

PRIMARY RESEARCH ARTICLE

The importance of 1.5°C warming for the Great Barrier Reef

Jennifer K. McWhorter^{1,2}  | Paul R. Halloran²  | George Roff¹  | William J. Skirving^{3,4}  | Chris T. Perry²  | Peter J. Mumby¹ ¹Marine Spatial Ecology Lab, School of Biological Sciences & ARC Centre of Excellence for Coral Reef Studies, University of Queensland, St Lucia, Queensland, Australia²College of Life and Environmental Sciences, University of Exeter, Exeter, UK³Coral Reef Watch, National Oceanic and Atmospheric Administration, Washington, District of Columbia, USA⁴ReefSense Pty Ltd, Townsville, Queensland, Australia**Correspondence**Jennifer K. McWhorter, Marine Spatial Ecology Lab, School of Biological Sciences & ARC Centre of Excellence for Coral Reef Studies, University of Queensland, St Lucia, Qld 4072, Australia.
Email: jm953@exeter.ac.uk**Funding information**

Financial support for this study was provided by the QUEx Institute, a University of Exeter and the University of Queensland partnership. PRH, WS, and PJM were supported by the UK Research and Innovation grant NE/V00865X/1 and ARC Centre of Excellence for Coral Reef Studies grants. WS was supported by NOAA grant NA19NES4320002 (Cooperative Institute for Satellite Earth System Studies) at the University of Maryland/ESSIC. The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the author(s) and do not necessarily reflect the views of NOAA or the Department of Commerce.

Abstract

Tropical coral reefs are among the most sensitive ecosystems to climate change and will benefit from the more ambitious aims of the United Nations Framework Convention on Climate Change's Paris Agreement, which proposed to limit global warming to 1.5° rather than 2°C above pre-industrial levels. Only in the latest Intergovernmental Panel on Climate Change focussed assessment, the Coupled Model Intercomparison Project phase 6 (CMIP6), have climate models been used to investigate the 1.5° warming scenario directly. Here, we combine the most recent model updates from CMIP6 with a semi-dynamic downscaling to evaluate the difference between the 1.5 and 2°C global warming targets on coral thermal stress metrics for the Great Barrier Reef (GBR). By ~2080, severe bleaching events are expected to occur annually under intensifying emissions (shared socioeconomic pathway SSP5-8.5). Adherence to 2° warming (SSP1-2.6) halves this frequency but the main benefit of confining warming to 1.5° (SSP1-1.9) is that bleaching events are reduced further to 3 events per decade. Attaining low emissions of 1.5° is also paramount to prevent the mean magnitude of thermal stress from stabilizing close to a critical thermal threshold (8 Degree Heating Weeks). Thermal stress under the more pessimistic pathways SSP3-7.0 and SSP5-8.5 is three to fourfold higher than the present day, with grave implications for future reef ecosystem health. As global warming continues, our projections also indicate more regional warming in the central and southern GBR than the far north and northern GBR.

KEYWORDS

climate change, CMIP6, coral bleaching, coral mortality, downscaling, global warming, Great Barrier Reef, SSP1-1.9

1 | INTRODUCTION

Global average temperatures have increased by ~1°C since the 1880s, with the ocean surface warming by ~0.11°C per decade [CI 0.09–0.13]°C since the 1970s (IPCC, 2021; Stocker, 2014). In

comparison, the increases in average temperatures over the period 1871–2017 for the northern, central and southern Great Barrier Reef (GBR) were 0.71, 0.85, and 0.86°C, respectively (Lough et al., 2018).

Within the tropical oceans, periods of anomalously warm sea temperatures have increased in frequency (Eakin et al., 2010;

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2021 The Authors. *Global Change Biology* published by John Wiley & Sons Ltd.

Hughes, Kerry, et al., 2018; Skirving et al., 2019) and severity, resulting in the deterioration of global coral ecosystems (Wilkinson & Souther, 2008). Recent mass coral bleaching events on the GBR (1998, 2002, 2016, 2017, 2020) occurred as a result of thermal stress (Bozec et al., 2021; Eakin et al., 2010; Great Barrier Reef Marine Park Authority, 2019; Hughes, Kerry, et al., 2018; Hughes et al., 2017), often after several weeks of temperatures exceeding their usual summer temperature by 1–2°C (Berkelmans & Willis, 1999; Glynn & D'cruz, 1990; Reaser et al., 2000). The term 'bleaching' refers to the breakdown of the relationship between corals and their photosynthetic symbiont, zooxanthellae, more commonly under radiative stress associated with higher temperatures (Enríquez et al., 2005; Jokiel & Coles, 1990). Bleaching can result in mass coral mortality if stress is sufficiently prolonged or intense (Eakin et al., 2010; Hughes, Kerry, et al., 2018). In the early 1980s, global severe coral bleaching was occurring once every 25–30 years, the frequency of severe bleaching has since increased to approximately once every 6 years in 2016 (Hughes, Kerry, et al., 2018).

The widespread mass coral bleaching events that occurred on the GBR during the austral summer of 2016, 2017, and 2020 have been the most severe events to date in the region. Corals were impacted throughout the entire GBR by the 2017 and 2020 events while the 2016 event was mainly concentrated in the far north and northern GBR (Hughes et al., 2017). The impact of these recent events on corals has been unprecedented with estimated losses of coral ranging from 30% across the entire GBR (Bozec et al., 2021) to 50% in shallow waters after the 2016 event alone (Hughes et al., 2017). Moreover, Cheung et al. (2021) estimated that the average supply of coral larvae to reefs could have declined by 70% (Cheung et al., 2021).

The implications of global warming for coral reefs (Donner et al., 2005; Frieler et al., 2013; Hoegh-Guldberg, 1999; Hoegh-Guldberg et al., 2014; King et al., 2017; Schleussner et al., 2016; Van Hooidonk et al., 2016) have contributed to the rallying call for more ambitious emissions reductions as part of the Paris Agreement under the 2016 Convention of Parties on Climate Change (Gattuso et al., 2015; Hoegh-Guldberg et al., 2018; IPCC, 2018, 2019, 2021; Shukla et al., 2019). Indeed, the Intergovernmental Panel on Climate Change (IPCC), recently discussed the putative benefits of achieving the most optimistic warming scenario of 1.5° above pre-industrial (cf. the original target of 2° warming; Hoegh-Guldberg et al., 2018; IPCC, 2018, 2021; Shukla et al., 2019). Previous studies suggest that 70%–90% of global coral reefs will be lost under the 1.5° target and 99% of reefs lost under the 2° target (Frieler et al., 2013; Hoegh-Guldberg et al., 2018; Schleussner et al., 2016). Specific to the GBR, King et al. (2017) estimate that events like the 2016 bleaching event would be ~25% less likely to occur under the 1.5° target than the 2° target. A formal analysis of the potential benefits that might accrue from adopting the 1.5° versus 2.0° warming scenarios is now feasible given the newly-released 6th phase of Coupled Model Intercomparison Project (CMIP6), which distinguishes the 1.5° focused pathway SSP1-1.9 (Riahi et al., 2017) from alternatives (O'Neill et al., 2016). Additionally, we allow for a more

focused study of the GBR which provides a more detailed account of climate projections due to the availability of the 1.5° scenario and our downscaling process.

Given that global ocean warming and the associated meteorological changes interact with local-scale oceanographic processes, we downscaled five CMIP6 models (see Section 2) to a resolution of 10 km using a semi-dynamic mechanistic approach (Halloran et al., 2021). This method uses a vertical 1-D physical-biogeochemical model at each grid box to capture the temperature response resulting from the interaction of the CMIP6 models' meteorology with local tides and bathymetry. The five selected models were chosen based on the availability of their atmospheric variables, surface air temperature, winds, air pressure, humidity, and net longwave and shortwave radiation, at the time of analysis (April 2020). Downscaled sea surface temperatures were used to derive standard metrics of coral thermal stress using Degree Heating Weeks (DHW), a measure of accumulated anomalous warm sea surface temperatures (Donner et al., 2005; Skirving et al., 2020). We calculate two elements of stress upon corals. First, the magnitude of stress, measured by the absolute maximum DHW value in each year. Second, the number of bleaching events within a decade where such events occur once $DHW \geq 8$ (Donner et al., 2005). It has been well established through independent coral bleaching reports that some bleaching occurs at 4 DHW and severe coral mortality tends to occur at around 8 DHW (Baird et al., 2018; Donner et al., 2005; Eakin et al., 2010; Hughes, Anderson, et al., 2018; Hughes et al., 2017). These updated climate projections of coral stress help illuminate the consequences of various emission trajectories and any benefits from achieving the 1.5°C target.

2 | MATERIALS AND METHODS

2.1 | Downscaling model data

Our semi-dynamic downscaling method applies the S2P3-R v2.0 model (Halloran et al., 2021), driven by surface air temperature, winds, air pressure, humidity, and net longwave and shortwave radiation, as simulated by the fully coupled global climate models. The atmospheric forces are used in conjunction with high-resolution bathymetry (Beaman, 2010) and tidal forcing (Egbert & Erofeeva, 2002) to simulate water column properties in the vertical dimension. The S2P3-R v2.0 model has been applied over the domain 142.0 W, 157.0 E, 30.0 S, 10.0 S from 4 to 50 m water depth, at a 10-km horizontal resolution and 2-m vertical resolution. We drive the model with surface-level atmospheric data from the CMIP6 models, MRI-ESM2-0 (Adachi et al., 2013), EC-Earth3-Veg (Döscher et al., 2021), UKESM1-0-LL (Sellar et al., 2019), CNRM-ESM2-1 (Séférian et al., 2019), and IPSL-ESM2-0 (Boucher et al., 2020). Sea surface temperature data were output daily from 1950 to 2100 (inclusive) and masked to contain values just within the Great Barrier Reef Marine Park Authority Boundary (Great Barrier Reef Marine Park Authority, 2004).

The S2P2-R v2.0 physical component is driven by tides and winds to simulate vertical profiles of temperature, turbulence, and currents.

A tidal slope is calculated from M2, S2, N2, O1, and K1 ellipses to then calculate the water's velocity 1 m above the seabed. The bottom stress is calculated as a function of this velocity and a prescribed bottom drag coefficient (Sharples et al., 2006). Wind stress is calculated as a function of the surface drag coefficient, air pressure, and wind speed, and direction with respect to tides (Smith & Banke, 1975). Mixing profiles are then calculated from these in a turbulence closure scheme as a function of vertical density (Canuto et al., 2001). Importantly, the temperature is considered the only factor in the density calculation, with salinity variability being considered second order. We would expect this model to fail in areas where (1) the horizontal controls, i.e., advection, exceed vertical controls, i.e., atmospheric forcing, and (2) where density variations are strongly dependent on salinity (Halloran et al., 2021; Marsh et al., 2015; Sharples et al., 2006).

2.2 | Coral stress metrics

To calculate coral stress, two metrics were applied to the sea surface temperature output: DHW and the frequency of severe bleaching years. The DHW values are a potential trigger for coral bleaching and have been strongly correlated to bleaching events in the past (Bozec et al., 2021; Hughes, Anderson, et al., 2018; Hughes et al., 2017; Skirving et al., 2020), but do not necessarily provide evidence of coral bleaching. The DHW values were calculated using the National Oceanic and Atmospheric Administration (NOAA) Coral Reef Watch methodology described below (Heron et al., 2014; Skirving et al., 2020). Importantly, prior to the calculation of the annual maximum DHW, calendar years were modified to be centered on the austral summer (e.g., August 1, 2014–July 31, 2015) to avoid double counting severe bleaching events that cross from one calendar year to the next (Skirving et al., 2019).

2.2.1 | Maximum monthly mean climatology

For each grid point, the monthly mean climatology was calculated. The monthly mean is a set of 12 temperature values that represent the average temperature at each point for each month calculated over the period 1985–2012, adjusted to 1988.2857. This is the average of the years used in the original NOAA Coral Reef Watch climatology, i.e., 1985–1990 and 1993 (the missing years were originally necessary due to aerosol contamination from the Mt. Pinatubo eruption, modern satellite data now account for this contamination but, the climatology remains adjusted). The daily sea surface temperature values in each month were averaged to produce 12 mean sea surface temperature values for each of the 28 years from 1985 to 2012. Next, a least squares linear regression was applied to each month, i.e., the 28 values for each of the January values were regressed against the years, and the temperature value corresponding to $x = 1988.2857$ was assigned as the monthly mean value for January for each point separately. This was repeated for each month until each point had a set of 12 monthly mean values, representing

the monthly mean climatology. This method maintained a similar monthly mean value to the original Coral Reef Watch climatology while increasing the number of years that contributed to the climatology. (Skirving et al., 2020).

2.2.2 | DHW calculation

Using the maximum monthly mean, a warm sea surface temperature anomaly was created called a “HotSpot.” The “HotSpot” (Skirving et al., 2020) is calculated by subtracting the maximum monthly mean from daily sea surface temperature values. To select only warm anomalies, all negative values were reset to zero, so “HotSpot” ≥ 0 . The DHW product is a daily summation of “HotSpot” values over an 84-day running window which represents the summer duration. Since thermal stress is considered to begin at maximum monthly mean +1, the DHW is an accumulation of all “HotSpot” values greater than or equal to 1. (Skirving et al., 2020) The median DHW value was then taken annually across the spatial domain for each model in each scenario. Then the median DHW value was further averaged using all models within each scenario resulting in an ensemble mean per scenario.

2.2.3 | Frequency of severe bleaching per decade calculation

The maximum DHW was extracted for each reef cell, from each year of the 2014–2100 time series (exclusive) for each model and each scenario. For each reef cell, the frequency of severe bleaching (≥ 8 DHW) was determined over an 11-year moving average giving a near decadal projection. The median frequency value was then taken annually across the spatial domain for all models and scenarios. The time series was then averaged using all models within each scenario resulting in an ensemble mean per scenario and scaled to a decade.

2.3 | Statistical analysis

We used generalized additive mixed-effects models (GAMMs) to model the changes in the magnitude and frequency of severe bleaching among climate-change scenarios through time. Models were fit using the bam function in the “mgcv” package in R, where CMIP6 models were used as a random effect to account for variance between models. Penalized regression splines ($k = 4$) were fit across years and allowed to vary across climate-change scenarios. The longitude and latitude of each grid cell ($n = 1100$ cells) were included as a smoothed interaction term in the model to account for spatial autocorrelation (Wood, 2017). We used four knots ($k = 4$) to reduce overfitting in models, allowing smoothing every 20 years. Models were fit in bam using the scaled t family with a logarithmic scale ($link = “log”$) for the number of severe bleaching events and an inverse fit for DHW ($link = “inverse”$). Significant differences between

climate-change scenarios were tested using Tukey adjusted pairwise comparisons using the *emmeans* function in the “*emmeans*” package (Lenth et al., 2018), and standard deviations calculated per year across the spatial grid within each climate-change scenario.

To determine differences in the magnitude and frequency of severe bleaching events among regions, we separated the GBR into far north, north, central, and south zones following the Great Barrier Marine Park zoning (Great Barrier Reef Marine Park Authority, 2004). GAMM models were repeated as previously but with zone included as an interactive effect with climate-change scenarios, and penalized regression splines ($k = 6$) allowed to vary across climate-change scenarios and zones. Significant differences between climate-change scenarios were tested using Tukey-adjusted pairwise comparisons using the *emmeans* function in the “*emmeans*” package (Lenth et al., 2018), and standard deviations calculated per year across the spatial grid within each climate-change scenario.

3 | RESULTS

3.1 | The magnitude of thermal stress

The magnitude of thermal stress upon GBR corals intensifies dramatically over time, particularly under scenarios that exclude strong international efforts to tackle climate change (SSP3-7.0; Riahi et al., 2017) or assume an energy-intensive fossil-based economy (SSP5-8.5; Figure 1a; O'Neill et al., 2016; Riahi et al., 2017). These scenarios lead to a three to fourfold increase in the magnitude of thermal stress upon corals (Figure 1a) compared to the worst of recent bleaching events, which have already caused mass mortality on many GBR reefs (Bozec et al., 2021; Hughes et al., 2018). In contrast, long-term projections under a scenario built around global collaboration on climate policy targeting mean warming above preindustrial of 2° (SSP1-2.6; Riahi et al., 2017), or a scenario which embraces large net negative emissions to limit warming to 1.5° (SSP1-1.9; O'Neill et al., 2016; Riahi et al., 2017), lead to far smaller increases in absolute stress. Long-term bleaching projections under these scenarios have a similar mean magnitude to that experienced already but with higher variability (Figure 1a). Adopting the SSP1-1.9 pathway results in mean thermal stress remaining below the 8 DHW threshold with thermal stress returning to near present-day levels by 2100 (Figure 1c), whereas the SSP1-2.6 pathway stabilizes after 2050 and remains close to the 8 DHW threshold until 2100 (Figure 1c). Note that while a DHW of 8 has been reached, and even exceeded, in some recent bleaching events, our analyses reveal the GBR-wide median DHW. The equivalent, GBR-wide median warming during the most severe event to date (2020) was 6.40, which is consistent with ensemble model predictions (Table S1; Figure 1c).

3.2 | Frequency of thermal stress

Pathways SSP1-1.9 and SSP1-2.6 differ markedly in the frequency at which severe bleaching stress would occur (Figure 1b,d; Table S1).

From 2060 onwards, major bleaching events are expected approximately every other year under SSP1-2.6 (i.e., 5 events per decade) whereas the rate of bleaching is eventually lower at three events per decade under SSP1-1.9 (Figure 1b,c). In marked contrast, bleaching eventually becomes an annual event (10 events/decade) under the higher emission pathways (Figure 1b).

Our results highlight the effects of committed warming even under SSP1-1.9, where bleaching frequency peaks at around 2050 with 4.4 ± 1.4 events per decade (Figure 1b) of average magnitude $7.4 \text{ DHW} \pm 2.1$ (Figure 1a, from 2051 to 2061 inclusive). Based on this outcome, we would expect a temporary worsening of present-day conditions even under the best-case scenario. We define present-day conditions as $1.9 \text{ events/decade} \pm 0.2$ (Figure 1b) and $3.5 \text{ DHW} \pm 0.9$ (Figure 1a), or the average of our initial conditions across all scenarios from 2014 to 2025 (inclusive).

3.3 | The regional magnitude of thermal stress under low emissions

As warming continues in the 21st century, the magnitude of DHW increases more in the southern and central GBR relative to the far north and northern GBR (Figure 2a). However, the scenario with the least warming, SSP1-1.9, shows no discernible regional separation in the magnitude of warming while regions remain under 8 DHW on average (Figure 2a). Meanwhile, even in SSP1-2.6, there is an increase in warming in the southern GBR by ~1 DHW in 2060 relative to other regions (Figure 2a; Table 1b). The magnitude of stress in the far north and north uniquely remains closer to 8 DHW in SSP1-2.6, while the southern and central GBR rise above 8 DHW just after mid-century (Table 1b) and again at the end of the century (Figure 2a). Under the most intense warming scenarios, SSP3-7.0 and SSP5-8.5, the central and southern GBR are generally warming more than the far north and northern GBR and by ~1–3 DHW in 2060 (Figure 2a; Table 1c,d).

3.4 | Regional frequency of thermal stress under low emissions

As warming continues, our results indicate an increase in the frequency of severe bleaching years in the central and southern GBR under all emissions scenarios (SSP1-1.9, SSP1-2.6, SSP3-7.0, SSP5-8.5; Figure 2b). The regional separation becomes most apparent in higher emissions scenarios such that the drastic increase in warming causes approximately two more severe bleaching years/decade in the central and southern GBR relative to the far north and northern GBR (Figure 2b; Table 1c,d). SSP1-1.9 only exhibits this regional separation around mid-century before the expected extraction of CO₂ from the atmosphere in the latter half of the century. In the year 2060 under SSP1-1.9, the far north and northern regions can expect ~0.50 severe bleaching events/decade less than central and southern regions (Figure 2b; Table 1a). While SSP1-2.6 also shows the same latitudinal separation, the far north and northern regions

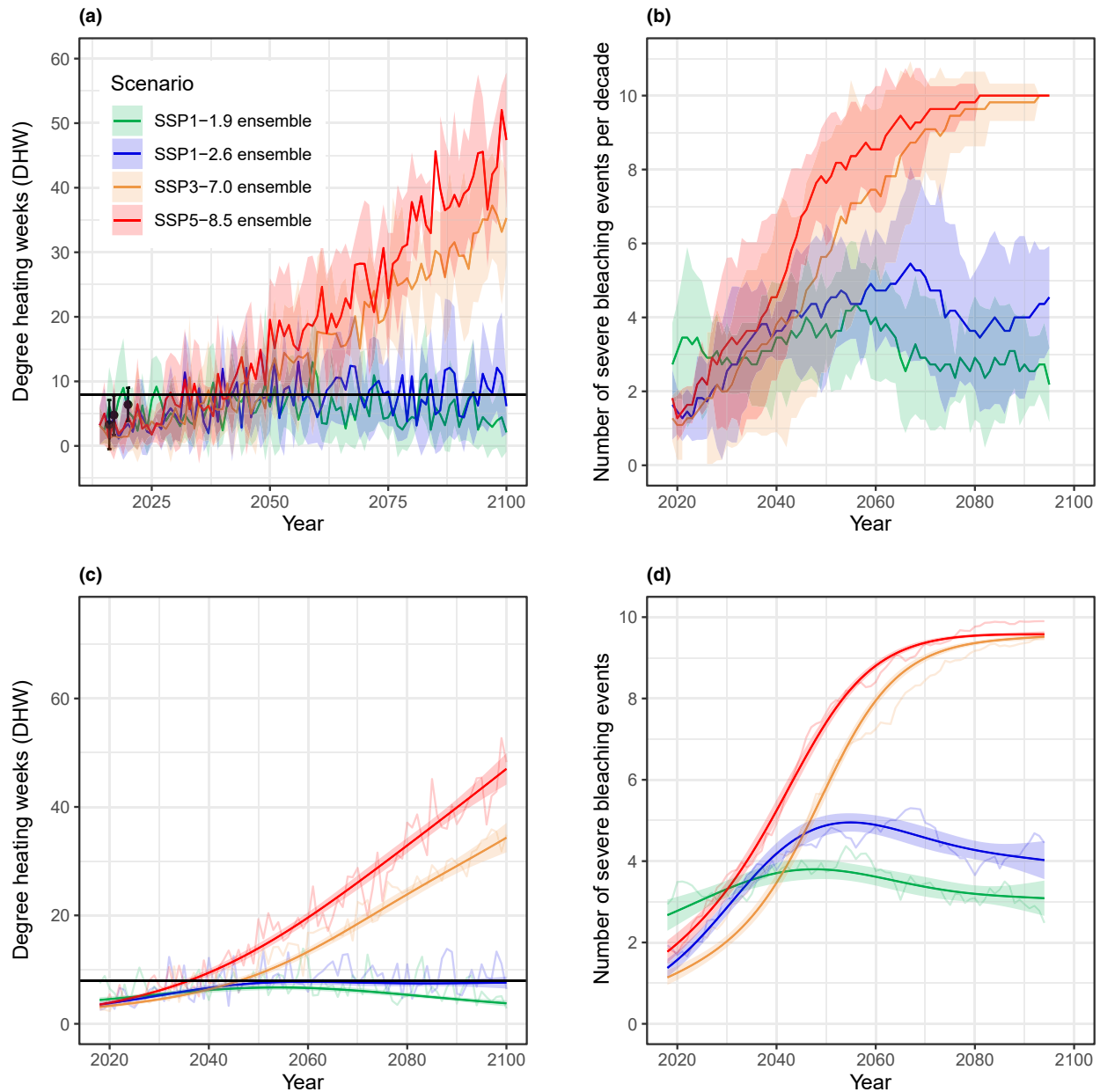


FIGURE 1 Metrics of coral stress averaged across the Great Barrier Reef for four socioeconomic pathways and an ensemble of five climate models. Coral stress metrics disaggregate magnitude as Degree Heating Weeks (DHW) (a, c), and frequency as the number of severe bleaching years per decade (b, d). Top row presents the multi-model ensemble mean (a, b) whereas the bottom row is the smoothed Generalised Additive Model fitted to the data, which helps visualize underlying trends. The multi-model ensemble is made up of MRI-ESM2-0, EC-Earth3-Veg, UKESM1-0-LL, CNRM-ESM2-1, and IPSL-ESM2-0. Shaded areas denote the standard deviation for each scenario averaged across models (a–d). The points and error bars (a) show the median and standard deviation DHW from recent bleaching events, 2016, 2017, 2020, satellite observations of reef pixels. The horizontal black line (a, c) marks 8 DHW, a metric of coral stress that often leads to mortality

project ~1 severe bleaching year/decade less than central and southern regions in 2060 (Figure 2b; Table 1b).

4 | DISCUSSION

An earlier global assessment of the difference between 1.5 and 2° of warming (Schleussner et al., 2016), followed Frieler et al. (2013)

in setting a reef degradation threshold of >2 bleaching events per decade. Applying these criteria to reef cells, they found that virtually all cells risk degradation after 2050 under 2° of warming, while the 1.5° scenario reduces this to 90% of cells in 2050 and 70% in 2100 (Schleussner et al., 2016). Their analysis used a simple relationship between global average temperature and the fraction of reefs at risk of long-term degradation. We update this analysis for the GBR by examining climate model simulations which explicitly

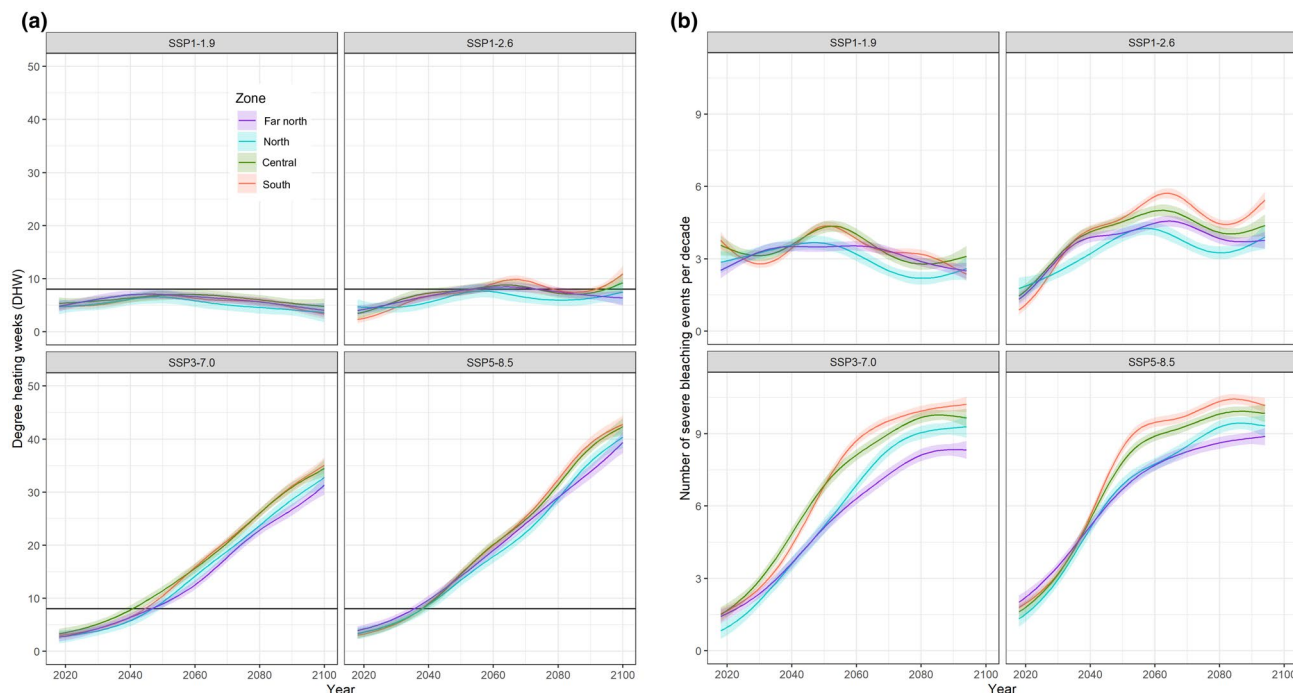


FIGURE 2 Metrics of coral stress averaged regionally across the Great Barrier Reef for low emission socioeconomic pathways and an ensemble of five climate models. Coral stress metrics disaggregate magnitude as Degree Heating Weeks (DHW) (a), and frequency as the number of severe bleaching years per decade (b). A smoothed Generalised Additive Model was fitted to the data, which helps visualize underlying regional trends. The multi-model ensemble is made up of MRI-ESM2-0, EC-Earth3-Veg, UKESM1-0-LL, CNRM-ESM2-1, and IPSL-ESM2-0. Shaded areas denote the standard deviation for each zone averaged across models (a, b). The horizontal black line in (a) marks the 8 DHW, a metric of coral stress that often leads to mortality

examine the more ambitious socio-economic pathways, utilize the latest generation of climate models, downscale the results to account for the influence of local bathymetry and tides, and consider the magnitudes, as well as the frequency of stress. None of the updated shared socioeconomic pathways in this study were able to demonstrate limiting bleaching frequency to two events per decade for the GBR. Yet, like Schleussner et al. (2016), moving from 2 to 1.5° of warming does reduce the incidence of bleaching. Specifically, it reduces the rate of bleaching by up to 2 events per decade and keeps the magnitude approximately below 8 DHW towards the end of the century.

Less intense and less frequent warming in the far north and northern GBR are likely attributed to projected changes in large-scale atmospheric processes influencing the summer monsoon in the far north and northern GBR and the location of the subtropical ridge in the central and southern GBR. McGowan and Theobald (2017) found that reduced cloud coverage and anomalously high pressures and temperatures were positively correlated with bleaching conditions. An intensification and poleward shift of the Subtropical Ridge has been shown in model ensemble projections for both, CMIP3 (Dey et al., 2019; Kent et al., 2013) and CMIP5 (Dey et al., 2019; Grose et al., 2015) which would reduce cloud cover over the southern GBR. Projected increases in the summer monsoon based on CMIP5 (Brown et al., 2016; Dey et al., 2019) could contribute to reduced warming in the far north and northern GBR region in comparison to the central and southern GBR.

The S2P3-R v2.0 downscaling of CMIP6 models is not without limitations. First, is the uncertainty within the underlying CMIP6 model projections. Typically, the more models used, the more skillful the outcome of the ensemble projection (IPCC, 2018). Second, is the downscaling process, S2P3-R v2.0 does not resolve horizontal advection or changes in salinity (Halloran et al., 2021; Figure 3). Therefore, not simulated are the effects of the South Equatorial Current, the Hiri Current, and the Eastern Australian Current as well as eddies, internal waves, and the impacts of freshwater on stratification and mixing in areas of river runoff. We would expect the largest error in the downscaling process to be in the location of bifurcation from the South Equatorial Current due to the large input of horizontal advection. The third uncertainty is the inclusion of a variety of socioeconomic pathways and the implicit assumption that they represent the range of possible futures. Although limiting climate change to 1.5° C will be extremely difficult, it is recognized as an achievable, albeit highly ambitious, target (Rogelj et al., 2015). Arguably the technology exists to meet this target, though this can involve high-risk methods of geoengineering (MacMartin et al., 2018; Sanderson et al., 2016). Some underlying themes exist within all the SSPs to reduce the impacts of climate change, such as investing in technology to extract CO₂ and focusing on global human well-being (Riahi et al., 2017).

Even under SSP1-1.9, a bleaching frequency of once every 3–4 years will be challenging for coral ecosystems. Yet, if the average magnitude of events is constrained below 8 DHW, which is still possible under low

TABLE 1 The values for each region, far north, north, central, and south Great Barrier Reef, for year 2060 were extracted for Degree Heating Weeks (DHW) and the frequency as the number of severe bleaching years per decade. The scenarios are separated as (a) SSP1-1.9, (b) SSP1-2.6, (c) SSP3-7.0 and (d) SSP5-8.5

Region	DHW $\pm$ SE	Frequency $\pm$ SE
(a) SSP1-1.9, year 2060		
Far North	6.6 $\pm$ 0.05	3.5 $\pm$ 0.01
North	5.9 $\pm$ 0.07	3.2 $\pm$ 0.02
Central	7.0 $\pm$ 0.05	4.0 $\pm$ 0.01
South	6.3 $\pm$ 0.04	3.8 $\pm$ 0.01
(b) SSP1-2.6, year 2060		
Far North	8.4 $\pm$ 0.05	4.3 $\pm$ 0.01
North	7.5 $\pm$ 0.07	4.2 $\pm$ 0.02
Central	8.7 $\pm$ 0.05	5.0 $\pm$ 0.01
South	9.1 $\pm$ 0.04	5.6 $\pm$ 0.01
(c) SSP3-7.0, year 2060		
Far North	12.5 $\pm$ 0.05	6.3 $\pm$ 0.01
North	14.2 $\pm$ 0.07	6.9 $\pm$ 0.02
Central	15.6 $\pm$ 0.05	8.1 $\pm$ 0.01
South	15.9 $\pm$ 0.04	8.7 $\pm$ 0.01
(d) SSP5-8.5, year 2060		
Far North	19.0 $\pm$ 0.05	7.7 $\pm$ 0.01
North	17.9 $\pm$ 0.07	7.8 $\pm$ 0.02
Central	20.1 $\pm$ 0.06	8.9 $\pm$ 0.01
South	20.1 $\pm$ 0.04	9.5 $\pm$ 0.01

emissions, then we can hope that genetic adaptation will help maintain functioning ecosystems. At this stage, our empirical understanding of genetic adaptation is only beginning to emerge, in part because of the complexity of the holobiont which includes corals, their zooxanthellate symbionts, and microbiome (Logan et al., 2021; Van Oppen & Medina, 2020). Moreover, any reduction in the frequency of bleaching events is likely to be beneficial, particularly if their magnitude remains under 8 DHW. Thus, although the average benefit of moving to 1.5° warming rather than 2°, is a reduction of two bleaching events per decade, the existence of substantial spatial and temporal variation means that some reefs will experience longer recovery periods between events (Bozec et al., 2021; Cheung et al., 2021). This is because not all reefs bleach during a given event (Hughes, Kerry, et al., 2018; Mumby et al., 2011) and many acute disturbances are temporally clustered giving longer recovery periods (Mumby et al., 2011). What is clear, however, is that failure to achieve either of the low emission scenarios will be devastating for future reefs. The functioning of coral reefs requires ambitious emissions targets and well-targeted management of local stressors, in part to facilitate natural processes of adaptation (Walsworth et al., 2019).

ACKNOWLEDGMENTS

Previous research and model availability makes this work possible, especially the initial development of S2P3 by Jonathan Sharples followed by Robert Marsh. Model data was extracted from CMIP6 modeling groups, MRI-ESM2-0, EC-Earth3, UKESM1-0-LL, CNRM-ESM2-1, IPSL-ESM2-0. Computing support was provided by David Hein-Griggs and the Exeter Supercomputer Centre ISCA staff. Benjamin

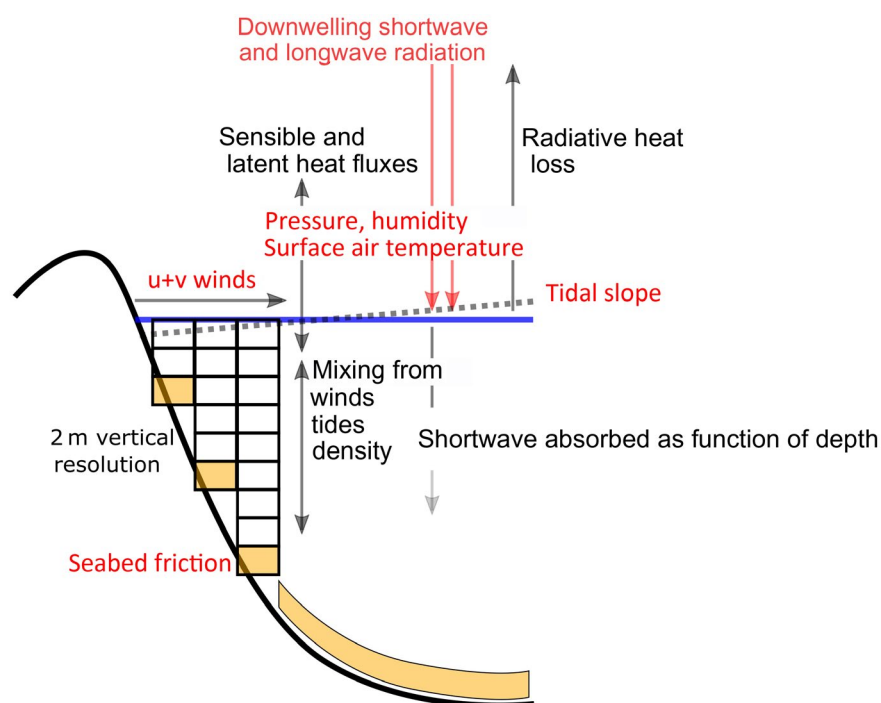


FIGURE 3 Schematic describing the S2P3-R v2.0 downscaling process including prescribed quantities for forcing's and constants

Marsh, NOAA, supported Degree Heating Weeks script validation. Statistical verification was supported by Simone Blomberg, UQ.

CONFLICT OF INTEREST

There are no potential conflicts of interest.

AUTHOR CONTRIBUTIONS

Conceptualization: JKM, PJM, PRH, CTP. Methodology: JKM, PRH, PJM, GR, WJS. Investigation: JKM, PRH, PJM, GR. Visualization: JKM, PJM, GR, PRH. Supervision: PJM, PRH, GR. Writing—original draft: JKM, PJM, PRH. Writing—review and editing: JKM, PJM, PRH, GR, WJS, CTP.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Zenodo at <https://doi.org/10.5281/zenodo.5534875>.

ORCID

Jennifer K. McWhorter  <https://orcid.org/0000-0003-1297-6599>

Paul R. Halloran  <https://orcid.org/0000-0002-9227-0678>

George Roff  <https://orcid.org/0000-0002-2823-0575>

William J. Skirving  <https://orcid.org/0000-0003-0167-6427>

Chris T. Perry  <https://orcid.org/0000-0001-9398-2418>

Peter J. Mumby  <https://orcid.org/0000-0002-6297-9053>

REFERENCES

- Adachi, Y., Yukimoto, S., Deushi, M., Obata, A., Nakano, H., Tanaka, T. Y., Hosaka, M., Sakami, T., Yoshimura, H., Hirabara, M., Shindo, E., Tsujino, H., Mizuta, R., Yabu, S., Koshiro, T., Ose, T., & Kitoh, A. (2013). Basic performance of a new earth system model of the Meteorological Research Institute (MRI-ESM1). *Papers in Meteorology and Geophysics*, 64, 1–19. <https://doi.org/10.2467/mripapers.64.1>
- Baird, A. H., Madin, J. S., Álvarez-Noriega, M., Fontoura, L., Kerry, J. T., Kuo, C. Y., Precoda, K., Torres-Pulliza, D., Woods, R. M., Zawada, K., & Hughes, T. P. (2018). A decline in bleaching suggests that depth can provide a refuge from global warming in most coral taxa. *Marine Ecology Progress Series*, 603, 257–264. <https://doi.org/10.3354/meps12732>
- Beaman, R. J. (2010). 3DGBR: A high-resolution depth model for the Great Barrier Reef and Coral Sea. *Marine and Tropical Sciences Facility (MTSRF) Project*, 2, 13.
- Berkelmans, R., & Willis, B. L. (1999). Seasonal and local spatial patterns in the upper thermal limits of corals on the inshore Central Great Barrier Reef. *Coral Reefs*, 18(3), 219–228. <https://doi.org/10.1007/s003380050186>
- Boucher, O., Servonnat, J., Albright, A. L., Aumont, O., Balkanski, Y., Bastrikov, V., Bekki, S., Bonnet, R., Bony, S., Bopp, L., Braconnot, P., Brockmann, P., Cadule, P., Caubel, A., Cheruy, F., Codron, F., Cozic, A., Cugnet, D., D'Andrea, F., ... Vuichard, N. (2020). Presentation and evaluation of the IPSL-CM6A-LR climate model. *Journal of Advances in Modeling Earth Systems*, 12(7), e2019MS002010. <https://doi.org/10.1029/2019MS002010>
- Bozec, Y.-M., Hock, K., Mason, R. A., Baird, M. E., Castro-Sanguino, C., Condie, S. A., Puotinen, M., Thompson, A., & Mumby, P. J. (2021). Cumulative impacts across Australia's Great Barrier Reef: A mechanistic evaluation. *BioRxiv*.
- Brown, J. R., Moise, A. F., Colman, R., & Zhang, H. (2016). Will a warmer world mean a wetter or drier Australian monsoon? *Journal of Climate*, 29(12), 4577–4596. <https://doi.org/10.1175/JCLI-D-15-0695.1>
- Canuto, V. M., Howard, A., Cheng, Y., & Dubovikov, M. S. (2001). Ocean turbulence. Part I: One-point closure model—Momentum and heat vertical diffusivities. *Journal of Physical Oceanography*, 31(6), 1413–1426.
- Cheung, M. W. M., Hock, K., Skirving, W., & Mumby, P. J. (2021). Cumulative bleaching undermines systemic resilience of the Great Barrier Reef. *Current Biology*. <https://doi.org/10.1016/j.cub.2021.09.078>
- Dey, R., Lewis, S. C., Arblaster, J. M., & Abram, N. J. (2019). A review of past and projected changes in Australia's rainfall. *Wiley Interdisciplinary Reviews: Climate Change*, 10(3), e577.
- Donner, S. D., Skirving, W. J., Little, C. M., Oppenheimer, M., & Hoegh-Guldberg, O. V. E. (2005). Global assessment of coral bleaching and required rates of adaptation under climate change. *Global Change Biology*, 11(12), 2251–2265. <https://doi.org/10.1111/j.1365-2486.2005.01073.x>
- Döscher, R., Acosta, M., Alessandri, A., Anthoni, P., Arneith, A., Arsouze, T., Bergmann, T., Bernadello, R., Bousetta, S., Caron, L.-P., Carver, G., Castrillo, M., Catalano, F., Cvijanovic, I., Davini, P., Dekker, E., Doblas-Reyes, F. J., Docquier, D., Echevarria, P., ... Zhang, Q. (2021). The EC-Earth3 Earth system model for the climate model inter-comparison project 6. *Geoscientific Model Development Discussions*, 2021, 1–90. <https://doi.org/10.5194/gmd-2020-446>
- Eakin, C. M., Morgan, J. A., Heron, S. F., Smith, T. B., Liu, G., Alvarez-Filip, L., Baca, B., Bartels, E., Bastidas, C., Bouchon, C., Brandt, M., Bruckner, A. W., Bunkley-Williams, L., Cameron, A., Causey, B. D., Chiappone, M., Christensen, T. R. L., Crabbe, M. J. C., Day, O., ... Yusuf, Y. (2010). Caribbean corals in crisis: Record thermal stress, bleaching, and mortality in 2005. *PLoS One*, 5(11), e13969. <https://doi.org/10.1371/journal.pone.0013969>
- Egbert, G. D., & Erofeeva, S. Y. (2002). Efficient inverse modeling of barotropic ocean tides. *Journal of Atmospheric and Oceanic Technology*, 19(2), 183–204. [https://doi.org/10.1175/1520-0426\(2002\)019<0183:EIMOBO>2.0.CO;2](https://doi.org/10.1175/1520-0426(2002)019<0183:EIMOBO>2.0.CO;2)
- Enríquez, S., Méndez, E. R., & Prieto, R. I. (2005). Multiple scattering on coral skeletons enhances light absorption by symbiotic algae. *Limnology and Oceanography*, 50(4), 1025–1032. <https://doi.org/10.4319/lo.2005.50.4.1025>
- Frieler, K., Meinshausen, M., Golly, A., Mengel, M., Lebek, K., Donner, S. D., & Hoegh-Guldberg, O. (2013). Limiting global warming to 2°C is unlikely to save most coral reefs. *Nature Climate Change*, 3(2), 165–170.
- Gattuso, J.-P., Magnan, A., Billé, R., Cheung, W. W., Howes, E. L., Joos, F., Allemand, D., Bopp, L., Cooley, S. R., & Eakin, C. M. (2015). Contrasting futures for ocean and society from different anthropogenic CO₂ emissions scenarios. *Science*, 349(6243). <https://doi.org/10.1126/science.aac4722>
- Glynn, P. W., & D'croz, L. (1990). Experimental evidence for high temperature stress as the cause of El Niño-coincident coral mortality. *Coral Reefs*, 8(4), 181–191.
- Great Barrier Reef Marine Park Authority. (2004). *Great Barrier Reef Marine Park Boundary (Version 2)*. Great Barrier Reef Marine Park Authority 2004, Great Barrier Reef Marine 1A604884-6982-4B05-93E3-F025623CB1E3. <http://www.gbrmpa.gov.au/geoportal>
- Great Barrier Reef Marine Park Authority. (2019). *Great Barrier Reef outlook report 2019*. Great Barrier Reef Marine Park Authority.
- Grose, M., Timbal, B., Wilson, L., Bathols, J., & Kent, D. (2015). The subtropical ridge in CMIP5 models, and implications for projections of rainfall in southeast Australia. *Australian Meteorological and Oceanographic Journal*, 65(1), 90–106. <https://doi.org/10.22499/2.6501.007>
- Halloran, P. R., McWhorter, J. K., Arellano Nava, B., Marsh, R., & Skirving, W. (2021). S2P3-R v2. 0: Computationally efficient

- modelling of shelf seas on regional to global scales. *Geoscientific Model Development Discussions*, 14, 6177–6195.
- Heron, S. F., Liu, G., Eakin, C. M., Skirving, W. J., Muller-Karger, F. E., Vega-Rodriguez, M., De La Cour, J. L., Burgess, T. F., Strong, A. E., & Geiger, E. F. (2014). *Climatology development for NOAA Coral Reef Watch's 5-km product suite*. NOAA Technical Report NESDIS, 145.
- Hoegh-Guldberg, O. (1999). Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research*. <https://doi.org/10.1071/mf99078>
- Hoegh-Guldberg, O., Cai, R., Poloczanska, E. S., Brewer, P. G., Sundby, S., Hilmi, K., Fabry, V. J., Jung, S., Skirving, W., Stone, D. A., Currows, M. T., Bell, J., Cao, L., Donner, S., Eakin, M. C., Eide, A., Halpern, B. S., McClain, C. R., O'Connor, M. I., ... McKinnell, S. M. (2014). The Ocean. *Climate change 2014: Impacts, adaptation, and vulnerability* (pp. 1655–1731). Cambridge University Press. <https://hdl.handle.net/10037/6969>
- Hoegh-Guldberg, O., Jacob, D., Bindi, M., Brown, S., Camilloni, I., Diedhiou, A., Djalante, R., Ebi, K., Engelbrecht, F., & Guiot, J. (2018). *Impacts of 1.5°C global warming on natural and human systems*. Global warming of 1.5°C. An IPCC special report.
- Hughes, T. P., Anderson, K. D., Connolly, S. R., Heron, S. F., Kerry, J. T., Lough, J. M., Baird, A. H., Baum, J. K., Berumen, M. L., & Bridge, T. C. (2018). Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science*, 359(6371), 80–83.
- Hughes, T. P., Kerry, J. T., Álvarez-Noriega, M., Álvarez-Romero, J. G., Anderson, K. D., Baird, A. H., Babcock, R. C., Beger, M., Bellwood, D. R., & Berkemans, R. (2017). Global warming and recurrent mass bleaching of corals. *Nature*, 543(7645), 373–377.
- Hughes, T. P., Kerry, J. T., Baird, A. H., Connolly, S. R., Dietzel, A., Eakin, C. M., Heron, S. F., Hoey, A. S., Hoogenboom, M. O., & Liu, G. (2018). Global warming transforms coral reef assemblages. *Nature*, 556(7702), 492–496.
- IPCC. (2018). *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C, above pre-industrial levels and related global greenhouse gas emission pathways, in the context of, strengthening the global response to the threat of climate change, sustainable development, and efforts to, & eradicate poverty* (V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, & T. Waterfield, Eds.). IPCC.
- IPCC. (2019). *IPCC special report on the ocean and cryosphere in a changing climate* (H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, & N. M. Weyer, Eds.). IPCC.
- IPCC. (2021). *Climate change 2021: The physical science basis*. Contribution of Working Group I to the sixth & Assessment Report of the Intergovernmental Panel on Climate Change (V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou, Eds.). Cambridge University Press.
- Jokiel, P. L., & Coles, S. L. (1990). Response of Hawaiian and other Indo-Pacific reef corals to elevated temperature. *Coral Reefs*, 8(4), 155–162. <https://doi.org/10.1007/BF00265006>
- Kent, D. M., Kirono, D. G., Timbal, B., & Chiew, F. H. (2013). Representation of the Australian sub-tropical ridge in the CMIP3 models. *International Journal of Climatology*, 33(1), 48–57. <https://doi.org/10.1002/joc.3406>
- King, A. D., Karoly, D. J., & Henley, B. J. (2017). Australian climate extremes at 1.5°C and 2°C of global warming. *Nature Climate Change*, 7(6), 412–416.
- Lenth, R., Singmann, H., Love, J., Buerkner, P., & Herve, M. (2018). Emmeans: Estimated marginal means, aka least-squares means. *R Package Version*, 1(1), 3.
- Logan, C. A., Dunne, J. P., Ryan, J. S., Baskett, M. L., & Donner, S. D. (2021). Quantifying global potential for coral evolutionary response to climate change. *Nature Climate Change*. <https://doi.org/10.1038/s41558-021-01037-2>
- Lough, J. M., Anderson, K. D., & Hughes, T. P. (2018). Increasing thermal stress for tropical coral reefs: 1871–2017. *Scientific Reports*, 8(1), 1–8. <https://doi.org/10.1038/s41598-018-24530-9>
- MacMartin, D. G., Ricke, K. L., & Keith, D. W. (2018). Solar geoengineering as part of an overall strategy for meeting the 1.5°C Paris target. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 376(2119), 20160454.
- Marsh, R., Hickman, A. E., & Sharples, J. (2015). S2P3-R (v1. 0): A framework for efficient regional modelling of physical and biological structures and processes in shelf seas. *Geoscientific Model Development*, 8(10), 3163–3178.
- McGowan, H., & Theobald, A. (2017). ENSO weather and coral bleaching on the Great Barrier Reef, Australia. *Geophysical Research Letters*, 44(20), 10601–10607. <https://doi.org/10.1002/2017GL074877>
- Mumby, P. J., Elliott, I. A., Eakin, C. M., Skirving, W., Paris, C. B., Edwards, H. J., Enríquez, S., Iglesias-Prieto, R., Cherubin, L. M., & Stevens, J. R. (2011). Reserve design for uncertain responses of coral reefs to climate change. *Ecology Letters*, 14(2), 132–140. <https://doi.org/10.1111/j.1461-0248.2010.01562.x>
- O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., & Sanderson, B. M. (2016). The scenario model intercomparison project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, 9(9), 3461–3482. <https://doi.org/10.5194/gmd-9-3461-2016>
- Reaser, J. K., Pomerance, R., & Thomas, P. O. (2000). Coral bleaching and global climate change: Scientific findings and policy recommendations. *Conservation Biology*, 14(5), 1500–1511. <https://doi.org/10.1046/j.1523-1739.2000.99145.x>
- Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., Kc, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., ... Tavoni, M. (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, 42, 153–168. <https://doi.org/10.1016/j.gloenvcha.2016.05.009>
- Rogelj, J., Luderer, G., Pietzcker, R. C., Kriegler, E., Schaeffer, M., Krey, V., & Riahi, K. (2015). Energy system transformations for limiting end-of-century warming to below 1.5°C. *Nature Climate Change*, 5(6), 519–527. <https://doi.org/10.1038/nclimate2572>
- Sanderson, B. M., O'Neill, B. C., & Tebaldi, C. (2016). What would it take to achieve the Paris temperature targets? *Geophysical Research Letters*, 43(13), 7133–7142. <https://doi.org/10.1002/2016GL069563>
- Schleussner, C.-F., Lissner, T. K., Fischer, E. M., Wohland, J., Perrette, M., Golly, A., Rogelj, J., Childers, K., Schewe, J., & Frieler, K. (2016). Differential climate impacts for policy-relevant limits to global warming: The case of 1.5°C and 2°C. *Earth System Dynamics*, 7(2), 327–351.
- Séférian, R., Nabat, P., Michou, M., Saint-Martin, D., Voldoire, A., Colin, J., Decharme, B., Delire, C., Berthet, S., Chevallier, M., Sénéci, S., Franchisteguy, L., Vial, J., Mallet, M., Joetzier, E., Geoffroy, O., Guérémy, J.-F., Moine, M.-P., Msadek, R., ... Madec, G. (2019). Evaluation of CNRM Earth System Model, CNRM-ESM2-1: Role of Earth system processes in present-day and future climate. *Journal of Advances in Modeling Earth Systems*, 11(12), 4182–4227. <https://doi.org/10.1029/2019MS001791>
- Sellar, A. A., Jones, C. G., Mulcahy, J. P., Tang, Y., Yool, A., Wiltshire, A., O'Connor, F. M., Stringer, M., Hill, R., Palmieri, J., Woodward, S., Mora, L., Kuhlbrodt, T., Rumbold, S. T., Kelley, D. I., Ellis, R., Johnson, C. E., Walton, J., Abraham, N. L., ... Zerroukat, M. (2019). UKESM1: Description and evaluation of the UK Earth System Model. *Journal*

- of *Advances in Modeling Earth Systems*, 11(12), 4513–4558. <https://doi.org/10.1029/2019MS001739>
- Sharples, J., Ross, O. N., Scott, B. E., Greenstreet, S. P., & Fraser, H. (2006). Inter-annual variability in the timing of stratification and the spring bloom in the North-western North Sea. *Continental Shelf Research*, 26(6), 733–751. <https://doi.org/10.1016/j.csr.2006.01.011>
- Shukla, P. R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H. O., Roberts, D. C., Zhai, P., Slade, R., Connors, S., & Van Diemen, R. (2019). *IPCC, 2019: Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. Intergovernmental Panel on Climate Change (IPCC).
- Skirving, W., Heron, S. F., Marsh, B. L., Liu, G., De La Cour, J. L., Geiger, E. F., & Eakin, C. M. (2019). The relentless march of mass coral bleaching: A global perspective of changing heat stress. *Coral Reefs*, 38(4), 547–557. <https://doi.org/10.1007/s00338-019-01799-4>
- Skirving, W., Marsh, B., De La Cour, J., Liu, G., Harris, A., Maturi, E., Geiger, E., & Eakin, C. M. (2020). CoralTemp and the coral reef watch coral bleaching heat stress product suite version 3.1. *Remote Sensing*, 12(23), 3856. <https://doi.org/10.3390/rs12233856>
- Smith, S. D., & Banke, E. G. (1975). Variation of the sea surface drag coefficient with wind speed. *Quarterly Journal of the Royal Meteorological Society*, 101(429), 665–673. <https://doi.org/10.1002/qj.49710142920>
- Stocker, T. (2014). *Climate change 2013: The physical science basis: Working group I contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
- Van Hooidonk, R., Maynard, J., Tamelander, J., Gove, J., Ahmadi, G., Raymundo, L., Williams, G., Heron, S. F., & Planes, S. (2016). Local-scale projections of coral reef futures and implications of the Paris Agreement. *Scientific Reports*, 6(1), 1–8. <https://doi.org/10.1038/srep39666>
- Van Oppen, M. J., & Medina, M. (2020). Coral evolutionary responses to microbial symbioses. *Philosophical Transactions of the Royal Society B*, 375(1808), 20190591. <https://doi.org/10.1098/rstb.2019.0591>
- Walsworth, T. E., Schindler, D. E., Colton, M. A., Webster, M. S., Palumbi, S. R., Mumby, P. J., Essington, T. E., & Pinsky, M. L. (2019). Management for network diversity speeds evolutionary adaptation to climate change. *Nature Climate Change*, 9(8), 632–636. <https://doi.org/10.1038/s41558-019-0518-5>
- Wilkinson, C. R., & Souter, D. (2008). *Status of Caribbean coral reefs after bleaching and hurricanes in 2005*. Status of coral reefs of the world. NOAA Institutional Repository. <https://repository.library.noaa.gov/view/noaa/486>
- Wood, S. N. (2017). *Generalized additive models: An introduction with R*. CRC Press.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: McWhorter, J. K., Halloran, P. R., Roff, G., Skirving, W. J., Perry, C. T., & Mumby, P. J. (2022). The importance of 1.5°C warming for the Great Barrier Reef. *Global Change Biology*, 28, 1332–1341. <https://doi.org/10.1111/gcb.15994>