percentage declines in Ωarag (Fig. 1d). In 2006 the average Ωarag value for all reef locations is 3.47. The average projected Ωarag at reef locations at the onset of annual severe bleaching is 2.98 and ranges from ~2 to ~4 (Figs 1b and 2b). Less than half (678 or 40%) of reef locations are projected to have a Ωarag above three at this time (Fig. 2b). There is high spatial variability in projected Ωarag when annual severe bleaching starts (Fig. 1b), but these patterns are hard to interpret as they do not account for the high variance in initial (2006) Ωarag values. This variance is caused by local differences in salinity, temperature, and physical processes such as upwelling. Spatial patterns in the changes in Ωarag are clear when the absolute value changes are visualized (Fig. 1c) and when the data are expressed as percentage change (Fig. 1d). The projected per unit and percent changes in Ωarag are far greater at higher latitudes than at reefs in the low latitudes between 2006 and the onset of severe annual bleaching. For the zonal reef areas shown in Fig. 3, the mean percent change in Ωarag decreases linearly as
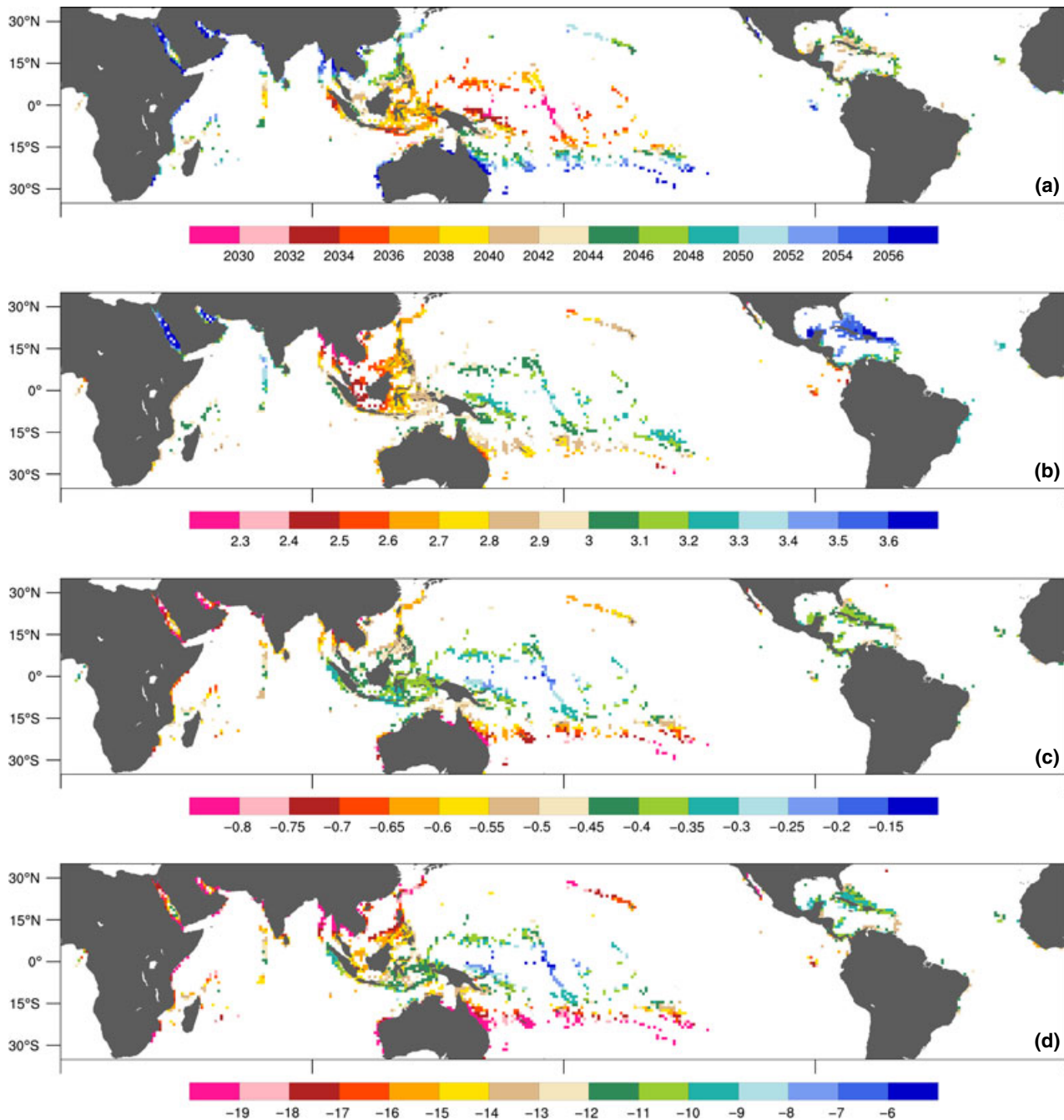
Fig. 1 Projections for coral reefs based on multimodel ensembles forced with RCP8.5 for the year reefs start to experience 8 DHWs annually (a). Ωarag in the year in (a) is shown in (b) and the reduction in Ωarag from 2006 until the year shown in (a) is shown in (c). The data shown in (c) are expressed as a percentage change from 2006 values in (d).

latitude decreases, ranging from 18% to 12% (purple and blue in Fig. 3).

The declines in Ωarag projected between 2006 and the onset of annual severe bleaching range from −0.1 to −1. During this time frame, only 30% of reef cells are projected to experience a decline in Ωarag less than 0.4 units. More than half of reef cells are projected to

experience a decline in Ωarag greater than 0.5 units. This equates to an average decline of 14.24% with 83% of reef locations projected to experience a decline in Ωarag greater than 10% (Fig. 2).

Declines in calcification range from 1% to 21% (Fig. 4b) between 2006 and the onset of annual severe bleaching when assuming a 15% decrease in calcification
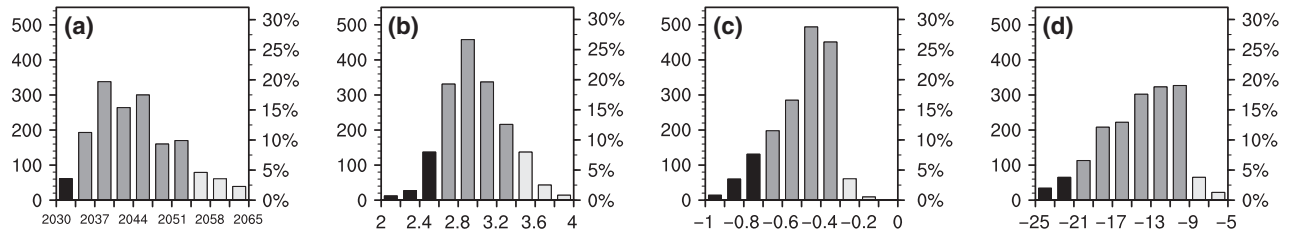
Fig. 2 Histograms of the number ($n = 1718$) and percent of coral reefs for the year when annual temperature stress exceeds 8 degree heating weeks (a), for the absolute value of Ωarag at the point of onset of annual severe bleaching (b) and for projected absolute (c) and percentage (d) changes in Ωarag between 2006 and the onset of annual severe bleaching. The darker and lighter colors indicate reefs 1 SD or more away from the global mean.
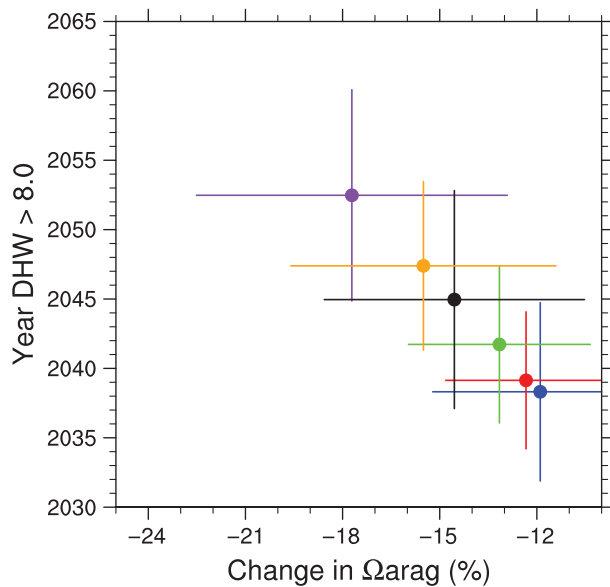

Fig. 3 Scatter plot for coral reefs in zonal bands of the % change in Ωarag between 2006 and the year when 8 degree heating weeks start to occur annually. Points are the means; lines represent ±1SD along each axis. Zonal bands are as follows: from −4 to 4° (blue, $n = 264$), and on both sides of the equator from 4 to 8° (red, $n = 277$), 8 to 12° (green, $n = 340$), 12 to 16° (black, $n = 191$), 16 to 20° (orange, $n = 259$), and for all latitudes higher than 20° (purple, $n = 387$).

per unit change in Ωarag (from Chan & Connolly, 2013). Locations with the earliest projections of the onset of annual severe bleaching, such as the reefs in Kiribati and the Gilbert Islands, are projected to experience the lowest declines in calcification from OA. Reefs projected to experience annual bleaching conditions the latest are projected to experience the greatest declines in calcification. Declines in calcification ≥5% are projected for 91% of reef locations before the onset of severe annual bleaching. Declines in calcification start to exceed 5% for all six of the zonal reef regions by 2033 (Fig. 5). The average year in which severe bleaching starts to occur annually is 5, 6, 9, 12, 14, and 19 years

later, respectively, for the six zonal areas as you move away from the equator (Fig. 5). Projections for the extremes in the findings of Chan & Connolly (2013) are shown in parts (a) and (c) of Fig. 4, representing 7% and 23% declines in calcification per unit Ωarag, respectively. In the 7% case, 11% of reef cells are projected to experience a decline in calcification ≥5% before the onset of severe annual bleaching. Over 99% of reef cells experience ≥5% decline in calcification before the onset of severe annual bleaching assuming 23% declines in calcification per unit Ωarag.

The same spatial patterns described above for RCP8.5 for the onset of annual severe bleaching and changes in Ωarag are seen for RCPs 2.6, 4.5, and 6.0 (Figs S1–S3 and S7–S9). The average year for the onset of annual severe bleaching is 18 years later under RCP6.0 than under RCP8.5 (2062 vs. 2044) so changes in Ωarag by the time severe bleaching occurs annually are slightly greater under RCP6.0 (Fig. S3). Even under RCPs 2.6 and 4.5, 88.3% and 99.7%, respectively, of reef locations are projected to experience severe bleaching annually by 2100, although changes in Ωarag are less than seen for RCPs 6.0 and 8.5 (Figs S1, S2, S7, and S8).

Discussion

The threshold used here of 8 DHWs to mark the onset of severe annual bleaching sets a time frame between now and the year in which it is extremely difficult to believe coral reefs could persist as we know them. That year is less than 40 years away for most reef locations (85% of reef locations) under the fossil fuel aggressive emissions scenario that best characterizes current conditions (RCP8.5, Peters et al., 2012). Timing of the onset of annual severe bleaching shows a strong latitudinal gradient. Our zonal bands for reefs show clearly that higher latitude reef locations are projected to experience the onset of annual bleaching more than a decade later than locations in lower latitudes. Our results and those of van Hooidonk et al. (2013) identify higher latitude reefs as potential temporary refugia from
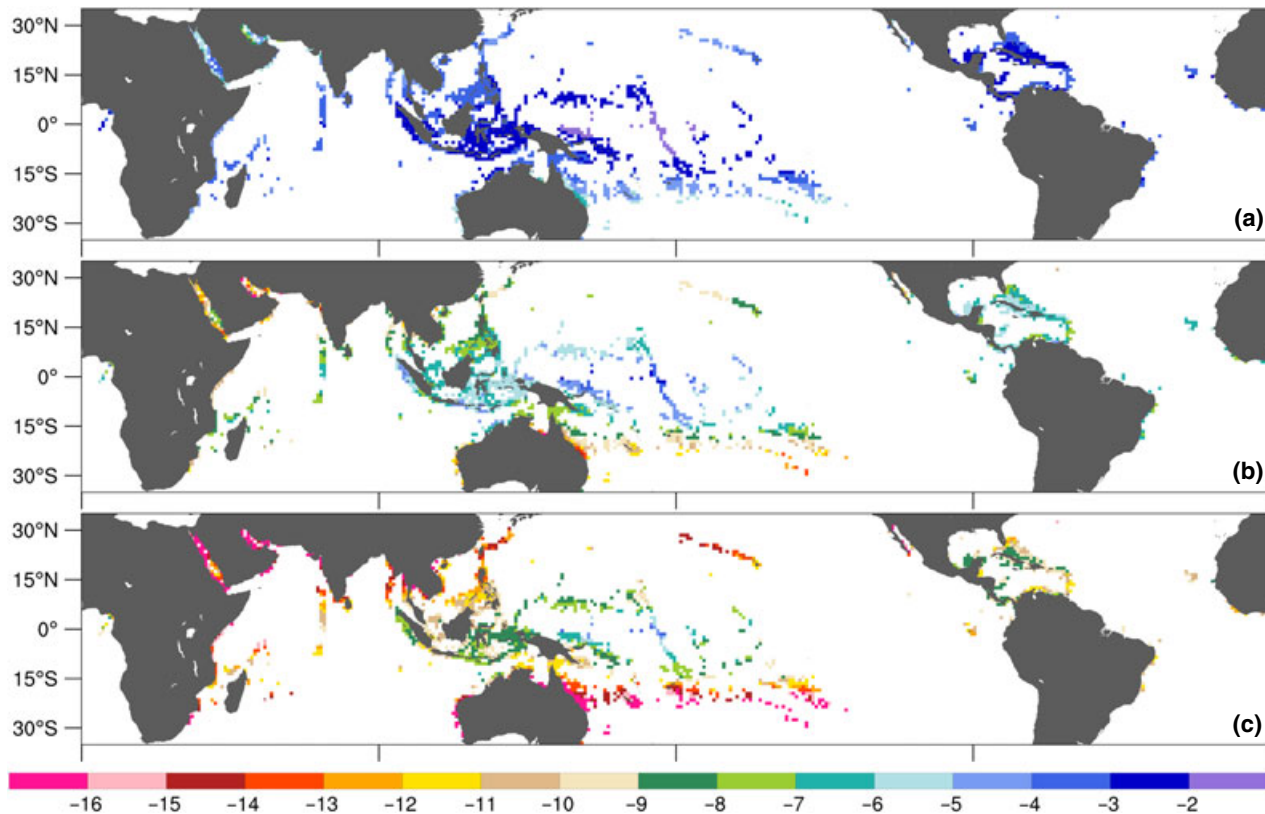
Fig. 4 Percentage change in calcification rate based on multiplying the Ωarag change shown in Fig. 1b by 7% (a), 15% (b), and 23% (c); these are the mean rate −1SD, the mean rate, and the mean rate +1SD, respectively, from the meta-analysis presented in Chan & Connolly (2013).

temperature stress. There is only a few years difference (3–5 years) between the median year when all locations are exposed to 6 DHWs annually and the year when all reefs are projected to experience 8 DHWs annually. This can be seen from the steepness of the trajectories shown for the zonal reef regions in Fig. 5. This suggests that corals and coral communities with a greater tolerance to thermal stress have a little but minimal more time prior to the onset of annual bleaching than those with lower tolerance to thermal stress.

We show here that barring significant adaptive capacity of coral reefs, not demonstrated at the required rates yet (Donner et al., 2005; Hoegh-Guldberg et al., 2007), there are no real refugia for coral reefs to the combined threats of warming SST and OA. The pattern for reefs and latitude with respect to acidification is opposite to that seen for the annual onset of severe coral bleaching. This limits the possible poleward extension of tropical corals due to warming as was also shown in Yara et al. (2012). Absolute and percentage declines in aragonite saturation state and thus declines in calcification are greatest at high-latitude reefs between 2006 and the onset of annual severe coral

bleaching. The high-latitude reefs have more time to be exposed to the effects of acidification because the onset of annual severe bleaching occurs later.

Rates of change in aragonite saturation state at high-latitude reefs potentially negate any benefit gained by being exposed to annual bleaching conditions later for several reasons. First, it is possible that CO_2 levels can increase sensitivity to bleaching in some coral species, so reefs in high latitudes exposed to lower levels of temperature stress may be more sensitive to that stress and bleach sooner than projected (Anthony et al., 2011). Second, severe tropical storms and cyclones affect regions poleward of 8° latitude. Acidification can reduce coral skeleton density (Fabricius et al., 2011), but the evidence is inconclusive (De'ath et al., 2009). If acidification weakens coral skeletons then in the coming decades higher latitude reefs will have a lower capacity to recover from the physical damage caused by tropical cyclones. This capacity will be critical given the projected increases in tropical cyclone intensity for some reef areas (Emanuel, 2005). Third, recruitment and colonization of higher latitude coral reefs will be slow because early life stages of corals may be more prone to
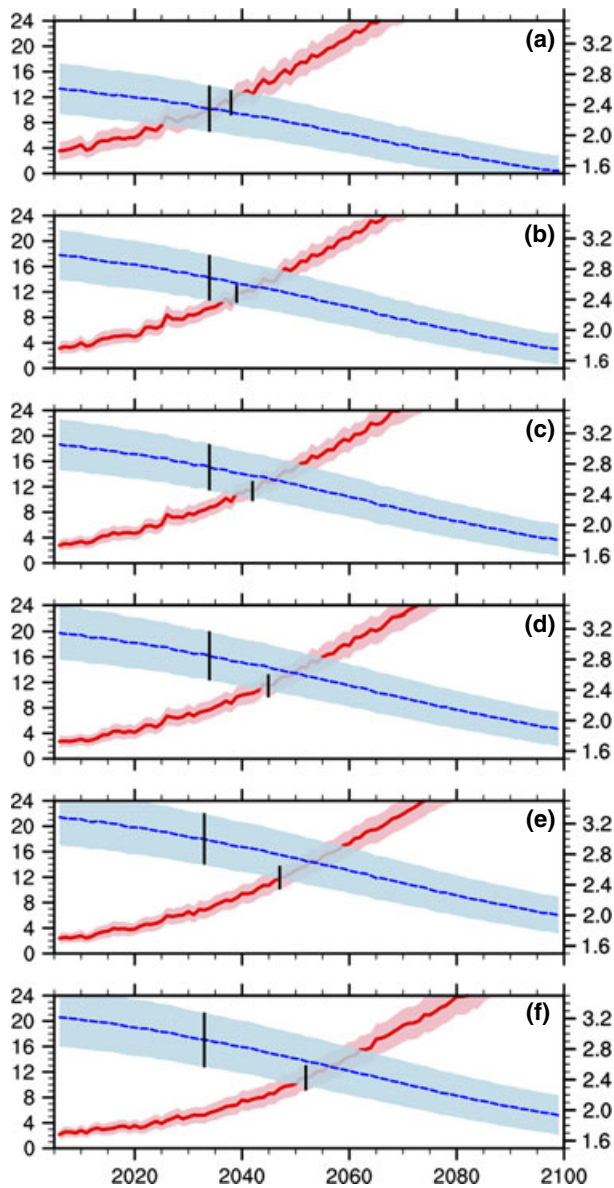
Fig. 5 Projected trajectories of annual degree heating weeks (DHW; red) and Ωarag (blue) from 2006 to 2100 under RCP8.5 for the zonal bands shown in Fig. 3. The panel shows −4 to 4° (a), and on both sides of the equator from 4 to 8° (b), 8 to 12° (c), 12 to 16° (d), 16 to 20° (e), and for all latitudes higher than 20° (f). The shaded areas show ±1 SD of the model ensemble at that time step. The short vertical lines represent the average years when 8 DHWs start to occur annually and when calcification is reduced by 5%.

represents the lowest observed Ωarag at reef locations when examining preindustrial conditions (Kleypas, 1999; Hoegh-Guldberg *et al.*, 2007). Other studies suggest that conditions are inadequate when Ωarag drops below 3.0 (Guinotte *et al.*, 2003; Yara *et al.*, 2012). There is little agreement in the literature on what the critical Ωarag thresholds value is below which calcification is inadequate to keep up with dissolution and erosion. This is in part because the effects of OA are complex and species dependent (McCulloch *et al.*, 2012). Factors such as light, temperature, and nutrients all influence the calcification rate of corals (Silverman *et al.*, 2009; Holcomb *et al.*, 2010). Net accretion on a reef is influenced by both organic carbon metabolism (photosynthesis and respiration) and inorganic carbon metabolism (calcification and dissolution). These are both influenced by environmental conditions and biological activity so any threshold will not be static on spatial, seasonal, or even diurnal scales (Albright *et al.*, 2013). Also, changing conditions including but not limited to temperature regimes and OA will alter species composition on reefs (Loya *et al.*, 2001; Fabricius *et al.*, 2011), in turn changing the resilience of the community. This potential for increased or decreased resilience is not included in this study.

Here, no explicit absolute threshold has been set for declines in Ωarag very purposefully. We employ a rigorous method to calculate Ωarag that includes the effects of SST and salinity and uses pH and surface pressure of CO_2 as inputs to calculate the other parts of the carbonate system and the Ωarag (Zeebe & Wolf-Gladrow, 2001; see also Pierrot *et al.*, 2006). In doing so, we find using CO2SYS routines (http://cdiac.ornl.gov/ftp/CO2sys/) that modeled Ωarag values were below three in 2006 throughout the world's center of coral reef biodiversity in SE Asia and the Coral Triangle (CT) (see Fig. 5f). Many corals have been lost due to disturbances such as the bleaching event in 1998 or 2010 on the reefs of SE Asia and the CT, but corals continue to grow prolifically there. Absolute thresholds of three and above for Ωarag are thus likely indefensible so we present absolute and percentage changes in Ωarag only and relate these to percentage declines in calcification.

Coral reefs are highly dynamic systems where in the past accretion and erosion have been roughly in balance or reefs have been slightly net accreting (Glynn, 1997; Perry *et al.*, 2012). Corals and other invertebrates grow at pace with or just ahead of the rate at which processes such as bio and chemical erosion erode the reef framework. Some reefs are believed to already be net eroding for parts of the year due to changes in Ωarag caused by OA (Yates & Halley, 2006; Albright *et al.*, 2013). The percentage decline in calcification required to shift reefs from net accreting to net eroding

depressed Ωarag than adults (Albright, 2011; but see Chua *et al.*, 2013 for an alternative view).

Some global studies similar to the one presented here use a threshold value of 3.3 for Ωarag. Values below this threshold are suggested as marginal for net reef accretion but this is not a true threshold. This value

systems remains unknown. This is certain to be variable at different spatial scales and will be driven at least in part by spatial and temporal variability in the frequency and severity of other disturbances that kill corals and set the coral growth clock back. In the Caribbean, 37% of reefs were already found to be net eroding and 26% had positive budgets, but net calcification rates were below 1 kg $CaCO_3$ m^{-2} yr^{-1} (Perry *et al.*, 2013). This indicates that many reefs are already at or close to net erosion so small declines in calcification could tip reefs toward net erosion.

Silverman *et al.* (2009) used a model for net growth based on Ωarag and optimal temperatures and suggest that half of the world's reefs will be net dissolving when atmospheric CO_2 doubles to 560 ppm. Under RCP8.5 560 ppm will be reached in the year 2052. The effect of pH buffering, the process where corals upregulate pH at their site of calcification thereby increasing calcification rates (McCulloch *et al.*, 2012), was not included in the Silverman *et al.* (2009) study. This pH buffering lowers the sensitivity of corals to OA, and would delay the year when half of the reefs are projected to be net eroding beyond 2052. That said, if 5% declines in calcification result in net erosion, then nearly all reefs are projected here to be in a state of net dissolution 12 years before. Silverman *et al.* (2009) suggest that half of reefs will be. Five percent declines in calcification are projected here for >90% of reef locations by 2040 assuming 15% declines in calcification per unit of Ωarag; the average rate from the meta-analysis in Chan and Connolly (Chan & Connolly, 2013). At that point only roughly a third (35.8%) of reef locations are projected to have started experiencing 8 DHWs annually. However, when severe bleaching occurs two to three times per decade it will likely result in reductions in coral growth as great as or greater than will be caused by projected declines in calcification.

The projections presented here are not meant to indicate whether acidification is likely to have a greater or lesser influence on the fate of coral reefs than projected increases in the frequency and severity of thermal bleaching. Rather the interplay between these ramp- and pulse-type disturbances is emphasized and no reef locations escape both threats during the first half of this century under RCP8.5. Both OA and the bleaching events caused by increasing sea temperatures reduce reef growth and resilience (Anthony *et al.*, 2011).

For the six zonal bands set here the range in the median year for the onset of severe annual bleaching is only 14 years between the lowest and highest latitude reefs. In contrast, for all reef locations combined, there are 20 years between the median year for projected severe annual bleaching under RCP8.5 and that projected for RCP6.0 (2043 vs. 2064). The reduction in

annual emissions in CO_2 in RCP6.0 compared to 8.5 buys many coral reefs a couple of decades, but delays rather than mitigates the threats posed to coral reefs by acidification and bleaching. Even so, 20 years is on the scale of a whole human generation or more and the two-decade delay applies to nearly all reefs. This captures the potential benefit for coral reefs and dependent communities of global action to reduce emissions outputs. Cutting emissions such that RCP6.0 better characterizes the global emissions trajectory results in growth toward 478 ppm CO_2 in 2050 rather than the 555 for RCP8.5 (van Vuuren *et al.*, 2011). These trajectories assume 395 ppm in 2013 as a midyear average, which is slightly lower than CO_2 concentration measurements that show as the actual midyear average for this year (http://www.esrl.noaa.gov/gmd/ccgg/trends/). At the end of May, weekly average CO_2 concentration at Mauna Loa, Hawaii, even exceeded 400 ppm. For all four previous versions of the IPCC climate models and emissions scenarios and for this, the 5th version, emissions have tracked (and are tracking) above the worst-case scenario devised by the scientific community (Peters *et al.*, 2012). Cutting emissions makes a dramatic 20+ year difference to the projected timing of the onset of annual severe bleaching. Emissions cuts have to be drastic and start now though or RCP8.5 is likely to slightly underestimate growth in emissions outputs.

Several caveats and assumptions need to be considered in this study. Climate model resolution is very coarse and in reef systems a $1 \times 1°$ cell can contain several to even several dozen individual coral reefs. Each reef within a cell can be highly diverse in the communities present, geomorphology, and level of stress from human activities. All of these will determine the local spatial and temporal patterns of impacts from OA and thermal stress. The models describe surface and oceanic waters only and thus do not resolve near-reef and near-coastal processes such as upwelling that can influence Ωarag and sea temperatures. Nor do the models reflect the temporal (diurnal, weekly) variability in Ωarag on reefs (Albright *et al.*, 2013). There are considerable biases in the representation of the annual cycle in the models (Wu *et al.*, 2008; van Hooidonk & Huber, 2012). Also, there are the standard issues with the use of climate model data, in that all models used have uncertainties and a varying capacity to project trends in key drivers of climate in the tropics such as the El Niño Southern Oscillation (ENSO Guilyardi *et al.*, 2009). There is some evidence that ENSO representation has improved from CMIP3 to the current generation of models, but the amplitude of ENSO is still lower in the current ensemble (Bellenger *et al.*, 2013).

Lower ENSO amplitude leads to lower levels of thermal stress, suggesting our results could be too optimistic. None of these assumptions is unique to this study. These are characteristic of all studies using climate models and ensembles of models to project future conditions in coral reef areas or elsewhere (Donner *et al.*, 2005; Donner, 2009). We did not include any potential for adaptation or acclimatization for coral to thermal stress. It has been suggested that historical temperature variability influences the sensitivity of a coral to thermal stress (Donner, 2011), but this form of acclimatization has not been quantified.

Coral reef conservationists and managers are increasingly aware of the threat posed to coral reefs by climate change as a result of the ongoing focus on and energy for this research area. As yet though, projections for coral reef areas of OA and climate change impacts such as bleaching have never been made publicly accessible in an interactive user-friendly tool. This is critical to raising awareness of what the future holds for coral reef areas based on the current state of climate science. Most coral reef managers and conservationists have low to no scope of influence over national-level policy and global agreements to reduce emissions and reliance on fossil fuels. However, a better understanding of what the future holds for reefs may galvanize managers in their efforts to implement the local-scale actions that can support the natural resilience of reefs (Hughes *et al.*, 2010). We have made the projections presented here into a KMZ file viewable through the Google Earth™ interface that can be accessed via the homepages of NOAA Coral Reef Watch and the Pacific Islands Climate Change Cooperative (coralreefwatch. noaa.gov and piccc.net). Users can navigate to locations of interest, store images, and compare projections for rises in sea temperature and declines in Ωarag for all four RCPs.

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Supporting Information

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

Figure S1. Climate model ensemble-based projections of coral bleaching and aragonite saturation state for reef locations under RCP2.6.

Figure S2. Climate model ensemble-based projections of coral bleaching and aragonite saturation state for reef locations under RCP4.5.

Figure S3. Climate model ensemble-based projections of coral bleaching and aragonite saturation state for reef locations under RCP6.0.

Figure S4. Histograms of the number (n = 1516) and percent of reef locations within bins for RCP2.6.

Figure S5. Histograms of the number (n = 1718) and percent of reef locations within bins for RCP4.5.

Figure S6. Histograms of the number (n = 1718) and percent of reef locations within bins for RCP6.0.

Figure S7. Percentage change in calcification rate based on multiplying the per unit Ωar change in RCP2.6 as shown in Fig. S1b by 7% (a), 15% (b), and 23% (c).

Figure S8. Percentage change in calcification rate based on multiplying the per unit Ωar change in RCP4.5 as shown in Fig. S2b by 7% (a), 15% (b), and 23% (c).

Figure S9. Percentage change in calcification rate based on multiplying the per unit Ωar change in RCP6.0 as shown in Fig. S3b by 7% (a), 15% (b), and 23% (c).

Figure S10. Average aragonite saturation state at tropical reef locations in the year 2006 calculated from RCP8.5 data.

Table S1. Table showing names of models used for calculating DHWs for each scenario.

Table S2. Models used to calculate aragonite saturation state.

Table S3. Comparison of modeled aragonite saturation state (for the year 2006) with observed 1972–1998 data (from Feely *et al.*, 2009).