ADVANCING EARTH AND SPACE SCIENCE

Earth's Future

RESEARCH ARTICLE

10.1029/2021EF002600

# Coral Reef Exposure to Damaging Tropical Cyclone Waves in a Warming Climate

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**Key Points:**

- Wave damage to coral communities from tropical cyclones depends on their intensity, size and duration while tracking near coral reefs
- Downscaled tracks capture observed cyclone characteristics impacting the Great Barrier Reef with mixed to poor performance in other regions
- Projections vary by region and cyclone characteristic with some models projecting increases and others decreases in future reef damage

**Supporting Information:**

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

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**Citation:**

Dixon, A. M., Puotinen, M., Ramsay, H. A., & Beger, M. (2022). Coral reef exposure to damaging tropical cyclone waves in a warming climate. *Earth's Future*, *10*, e2021EF002600. https://doi.org/10.1029/2021EF002600

Received 10 DEC 2021
Accepted 30 JUN 2022

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**Abstract** Tropical cyclones generate large waves that physically damage coral communities and are commonly cited as a worsening threat to coral reefs under climate change. However, beyond projections of ocean basin-scale changes in cyclone intensity, the other determinants of future coral reef damage such as cyclone size and duration remain uncertain. Here, we determine the extent to which downscaled cyclones represent observed cyclone characteristics that influence wave damage to Australian coral reef regions. We then investigate mid-century (2040–2060) and end of century (2080–2100) downscaled tracks to assess whether cyclone characteristics will change with future warming under a high-emissions scenario. We find that spatial uncertainties in downscaled cyclogenesis and track positions limit estimates of reef damage for individual coral reefs and regions. Further, the models are unable to reproduce the most reef damaging cyclones for any of the regions. The downscaled tracks capture observed cyclone characteristics, such as size, impacting the Great Barrier Reef well, but perform poorly for the Northern Territory, with mixed performance for the Coral Sea and Western Australia. We find no clear evidence that cyclones will cause more damage to Australian coral reef regions in the future, at least based on the climate models and downscaling approach examined here. There is increasing interest in using tropical cyclone projections to assess future coral reef exposure to damaging waves. We recommend caution when interpreting such projections due to large uncertainty in the mechanisms that influence reef damaging tropical cyclone characteristics and how these will change with future warming.

**Plain Language Summary** Tropical cyclone intensity, size and duration together determine the extent to which their waves damage coral reefs. Increased tropical cyclone intensity with climate change is often cited as evidence that tropical cyclones will cause more damage to coral reefs in the future but changes to size and duration remain uncertain. Here, we determine whether tropical cyclones simulated from climate models can represent the observed tropical cyclone characteristics that are important for estimating wave damage to coral reefs and assess how these characteristics might change in the future. We find that the tropical cyclones simulated from climate models capture the observed cyclone characteristics well for those impacting the Great Barrier Reef (with the exception of the most damaging cyclones) with mixed to poor performance for other regions. The projections of future reef damage are uncertain with some models projecting increases and others decreases. Tropical cyclone projections are used in conservation planning to identify and protect the coral reefs least exposed to future tropical cyclones. However, we find that the simulated tropical cyclone tracks explored here are unlikely to represent future reef damaging tropical cyclone characteristics well if used in conservation decision making.

## 1. Introduction

Tropical cyclones are often a key driver of coral reef condition where they commonly occur (De'ath et al., 2012; Zinke et al., 2018), potentially thwarting conservation success if not considered in management decisions. For example, protecting sites least exposed to thermal stress and able to provide larval recruits to other vulnerable reefs as a strategy for enhancing coral reef survival (Beyer et al., 2018) will fail if such sites are subjected to frequent and severe wave damage from tropical cyclones. The threat of tropical cyclones is rising as the increased severity and spatial extent of other stressors impedes recovery from storm damage (Blackwood et al., 2011; Dietzel et al., 2021). Conservation plans need to consider multiple environmental dimensions of climate change (Dixon et al., 2021; Groves et al., 2012) because climate change can lead to ecosystem collapse (Newton et al., 2021). For coral reefs, a key part of this is to identify the management areas experiencing the most damaging tropical

**Writing – review & editing:** Adele M. Dixon, Marji Puotinen, Hamish A. Ramsay, Maria Beger

cyclones now and in the future. Thus, there is increasing interest in the use of future simulated tracks in coral reef vulnerability assessments and conservation planning, though there has been no assessment of their suitability nor their ability to project robust changes in reef damage at the coral reef region scale. Here, we examined to what degree simulated historical cyclone tracks likely capture the key characteristics that underpin a cyclone's ability to damage reefs, assuming vulnerable colonies are present. Secondly, we determined whether robust changes in reef damaging tropical cyclone characteristics are projected at the scale of coral reef regions in tropical Australia.

Despite being localized short-term individual events, repeated tropical cyclones can cause long-term damage to coral reefs across broad scales. Recovery from this can take decades to centuries (Harmelin-Vivien, 1994), especially if damage affects the physical structure of the reef (Hughes & Connell, 1999) or recovery is impeded by other disturbances (Hughes, 1994). Yet, spatial variability in coral reef exposure to tropical cyclone waves at both local and regional scales means that damage is patchy (Beyer et al., 2018; Gilmour et al., 2019; Maynard et al., 2016; Puotinen et al., 2016; Wolff et al., 2016; Zinke et al., 2018), not least because equatorial coral reefs are outside the geographic range where tropical cyclones track (Puotinen et al., 2020). Tropical cyclones degrade coral reef ecosystems in various ways (Harmelin-Vivien, 1994). Heavy rainfall and flooding lowers salinity and increases nutrient concentration and terrestrial sediment influx, and large waves cause sediment resuspension and physical damage. Physical damage to coral communities ranges from breakage of branches in the most vulnerable and delicate species to the removal of entire sections of the reef structure (Beeden et al., 2015; Harmelin-Vivien, 1994; Puotinen et al., 2016).

The severity of physical damage from waves is dependent on storm characteristics such as intensity, size, duration and translation speed (Puotinen et al., 2020) as well as local-scale reef characteristics such as depth, structural complexity, community type and disturbance history (Blackwood et al., 2011; Harmelin-Vivien, 1994). At the coral colony scale, damage is always patchy because the individual characteristics (morphology, size) and spatial arrangement of colonies determine the extent to which physical damage from a potentially damaging wave climate actually occurs (Madin & Connolly, 2006). The worst possible wave damage can be expected from cyclones that are intense, large, and slow-moving with long-lived tracks that persist near reefs. This damage is most fully realized for vulnerable colonies within reef communities that are compromised by other stressors or are not routinely exposed to a high energy wave regime (Madin & Connolly, 2006). Tropical cyclone-induced wave damage can be exacerbated by other climate stressors, for example, where ocean acidification weakens coral skeletons and thus increases their vulnerability to physical damage (Madin et al., 2012).

Global climate models project increases in the frequency and severity of thermal stress events in coral reef regions in the future (Dixon et al., 2022). Though tropical cyclone projections have existed for coral reef regions for many years, they have focused on global and ocean basin-scale trends in tropical cyclone frequency and intensity (Emanuel et al., 2008; Knutson et al., 2013). At the global scale, there is medium to high confidence that the average tropical cyclone peak intensity and the proportion of storms that reach high intensity will increase in the future with climate change, but trends in the remaining tropical cyclone characteristics that influence wave-induced reef damage are less certain (Knutson et al., 2020). Future changes to translation speed are equivocal; one study has projected a significant decrease (Gutmann et al., 2018), while others project no change (Kim et al., 2014; Knutson et al., 2013; Wu et al., 2014). Projected changes in tropical cyclone size are also highly variable between studies: some studies project increases in some basins (Kim et al., 2014; Knutson et al., 2015; Yamada et al., 2017), and decreases in others (Knutson et al., 2015; Yamada et al., 2017), while other studies project no change (Gutmann et al., 2018).

The projected global and basin-scale increases in tropical cyclone intensity are often cited as evidence of greater tropical cyclone-induced coral reef damage with future climate change (Cheal et al., 2017; França et al., 2020; Gilmour et al., 2019; Harvey et al., 2018), but there are two key gaps in knowledge undermining this statement. First, global and basin-scale changes in tropical cyclone characteristics do not capture spatial variation in future tropical cyclone exposure within and between coral reef regions. For example, whether the projected increase in intensity differs between the coral reef regions within an ocean basin is unknown, much less between individual reefs. Second, a projected increase in intensity alone does not provide a complete picture of the future potential for coral reef damage as size, duration and location of tropical cyclone tracks also determine the coral reef wave damage severity and extent. For example, tropical cyclones may be more intense in the future but no longer track as close to coral reefs, be as large in size or move as slowly.

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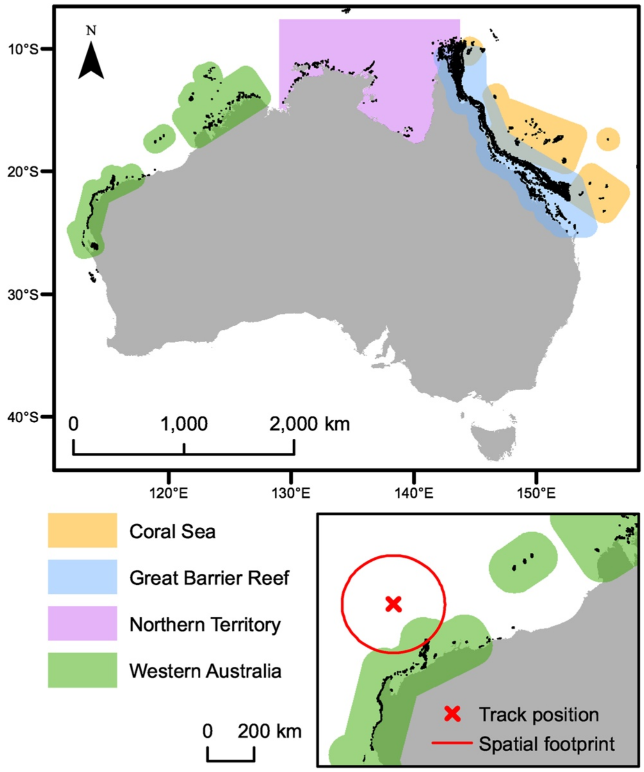


**Figure 1.** Map of Australia showing 100 km boundaries around the Coral Sea, Great Barrier Reef and Western Australia coral reef areas and the entire Northern Territory region. Coral reef areas are shown in black. The bottom panel shows a track position with its spatial footprint (maximum radius to gales) intersecting with the Western Australia region.

Vital for assessing damage potential to coral reefs is understanding where cyclones are likely to form and track. Numerous factors influence tropical cyclone formation including sea surface temperature, vertical wind shear, mid-level moisture and the Coriolis parameter (Emanuel, 2003). The link between tropical cyclone formation and climate is not fully understood, making projected changes in tropical cyclone formation with future climate change uncertain (Sobel et al., 2021; Walsh et al., 2016). Where a tropical cyclone tracks, and how quickly, is influenced by synoptic-scale atmospheric circulations, including major subtropical high pressure systems (Camp et al., 2019; Chan & Gray, 1982; Chu et al., 2012). Where a tropical cyclone tracks can affect its intensity and lifetime, as high sea surface temperature can cause a cyclone to intensify while low sea surface temperature, high wind shear and landfall can cause tropical cyclones to weaken and dissipate (Emanuel, 2003). Hence, the ability of climate models to project future changes in tropical cyclone characteristics hinges on the accurate simulation of the many mechanisms affecting the tropical cyclone life cycle.

Future changes to tropical cyclone characteristics are commonly estimated at global or ocean basin (e.g., South Pacific Ocean) scales. Only once have any projections of future changes for individual coral reef regions been undertaken (Great Barrier Reef, where Callaghan et al. (2020) used the HADGEM model to assess the extent to which reefs prevent coastal erosion from cyclones). We build upon that work to assess the current and future potential for cyclone waves to damage reefs based on a suite of six CMIP5 climate models and extending the study region to all of tropical northern Australia. Ideally, a numerical wave model would be used to simulate nearshore wave climates for future cyclones using high resolution bathymetry as per Callaghan et al. (2020) for the full suite of climate models and for all regions. However, running numerical wave analysis for large sets (thousands) of historical and future simulated tracks is computationally and time intensive, the requisite bathymetry data does not yet exist for Western Australia nor the Northern Territory, and model performance for the full suite of climate models has not yet been assessed. We therefore examined whether downscaled tropical cyclones (Emanuel et al., 2006, 2008) derived from historical climate model output can capture observed regional variability in individual potential reef damaging tropical cyclone characteristics such as intensity, size and duration near reefs. We used tropical Australia as a case study, as its northern coastlines are frequently exposed to tropical cyclone impacts (Chand et al., 2019) and there is regional variability in coral reef exposure to cyclone generated waves (Great Barrier Reef—Maynard et al., 2016; Puotinen et al., 2016; Western Australia—Gilmour et al., 2019; all tropical Australia—Puotinen et al., 2020). We then compared regional tropical cyclone reef damaging characteristics between the past and future climates under the high-emissions Representative Concentration Pathway (RCP) 8.5 scenario.

## 2. Materials and Methods

### 2.1. Calculating Observed Reef Damaging Tropical Cyclone Metrics

We identified tropical cyclones with the potential to have generated waves capable of damaging tropical coral reefs, henceforth called "reef damaging" cyclones, as those where the cyclone circulation (defined as maximum radius to gale force winds (~17 m/s) in any sector mapped around the cyclone track position each hour) intersects a 100 km boundary around any of three regional coral reef regions (Coral Sea, Great Barrier Reef and Western Australia; Figure 1)—termed the track position's spatial "footprint." This extends work done previously for the Great Barrier Reef (Wolff et al., 2018) by explicitly mapping how the size of the cyclone (the spatial footprint) varies along the track and intersecting that with the coral reef regions instead of assuming damage is possible at any reef within a uniform zone around each cyclone track. The 100 km zone was added to conservatively account for positional uncertainty in recorded cyclone track positions. In the satellite era (post 1970), such uncertainty is less than 150 km, and less than 50 km where the tropical cyclone has a clearly defined eye (D. Herndon, personal communication). We included a fourth region, Northern Territory, but due to uncertainty regarding the location of coral reefs in the Northern Territory we used the entire region rather than a 100 km buffer around the reef area (Figure 1).

Though cyclones can generate freshwater flood plumes whose lowered salinity and light-blocking turbidity can adversely affect coral communities (Brodie et al., 2012), here we limited our consideration to physical damage to corals from cyclone generated waves. As the magnitude of a given sea state depends on the combination of wind speed, duration and fetch (distance over which winds can blow consistently unobstructed), three key characteristics of cyclones contribute most to their potential to generate seas capable of damaging reefs: intensity, size of circulation, and duration near reefs (Puotinen et al., 2020). For each incidence of a tropical cyclone's spatial footprint intersecting a coral reef region between 1985 and 2020, the following three reef damaging tropical cyclone characteristics were calculated: maximum intensity, maximum radius to gales and duration of gales. Best track data prior to the early 1980s has a high number of missing records and tends to underestimate intensity (Ramsay et al., 2012). We further applied a reef damage index (*RDI*) that uses all three characteristics to estimate damage potential based on field data of past cyclone damage of reefs predominantly in the Great Barrier Reef (Table S1 in Supporting Information S1).

The three metrics were calculated only for the cyclone track positions located along the section of tracks whose spatial footprint intersects with the reef regions. The maximum intensity was calculated using the maximum 10-min wind speed extracted from the International Best Track Archive for Climate Stewardship (IBTrACS) (Knapp et al., 2010, 2018). The maximum radius to gales was calculated using the maximum distance from the cyclone eye to gale force winds at 17 m/s in any of the four geographic quadrants, reported in IBTrACS. Where the radius to gales was missing in IBTrACS, the maximum radius to gales from the Bureau of Meteorology database was used. Where the radius to gales was missing in both data sources, the basin average (210 km) was used (Chavas & Emanuel, 2010). Using a basin rather than a regional average avoids the modifiable areal unit problem where the average radius to gales may change depending on where the regional boundaries are drawn. The duration of gales is the number of days a tropical cyclone's spatial footprint intersects with a reef region while the maximum wind speed is greater than 17 m/s.

The reef damage index (*RDI*) was used to estimate the overall potential for reef damage from waves (assuming vulnerable corals are present) for each tropical cyclone track while impacting a region. The index is calculated by:

$$RDI = \left(\frac{MI}{MI_{\max}}\right) * \left(\frac{RG}{RG_{\max}}\right) * \left(\frac{DG}{DG_{\max}}\right) * 100$$

where $MI$ is the maximum intensity, $RG$ is the maximum radius to gales and $DG$ is the duration of gales. The reef damage index is a reasonable estimate of the reef damage potential of a tropical cyclone when compared to field data for nine cyclones from the Great Barrier Reef and Western Australia (Table S1 in Supporting Information S1).

The greatest potential for wave damage comes from a cyclone that is simultaneously intense, slow moving, large and generates gales for a long time within a reef region. No recorded cyclone in any of the Australian coral reef provinces has met all of these criteria. Cyclone Yasi in 2011 on the Great Barrier Reef (Beeden et al., 2015) and Cyclone Lua in 2012 in Western Australia (Puotinen et al., 2020) were simultaneously both intense and large, but not slow-moving. Cyclone Hamish in 2009 on the Great Barrier Reef generated gales near an unprecedented number of reefs due to its unusual track while it maintained high intensity, but it was not large (Puotinen et al., 2016). We categorized the tropical cyclone track position spatial footprints that intersect with the four Australian coral reef regions into four very damaging categories (Table 1) and one category containing all others. The translation speed was calculated using the distance between consecutive track positions (length of great circle arc between coordinates of track positions) divided by the time between the recorded track positions.

### 2.2. Calculating Downscaled Reef Damaging Tropical Cyclone Metrics

Tropical cyclone intensity is measured by maximum wind speeds, which occur over a relatively small area at the boundary of the cyclone eye. As most cyclone eye radii in the Australian region range between 10 and 40 km, accurately identifying and assessing cyclones from a global climate model requires relatively high spatial resolution (~20 km or less). This requirement combined with the fact that many tropical cyclones are short-lived, makes

**Table 1**
*The Four Reef Damaging Categories of Track Positions*

| Category | Name | Description |
|---|---|---|
| 1 | Intense and large | Maximum wind speed >33 m/s and radius to gales >275 km |
| 2 | Intense and slow-moving | Maximum wind speed >33 m/s and translation speed <5 m/s |
| 3 | Large and slow-moving | Radius to gales >275 km and translation speed <5 m/s |
| 4 | Intense, large and slow-moving | Maximum wind speed >33 m/s, radius to gales >275 km and translation speed <5 m/s |

their simulation by relatively coarse scale global climate models difficult (Knutson et al., 2010). The high spatial resolution necessary to simulate intense tropical cyclones can be obtained by dynamical and statistical-dynamical downscaling. Downscaling is thus commonly used to simulate observed tropical cyclones and examine basin-scale trends in tropical cyclone frequency and intensity (Camargo et al., 2008; Emanuel, 2006; Emanuel et al., 2008; Knutson et al., 2013, 2015; Villarini et al., 2011).

Here, we obtained downscaled tropical cyclone tracks (commonly referred to as "synthetic tracks") derived from six CMIP5 climate models (Table S2 in Supporting Information S1) from K. Emanuel (Emanuel, 2013) for the simulated historical (1985–2005), mid-century (2040–2060) and end of century (2080–2100) time periods under the RCP8.5 high-emission scenario. The tracks were downscaled using a statistical-dynamical technique. Detail on how the tracks were generated is described in Emanuel et al. (2006) and Emanuel et al. (2008). These simulations were used here due to the large number of downscaled tracks ($n = 3{,}000$) for historical, mid-century and end of century. These tracks provide robust statistics for predicting changes in tropical cyclone characteristics, especially for the less common but most destructive storms (Emanuel et al., 2006). Further, the tracks have demonstrated applicability to the Australia region (Ramsay et al., 2018) and mid-century tracks are available. Mid-century tracks are more relevant for coral reef timescales than the commonly used 2080–2100 future tracks, given the expected near-term decline of coral reefs due to climate warming (Dixon et al., 2022; Hughes et al., 2017). Finally, the downscaled tracks respond to the physics of climate change, for example, responding to changes in atmospheric water vapor, sea surface temperature and wind shear. The evolution of these large-scale, tropical cyclone-relevant parameters in CMIP5 models will therefore be reflected in the future tracks (Emanuel, 2006; Emanuel et al., 2008). Natural climate variability modes, such as El Niño Southern Oscillation (ENSO), can affect reef-damaging tropical cyclone characteristics such as intensity and duration as well as where they form and track in the Australia region (Ramsay et al., 2012). Changes to ENSO patterns under future climate change are simulated by the climate models that drive the downscaled tropical cyclone tracks and so are considered in the projected changes in tropical cyclone characteristics presented here. However, there is known uncertainty in projected changes to ENSO under future climates (Taschetto et al., 2014).

The reef damaging tropical cyclone characteristics were calculated for tracks whose spatial footprint intersects the coral reef regions for the downscaled historical, mid-century and end of century tracks. We converted the 1-min maximum wind speed provided by K. Emanuel to 10-min maximum wind speed (1-min maximum wind speed * 0.88 (Harper et al., 2010; Ramsay et al., 2018)) in order to calculate maximum intensity. The radius to gales is not explicitly simulated but can be estimated by constructing radial wind profiles using the maximum wind speed and radius to maximum wind. The historical radius to gales at each track position was calculated three times, each time constructing radial wind profiles using a different method: Holland et al. (2010), Emanuel (2010) and Emanuel and Rotunno (2011). We then compared the downscaled maximum radius to gales to the observed maximum radius to gales for each model and wind profile method using two-sided Mann-Whitney-Wilcoxon to test the null hypothesis that the observed and downscaled maximum radius to gales are from continuous distributions with equal medians. The wind profile method that produced maximum radius to gales that were not significantly different from observed at the 0.01 significance level was selected as the "best" method for each model. The selected wind profile was then used to calculate the radius to gales for the mid-century and end of century downscaled tracks. Scripts for calculating the radius to gales using the three wind profiles were provided by K. Emanuel. We calculated the duration of gales and the reef damage index in the same way as for the observed tracks and categorized the most damaging track positions in the same way as the observed tracks. Both observed and downscaled tracks were linearly interpolated to 1 hourly time steps.

### 2.3. Statitsical Analysis

We compared the spatial distributions of the observed and downscaled tracks at two spatial scales for the period 1985–2005: regional and reef. At the regional scale, we compared the number of tracks whose spatial footprint intersects each of the coral reef regions between simulated past and observed tropical cyclones. At the reef scale, we compared the number of tracks intersecting each of the reef areas within the coral reef regions between simulated past and observed. This analysis assessed the suitability of the downscaled tracks in representing future changes to tropical cyclones for finer than regional scales (e.g., within the Great Barrier Reef). Both were compared using a Chi Squared test to test whether the distribution of observed and downscaled tracks whose spatial footprints intersect each of the regions/reefs were different. We then visually compared kernel density estimates (KDE) of the tropical cyclone hourly track positions, and the median genesis (formation) positions and track positions for the first 10 days between observed and downscaled tracks (Ramsay et al., 2018) for tropical cyclones whose spatial footprint intersects with each of the coral reef regions between 1985 and 2005.

The observed reef damaging tropical cyclone characteristics were compared to the downscaled historical metrics for each model and region separately based on a two-sided Mann-Whitney-Wilcoxon test. This analysis tested the null hypothesis that the observed and downscaled metrics for tropical cyclones intersecting each region are from continuous distributions with equal medians. *P*-values greater than 0.01 indicated that the model was not significantly different from the observed regional reef damaging tropical cyclone metrics and indicated that models capture observed cyclone characteristics. One-sided Mann-Whitney-Wilcoxon was used to test the direction of differences. Observed and downscaled maximum intensity and duration of gales were compared for the period 1985–2005. For the maximum radius to gales, we compared the longer observed 1985–2020 period to the simulated past 1985–2005 period and assumed stationarity for the periods before and after 2005. The most reliable wind radii data has been recorded in best track databases for the Australian region since 2003, with some opportunity-based surface observations included earlier in the record (Courtney et al., 2021). We also used the 1985–2020 observed period to compare the reef damage index and number of tracks in each damage category as both require reliable radius to gales data. The number of track positions in each of the damage categories was compared between the observed (1985–2020) and simulated past (1985–2005) periods using a Chi Squared test to compare the distributions of the two populations (observed and downscaled) of categorical data.

Changes in reef damaging tropical cyclone characteristics with future climate change were determined by bootstrapping the difference in means following Ramsay et al. (2018). The mean change in reef damaging metric (e.g., maximum intensity) and 95% confidence intervals were calculated from 10,000 replicates using the bias-corrected and accelerated technique. If the confidence intervals did not cross zero, the projected change was considered statistically significant. Bootstrapped changes in means were analyzed for all tropical cyclones in the Southern Hemisphere ocean basins (South Indian Ocean and South Pacific Ocean) and for tropical cyclones impacting each of the coral reef regions for both the mid-century and end of century periods.

## 3. Results

### 3.1. Comparing Observed and Downscaled Past Tropical Cyclones

The maximum radius to gales calculated using the Emanuel (2010) wind profile correctly captured past cyclone size observations for four out of six of the models ($p > 0.01$; GFDL, HADGEM, MIROC and MPI; Figure S1 in Supporting Information S1). For CCSM and IPSL, the maximum radius to gales was correctly represented using the Holland et al. (2010) wind profile ($p > 0.01$). The maximum radius to gales calculated using the Emanuel and Rotunno (2011) wind profile was significantly higher than observed for all models ($p < 0.0001$). For the rest of the analysis, the Emanuel (2010) wind profile was thus used to calculate the radius to gales for GFDL, HADGEM, MIROC and MPI and the Holland et al. (2010) wind profile for CCSM and IPSL for the historical and future downscaled tracks.

#### 3.1.1. Spatial Distribution of Tracks and Cyclogenesis

The number of observed tracks whose spatial footprints intersect with each region was significantly different ($p < 0.01$) to the number of downscaled historical tracks for all but HADGEM ($\chi^2 = 2.39$, $p = 0.495$) and IPSL ($\chi^2 = 5.88$, $p = 0.117$). In the downscaled tracks, there was a greater proportion of tracks impacting the Coral Sea and Great Barrier Reef than observed and a smaller proportion of tracks impacting Western Australia (Figure 2).

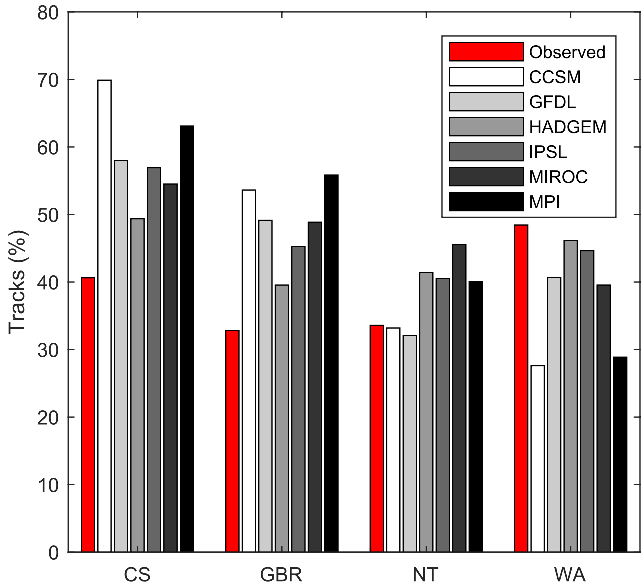


**Figure 2.** Percentage of tropical cyclone tracks whose spatial footprints intersect with each coral reef region out of the total number of tracks intersecting any region in the observed (1985–2005) and simulated past (1985–2005) periods. CS—Coral Sea, GBR—Great Barrier Reef, NT—Northern Territory, WA—Western Australia.

The number of tracks impacting the reefs within the Coral Sea was captured by CCSM, GFDL, HADGEM, MIROC and MPI (i.e., there was no significant difference between the observed and downscaled past distribution of tracks). There was a greater proportion of downscaled tracks impacting the Northern reef area (1 in Figure 3a) than observed and fewer tracks impacting the central sections (2–4 in Figure 3a) than observed. The number of observed tracks whose spatial footprints intersect with reefs within the Great Barrier Reef was correctly represented by all models ($p > 0.01$; Table S3 in Supporting Information S1; Figure 3b). The number of observed tracks that impact reefs within Western Australia was captured by CCSM, GFDL, HADGEM, IPSL and MPI. There was a greater proportion of downscaled tracks impacting Ashmore (1 in Figure 3c) and Scott Reef (2 in Figure 3c) in the north of the region than observed. The downscaled tracks in some of the models had a smaller proportion impacting the Kimberly (3 in Figure 3c) and Montebellos (5 in Figure 3c) on the Western Australian coastline than observed. This finding highlights how uncertainty increases at finer spatial scales, making it problematic to use these data at increasingly finer scales.

The observed median track for tropical cyclones impacting Western Australia initially followed the Western Australian coastline, and therefore a single tropical cyclone had the potential to impact many reefs during its track (Figure 4). The median downscaled tracks and track positions extended further west than observed. The downscaled tracks in CCSM, GFDL, HADGEM, IPSL and MPI captured the observed median track direction traveling east to west for tropical cyclones impacting the Northern Territory, though CCSM, GFDL and IPSL had genesis positions further east than observed. The observed median track for tropical cyclones impacting the Coral Sea and Great Barrier Reef tracked north to south while the downscaled median tracks started further east and tracked east to west before curving south. Downscaled track positions also extended further east in the north of the regions than observed. The median cyclone genesis positions in the models were at a lower latitude than observed for all coral reef regions (Figure S2 in Supporting Information S1).

### 3.1.2. Reef Damaging Tropical Cyclone Characteristics

The maximum intensity (Figure S3 in Supporting Information S1) was best captured for tracks whose spatial footprints intersect the Coral Sea and Great Barrier Reef, followed by Western Australia (five and four out of six models were not significantly different to observed, respectively). The maximum intensity was poorly represented for the Northern Territory (all six models were significantly different to observed). The maximum radius to gales (Figure S4 in Supporting Information S1) was captured for tracks whose spatial footprints intersect the Great Barrier Reef, Western Australia and the Coral Sea by six, five and three out of six models, respectively. All six models had significantly higher maximum radius to gales of tracks impacting the Northern Territory. The duration of gales (Figure S5 in Supporting Information S1) was best represented for tracks whose spatial footprints intersect the Great Barrier Reef and Northern Territory followed by Western Australia as six, five and two models were not significantly different to observed, respectively. None of the models captured the observed duration of gales for tracks impacting the Coral Sea. The observed reef damage index (Figure S6 in Supporting Information S1) was correctly represented for tracks whose spatial footprints intersect the Great Barrier Reef and Western Australia by all six models, and the Coral Sea by four models. All six models had significantly higher reef damage indices of tracks impacting the Northern Territory.

We found that CCSM and IPSL were the best performing models, as they were not significantly different from observed on 11 and 12 out of 16 occasions, respectively (Table 2). The Great Barrier Reef was the best represented region, as downscaled metrics were not significantly different from observed on 23 out of 24 occasions, followed by Western Australia (17/24) and then the Coral Sea (12/24). The Northern Territory was poorly represented by all six models for every metric but the duration of gales (5/24).

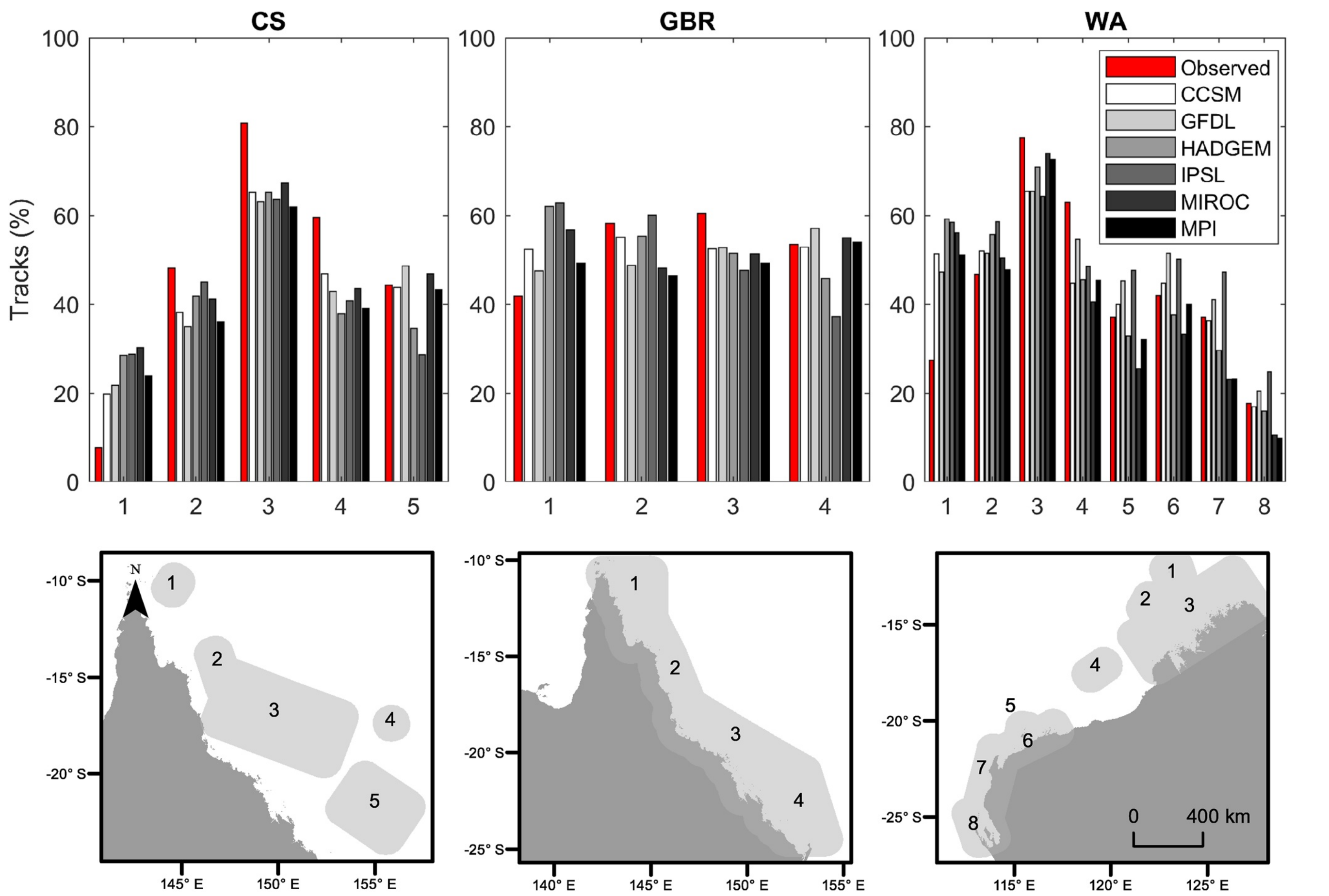


**Figure 3.** Percentage of tropical cyclone tracks whose spatial footprints intersect with each coral reef within the (a) Coral Sea, (b) Great Barrier Reef, and (c) Western Australia in the observed (1985–2005) and simulated past (1985–2005) periods. The Northern Territory is not included because it is not divided into coral reef areas due to uncertainty regarding the location of coral reefs within the region. In Western Australia, the reefs are 1—Ashmore, 2—Scott Reef, 3—Kimberly, 4—Rowley Shoals, 5—Montebello, 6—Pilbara, 7—Ningaloo, 8—Shark Bay.

### 3.1.3. Damaging Track Positions

There were no observed or downscaled track positions in the most damaging category (intense, large and slow-moving) whose spatial footprints intersect with coral reef regions (Figure S7 in Supporting Information S1). Observations in the Coral Sea and Great Barrier Reef regions showed similar distributions across the categories, with lower percentages of intense and large cyclones compared to intense and slow and large and slow. In contrast, observations in the Northern Territory and Western Australia both showed by far the greatest percentage in the intense and slow category with relatively few in the other categories.

The downscaled tracks simulated track positions in every damage category represented by the observed tracks, indicating that the downscaled tracks are able to simulate reef damaging tropical cyclones (Figure S7 in Supporting Information S1). However, the number of downscaled historical tracks in each of the damage categories was not correctly represented by any of the models for any region ($p < 0.01$; Table S5 in Supporting Information S1). For the Great Barrier Reef and Coral Sea, all six models had more intense and large track positions and fewer large and slow-moving track positions than observed (Figure S7 in Supporting Information S1). For Western Australia and the Northern Territory, the models captured the low occurrence of large and slow-moving track positions impacting the region but had more intense and large track positions than observed in both regions. For the Northern Territory, many models had more intense and slow-moving track positions than observed, while in Western Australia many models had fewer than observed of these track positions. Projections of the number of track positions in each of the damage categories in the future are not included here due to the downscaled tracks' inability to capture the observed distribution of damaging track positions.

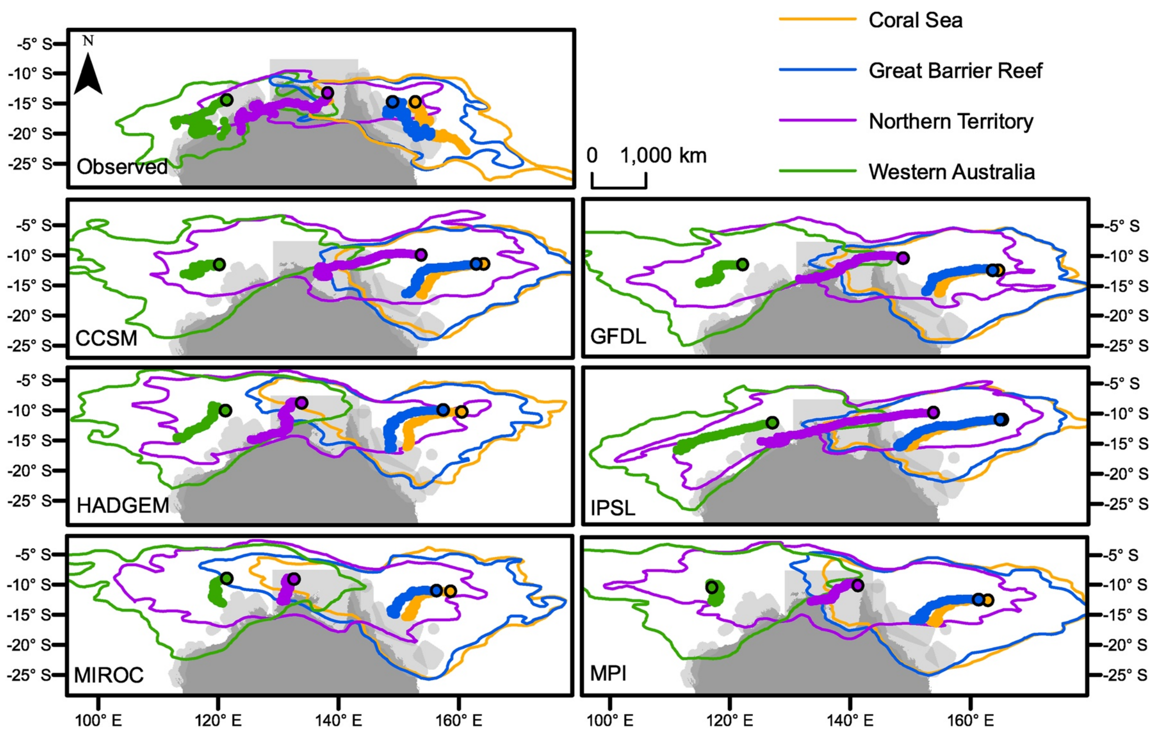


**Figure 4.** Kernel density estimates (KDE) of observed (1985–2005) and downscaled past (1985–2005) tropical cyclone track positions for tropical cyclones whose spatial footprints intersect with each of the four coral reef regions. The median hourly track positions for the first 10 days are shown by the circles and the 75% KDE contours are shown by the lines. The median genesis positions are shown by the black outlined circles.

### 3.2. Projected Changes in Reef Damaging Tropical Cyclone Characteristics

The downscaled tracks exhibited a significant increase in the maximum intensity of tropical cyclones during the mid-century period (2040–2060) (Figure S8 in Supporting Information S1) in the CCSM, GFDL and MIROC models for the Southern Hemisphere ocean basins (South Indian Ocean and South Pacific Ocean). By the end of the century (2080–2100), five models exhibited a significant increase in maximum intensity (CCSM, GFDL, HADGEM, MIROC and MPI). The downscaled tracks in the IPSL model decreased significantly in their maximum intensity in the end of century period. Five models (CCSM, GFDL, IPSL, MIROC and MPI) exhibited a significant increase in the maximum radius to gales in the mid-century extending to all six models in the end of century (Figure S8 in Supporting Information S1). The projected change in the duration of gales showed opposite tendencies between the mid and end of century periods, with four models displaying a significant decrease (GFDL, HADGEM, IPSL and MIROC) and increase (CCSM, GFDL, HADGEM and MPI) during the mid and end of century periods, respectively. CCSM and IPSL were best able to reproduce the observed reef damaging tropical cyclone characteristics for the historical period (Table 2) but had opposite projections to each other for maximum intensity and duration of gales. Both models exhibited a significant increase in maximum radius to gales.

#### 3.2.1. Cyclone Projections for the Mid-Century (2040–2060)

Projected changes in the reef damaging tropical cyclone characteristics varied in sign in the mid-century. The tracks driven by the MIROC model exhibited a significant increase in maximum intensity (Figure 5) for tropical cyclones impacting all four regions. The tracks in CCSM exhibited significant increases in the maximum intensity of tropical cyclones impacting the Coral Sea and Western Australia. Tracks impacting the Coral Sea, the Great Barrier Reef and the Northern Territory exhibited significant decreases in maximum intensity in a third of models (IPSL and MPI for the Great Barrier Reef and the Northern Territory, and GFDL and IPSL for the Coral Sea). For the maximum radius to gales, a significant increase was projected in four models for Western Australia and the Coral Sea, three models for the Great Barrier Reef and two models for the Northern Territory. The only model with a significant decrease in the maximum radius to gales was HADGEM (for tracks impacting the

**Table 2**
*p-Values for Two-Sided Mann-Whitney-Wilcoxon Test to Test the Null Hypothesis That the Following Observed and Downscaled Metrics for Tropical Cyclones Whose Spatial Footprints Intersect Each Region Are From Continuous Distributions With Equal Medians: Maximum Intensity, Maximum Radius to Gales, Duration of Gales and Reef Damage Index*

| Metric | Region | CCSM | GFDL | HADGEM | IPSL | MIROC | MPI | Region performance (out of 24)[c] |
|---|---|---|---|---|---|---|---|---|
| Maximum intensity (m/s) | CS | **0.888**[a] | **0.099** | **0.894** | **0.586** | 0.002 | **0.439** | 5 |
| | GBR | **0.308** | **0.064** | **0.156** | **0.256** | 0.001 | **0.058** | 5 |
| | NT | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0 |
| | WA | **0.055** | 0.008 | 0.001 | **0.732** | **0.016** | **0.040** | 4 |
| Maximum radius to gales (km) | CS | **0.353** | 0.000 | 0.000 | **0.103** | **0.059** | 0.000 | 3 |
| | GBR | **0.033** | **0.661** | **0.934** | **0.127** | **0.384** | **0.184** | 6 |
| | NT | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0 |
| | WA | **0.863** | **0.385** | 0.003 | **0.397** | **0.058** | **0.234** | 5 |
| Duration of gales (days) | CS | 0.003 | 0.004 | 0.000 | 0.001 | 0.009 | 0.000 | 0 |
| | GBR | **0.346** | **0.356** | **0.313** | **0.226** | **0.638** | **0.345** | 6 |
| | NT | **0.801** | **0.070** | 0.002 | **0.993** | **0.031** | **0.021** | 5 |
| | WA | 0.000 | **0.087** | 0.004 | **0.015** | 0.001 | 0.007 | 2 |
| Reef damage index | CS | **0.193** | **0.081** | 0.003 | **0.087** | **0.690** | 0.003 | 4 |
| | GBR | **0.445** | **0.807** | **0.843** | **0.646** | **0.127** | **0.994** | 6 |
| | NT | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0 |
| | WA | **0.057** | **0.109** | **0.068** | **0.901** | **0.788** | **0.477** | 6 |
| Regional model performance (out of 4) | CS | 3 | 2 | 1 | 3 | 2 | 1 | **12** |
| | GBR | 4 | 4 | 4 | 4 | 3 | 4 | **23** |
| | NT | 1 | 1 | 0 | 1 | 1 | 1 | **5** |
| | WA | 3 | 3 | 1 | 4 | 3 | 3 | **17** |
| Model performance (out of 16)[b] | | **11** | **10** | **6** | **12** | **9** | **9** | |

*Note*. The full results (medians, sample sizes, U test statistics and $p$ values) are reported in Table S4 in Supporting Information S1.
[a]Bold values indicate where the test hypothesis cannot be rejected ($p > 0.01$); that is, the model simulates a similar distribution to observed. [b]Model performance is the number of times a model succeeds in simulating the observed distribution ($p > 0.01$). Model performance is out of 16 (four metrics * four regions). [c]Region performance is out of 24 (four metrics * six models).

Northern Territory and Western Australia). For the duration of gales, only MIROC and CCSM exhibited significant increases for cyclones impacting the Coral Sea and Western Australia, respectively. A significant decrease in the duration of gales was projected for tracks impacting the Great Barrier Reef when driven by IPSL, GFDL and MPI, for the Northern Territory in the IPSL and MPI models, and for Western Australia in the GFDL and MPI models. The reef damage index exhibited mixed projections, with MIROC tracks displaying a significant increase for all four regions, and CCSM producing a significant increase for the Western Australia region only. The IPSL tracks exhibited a significant decrease in the reef damage index in three regions, while the tracks driven by HADGEM and MPI exhibited a significant decrease in two regions each.

#### 3.2.2. Cyclone Projections for the End of the Century (2080–2100)

The MIROC model tracks exhibited a significant increase in maximum intensity during the end of century period for tropical cyclones impacting every region (Figure 6), although the projected increase was lower than for the mid-century for cyclones impacting the Coral Sea and Great Barrier Reef. Other models with significant increases in maximum intensity at the end of the century included CCSM for three regions (Coral Sea, Great Barrier Reef and Western Australia), and GFDL for two regions (Northern Territory and Western Australia). On the other hand, a significant decrease in maximum intensity was found for tropical cyclones impacting the Coral Sea, Great Barrier Reef and Northern Territory when driven by IPSL. For the maximum radius to gales, many models exhibited significant increases, including for tropical cyclones impacting the Coral Sea (five out of six models), the Great Barrier Reef, Northern Territory and Western Australia (four models each). The tracks driven

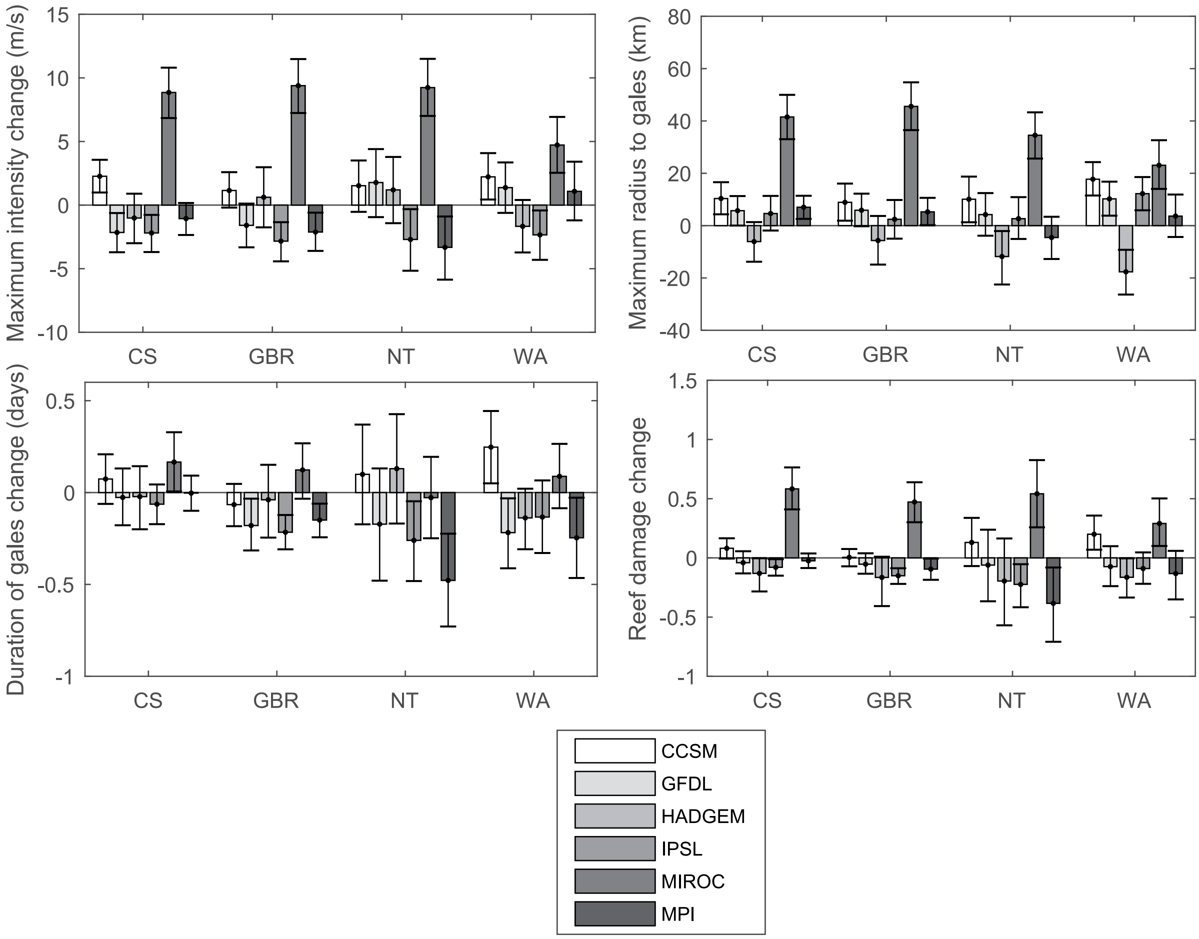


**Figure 5.** Mean projected change from the simulated past (1985–2005) to simulated mid-century (2040–2060) period in reef damaging tropical cyclone metric of 10,000 replicates. The error bars depict 95% confidence intervals.

by HADGEM were the only tracks to exhibit a significant decrease in maximum radius to gales in the end of the century, which was for tropical cyclones impacting the Great Barrier Reef and Northern Territory. For the duration of gales, the downscaled tracks exhibited a significant increase for tropical cyclones impacting the Coral Sea and Western Australia for three models each and two models each for the Great Barrier Reef. Conversely, the MPI tracks exhibited a significant decrease in the duration of gales in the Northern Territory. Finally, assessment of the reef damage index revealed that three out of six models yielded a significant increase in this metric for tropical cyclones impacting Western Australia, as did two models for the Coral Sea, Great Barrier Reef and Northern Territory. The tracks driven by MPI exhibited a significant decrease in the reef damage index for tropical cyclones impacting Western Australia.

The projected changes in coral reef damaging tropical cyclone characteristics for both the mid-century and end of century are dependent on projected changes in where tropical cyclones will track (Figures S9 and S10 in Supporting Information S1). Spatial uncertainties in downscaled track trajectories for the historical period highlight uncertainty in the projected changes to the characteristics presented here.

## 4. Discussion

Increased tropical cyclone peak intensities under future climate change are a well-established climate change signal at global and ocean-basin scales (Knutson et al., 2020) and are commonly cited as a threat to coral reefs (Cheal et al., 2017; França et al., 2020; Gilmour et al., 2019; Harvey et al., 2018). However, the extent to which future tropical cyclones will damage coral reefs more than in the recent historical climate has been unknown.

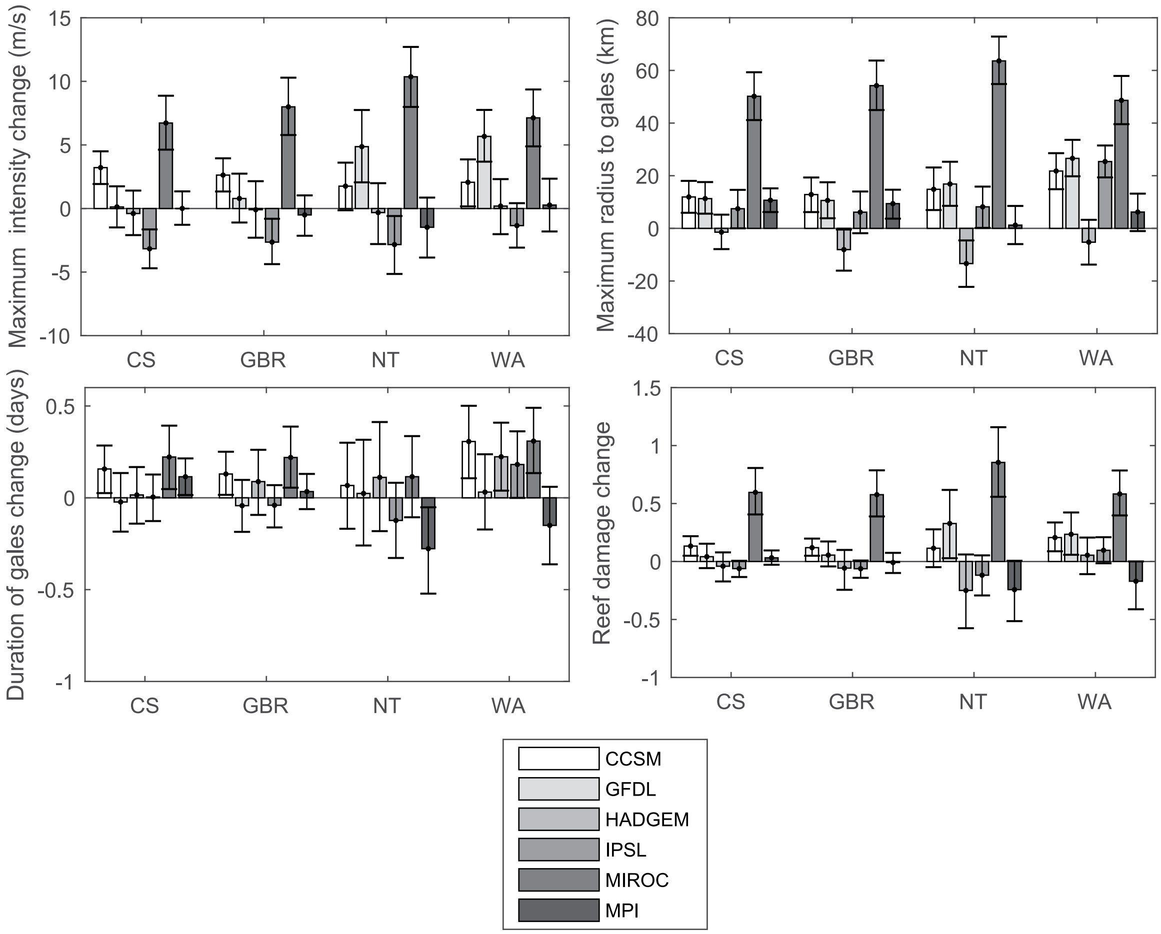


**Figure 6.** Mean projected change from the simulated past (1985–2005) to simulated end of century (2080–2100) period in reef damaging tropical cyclone metric of 10,000 replicates. The error bars depict 95% confidence intervals.

Here, we found that model projections of future reef damage in the mid century and end of century are uncertain, with some models projecting increases in future reef damage and reef damaging characteristics (e.g., intensity) and others decreases. Perhaps this is to be expected given the considerable uncertainty in the projections presented here, in part due to a limited understanding of the mechanisms that influence the reef damaging characteristics of tropical cyclones (e.g., size and translation speed) and how these will change in the future. It should also be noted that the observations themselves carry uncertainty due to the limited observational period, changes in tropical cyclone observing practices over time (Courtney et al., 2021), and the fine-scale spatial nature of the tracks examined which also limits their sample size. The similarity of tropical cyclone characteristics between the simulated and observed historical tracks was closest for the Great Barrier Reef. This finding may indicate that downscaled future tropical cyclone tracks could be credible in some instances, but nevertheless we recommend caution given the spatial uncertainties in track behavior, particularly when making predictions at the sub-regional scale, and the poor representation of the most damaging tropical cyclones for coral reefs.

### 4.1. Spatial Distribution of Tracks and Cyclogenesis

The formation locations and trajectories of the downscaled tracks exhibited pronounced differences in some instances compared with the observed tracks. There is therefore some uncertainty in where they will generate seas capable of damaging coral reefs. The median genesis position of downscaled tropical cyclones impacting all four coral reef regions was at lower latitudes than observed (Ramsay et al., 2018). This finding is likely due to the random seeding technique used to generate the downscaled tracks where tropical cyclones can form anywhere south of 2°S (Emanuel et al., 2008). The lower latitude of cyclogenesis positions in the downscaled tracks influenced the subsequent track trajectories, causing more of the northern reef areas to be projected to be impacted in the past than was observed in the Coral Sea and Western Australia. The models underestimated the proportion of tropical cyclones impacting Western Australian reefs and overestimated the proportion of tropical cyclones impacting reefs in the Coral Sea and Great Barrier Reef. The median track for the first 10 days for tropical cyclones impacting Western Australia was further west than observed resulting in the outer reefs being more frequently impacted than observed. Differences in track direction between the models and observations may be due to misrepresentations of the large-scale steering flow which predominantly influences downscaled storm movement (Ramsay et al., 2018). The spatial uncertainties in cyclogenesis and track trajectory, shown by the median genesis and track positions, impact all subsequent metrics (intensity, size, etc.) as they determine which sections of a tropical cyclone track impacts a coral reef region. That said, there was still considerable overlap in the observed and downscaled KDE areas for both the cyclogenesis and track positions, and therefore the exposure to tropical cyclones, at the reef region scale supporting their use in comparisons of observed and downscaled tropical cyclone characteristics and projections of future change. However, the spatial uncertainty limits the suitability of future downscaled tracks for projecting changes at the scale of coral reefs within regions.

### 4.2. Reef Damaging Tropical Cyclone Characteristics

Only one out of six models exhibited a significant increase in the reef damage index in the mid-century, and two models in the end of century, for the Coral Sea, Great Barrier Reef and Northern Territory. For Western Australia, two and three models exhibited a significant increase in the reef damage index in the mid and end of the century periods, respectively. The significant increase was predominantly due to increases in two of the three components of the reef damage index: intensity and size. When considering the entire Southern Hemisphere region, we found that half of the models projected a significant increase in maximum intensity in the mid-century, expanding to the majority (five out of six models) by the end of the century. Previous studies reported a significant increase in the intensity of South Indian Ocean tropical cyclones (Knutson et al., 2015; Murakami et al., 2012; Yamada et al., 2017; Yoshida et al., 2017), but no significant change in the intensity of Southwest Pacific tropical cyclones in the future (Emanuel, 2021; Emanuel et al., 2008; Knutson et al., 2015; Oouchi et al., 2006; Yamada et al., 2017; Yoshida et al., 2017). Regional differences in tropical cyclone intensity projections, including the physical mechanisms behind such differences, is currently a topic of active research. This hemisphere-scale increase in intensity was not as robust when examined at coral reef scales. A significant increase in the maximum intensity was only projected by two and three out of six models in the mid-century and end of the century periods, respectively. The large increase in intensity projected by MIROC downscaled tropical cyclones may be an outlier as it was not projected by the other models, especially those that represent the observed characteristics well. This disagreement in projected changes between models highlights the importance of considering projections from a model ensemble rather than a single model. In addition, even if more of the cyclones that form in the future are more intense, the overall frequency of cyclones is most often predicted to stay the same or drop (Sobel et al., 2021). This means that the absolute frequency of intense cyclones may not rise, depending on how much overall cyclone frequency changes.

Tropical cyclone size is a key determinant of the coral reef damage extent, as demonstrated for tropical cyclone Lua in Western Australia in 2012 which caused major coral loss 800 km away from its track (Puotinen et al., 2020). Four to five out of six models projected a significant increase in the maximum radius to gales of tropical cyclones impacting all four regions by the end of century indicating a robust change in tropical cyclone size in the future. However, there is uncertainty in the mechanisms that determine tropical cyclone size and therefore how these will change in the future limiting robust projections of size at the coral reef region scale and even more so at the within reef scale. Knutson et al. (2015) and Yamada et al. (2017) found significant increases in tropical cyclone size with future warming in both the South Indian and South Pacific oceans. Kim et al. (2014) found significant increases in tropical cyclone size from a doubling of $CO_2$ in every ocean basin except the South Indian Ocean. Intensity is suggested to influence changes in tropical cyclone size because size metrics are often based on wind speed (e.g., radius to 17 m/s winds) (Kim et al., 2014). Here, radius to gales is estimated by constructing wind profiles based on maximum wind speed so projected changes in tropical cyclone size are influenced by changes in intensity. However, Chavas et al. (2016) find that relative sea surface temperature (i.e., surface temperature (locally) minus the tropical-mean value) is the better determinant of tropical cyclone size. Without a better understanding of these mechanisms, there will be large uncertainty in the magnitude and spatial distribution of projected coral reef damage as intensity is not the only driver of reef damage.

### 4.3. Damaging Track Positions

The ability of downscaled cyclone tracks to capture observed cyclone characteristics differs by geographic region. The downscaled tracks generally captured the observed characteristics of tropical cyclones that generate reef damaging wave climates (intensity, size and duration) for the Great Barrier Reef, but not the Northern Territory, and only partially for the Coral Sea and Western Australia. The distribution of downscaled tropical cyclones whose spatial footprints intersect with reef areas within the regions in most models (five to six out of six models depending on the region) was not significantly different to observed, indicating that the downscaled tracks are suitable for projecting within region changes to reef damaging tropical cyclone characteristics. However, the models do not capture the frequency of track positions in the most damaging categories which are the most important for determining severe or large-scale reef damage. Cheal et al. (2017) report that three tropical cyclones were the biggest drivers of coral decline on the Great Barrier Reef from 1985 to 2012 as shown by De'ath et al. (2012): Cyclone Hamish (2009), Cyclone Yasi (2011) and Cyclone Ita (2014). Hamish and Ita were both intense and slow-moving, and Yasi was intense and large while their spatial footprints intersected with the Great Barrier Reef. Accurately simulating these "most damaging" tropical cyclones is crucial for estimating future reef damage severity and extent. However, comparing the most reef damaging tropical cyclones between observed and downscaled historical tracks is complex because reef damaging tropical cyclones are relatively rare in the observed record. Thus, the observed past represents just one realization of possible past tropical cyclone tracks while the downscaled tracks provide a large sample of track positions. Caution is therefore recommended when interpreting projected changes to tropical cyclone-induced reef damage at the regional scale in the future in all coral reef regions.

### 4.4. Future Research

We focus here on physical damage to coral reefs caused by tropical cyclone-induced waves, and found considerable uncertainty in projections of the reef damage index in the mid-century (2040–2060) and the end of century (2080–2100) based on a commonly-used tropical cyclone downscaling approach (Emanuel et al., 2006). Examinations of other cyclone-related drivers of coral reef damage, such as rainfall and flooding (Van Woesik et al., 1995), should be considered alongside wave damage in future to provide a holistic view of tropical cyclone impacts to coral reefs with climate change. An alternative investigation of explicitly-simulated tropical cyclones in climate models is also recommended as recent studies have shown that such projections are sensitive to the approach used to simulate tropical cyclones (i.e., explicitly-simulated vs. downscaled) in addition to the downscaling method applied (Jing et al., 2021). Further, temporal clustering can impact coral reef degradation as successive tropical cyclone events mean that tropical cyclones following a very damaging first strike may cause relatively little further damage compared to a random regime where corals have had time to recover in between strikes (Mumby et al., 2011; Wolff et al., 2016). However, clustered tropical cyclones may also destabilize the substrate preventing the survival of coral larval recruits and inhibiting recovery (Ceccarelli et al., 2020).

Tropical cyclones interact with other anthropogenic stressors exacerbating (i.e., ocean acidification) or reducing coral reef damage. Tropical cyclones generate a cooling wake through mixing of cooler deeper waters and enhanced surface fluxes which can provide respite to coral reefs experiencing thermal stress-induced coral bleaching (Carrigan & Puotinen, 2014). Both the intensity and spatial extent of the cool wake are maximized for tropical cyclones that are both intense and slow-moving, assuming favorable ocean conditions (Mei & Pasquero, 2013). Coral reef damage risk is also dependent on the coral species present, and the depth and exposure of a site (Blackwood et al., 2011; Harmelin-Vivien, 1994). We set thresholds for damaging track positions here that are assumed have the potential to cause coral reef damage to vulnerable colonies that are present, recognizing that coral reef damage is likely to be patchy at local scales within broadly defined risk zones (Puotinen et al., 2016).

ENSO is known to impact tropical cyclone frequency, genesis, track, intensity and duration in the Southern Hemisphere causing changes in tropical cyclone activity in different parts of the region during different phases (Lin et al., 2021). For example, tropical cyclone activity in the Australia region is enhanced during La Niña years (Ramsay et al., 2012). Changes to ENSO patterns under future climate change are therefore likely to affect reef damaging tropical cyclone characteristics. However, uncertainty in how ENSO will change with climate change limits projections of the influence of ENSO on tropical cyclones in the future.

Incorporating additional factors affecting coral reef damage risk from tropical cyclones such as rainfall, temporal patterns of tropical cyclones, interacting stressors, local-scale ecological data and improved estimates of natural climate variability into future research will contribute to a holistic picture of the future tropical cyclone threat to coral reefs.

## Data Availability Statement

The observed tropical cyclone tracks for the period 1985–2020 used in this analysis are publicly available online from the International Best Track Archive for Climate Stewardship (IBTrACS) at: https://www.ncei.noaa.gov/products/international-best-track-archive?name=ib-v4-access. The downscaled historical (1985–2005) and RCP8.5 mid-century (2040–2060) and end of the century (2080–2100) tropical cyclone tracks were provided by Kerry Emanuel. The tracks are to be used for nonprofit research only and so are not openly available but they can be requested for research purposes from K. Emanuel (emanuel@mit.edu). Researchers using these tracks are asked to sign a data agreement stating that the tracks will not be redistributed to ensure that the data is used only for non-profit research.

**Acknowledgments**
The authors would like to thank Kerry Emanuel for providing the downscaled tracks used in this study. A. M. Dixon was supported by the UK Natural Environment Research Council (NERC) Spheres Doctoral Training Partnership (NE/L002574/1). H. A. Ramsay acknowledges funding from the Climate Systems Hub of the Australian Government's National Environmental Science Program (NESP). We acknowledge the World Climate Research Programme's Working Group on Coupled Modeling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Table S2 in Supporting Information S1 of this paper) for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

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