

MS. JENNIFER KRIS MCWHORTER (Orcid ID : 0000-0003-1297-6599)

PROF. CHRIS PERRY (Orcid ID : 0000-0001-9398-2418)

PROF. PETER J MUMBY (Orcid ID : 0000-0002-6297-9053)

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

Jennifer K. McWhorter^{a,b*}, Paul R. Halloran^b, George Roff^a, William J. Skirving^{c,d}, Chris T. Perry^b, Peter J. Mumby^a

^a *Marine Spatial Ecology Lab, School of Biological Sciences & ARC Centre of Excellence for Coral Reef Studies, University of Queensland, St Lucia, Qld 4072, Australia.*

^b *University of Exeter, College of Life and Environmental Sciences*

^c *Coral Reef Watch, National Oceanic and Atmospheric Administration*

^d *ReefSense Pty Ltd*

ORCID iDs

Jennifer K. McWhorter - 0000-0003-1297-6599

Paul R. Halloran - 0000-0002-9227-0678

George Roff - 0000-0002-2823-0575

William J. Skirving - 0000-0003-0167-6427

Chris T. Perry – 0000-0001-9398-2418

Peter J. Mumby - 0000-0002-6297-9053

Corresponding author

Jennifer K. McWhorter +17326788744, jm953@exeter.ac.uk

ABSTRACT

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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 IPCC 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°C and 2°C global warming targets on coral thermal stress metrics for the Great Barrier Reef. 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 DHW). Thermal stress under the more pessimistic pathways SSP3-7.0 and SSP5-8.5 is 3- to 4-fold higher than 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 Great Barrier Reef than the far north and northern Great Barrier Reef.

Keywords

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

Introduction

Global average temperatures have increased by $\sim 1^{\circ}\text{C}$ since the 1880s, with the ocean surface warming by $\sim 0.11^{\circ}\text{C}$ per decade [CI 0.09 to 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°C , 0.85°C 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; Hughes et al., 2018b; Skirving et al., 2019) and severity, resulting in the deterioration of global coral ecosystems (Wilkinson & Souter, 2008). Recent mass coral bleaching events on the GBR (1998, 2002, 2016, 2017, 2020) occurred as a result of thermal stress (GBRMPA, 2019; Bozec et al., In press; Eakin et al., 2010; Hughes et al., 2017; Hughes et al., 2018b), often after several weeks of temperatures exceeding their usual summer temperature by 1° to 2°C (Berkelmans & Willis, 1999; Glynn & D'croz, 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 et al., 2018b). 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, et al., 2018b).

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 one third across the entire GBR (Bozec et al., In press) to 50% in shallow waters after the 2016 event alone (Hughes et al 2017). Moreover, Cheung et al (2021) estimated that average supply of coral larvae to reefs could have declined by 70% (Cheung et al., In press).

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; IPCC, 2019; IPCC, 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; IPCC, 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) estimates 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° vs 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 methods) to a resolution of 10 km using 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 et al., 2017; Hughes et al., 2018a). 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.

Materials and Methods

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 forcing's 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 4-50m water depth, at a 10km horizontal resolution and 2m 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), IPSL-ESM2-0 (Boucher et al., 2020). Sea surface temperature data were output daily from 1950-2100 (inclusive) and masked to contain values just within the Great Barrier Reef Marine Park Authority Boundary (GBRMPA, 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 1m 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 vertical density (Canuto et al., 2001). Importantly, 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).

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., In press; Hughes et al., 2017; Hughes et al., 2018a; 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 annual maximum DHW, calendar years were modified to be centred 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).

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 to 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, e.g., 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)

Degree Heating Week 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.

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 timeseries was then averaged using all models within each scenario resulting in an ensemble mean per scenario and scaled to a decade.

Statistical analysis.

We used generalised 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. Longitude and latitude of each grid cell (n = 1100 cells) was 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 DHWs (*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 (GBRMPA, 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.

Results

Magnitude of thermal stress.

The magnitude of thermal stress upon GBR corals intensifies dramatically over time, particularly under scenarios which excludes 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 3- to 4-fold 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., In press; Hughes, Kerry, et al., 2018). In contrast, long-term projections under a scenario built around global collaboration on climate policy targeting a 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; Fig. 1c).

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, Figure 1d, 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, Figure 1c). 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 a 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 2051-2061 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 2014-2025 (inclusive).

Regional magnitude of thermal stress under low emissions.

As warming continues in the 21st century, the magnitude of DHWs 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 $\sim 1-3$ DHWs in 2060 (Figure 2a, Table 1c, Table 1d).

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 southern and central 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 southern and central GBR relative to the far north and northern GBR (Figure 2b, Table 1c, Table 1d). 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 year 2060 under SSP1-1.9 the far north/northern regions can expect ~0.50 severe bleaching events/decade less than central/southern regions (Figure 2b, Table 1a). While SSP1-2.6 also shows the same latitudinal separation, the far north/northern regions project ~1 severe bleaching year/decade less than central/southern regions in 2060 (Figure 2b, Table 1b).

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 examine the more ambitious socio-economic pathways, utilise the latest generation of climate models, downscale the results to account for the influence of local bathymetry and tides, and to 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 skilful 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). Therefore, not simulated are the effects of the South Equatorial currents, 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. Third 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 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., In press; Cheung et al., In press). This is because not all reefs bleach during a given event (Hughes et al., 2018b; 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).

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

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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 & editing: JKM, PJM, PRH, GR, WJS, CTP

Table 1. The values for each region, far north, north, central, and south GBR, 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.

(a)

SSP1-1.9, Year 2060		
Region	DHW \pm SE	Frequency \pm SE
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		
Region	DHW \pm SE	Frequency \pm SE
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		
Region	DHW \pm SE	Frequency \pm SE
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		
Region	DHW \pm SE	Frequency \pm SE
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

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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,b,c,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.

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.

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

Table 1. The values for each region, far north, north, central, and south GBR, 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.

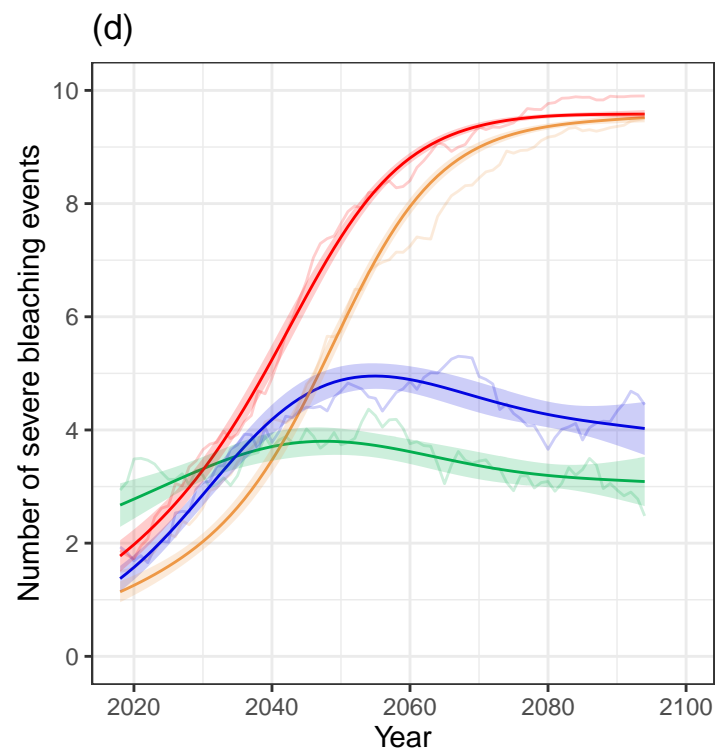
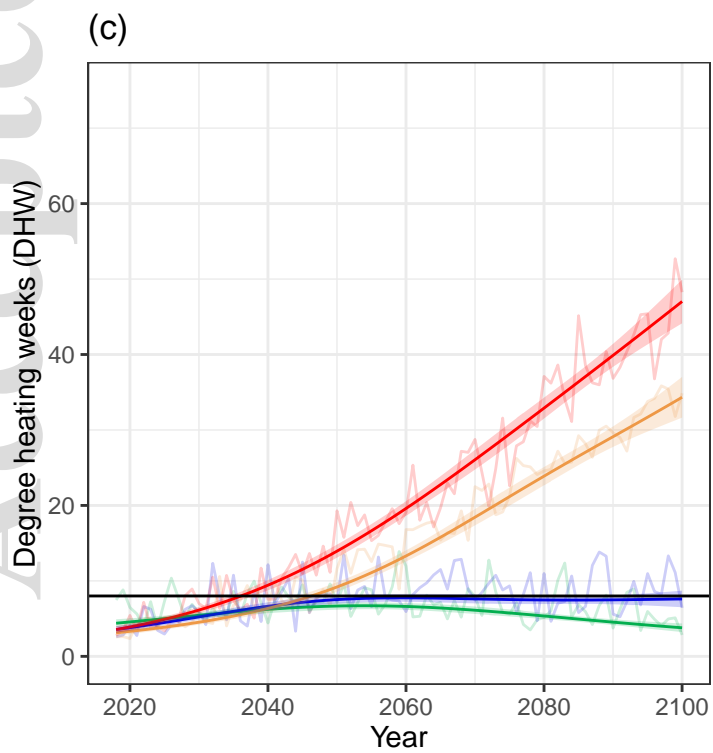
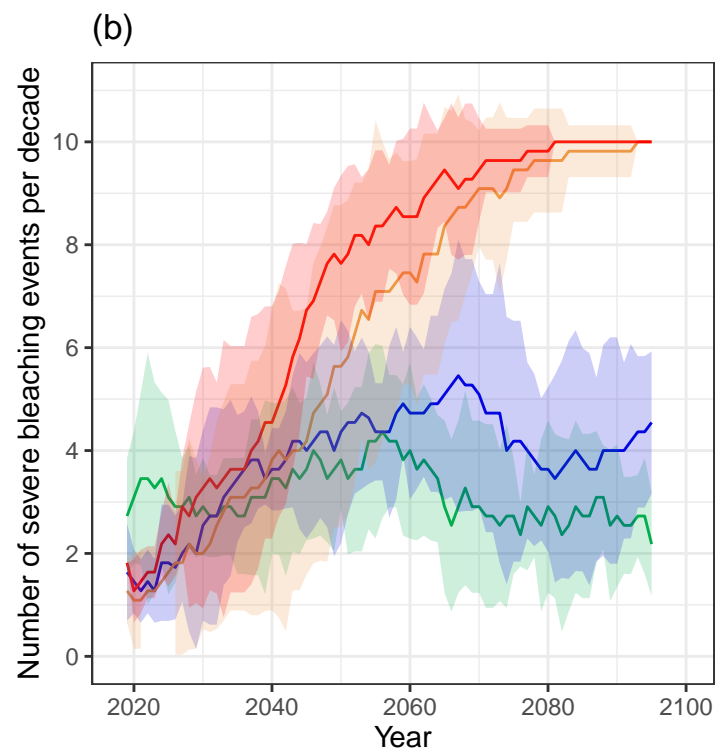
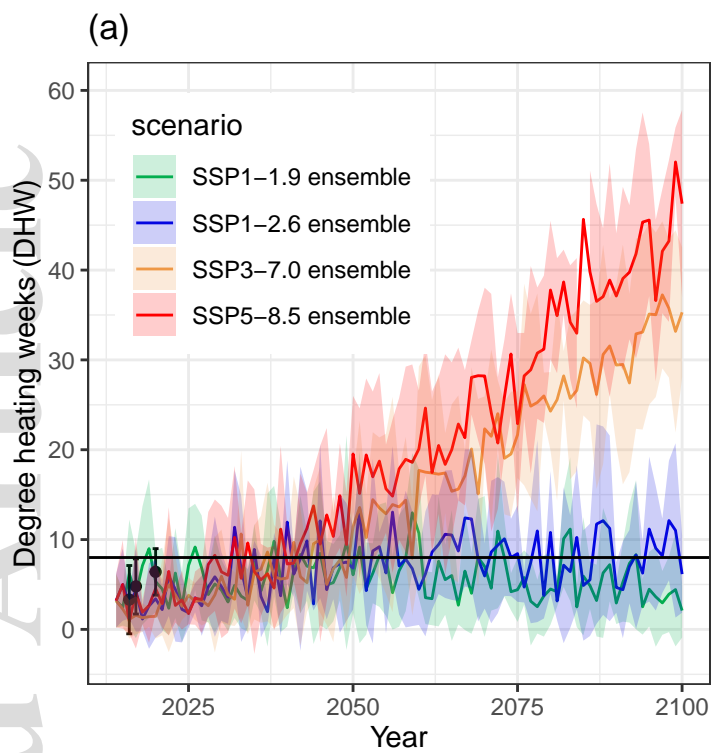
Table S1. Present-day average intensities of coral bleaching stress on reefs of the Great Barrier Reef expressed in units of Degree Heating Weeks (DHW) as determined from satellite surface temperature (SST). Std denotes standard deviation.

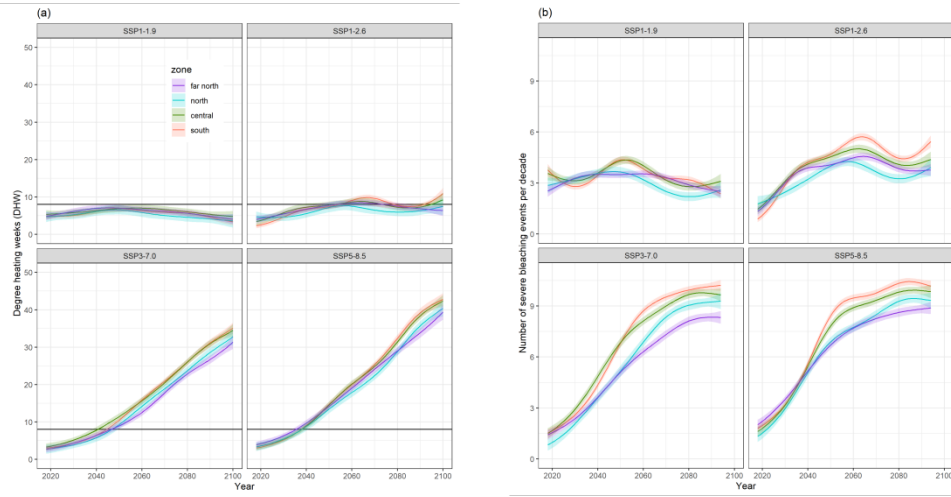
Table S2. Complementary to Figure 1c, and Figure 1d, this table shows main effects and pairwise comparisons from generalized additive mixed effects models for degree heating weeks and mean frequency of severe bleaching years per decade for 2060.

Table S3. Complementary to Figure 2a, and Figure 2b, these tables show the main effects and pairwise comparisons from generalized additive mixed effects models for degree heating weeks and mean frequency of severe bleaching years per decade for 2060 between regions by scenario.

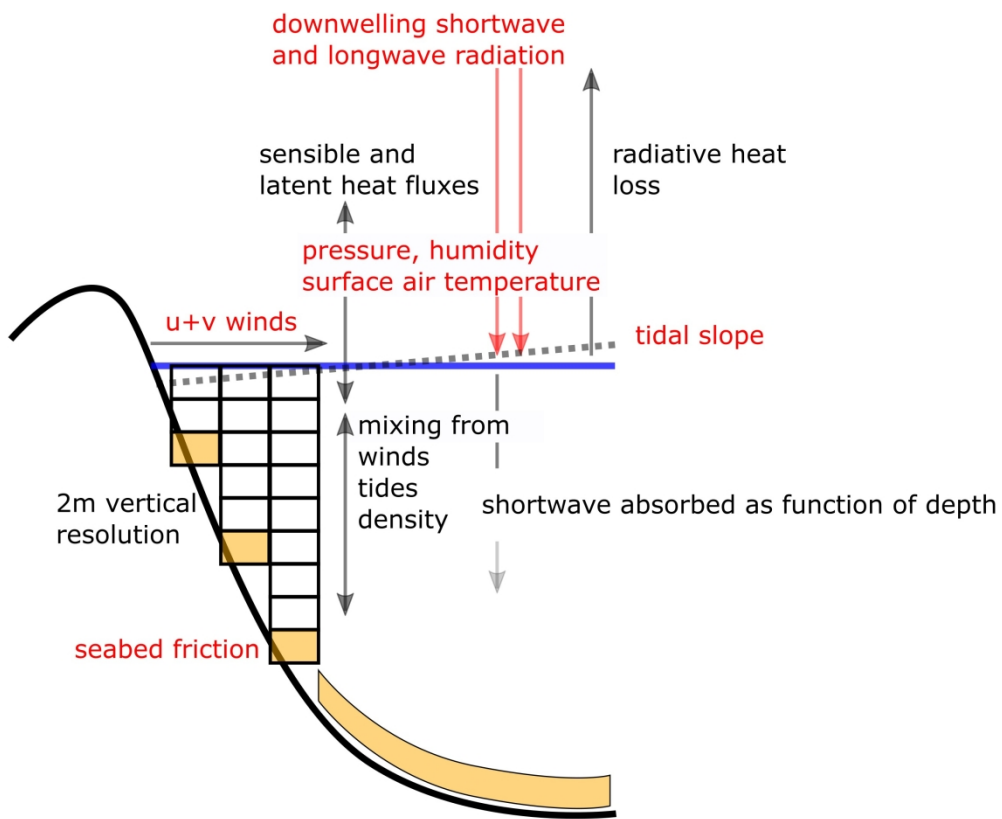
Supplementary Figure 2. The trends for SSP1-1.9 and SSP1-2.6 as well as the differences between these two scenarios are shown for (a) mean Degree Heating Weeks (DHW) and (b)

mean frequency of severe bleaching per decade relative to the maximum monthly mean from 1985-2012 (inclusive). The shaded areas represent the standard deviation.





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red = prescribed quantity
black = modelled quantity/process

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