Received: 30 May 2023 | Revised: 21 November 2023 | Accepted: 6 January 2024

DOI: 10.1002/cli2.66

Climate Resilience and Sustainability
Interdisciplinary Approaches Towards Solutions for Climate Change
Open Access
RMetS

ORIGINAL ARTICLE

Applying ensemble climate models to predict the fate of marginal coral reefs already existing at thermal and turbidity limits in arid tropical Australia

Paula Cartwright[1,2] | **Nicola Browne**[3] | **Peter Fearns**[4] | **Mick O'Leary**[2,5] | **Ryan Lowe**[2,5]

[1]Centre for Tropical Water and Aquatic Ecosystems (TropWATER), James Cook University, Townsville, Queensland, Australia

[2]Oceans Graduate School & UWA Oceans Institute, The University of Western Australia, Crawley, Perth, Australia

[3]School of Molecular and Life Sciences, Curtin University, Bentley, Perth, Australia

[4]Curtin Medical School, Curtin University, Bentley, Perth, Australia

[5]School of Earth Sciences, The University of Western Australia, Crawley, Perth, Australia

Correspondence
Paula Cartwright, Level 1, ATSIP Building 145, 1 James Cook Drive, Douglas, Townsville, Queensland, 4814, Australia.
Email: paula.cartwright@jcu.edu.au

Funding information
The Australian Government Research Training Program and The University of Western Australia

Abstract

Marine fauna, including coral reefs, exist under particular oceanographic and meteorological (metocean) processes that maintain water quality within the range limits to which they have adapted over millennia. Climate-induced changes to these metocean processes could alter ambient marine water quality to ranges beyond those limits and at rates faster than species can adapt. Extreme (or marginal) coral reefs, such as those in arid tropical regions, already exist at the limits of their ranges for water quality parameters such as temperature and turbidity. Here, we apply projected anomalies from ensemble climate models to the metocean processes that drive turbidity in the Exmouth Gulf region of north Western Australia where habitats of significant environmental value exist. We also apply projected sea surface temperature anomalies to look at how a combined effect of turbidity and temperature might impact important habitats. We find that turbidity is predicted to increase in some parts of the Gulf and decrease in others due to differing metocean drivers of turbidity throughout the region. Temperature anomalies reveal year-round increases in temperature consistent with current summer marine heat wave events (>2.5°C above mean temperatures). Climate models used in the predictions varied between themselves underscoring the importance of model choice and of using ensembles.

KEYWORDS
ensemble climate models, Exmouth Gulf, metocean processes, turbid coral reefs

1 | INTRODUCTION

Climate change is already resulting in the degradation of tropical marine near-coastal ecosystems (IPCC, 2022; Thirukanthan et al., 2023), with impacts expected to worsen significantly by the end of the century (Babcock et al., 2019; Doney et al., 2012; Lu et al., 2018). Predicted future events include prolonged marine heatwaves (Smale et al., 2019), sea-level rise (Lowe et al., 2021b; Nerem et al., 2018), changes in seasonal wind and wave power (Morim et al., 2019; Reguero et al., 2019), more intense cyclones (Knutson et al., 2020) and alterations to oceanic circulation patterns (Palter et al., 2018), as well as changes in freshwater input and precipitation (Konapala et al., 2020). While outcomes will likely differ regionally, the consequences for many tropical marine ecosystems could include reduced water quality through nutrification (Hull, 2021), turbidity (Cartwright et al., 2021; Chen et al., 2018), acidification (Doney et al., 2020), the physical destruction of reefs (Puotinen et al., 2020), coral bleaching (Hughes et al., 2017), permanent functional changes including coral–algal regime shifts (Norström et al., 2009), altered trophic flows (Ullah et al., 2018), species migrations (Birkmanis et al., 2020), marine animal biomass decline (Lotze et al., 2019) and extinctions (Song et al., 2021). In addition, increasing land-use change and industrialisation along coastlines could worsen the impacts of climate change by further reducing water quality in marine habitats (Kunzmann et al., 2018; Lu et al., 2018).

One critical component of tropical marine water quality is turbidity due to its multifaceted effects on the health, morphology and distribution of benthic assemblages including coral reefs. Turbidity, defined as total suspended matter (TSM) in the water column, reduces the light available for benthic primary productivity (Kirk, 1994), limits coral larval settlement (Hodgson, 1990) and can smother coral recruits (Bothner et al., 2006). Further, turbidity can enhance algal overgrowth (Tebbett & Bellwood, 2019) and negatively affect the feeding ability of fish and other organisms (Lowe et al., 2015). Ecological thresholds for turbidity in Australian coastal waters follow the guidelines set by the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC & ARMCANZ, 2000); however, these do not provide a discreet guideline value for turbidity but rather a range that considers ecosystem-specific modifiers. For coral reef ecosystems, threshold values for exposure to turbidity have been published as 1.5 mg/L (chronic exposure), with values above this leading to macroalgal colonisation and steep declines in coral richness (De'ath & Fabricus, 2010). However, moderate turbidity may also increase the resilience of corals to UV-induced bleaching events due to its 'shading' effect (Zvifler et al., 2021), and marginal coral reefs existing at the limits of their turbidity range are increasingly being examined for their ability to withstand environmental extremes such as marine heat waves (Browne et al., 2019; Burt et al., 2020).

Marine heat waves have been increasing in occurrence this century with the trend expected to continue over the coming decades under climate change (Frölicher & Laufkötter, 2018). Coral reefs and other marine coastal ecosystems are likely to respond differently to heat stress depending on their region and the environmental conditions to which they are adapted (Heidemann & Ribbe, 2019; Hughes et al., 2017). Habitats already existing close to the limits of their range may not persist in their same state, while habitats with more scope for change may persist but be closer to their range limits (Hughes et al., 2003; Wooldridge, 2009). Understanding how tropical marine ecosystems may be affected by climate change can be achieved by utilising our current understanding of the long-term baseline metocean conditions to which an environment has been exposed and projecting how those metocean conditions are likely to change under climate forcing. For example, if we have a model that best describes the historical contribution of metocean processes (wind, waves, etc.) to water turbidity, we can apply future climate anomaly projections to metocean data to predict how turbidity could change in the future, and therefore how benthic assemblages may be impacted. A similar approach was used by Birkmanis et al. (2020), who applied sea surface temperature (SST) anomaly projections to predict future habitat suitability for sharks in Australian waters, by Goldsmit et al. (2020) who used projected temperature, salinity and sea ice thickness anomalies to predict invasion hotspots in Arctic seas and by Harrison (2021) to identify ideal locations and species for ecosystem restoration endeavours in Tasmania.

Marine ecosystems in arid tropical north Western Australia are already impacted by climate-related events such as marine heatwaves (Lafratta et al., 2017) and cyclones (Goebbert & Leslie, 2010) on inter-annual timescales. Metocean conditions in the region are influenced by phases of the El Niño-Southern Oscillation (ENSO) that effect local/regional sediment transport dynamics, water turbidity, wind-wave conditions, cyclone intensity and sea surface heights (Cartwright et al., 2021; Cuttler et al., 2020; Lowe et al., 2021a). Nearshore environments, in particular, are considered marginal, with many marine species existing close to the limit of their temperature and turbidity range, making them highly susceptible to further climate-induced impacts (Evans et al., 2020; Gilmour et al., 2019). An improved understanding of how environmental conditions, including water quality, could change by the end of the century is required to assess risk to important species and their habitats, and therefore provide more robust guidance on how to best manage or protect nearshore marine habitats.

Future climate predictions based on ensemble climate models can be projected from the Coupled Model Intercomparison Phases 5 and 6 (CMIP5, CMIP6) to evaluate how ecosystem health might look under future climate states with varying degrees of emissions scenarios (Freer et al., 2018). For CMIP5, these scenarios are called Representative Concentration Pathways (RCPs) and consist of four plausible greenhouse gas trajectories that describe potential future discharges affecting Earth's radiation balance (Moss et al., 2010). RCP 4.5 (the 'stabilisation pathway') and RCP 8.5 ('business as usual') are commonly used for predicting 'middle-of-the-road' and 'worst-case' scenarios, respectively, of future environmental changes (Arias et al., 2021; Van Vuuren et al., 2011). The more recent CMIP6 simulations represent almost a decade of updated modelling over its predecessor CMIP5 (CMIP6 landscape, 2019). Instead of using only RCPs to predict radiative forcing, CMIP6 includes socio-economic policies that may mitigate or enhance radiative forcing. CMIP6 describes five shared socioeconomic pathways (SSPs) that work in conjunction with the four RCPs to give a wider range of forcing potential into the scenario matrix (Bourdeau-Goulet & Hassanzadeh, 2021). Top priority scenarios include SSP1-2.6 (the 'sustainability' pathway), SSP3-7.0 ('regional rivalry' pathway) and SSP5-8.5('fossil fuel development' pathway; O'Neill et al., 2016). CMIP6 also better represents physical processes at smaller scales than CMIP5 and shows an improved representation of seasonality and spatial patterns during the historical period (Grose et al., 2020).

This study builds on Cartwright et al (2021) where regression modelling was applied to in situ validated, remotely sensed turbidity data spanning from 2002 to 2020, to establish the primary metocean processes responsible for driving elevated turbidity in the Exmouth Gulf region of north Western Australia (Cartwright et al., 2021). Here, we apply future climate projections of CMIP6 scenarios (SSP3-7.0, SSP5-8.5) and CMIP5 scenarios (RCP4.5, RCP8.5) to predict how end-of-century environmental conditions affecting the Exmouth Gulf could alter water quality, specifically turbidity and SST, and therefore affect benthic habitats such as coral reefs in the region. The objective is to provide a practical application of climate model science that can be utilized by managers to identify potential refugia and enhance the conservation and stewardship of important marine habitats.

2 | METHODS

2.1 | Site description

The Exmouth Gulf is a large (~3000 km^2) embayment lying within the Gascoyne bioregion of north Western Australia, approximately 1000 km north of Perth. The Gulf marks the transition zone from the deep Indian Ocean waters off the Ningaloo Reef coast to the shallow, turbid North West Shelf. Water depths in the Gulf vary from <2 m along the eastern and southern shorelines to ~20 m in the northern and central regions. The Gulf contains a diverse range of ecosystems (sand islands, coral–algal reefs, mangroves, seagrasses, tidal creeks, cyanobacterial mats and salt flats), together supporting one of the most fauna-rich coastal regions in Australia (Irvine et al., 2018; Oceanica, 2006; Preen et al., 1997). Habitats here are exposed to a spatially and temporally variable turbidity regime that is partially driven by both regional (winds, tides) and large-scale (ENSO and Indian Ocean Dipole [IOD]) metocean processes (Cartwright et al., 2021).

The region experiences an arid tropical climate, with less than 300 mm of precipitation annually and has no permanent riverine inputs. Regional wind patterns are due to low-pressure troughs extending over the inland Pilbara rangelands during summer resulting in a mostly south-to-south-easterly regime. However, localized sea breezes are often present due to differential land/sea temperatures causing south-westerly and north-easterly wind patterns. Cyclones form one to three times a year with a severe cyclone occurring approximately every 25 years. In the past, these have caused irreversible damage to reefs, seagrasses, mangroves and foredunes, significantly altered nearshore bathymetry and water flow paths and shifted entire tidal creeks (Loneragan et al., 2013). Dust storms here also occur during strong wind conditions across the adjacent arid rangelands, and these aeolian dusts are dominant contributors to the marine sediments of the North West Shelf (Brunskill et al., 2001; Gingele et al., 2001; McTainsh et al., 2011).

Coral reefs in the Exmouth Gulf mostly exist along the eastern and northern Gulf and are exposed to a highly variable turbidity regime (Cartwright et al., 2021). While turbidity may offer these reefs some protection from bleaching events (Morgan et al., 2017; Zvifler et al., 2021), severe bleaching related to marine heatwaves has occurred in the region in recent years, for example, in 2011 (north-west Gulf; Depczynski et al., 2013) and 2013 (Pilbara coast east of the Gulf; Lafratta et al., 2017). Post-bleaching recovery from these events has, in some cases, involved a strong shift in dominant taxa away from branching/foliose corals to low densities of massive corals and turfing-algae-dominated reefscapes (Cartwright et al., 2023; Depczynski et al., 2013). The Gulfs reefs include stand-alone shoals, as well as fringing reefs along islands and the mainland coast, mostly in depths of 3–7 m. Since the first known benthic surveys were conducted here (over 25 years ago), macroalgae (mostly *Sargassum* spp.) has been apparent in these reef areas (McCook et al., 1995). Primary productivity is disproportionately high for a nutrient-poor arid tropical region, and this has been attributed to the cyanobacterial mats along the eastern coastline as well as iron-rich terrestrial input (Ayukai & Miller, 1998; Loneragan et al., 2013; Lovelock et al., 2010; McTainsh & Strong, 2007). This productivity has driven a large prawn fishing industry that has trawled up to 40% of the Gulf's waters for

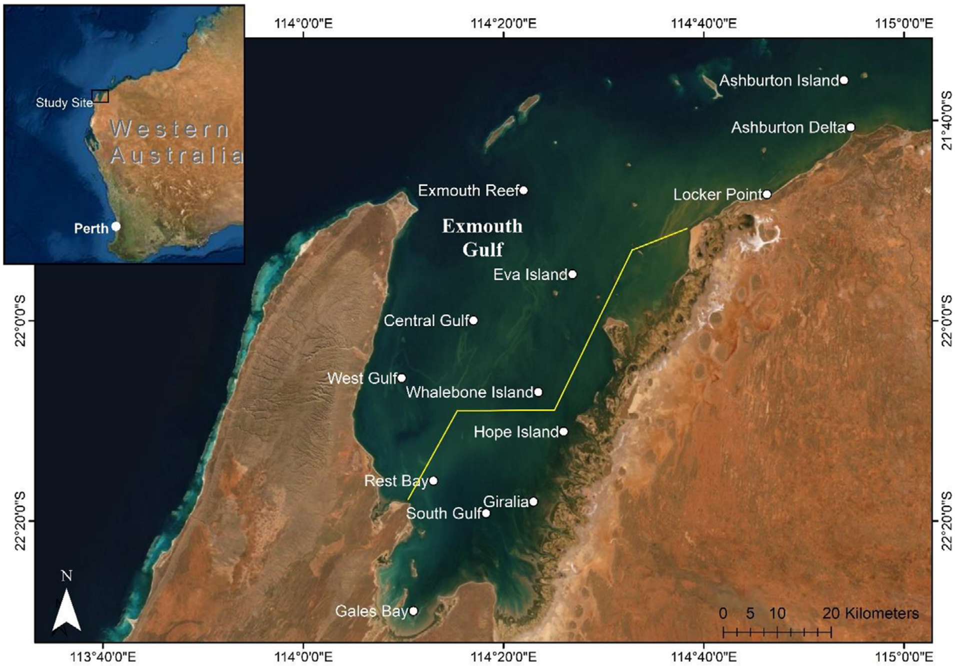

FIGURE 1 The Exmouth Gulf region in north Western Australia, showing 13 locations where future projections of turbidity under two climate change scenarios were modelled. Yellow line indicates north-western limit of the fisheries sanctuary zone.

decades (~1000–1500 tonnes biomass removed annually, not including bycatch). Further, the Gulf is heavily fished recreationally, and decreases in catch limits have been applied in recent years (Department of Fisheries, 2017). A fisheries sanctuary zone and newly named Marine Park (extent yet to be finalized) exist in the south-east third of the Gulf, while the rest of the Gulf is used heavily by commercial and recreational fishers (Figure 1).

2.2 | Modelling baseline and future climate data

In Cartwright et al. (2021), we developed linear models that best describe the relationship between measured (2002–2020) metocean climate variables and turbidity measured as TSM at 13 locations in the Exmouth Gulf (Figure 2). The historical turbidity values were derived from moderate spatial resolution (250 m^2) and high temporal resolution (daily) remotely sensed MODIS satellite data (NASA), using an in situ validated turbidity algorithm derived and calibrated in the same optically complex marine waters as this study (Dorji et al., 2016). The models metocean variables included u (zonal velocity) and v (meridional velocity) wind components, mean sea level, wave power, tidal maxima, tidal range, rainfall, ENSO and the IOD. For the historical analysis, each model contained only the metocean variables that best described turbidity, by applying the lowest Akaike Information Criterion value (Akaike, 1987). To predict future turbidity in the region, we updated the models to include all metocean variables that significantly contributed to turbidity, with $p \leq 0.05$ (Figure 2; full model regression tables in Supporting Information). Into these updated models, we input projected future climate variables under two levels of forcing (RCP4.5 and RCP8.5), replacing the historical climate values, to derive a projected turbidity value for end-of-century scenarios. All linear models were produced in the R stats package (RStudio, 2020).

2.3 | Metocean climate data

Historical climate data between 2002 and 2020 were sourced for the Exmouth Gulf region as described in Cartwright et al. (2021). Historical SST data were extracted from MODIS Level 3 SST 4-km spatial resolution satellite imagery (NASA, 2018) to obtain a monthly average SST from 2003 to 2020 for all sites in the Gulf. Future climate predictions were retrieved from the Climate Change Web Portal developed by the National Oceanic and Atmospheric Administration's Earth (NOAA) System Research Laboratory to collate and regionally downscale (to approximately 1° spatial resolution) the climate model outputs from CMIP5 and CMIP6 (Scott et al., 2016). The portal calculates the anomaly as the difference in the mean SST, precipitation and surface wind speeds between the future climate (2070–2099) and the model baseline reference

Climate Resilience and Sustainability
Interdisciplinary Approaches Towards Solutions for Climate Change
Open Access
RMetS

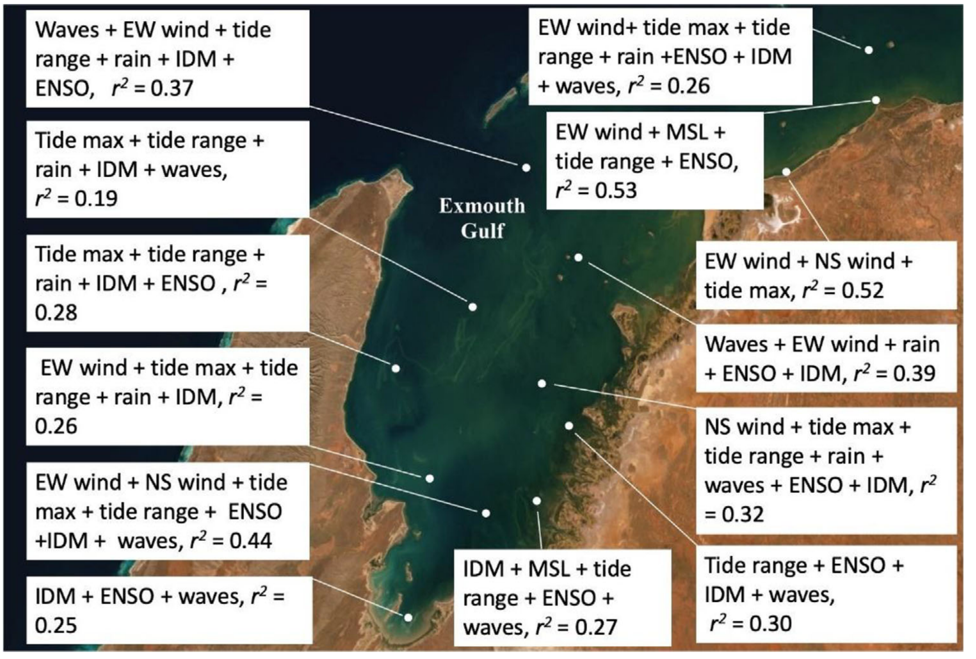

FIGURE 2 Linear regression models describing the relationship between metocean processes and turbidity at 13 locations in the Exmouth Gulf; adapted from Cartwright et al. (2021). Input variables include wave power (waves), tidal maximum (tide max), tidal range, rainfall, zonal velocity winds (EW wind), meridional velocity winds (NS wind), mean sea level (MSL), Indian Ocean Dipole (IDM) and El Niño Southern Oscillation (ENSO).

periods, which are CMIP6 (1985–2014) and CMIP5(1956–2005).

Projected SST anomalies were extracted from an ensemble of six CMIP6 global climate models, under two climate forcing scenarios, SSP3-7.0 and SSP5-8.5 (Table 1). The CMIP6 models were chosen for the SST analysis as they are shown to have an improved equilibrium climate sensitivity—the global temperature change estimated from a doubling of CO_2, over CMIP5 (CMIP6 landscape, 2019; O'Neill et al., 2016). The six climate models were chosen for use in the ensemble as they have shown the best performance against the historical climate of northern Australia (Ridder et al., 2021). The models used were CESM2-WACCM (NSF-DOE-NCAR, USA), FGOALS-G3 (Chinese Academy of Sciences), INM-CM5-0 (INM, Russia), ACCESS-CM2 (CSIRO-BOM, Australia), MRI-ESM2-0 (MPI-M, Germany) and NorESM2-MM (NCC, Norway, SSP5-8.5 only).

Projected eastward (*u* wind) and northward (*v* wind) near-surface wind speed anomalies and precipitation anomalies (Tables 1–3) were extracted from an ensemble of eight CMIP5 models, under two RCPs, RCP4.5 and RCP 8.5. The CMIP5 portal was used for this part of the analysis, as the CMIP6 portal does not yet contain the wind forcing anomalies that are needed in the turbidity model. (The metocean turbidity model anomalies here are analysed separately from the SST anomalies, as the temperature was not found to be a driver of turbidity, so there is no mixing of CMIP5 and CMIP6 models.) This eight model sub-set was chosen as they are representative of the range of seasonal rainfall projections for Australia and achieved a high ranking across a suite of performance metrics (CSIRO and Bureau of Meteorology, 2015). These models were MIROC5 (JAMSTEC, Japan), GFDL-ESM2M (NOAA, USA), CNRM-CM5 (CNRM-CERFACS, France), CESM1-CAM5 (NSF-DOE-NCAR, USA; precipitation only), CAN-ESM2 (CCCMA, Canada), ACCESS1-0 (CSIRO-BOM, Australia), HADGEM2-CC (MOHC, UK) and NORESM1-M (NCC, Norway).

Future wave climate predictions were taken from Morim et al. (2019), which used a multi-method ensemble of future global wave climate scenarios derived from 10 independent studies to identify robust regional future changes in significant wave height and wave period for 2081–2100 relative to a 1979–2004 baseline. Wave power values used in the historical regression model of Cartwright et al. were extracted from a 20-year regional-scale, fully coupled wave-circulation hindcast (Delft3D-SWAN) that has been extensively validated along the Pilbara coast (Branson & Sun, 2017; Cuttler et al., 2020). Proportional wave power (p) was calculated using the equation:

$$p = H^2\, T, \tag{1}$$

where H^2 is the squared significant wave height, and T is the peak wave period. The anomalies were added to the historical equation components separately before recalculating a new projected wave power. Wave power was

TABLE 1 Sea surface temperature (SST) anomalies for the Exmouth Gulf region of north Western Australia. for the period 2077–2099 (SSP3-7.0, SSP5-8.5) as projected by six CMIP6 global climate models.

SST anomalies (°C)—Mean (SD)										
SSP3-7.0										
CMIP6 model	**Annual**		**JFM**		**AMJ**		**JAS**		**OND**	
CESM2-WACCM	2.6	0.0	2.3	0.1	2.8	0.0	2.6	0.0	2.7	0.0
FGOALS-G3	1.5	-	1.3	-	1.8	-	1.7	-	1.4	-
INM-CM5-0	1.8	0.1	1.8	0.0	1.6	0.1	1.7	0.1	2.1	0.0
ACCESS-CM2	2.5	0.2	2.4	0.0	2.7	0.2	2.6	0.2	2.7	0.2
MRI-ESM2-0	2.1	0.1	2.0	0.1	2.2	0.1	2.1	0.1	2.2	0.0
Ensemble	**2.1**	**0.5**	**1.9**	**0.4**	**2.2**	**0.5**	**2.2**	**0.4**	**2.2**	**0.5**
SSP5-8.5										
	Annual		**JFM**		**AMJ**		**JAS**		**OND**	
CESM2-WACCM	3.5	0.0	3.1	0.1	3.7	0.0	3.6	0.0	3.5	0.0
FGOALS-G3	1.8	-	1.7	-	1.9	-	2.0	-	2.0	-
INM-CM5-0	2.0	0.1	1.9	0.1	1.9	0.0	2.0	0.1	2.4	0.0
ACCESS-CM2	3.2	0.2	2.9	0.0	3.3	0.3	3.3	0.2	3.5	0.3
MRI-ESM2-0	2.6	0.1	2.3	0.1	2.6	0.1	2.6	0.1	2.8	0.1
NorESM2-MM	2.1	0.0	2.1	0.0	2.2	0.1	2.0	0.1	2.2	0.0
Ensemble	**2.5**	**0.7**	**2.3**	**0.5**	**2.6**	**0.8**	**2.6**	**0.7**	**2.7**	**0.7**

Note: JFM—January February March, AMJ—April May June, JAS—July August September, OND—October November December. NorESM2-MM does not have SSP3-7.0 anomalies.
Abbreviations: CMIP6, Coupled Model Intercomparison Phase 6; SSP, shared socioeconomic pathway.

TABLE 2 North-south (*v* wind) anomalies for the Exmouth Gulf region of north Western Australia for the period 2077–2099 (RCP4.5, RCP8.5) as projected by six CMIP5 global climate models.

North-south (*v*) wind anomalies—Mean (SD)										
RCP 4.5										
CMIP5 model	**Annual**		**JFM**		**AMJ**		**JAS**		**OND**	
MIROC5	−0.7	0.1	−1.7	0.1	0.2	0.0	0.5	0.0	−1.8	0.3
GFDL-ESM2M	0.7	0.0	0.6	0.1	1.5	0.0	0.9	0.1	−0.1	0.0
CNRM-CM5	−0.1	0.1	−0.5	0.1	0.4	0.1	0.4	0.2	−0.5	0.1
CAN-ESM2	0.8	0.1	−0.3	0.2	1.5	0.1	1.1	0.3	0.7	0.0
ACCESS1-0	0.2	0.1	0.0	0.1	0.5	0.1	0.4	0.1	−0.1	0.0
HADGEM2-CC	0.8	0.0	0.3	0.2	1.1	0.1	0.7	0.0	1.1	0.1
NORESM1-M	0.1	0.1	−0.4	0.1	0.2	0.2	0.4	0.1	0.4	0.0
Ensemble	**0.3**	**0.6**	**−0.3**	**0.8**	**0.8**	**0.6**	**0.6**	**0.3**	**−0.1**	**0.9**
RCP 8.5										
	Annual		**JFM**		**AMJ**		**JAS**		**OND**	
MIROC5	−1.1	0.0	−2.2	0.0	0.3	0.1	−0.1	0.1	−2.4	0.1
GFDL-ESM2M	0.6	0.0	0.7	0.1	1.8	0.0	0.4	0.1	−0.5	0.0
CNRM-CM5	0.0	0.2	−1.4	0.1	0.9	0.0	0.7	0.3	−0.1	0.4
CAN-ESM2	1.6	0.1	0.7	0.3	2.2	0.2	1.1	0.5	1.8	0.0
ACCESS1-0	0.6	0.1	0.7	0.2	0.8	0.1	0.1	0.2	0.6	0.1
HADGEM2-CC	1.4	0.1	1.6	0.2	2.6	0.2	0.6	0.3	0.7	0.1
NORESM1-M	−0.7	0.1	−2.0	0.0	−0.2	0.1	0.3	0.2	−1.0	0.3
Ensemble	**0.3**	**1.0**	**−0.3**	**1.6**	**1.2**	**1.0**	**0.5**	**0.4**	**−0.1**	**1.4**

Note: JFM—January February March, AMJ—April May June, JAS—July August September, OND—October November December.
Abbreviations: CMIP5, Coupled Model Intercomparison Phase 5; RCP, Representative Concentration Pathway.

TABLE 3 East west (*u* wind) anomalies for the Exmouth Gulf region of north Western Australia for the period 2077–2099 under two emission scenarios (RCP4.5, RCP8.5) as projected by seven CMIP5 global climate models.

East-west (*u*) wind anomalies—Mean (SD)										
RCP 4.5										
CMIP5 model	**Annual**		**JFM**		**AMJ**		**JAS**		**OND**	
MIROC5	−0.1	0.1	−0.3	0.3	−0.1	0.0	−0.2	0.0	0.1	0.1
GFDL-ESM2M	0.9	0.3	0.9	0.2	1.9	0.5	0.2	0.3	0.7	0.1
CNRM-CM5	0.5	0.1	0.8	0.1	0.3	0.1	−0.4	0.1	1.0	0.0
CAN-ESM2	1.5	0.2	2.0	0.3	1.7	0.4	0.6	0.2	1.4	0.1
ACCESS1-0	1.0	0.1	1.4	0.1	1.5	0.2	0.7	0.2	0.3	0.0
HADGEM2-CC	1.0	0.3	0.8	0.3	1.5	0.4	1.1	0.3	0.6	0.2
NORESM1-M	0.9	0.3	1.2	0.5	0.8	0.2	0.6	0.3	1.2	0.2
Ensemble	**0.8**	**0.2**	**1.0**	**0.3**	**1.1**	**0.3**	**0.4**	**0.2**	**0.8**	**0.1**
RCP 8.5										
CMIP5 model	**Annual**		**JFM**		**AMJ**		**JAS**		**OND**	
MIROC5	0.2	0.1	0.1	0.3	0.5	0.1	−0.7	0.1	−0.7	0.1
GFDL-ESM2M	1.1	0.3	1.5	0.3	1.7	0.6	0.3	0.3	0.3	0.3
CNRM-CM5	0.3	0.2	0.8	0.3	0.4	0.2	−0.4	0.2	−0.7	0.1
CAN-ESM2	2.8	0.3	5.8	0.5	2.7	0.6	−0.4	0.2	1.6	0.2
ACCESS1-0	1.6	0.2	2.4	0.2	1.8	0.3	1.1	0.4	1.1	0.4
HADGEM2-CC	1.6	0.2	3.3	0.6	2.4	0.7	1.4	0.6	1.4	0.6
NORESM1-M	0.8	0.2	1.9	0.1	0.2	0.1	0.1	0.4	0.1	0.4
Ensemble	**1.2**	**0.2**	**2.3**	**0.3**	**1.4**	**0.4**	**0.2**	**0.3**	**0.4**	**0.3**

Note: JFM—January February March, AMJ—April May June, JAS—July August September, OND—October November December.
Abbreviations: CMIP5, Coupled Model Intercomparison Phase 5; RCP, Representative Concentration Pathway.

the only variable in the turbidity model analysis where input values were specified separately at all locations of the study region due to the availability of high spatial resolution wave data from the Delft-3D model and because wave energy is heterogeneous throughout the Gulf.

Predicted mean sea-level rise was taken from Kopp et al. (2014), who present a global dataset of localized sea-level projections using the aggregation of individual components that contribute to sea-level change as outlined in Milne et al. (2009). Because proportional changes between maximum tidal height and mean sea level are not predicted to be significantly different with sea-level rises below 1 m (Pickering et al., 2017), as considered in this analysis, tidal maximum values were predicted based on the historical relationship (2002–2020) with mean sea level in this region. The relationship can be described by the equation:

$$y = 1.0019x - 423.25\left(R^2 = 0.4282\right), \qquad (2)$$

where y is the tidal maximum (cm), and x is the mean sea level (cm).

Tidal range in north Western Australia is expected to reduce along shelf areas where there are presently large amplitudes; however, for scenarios where the projected sea-level rise is less than 1 m (as we have considered here in both scenarios), tidal range is not expected to alter significantly (Harker et al., 2019). Therefore, we have left it at the historical amplitude in this analysis.

The ENSO is expected to increase in variability and exhibit more extreme El Niño and La Niña events with anthropogenic warming (Cai et al., 2021). It is not, however, possible to forecast values for this variability, and therefore we have maintained historical ENSO values for the forecast models. We give the same treatment to the IOD, as despite being expected to increase in variability with climate forcing (Wang et al., 2020), it can be considered a covariate of ENSO (Kug & Kang, 2006; Wang et al., 2019), and we leave it at historical values in the forecast model.

3 | RESULTS

3.1 | Projected climate anomalies

Metocean anomalies projected from the CMIP5 and CMIP6 ensemble climate models for SST, precipitation, winds, waves and sea surface heights in the Exmouth Gulf varied from the baseline under the different climate forcing emission scenarios (Tables 1–5). SST, u and v winds, mean

TABLE 4 Precipitation anomalies for the Exmouth Gulf region of north Western Australia. for the period 2077–2099 (RCP4.5, RCP8.5) as projected by eight CMIP5 global climate models.

Precipitation anomalies (mm)—Mean (SD)										
RCP 4.5										
CMIP5 model	**Annual**		**JFM**		**AMJ**		**JAS**		**OND**	
MIROC5	84.4	12.8	56.9	6.1	14.5	2.7	−2.2	0.7	25.0	7.6
GFDL-ESM2M	−103.5	2.6	−30.5	8.8	−54.0	6.4	−7.4	1.1	−5.5	1.5
CNRM-CM5	27.6	12.2	34.7	3.5	3.7	8.8	−6.5	2.1	−0.6	1.3
CESM1-CAM5	−59.3	1.1	−44.7	1.7	−18.5	1.4	−1.4	1.3	8.0	1.0
CAN-ESM2	−15.1	6.4	16.8	5.7	−7.8	0.7	−14.1	2.3	−1.8	0.3
ACCESS1-0	−4.7	5.2	2.8	2.7	−1.8	2.4	−5.1	2.7	0.9	0.5
HADGEM2-CC	−38.7	9.3	−15.7	8.0	−15.3	0.5	−5.5	1.3	−0.4	0.2
NORESM1-M	−18.1	3.8	14.2	0.5	−18.4	1.6	V11.2	1.2	−13.4	0.1
Ensemble	**−15.9**	**56.3**	**4.3**	**33.7**	**−12.2**	**20.5**	**−6.7**	**4.3**	**1.5**	**11.3**
RCP 8.5										
	Annual		**JFM**		**AMJ**		**JAS**		**OND**	
MIROC5	28.7	18.7	41.8	14.4	−14.6	2.7	−2.1	2.2	10.3	0.5
GFDL-ESM2M	−105.5	2.5	−25.9	9.1	−58.8	8.6	−10.5	0.2	−5.8	0.8
CNRM-CM5	22.6	6.1	48.7	1.4	−14.3	2.9	−14.5	0.3	1.9	4.2
CESM1-CAM5	−126.3	11.2	−93.4	17.9	−17.0	7.2	−10.3	1.1	1.9	1.2
CAN-ESM2	−87.2	11.8	−40.2	15.5	−23.7	0.9	−20.4	4.2	−1.3	0.4
ACCESS1-0	−33.8	6.8	−11.0	2.5	−15.6	8.3	−6.2	1.5	0.4	0.5
HADGEM2-CC	−78.8	23.6	−47.5	19.5	−24.3	6.6	−9.7	2.7	2.9	1.4
NORESM1-M	28.6	6.1	46.0	3.3	−13.7	6.3	−8.0	0.6	9.1	3.3
Ensemble	**−44.0**	**64.1**	**−10.2**	**51.8**	**−22.7**	**15.1**	**−10.2**	**5.4**	**2.4**	**5.3**

Note: JFM—January February March, AMJ—April May June, JAS—July August September, OND—October November December.
Abbreviations: CMIP5, Coupled Model Intercomparison Phase 5; RCP, Representative Concentration Pathway.

sea level and significant wave heights all increased from baseline values, while precipitation and wave period both showed decreases from the baseline (Table 5). For *u* and *v* winds, this equates to increased westerly and southerly wind forcing (the positive components of *u* and *v* winds) and lower easterly and northerly wind forcing (the negative components of *u* and *v* winds). For wave power, the increased significant wave height was offset by a decreased wave period, and the projected wave power values were (slightly) lower than historical values.

Seasonal anomalies differed for all the metocean conditions under both emission scenarios. SST anomalies were similar across most of the year (SSP3-7.0–2.2°C, SSP5-8.5–2.6°C) apart from January–March (SSP3-7.0–1.9°C, SSP5-8.5–2.3°C) coinciding with the hottest time of the year (Table 1, Figure 3). The seasonal differences also varied with other metocean processes. For example, *v* winds show an overall annual increase that would result in increased southerly wind forcing; however, these increases are mostly from April to September (incorporating Austral winter). The warmer months from October to March show a decrease in *v* winds and therefore predict an increase in northerly winds during that time of year (Table 2). In contrast, *u* winds show increased anomalies during all seasons with the largest increase from January through March and only a small increase from July to September. These results indicate that increased westerly wind forcing will be strongest during Austral summer (Table 3).

Precipitation also showed varied seasonal anomalies for both emission scenarios (RCP4.5 and RCP8.5). While annual precipitation showed an overall decrease, the largest decreases occur during the cooler months of April to June, while the warmer months see a slight increase in rainfall, particularly in October to December (Table 4).

The global climate models for both CMIP5 and CMIP6 that were used in the ensembles themselves showed a large variation in their anomaly results (Tables 1–4). For example, the annual SST anomaly for 2100 under SSP5-8.5 from the CESM2-WACCM (NSF-DOE-NCAR, USA) model was 3.5°C, compared to FGOALS-G3 (Chinese Academy of Sciences) at 1.8°C (Table 1). Other large discrepancies between the climate models included precipitation anomalies projected by GFDL-ESM2M (NOAA, USA) and MIROC5 (JAMSTEC, Japan), which were (−103.5 mm/year) and (+84.4 mm/year), respectively (Table 4), and *v* wind anomalies projected by CAN-ESM2 (CCCMA, Canada)

Climate Resilience and Sustainability
Interdisciplinary Approaches Towards Solutions for Climate Change Open Access RMetS

TABLE 5 Historical climate data and future percentage change projections for the Exmouth Gulf region of north Western Australia.

Metocean variables	Historical mean (SD) (2002 –2020)	Projected % change by 2100 SSP3-7.0/RCP4.5 (% change)	SSP5-8.5/RCP8.5 (% change)	Source
SST (°C)	25.7 (0.11)	8.2	10.0	CMIP6–NOAA https://psl.noaa.gov/ipcc/cmip6/ccwp6.html
u wind (km/h)	5.0 (7.7)	20.0	24.3	CMIP5–NOAA https://psl.noaa.gov/ipcc/ocn/ccwp.html
v wind (km/h)	6.1 (3.9)	5.4	7.0	CMIP5–NOAA https://psl.noaa.gov/ipcc/ocn/ccwp.html
Precipitation (mm/year)	236.3 (127.2)	−7.0	−20.0	CMIP5–NOAA https://psl.noaa.gov/ipcc/ocn/ccwp.htm
Mean Sea Level (mm)	6908.9 (116.9)	9.4	14.5	Kopp et al. (2014) Permanent Service for Mean Sea Level (MSL) https://www.psmsl.org/data/
Wave period (*T*) Wave height (*Hs*)	Large variation in wave power per site in Gulf, 0.2–2.8(Hs^2*T)	−5.0 2.5	−10.0 5.0	Morim et al. (2019)
Tidal Max (cm)	269.0 (17.8)	24.2	37.2	Product of MSL; Pickering et al. (2017)

Abbreviations: CMIP6, Coupled Model Intercomparison Phase 6; NOAA, National Oceanic and Atmospheric Administration's Earth; RCP, Representative Concentration Pathway; SSP, shared socioeconomic pathway.

and MIROC5 (JAMSTEC, Japan), which were (−1.1) and (+1.6), respectively (Table 2).

3.2 | Projected turbidity

Projected increases in annual turbidity by 2100 were found in central and western Exmouth Gulf locations under both climate forcing scenarios (Figures 4a and 5). The highest projected increases here were found in the South Gulf (37% increase under RCP4.5 and 58% under RCP8.5), West Gulf (32% increase under RCP4.5 and 59% under RCP8.5) and Rest Bay (41% increase under RCP4.5 and 63% under RCP8.5). Ashburton Island, offshore to the northeast of the Gulf, also showed turbidity increases under both forcing scenarios (13% and 21%). In contrast, locations in the far south and eastern coastal regions showed either decreased turbidity (e.g., Giralia—20% and 29% reduction) or no change (<10%; e.g., Hope Island, Eva Island) in turbidity. The north-eastern near-coastal locations displayed the largest decreases in projected turbidity with both RCP4.5 and RCP8.5 scenarios (Ashburton Delta—40% and 62% reduction, respectively, and Locker Point—32% and 48% reduction, respectively, Figures 3b and 4).

Seasonal changes in turbidity anomalies (greater than 0.1 mg/L TSM) were apparent at four locations in the Exmouth Gulf for both CMIP5 climate forcing scenarios, RCP4.5 and RCP8.5 (Figure 6). For Eva Island, despite overall annual turbidity not increasing under either scenario, October to December sees a large increase in turbidity, while April to June shows a large decrease in turbidity. In contrast, Locker Point shows a steep decline in turbidity from October to December under RCP4.5 and its lowest turbidity from January to March under RCP8.5. Rest Bay, where overall turbidity increases are the largest in the region, would see a large turbidity increase from July to September under RCP4.5; however, under RCP8.5, all months of the year would see a similarly high level of turbidity. Seasonal trends remain similar under both scenarios for the South Gulf region, where turbidity is highest during Austral summer.

4 | DISCUSSION

Climate-driven shifts in the distribution and survival of marine species are an increasing global impact of anthropogenic climate change (Gervais et al., 2021). Our results

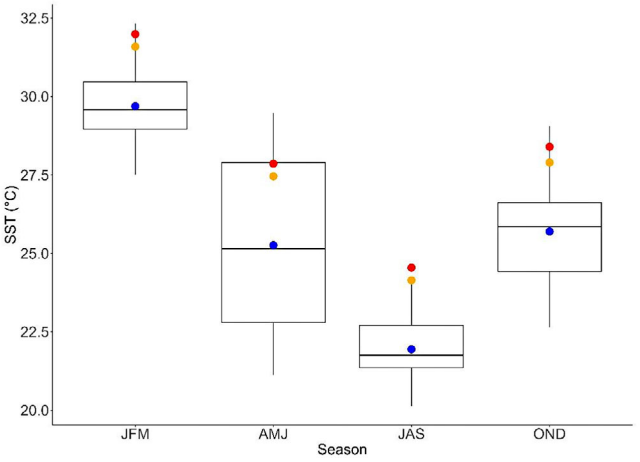

FIGURE 3 Boxplots of seasonal sea surface temperature (SST) variation at Eva Island in the Exmouth Gulf between 2003 and 2020 (boxplots), overlayed with mean historical SST between 2003 and 2020, (blue circles), mean future temperature by 2100 under SSP3-7.0 (orange circles) and mean future temperature by 2100 under SSP5-8.5 (red circles). Note that the anomalies are relative to a 1984–2014 baseline. Seasons on x-axis are JFM—January, February March; AMJ—April, May, June; JAS—July, August, September; OND—October, November, December. SSP, shared socioeconomic pathway.

indicate that arid tropical coral reefs in north Western Australia are likely to be exposed to significant changes in their environmental conditions by the year 2100, including increased SSTs and, in some locations, increased turbidity (TSM), that are likely to impact the ongoing composition, integrity and functioning of the benthic habitats in this region. While coral reefs in the Gulf are accustomed to a variable turbidity regime, it is likely that many corals are close to the limit of their tolerance for low light and sedimentation. We found that TSM is projected to increase up to 63% in some parts of the Exmouth Gulf, potentially threatening benthic habitats through multiple pathways including limitation to photosynthesis, smothering of larval recruits and colonisation of algae. Hard coral richness steeply declines with increasing TSM, with the highest richness at less than 0.8 mg/L TSM exposure and low richness at greater than 2.0 mg/L (GBRMPA, 2009). Further, macroalgal stands will potentially thicken across the reefs where turbidity increases (De'ath & Fabricus, 2010). Macroalgal cover is known to increase four-fold with a TSM increase from 1.2 to 2.0 mg/L and remains high above 2.0 mg/L (GBRMPA, 2009), and the combination of turbidity and temperature increases at currently healthy reefs may exceed a combined threshold for coral–algal colonisation that already appears to impact some regions of the Gulf (Cartwright et al., 2023).

Seasonal changes in turbidity may also have an impact on the resilience of reefs to marine heatwave events. For example, increased turbidity at Eva Island during the beginning of summer (October to December), despite the minimal overall annual increase in turbidity, may protect the reefs here from future heatwave events as these months also coincide with the largest projected seasonal anomalies in SST (Table 1). This may be particularly relevant if marine heatwaves were to extend more regularly to this time of year, which appears inevitable under the climate scenarios presented here. North Western Australia has already been exposed to an increasing number of marine heatwaves in recent years (Le Nohaïc et al., 2017), as have reefs globally (Oliver et al., 2018), and these have already led to mass bleaching and changes in coral community structure in the Exmouth Gulf region (Depczynski et al., 2013; Moore et al., 2012).

Temperature variability may also play a role in how these reefs respond to climate change. Coral reefs that show the least amount of SST variability historically, or leading up to heatwave events, are the most vulnerable to bleaching (Carilli et al., 2012; Donner, 2011; Langlais et al., 2017). While historical temperature variability differed throughout the Gulf, Exmouth Reef displayed the lowest overall variability in SST (Figure 7). As one of the least turbid reefs in the Gulf (and expected to reduce in turbidity under these climate change projections), Exmouth Reef is potentially one of the higher-risk reefs in the Exmouth Gulf for bleaching and/or functional changes.

Because these ecosystems are already considered marginal, existing at the extremes of coral thermal tolerance, the projected temperature anomalies under both emission scenarios could exceed the adaptive capacity of the corals, affecting their ability to maintain reef rugosity and perform the same functional services. These findings are consistent with predicted tropical coral reef habitat impacts in the Great Barrier Reef (Graham et al., 2015; Kubicek et al., 2019) as well as temperate reefs in Japan (Kumagai et al., 2018; Sato et al., 2020) and the degradation of 94% of coral reefs globally under the current RCP8.5 trajectory of climate change (Cornwall et al., 2021).

Sea-level rise predictions also pose a significant threat to the coral and seagrass communities in the Exmouth Gulf. Many of these habitats currently exist in shallow water (2–5 m) that allows them to utilize light despite some level of turbidity in the water column. Projected sea-level rise will not only increase turbidity according to our models, but the increasing water depth would further limit light to benthic habitats. Others have considered this; for example, a study in the Great Barrier Reef modelled sea-level rise effects on turbid coral reefs and found that under an RCP4.5 scenario, the spatial extent of 'framework habitat' reefs would decline to 5% by +100 years, and low coral cover and rugosity habitats would expand to 51% of the total reef area as

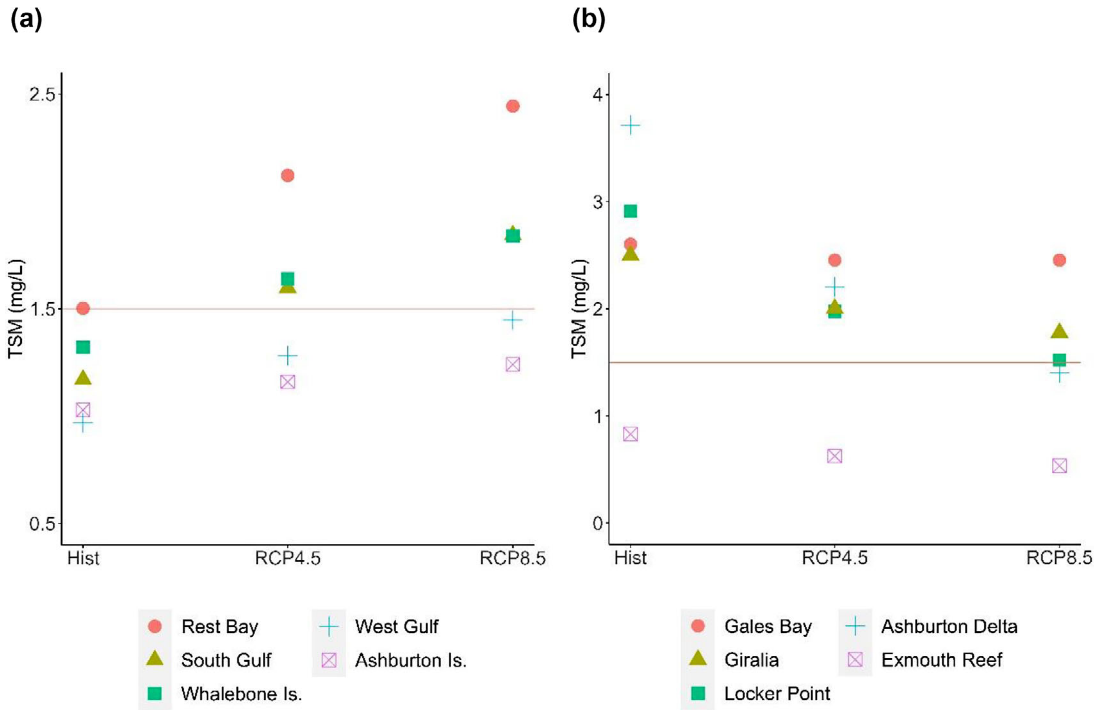

FIGURE 4 Locations in the Exmouth Gulf where turbidity (total suspended matter [TSM]) is projected to (a) increase, and (b) decrease, from historical levels by 2100 under two climate emission scenarios (RCP4.5 and RCP8.5) using an ensemble of eight climate models from CMIP5. Red line indicates guideline trigger value for TSM in coral reef ecosystems from De'ath and Fabricius (2010). CMIP, Coupled Model Intercomparison Phase; RCP, Representative Concentration Pathway.

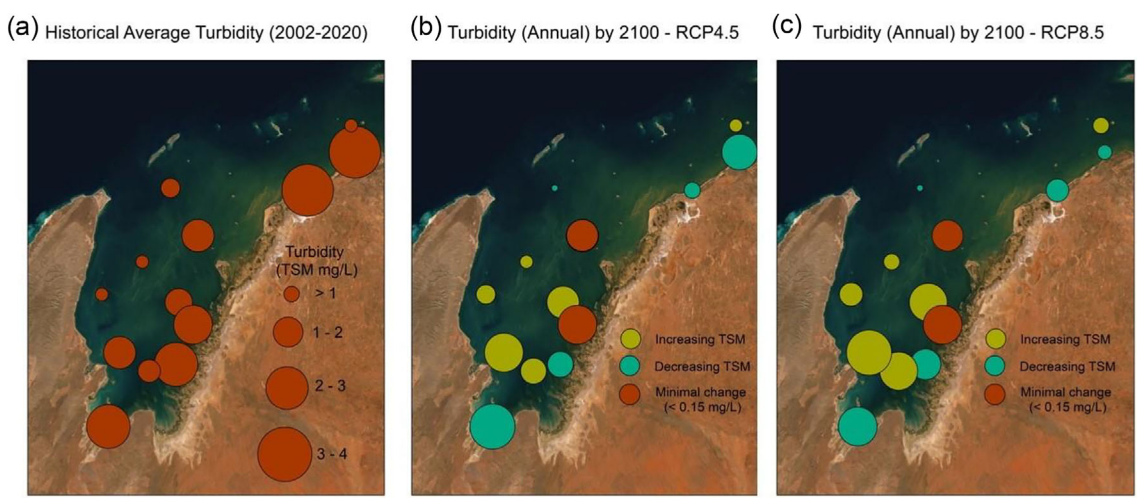

FIGURE 5 Turbidity (TSM) in the Exmouth Gulf showing (a) historical turbidity (2002–2020) derived from in situ validated, high resolution, remotely sensed MODIS satellite data; (b) projected turbidity for 2100 under middle-of-the-road climate scenario RCP4.5; and (c)projected turbidity for 2100 under high-emission scenario RCP8.5. Size of circle at each location represents level of turbidity(as per (a)). RCP, Representative Concentration Pathway.

the deeper reef slope coral communities move below the euphotic depth (Morgan et al., 2020).

It is worth noting that the seal-level rise projections used in this study are moderate projections that do not consider the implications of, for example, the Antarctic ice sheet melt. In the scenario presented by Kopp et al. (2017), global mean sea-level (GMSL) rises of 2 m could occur due to Antarctic melt by 2100 under RCP8.5 emissions.

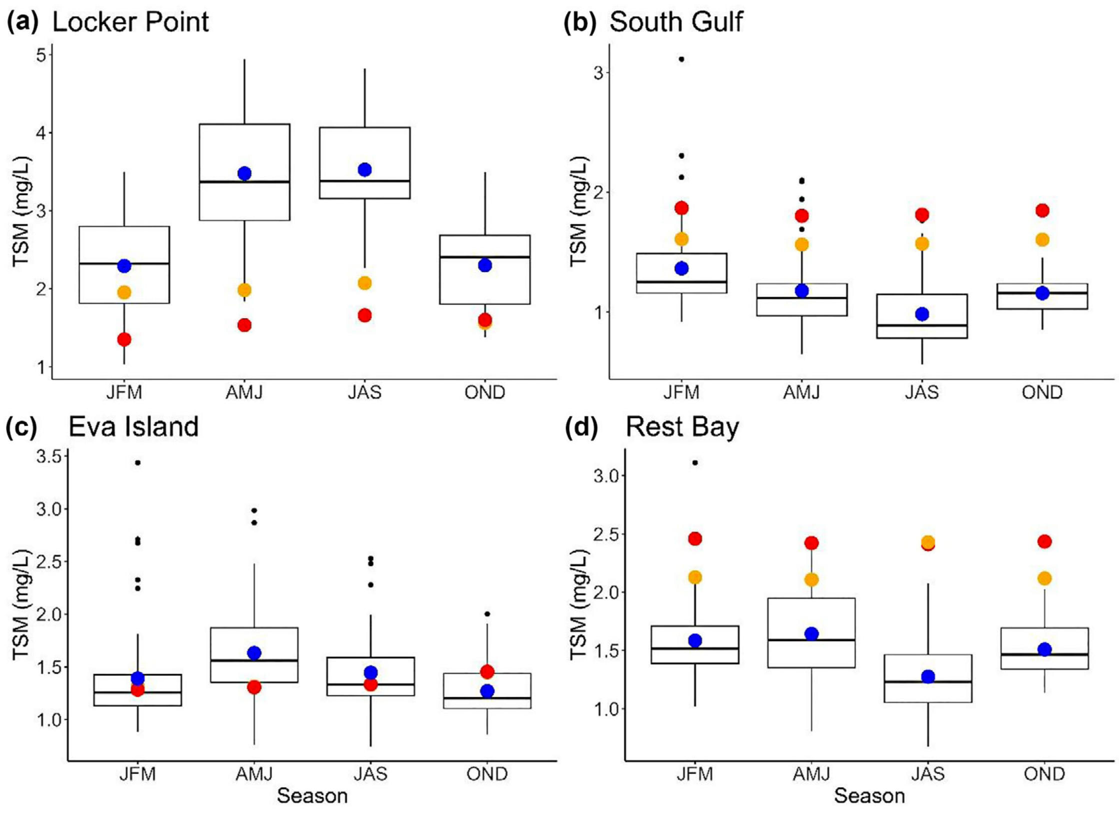

FIGURE 6 Seasonal changes in turbidity by 2100 at four locations in the Exmouth Gulf under RCP4.5 emission scenario (orange circles) and RCP8.5 climate emission scenario (red circles).Box plots show historical seasonal turbidity. Blue circles are historical mean turbidity. Seasons on x-axis are JFM—January, February March; AMJ—April, May, June; JAS—July, August, September; OND—October, November, December.

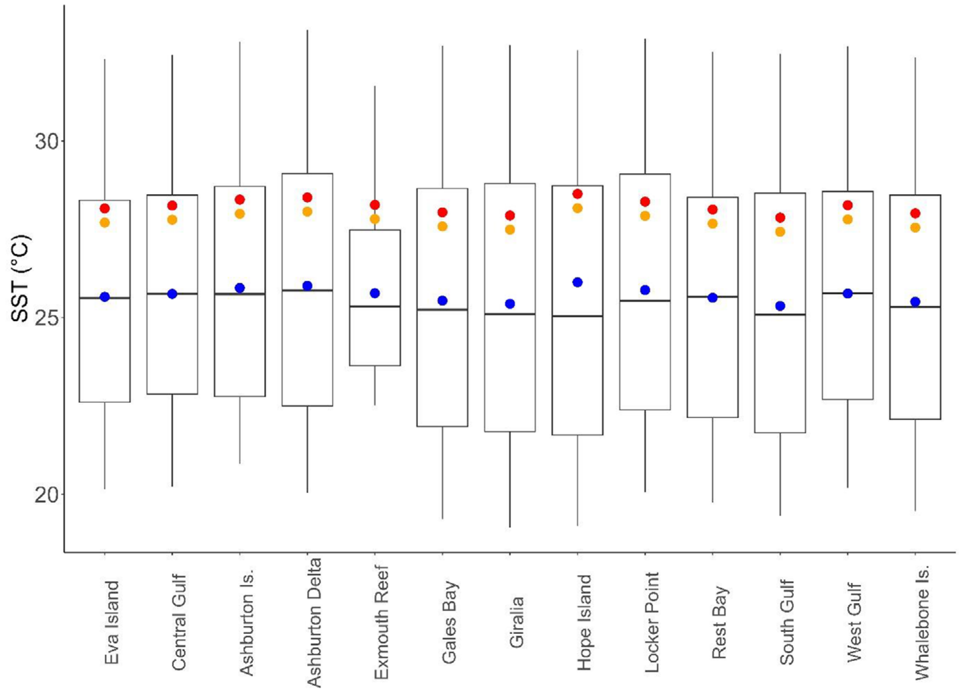

FIGURE 7 Historical SST variability (boxplots) at 13 sites in the Exmouth Gulf, overlayed with historical mean SST (blue circles), future SST under SSP3-7.0 (orange circles), and future SST under SSP5-8.5 (red circles). Historical SST is from 2002 to 2020. Anomalies are above 1984–2014 baseline.

Others have revised this figure to 1 m (Frederikse et al., 2020); however, by the year 2300, the median contribution to GMSL from Antarctica is 9.6 m according to DeConto et al. (2021), almost 10 times more than simulations limiting warming to +1.5°C. These predictions would obviously have dramatic implications for coastline changes globally.

One of the notable climate change anomalies that we found for this region is the weakening of easterly wind forcing. Easterly winds are a strong predictor for turbidity in some parts (particularly the north-eastern coastline) of the Exmouth Gulf (Cartwright et al., 2021), and this is why we see reduced turbidity in these locations in the projected turbidity models. However, this weakening does not account for irregular storm/cyclone activity from the east that will potentially increase in intensity (though not frequency) with climate change (Abbs, 2012; Knutson et al., 2020). Further, lower rainfall and longer periods of drought in the adjacent rangelands would increase the amount of terrestrial sediment available as aeolian dusts, which could potentially enter the Gulf during these storm events. Dust storms are already a feature of the region (McTainsh et al., 2011) and may become more severe with climate forcing, offsetting the projected decrease in turbidity in the north-east coastal locations. Extreme cyclones also have implications for post-bleaching recovery and the potential for regime shifts in the coral reefs of north Western Australia (Puotinen et al., 2020). Previous severe cyclones in the region, including Cyclone Vance in 1998, permanently destroyed vast swathes of benthic habitat (Loneragan et al., 2013; Paling et al., 2008). This is consistent with other regions, for example, the Great Barrier Reef where cyclones have more impact than any other factor and have been responsible for 48% of overall coral cover loss (De'Ath et al., 2012).

There are some limitations in this study that should be addressed. First, the baseline periods from which the CMIP5 anomalies are projected (1956–2005) differ from the historical period of the turbidity and metocean models (2002–2020) that were adapted from Cartwright et al. (2021). Second, predictions for end-of-century metocean anomalies are highly dependent on the chosen global climate model and emission scenario. For example, some models predict an increase in precipitation for north Western Australia, while others predict a decrease, highlighting the importance of using an ensemble model. Further, allowances need to be made for the metocean conditions that do not have projected climate change anomalies (e.g., ENSO, IOD) but which will potentially undergo change. Despite the uncertainties when projecting future climate data, studies such as this that combine long-term remote sensing of water quality with metocean modelling of climate anomalies can provide a valuable addition to the literature on potential impacts of climate change on important marine benthic habitats and provide guidance to conservation managers.

5 | CONCLUSION

We have shown here that future changes to the environments of turbid coral reefs in arid tropical Australia will be dependent upon the metocean conditions that drive the turbidity to those reefs and how climate change will affect those processes. The drivers of turbidity differ between reefs even at scales <20 km, and therefore it is likely that some reefs will be affected more than others. For some reefs, the conditions are likely to contribute to degradation, or at the least, structural composition changes, particularly when temperature predictions are superimposed on top of turbidity increases. However, predicted environmental changes that appear to be seasonally related may determine some regions that could be resilient and persist into the future.

ACKNOWLEDGEMENTS

Paula Cartwright received funding from the Australian Government Research Training Program and The University of Western Australia.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Paula Cartwright https://orcid.org/0000-0003-1717-2469

REFERENCES

Abbs, D. (2012) The impact of climate change on the climatology of tropical cyclones in the Australian region. Climate Adaptation Flagship Working Paper No. 11, CSIRO.

Akaike, H. (1987) Factor analysis and AIC. In: Akaike, H., Parzen, E., Tanabe, K. & Kitagawa, G. (Eds.) *Selected papers of Hirotugu Akaike*. New York: Springer, pp. 371–386.

ANZECC & ARMCANZ. (2000) *Australian and New Zealand guidelines for fresh and marine water quality*. Canberra: Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand.

Arias, P., Bellouin, N., Coppola, E., Jones, R., Krinner, G., Marotzke, J., Naik, V., Palmer, M., Plattner, G.K. & Rogelj, J. (2021) Climate change 2021: the physical science basis. Technical Summary, Contribution of Working Group14 I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Ayukai, T. & Miller, D. (1998) Phytoplankton biomass, production and grazing mortality in Exmouth Gulf, a shallow embayment on the arid, tropical coast of Western Australia. *Journal of Experimental Marine Biology and Ecology*, 225(2), 239–251.

Babcock, R.C., Bustamante, R.H., Fulton, E.A., Fulton, D.J., Haywood, M.D.E., Hobday, A.J., Kenyon, R., Matear, R.J., Plagányi, E.E., Richardson, A.J. & Vanderklift, M.A. (2019) Severe continental-scale impacts of climate change are happening now: extreme climate events impact marine habitat forming communities along 45% of Australia's coast. *Frontiers in Marine Science*, 6, 159–165. https://doi.org/10.3389/fmars.2019.00411

Birkmanis, C.A., Freer, J.J., Simmons, L.W., Partridge, J.C. & Sequeira, A.M.M. (2020) Future distribution of suitable habitat for pelagic sharks in Australia under climate change models. *Frontiers in Marine Science*, 7, 570. https://doi.org/10.3389/fmars.2020.00570

Bothner, M.H., Reynolds, R.L., Casso, M.A., Storlazzi, C.D. & Field, M.E. (2006) Quantity, composition, and source of sediment collected in sediment traps along the fringing coral reef off Molokai, Hawaii. *Marine Pollution Bulletin*, 52(9), 1034–1047.

Bourdeau-Goulet, S.C. & Hassanzadeh, E. (2021) Comparisons between CMIP5 and CMIP6 models: simulations of climate indices influencing food security, infrastructure resilience, and human health in Canada. *Earth's Future*, 9(5), e2021EF001995. https://doi.org/10.1029/2021EF001995

Branson, P.M. & Sun, C. (2017) Wamsi dredging science node: plume modelling uncertainty-hydrodynamics. In: *Australasian coasts & ports 2017: working with nature*. Barton, Australia: Engineers Australia, PIANC Australia and Institute of Professional Engineers New Zealand, pp. 159–165.

Browne, N., Braoun, C., McIlwain, J., Nagarajan, R. & Zinke, J. (2019) Borneo coral reefs subject to high sediment loads show evidence of resilience to various environmental stressors. *PeerJ*, 7, e7382 https://doi.org/10.7717/peerj.7382

Brunskill, G., Orpin, A., Zagorskis, I., Woolfe, K. & Ellison, J. (2001) Geochemistry and particle size of surface sediments of Exmouth Gulf, Northwest Shelf, Australia. *Continental Shelf Research*, 21(2), 157–201.

Burt, J., Camp, E., Enochs, I., Johansen, J., Morgan, K., Riegl, B. & Hoey, A. (2020) Insights from extreme coral reefs in a changing world. *Coral Reefs*, 39(3), 495–507.

Cai, W., Santoso, A., Collins, M., Dewitte, B., Karamperidou, C., Kug, J.S., Lengaigne, M., McPhaden, M.J., Stuecker, M.F., Taschetto, A.S., Timmermann, A., Wu, L., Yeh, S.W., Wang, G., Ng, B., Jia, F., Yang, Y., Ying, J., Zheng, X.T., Bayr, T., Brown, J.R., Capotondi, A., Cobb, K.M., Gan, B., Geng, T., Ham, Y.-G., Jin, F.-F., Jo, H.-S., Li, X., Lin, X., McGregor, S., Park, J.-H., Stein, K., Yang, K., Zhang, L. & Zhong, W. (2021) Changing El Niño–Southern Oscillation in a warming climate. *Nature Reviews Earth & Environment*, 2(9), 628–644. https://doi.org/10.1038/s43017-021-00199-z

Carilli, J., Donner, S.D. & Hartmann, A.C. (2012) Historical temperature variability affects coral response to heat stress. *PLoS ONE*, 7(3), e34418. https://doi.org/10.1371/journal.pone.0034418

Cartwright, P.J., Browne, N.K., Belton, D., Parnum, I., O'Leary, M., Valckenaere, J., Fearns, P. & Lowe, R. (2023) Long-term spatial variations in turbidity and temperature provide new insights into coral-algal states on extreme/marginal reefs. *Coral Reefs*, 42, 859–872. https://doi.org/10.1007/s00338-023-02393-5

Cartwright, P.J., Fearns, P.R., Branson, P., Cutler, M.V., O'leary, M., Browne, N.K. & Lowe, R.J. (2021) Identifying metocean drivers of turbidity using 18 years of MODIS satellite data: implications for marine ecosystems under climate change. *Remote Sensing*, 13(18), 3616.

Chen, N., Krom, M.D., Wu, Y., Yu, D. & Hong, H. (2018) Storm induced estuarine turbidity maxima and controls on nutrient fluxes across river-estuary-coast continuum. *Science of The Total Environment*, 628–629, 1108–1120. https://doi.org/10.1016/j.scitotenv.2018.02.060

Cornwall, C.E., Comeau, S., Kornder, N.A., Perry, C.T., Hooidonk, R.V., DeCarlo, T.M., Pratchett, M.S., Anderson, K.D., Browne, N., Carpenter, R., Diaz-Pulido, G., D'Olivo, J.P., Doo, S.S., Figueiredo, J., Fortunato, S.A.V., Kennedy, E., Lantz, C.A., McCulloch, M.T., González-Rivero, M., Schoepf, V., Smithers, S.G. & Lowe, R.J. (2021) Global declines in coral reef calcium carbonate production under ocean acidification and warming. *Proceedings of the National Academy of Sciences*, 118(21), e2015265118. https://doi.org/10.1073/pnas.2015265118

CSIRO and Bureau of Meteorology. (2015) *Climate change in Australia information for Australia's natural resource management regions*. Technical Report, CSIRO and Bureau of Meteorology.

Cuttler, M.V., Vos, K., Branson, P., Hansen, J.E., O'Leary, M., Browne, N.K. & Lowe, R.J. (2020) Interannual response of reef islands to climate-driven variations in water level and wave climate. *Remote Sensing*, 12(24), 4089.

De'ath, G. & Fabricius, K. (2010) Water quality as a regional driver of coral biodiversity and macroalgae on the Great Barrier Reef. *Ecological Applications*, 20(3), 840–850. https://doi.org/10.1890/08-2023.1

De'Ath, G., Fabricius, K.E., Sweatman, H. & Puotinen, M. (2012) The 27–year decline of coral cover on the Great Barrier Reef and its causes. *Proceedings of the National Academy of Sciences*, 109(44), 17995–17999.

DeConto, R.M., Pollard, D., Alley, R.B., Velicogna, I., Gasson, E., Gomez, N., Sadai, S., Condron, A., Gilford, D.M., Ashe, E.L., Kopp, R.E., Li, D. & Dutton, A. (2021) The Paris Climate Agreement and future sea-level rise from Antarctica. *Nature*, 593(7857), 83–89. https://doi.org/10.1038/s41586-021-03427-0

Department of Fisheries, W. A. G. (2017) *Exmouth Gulf prawn sustainability*. Australian Ocean Data Network. Available at: https://catalogue.aodn.org.au:443/geonetwork/srv/en/metadata.show?uuid=516811d7-ccbd-207a-e0440003ba8c79dd, https://researchdata.edu.au/exmouth-gulf-prawn-sustainability [Accessed 13th February 2022].

Depczynski, M., Gilmour, J., Ridgway, T., Barnes, H., Heyward, A., Holmes, T., Moore, J., Radford, B., Thomson, D. & Tinkler, P. (2013) Bleaching, coral mortality and subsequent survivorship on a West Australian fringing reef. *Coral Reefs*, 32(1), 233–238.

Doney, S.C., Busch, D.S., Cooley, S.R. & Kroeker, K.J. (2020) The impacts of ocean acidification on marine ecosystems and reliant human communities. *Annual Review of Environment and Resources*, 45, 83–112.

Doney, S.C., Ruckelshaus, M., Duffy, J.E., Barry, J.P., Chan, F., English, C.A., Galindo, H.M., Grebmeier, J.M., Hollowed, A.B. & Knowlton, N. (2012) Climate change impacts on marine ecosystems. *Annual Review of Marine Science*, 4, 11–37.

Donner, S.D. (2011) An evaluation of the effect of recent temperature variability on the prediction of coral bleaching events. *Ecological Applications*, 21, 1718–1730. https://doi.org/10.1890/10-0107.1

Dorji, P., Fearns, P. & Broomhall, M. (2016) A semi-analytic model for estimating total suspended sediment concentration in turbid coastal waters of northern Western Australia using MODIS-Aqua 250 m data. *Remote Sensing*, 8(7), 556. https://doi.org/10.3390/rs8070556

Evans, R.D., Wilson, S.K., Fisher, R., Ryan, N.M., Babcock, R., Blakeway, D., Bond, T., Dorji, P., Dufois, F., Fearns, P., Lowe, R.J., Stoddart, J. & Thomson, D.P. (2020) Early recovery dynamics of turbid coral reefs after recurring bleaching events. *Journal of Environmental Management*, 268, 110666. https://doi.org/10.1016/j.jenvman.2020.110666

Frederikse, T., Buchanan, M.K., Lambert, E., Kopp, R.E., Oppenheimer, M., Rasmussen, D.J. & van de Wal, R.S.W. (2020) Antarctic Ice Sheet and emission scenario controls on 21st-century extreme sea-level changes. *Nature Communications*, 11(1), 390. https://doi.org/10.1038/s41467-019-14049-6

Freer, J.J., Partridge, J.C., Tarling, G.A., Collins, M.A. & Genner, M.J. (2018) Predicting ecological responses in a changing ocean: the effects of future climate uncertainty. *Marine Biology*, 165(1), 1–18.

Frölicher, T.L. & Laufkötter, C. (2018) Emerging risks from marine heat waves. *Nature Communications*, 9(1), 650. https://doi.org/10.1038/s41467-018-03163-6

Gervais, C.R., Champion, C. & Pecl, G.T. (2021) Species on the move around the Australian coastline: a continental-scale review of climate-driven species redistribution in marine systems. *Global Change Biology*, 27(14), 3200–3217. https://doi.org/10.1111/gcb.15634

Gilmour, J.P., Cook, K.L., Ryan, N.M., Puotinen, M.L., Green, R.H., Shedrawi, G., Hobbs, J.P.A., Thomson, D.P., Babcock, R.C., Buckee, J., Foster, T., Richards, Z.T., Wilson, S.K., Barnes, P.B., Coutts, T.B., Radford, B.T., Piggott, C.H., Depczynski, M., Evans, S.N., Schoepf, V., Evans, R.D., Halford, A.R., Nutt, C.D., Bancroft, K.P., Heyward, A.J., & Oades, D. (2019) The state of Western Australia's coral reefs. *Coral Reefs*, 38(4), 651–667. https://doi.org/10.1007/s00338-019-01795-8

Gingele, F.X., De Deckker, P. & Hillenbrand, C.D. (2001) Clay mineral distribution in surface sediments between Indonesia and NW Australia—source and transport by ocean currents. *Marine Geology*, 179(3), 135–146. https://doi.org/10.1016/S0025-3227(01)00194-3

Goebbert, K.H. & Leslie, L.M. (2010) Interannual variability of northwest Australian tropical cyclones. *Journal of Climate*, 23(17), 4538–4555.

Goldsmit, J., McKindsey, C.W., Schlegel, R.W., Stewart, D.B., Archambault, P. & Howland, K.L. (2020) What and where? Predicting invasion hotspots in the Arctic marine realm. *Global Change Biology*, 26(9), 4752–4771. https://doi.org/10.1111/gcb.15159

Graham, N.A., Jennings, S., MacNeil, M.A., Mouillot, D. & Wilson, S.K. (2015) Predicting climate-driven regime shifts versus rebound potential in coral reefs. *Nature*, 518(7537), 94–97.

Great Barrier Reef Marine Park Authority. (2009) *Water quality guidelines for the Great Barrier Reef Marine Park*. Townsville, QLD: Great Barrier Reef Marine Park Authority.

Grose, M.R., Narsey, S., Delage, F.P., Dowdy, A.J., Bador, M., Boschat, G., Chung, C., Kajtar, J.B., Rauniyar, S., Freund, M.B., Lyu, K., Rashid, H., Zhang, X., Wales, S., Trenham, C., Holbrook, N.J., Cowan, T., Alexander, L., Arblaster, J.M. & Power, S. (2020) Insights from CMIP6 for Australia's future climate. *Earth's Future*, 8(5), e2019EF001469. https://doi.org/10.1029/2019EF001469

Harker, A., Green, J.A.M., Schindelegger, M. & Wilmes, S.B. (2019) The impact of sea-level rise on tidal characteristics around Australia. *Ocean Science*, 15(1), 147–159. https://doi.org/10.5194/os-15-147-2019

Harrison, P.A. (2021) Climate change and the suitability of local and non-local species for ecosystem restoration. *Ecological Management & Restoration*, 22(S2), 75–91. https://doi.org/10.1111/emr.12520

Heidemann, H. & Ribbe, J. (2019) Marine heat waves and the influence of El Niño off Southeast Queensland, Australia. *Frontiers in Marine Science*, 6, 56. https://doi.org/10.3389/fmars.2019.00056

Hodgson, G. (1990) Sediment and the settlement of larvae of the reef coralPocillopora damicornis. *Coral Reefs*, 9(1), 41–43.

Hughes, T.P., Baird, A.H., Bellwood, D.R., Card, M., Connolly, S.R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J.B.C., Kleypas, J., Lough, J.M., Marshall, P., Nyström, M., Palumbi, S.R., Pandolfi, J.M., Rosen, B. & Roughgarden, J. (2003) Climate change, human impacts, and the resilience of coral reefs. *Science*, 301(5635), 929–933. https://doi.org/10.1126/science.1085046

Hughes, T.P., Barnes, M.L., Bellwood, D.R., Cinner, J.E., Cumming, G.S., Jackson, J.B.C., Kleypas, J., van de Leemput, I.A., Lough, J.M., Morrison, T.H., Palumbi, S.R., van Nes, E.H. & Scheffer, M. (2017) Coral reefs in the Anthropocene. *Nature*, 546, 82. https://doi.org/10.1038/nature22901

Hull, E.V. (2021) Climate change and harmful algal blooms: legal and policy responses to protect human health, marine environments, and coastal economies. *NYU Environmental Law Journal*, 29, 59.

IPCC. (2022) *Climate Change 2022: impacts, adaptation, and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Irvine, L.G., Thums, M., Hanson, C.E., McMahon, C.R. & Hindell, M.A. (2018) Evidence for a widely expanded humpback whale calving range along the Western Australian coast. *Marine Mammal Science*, 34(2), 294–310. https://doi.org/10.1111/mms.12456

Kirk, J.T. (1994) *Light and photosynthesis in aquatic ecosystems*. Cambridge: Cambridge University Press.

Knutson, T., Camargo, S.J., Chan, J.C.L., Emanuel, K., Ho, C.H., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K. & Wu, L. (2020) Tropical cyclones and climate change assessment: part II: projected response to anthropogenic warming. *Bulletin of the American Meteorological Society*, 101(3), E303–E322. https://doi.org/10.1175/bams-d-18-0194.1

Konapala, G., Mishra, A.K., Wada, Y. & Mann, M.E. (2020) Climate change will affect global water availability through compounding changes in seasonal precipitation and evaporation. *Nature Communications*, 11(1), 3044. https://doi.org/10.1038/s41467-020-16757-w

Kopp, R.E., DeConto, R.M., Bader, D.A., Hay, C.C., Horton, R.M., Kulp, S., Oppenheimer, M., Pollard, D. & Strauss, B.H. (2017) Evolving understanding of Antarctic ice-sheet physics and ambiguity in probabilistic sea-level projections. *Earth's Future*, 5(12), 1217–1233.

Kopp, R.E., Horton, R.M., Little, C.M., Mitrovica, J.X., Oppenheimer, M., Rasmussen, D., Strauss, B.H. & Tebaldi, C. (2014) Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future*, 2(8), 383–406.

Kubicek, A., Breckling, B., Hoegh-Guldberg, O. & Reuter, H. (2019) Climate change drives trait-shifts in coral reef communities. *Scientific Reports*, 9(1), 3721. https://doi.org/10.1038/s41598-019-38962-4

Kug, J.S. & Kang, I.S. (2006) Interactive feedback between ENSO and the Indian Ocean. *Journal of Climate*, 19(9), 1784–1801.

Kumagai, N.H., Molinos, J.G., Yamano, H., Takao, S., Fujii, M. & Yamanaka, Y. (2018) Ocean currents and herbivory drive macroalgae-to-coral community shift under climate warming. *Proceedings of the National Academy of Sciences*, 115(36), 8990–8995. https://doi.org/10.1073/pnas.1716826115

Kunzmann, A., Arifin, Z. & Baum, G. (2018) Pollution of coastal areas of Jakarta Bay: water quality and biological responses. *Marine Research in Indonesia*, 43(1), 37.

Lafratta, A., Fromont, J., Speare, P. & Schönberg, C. (2017) Coral bleaching in turbid waters of north-western Australia. *Marine and Freshwater Research*, 68(1), 65–75.

Langlais, C., Lenton, A., Heron, S., Evenhuis, C., Sen Gupta, A., Brown, J.N. & Kuchinke, M. (2017) Coral bleaching pathways under the control of regional temperature variability. *Nature Climate Change*, 7, 839–844. https://doi.org/10.1038/nclimate3399

Le Nohaïc, M., Ross, C.L., Cornwall, C.E., Comeau, S., Lowe, R., McCulloch, M.T. & Schoepf, V. (2017) Marine heatwave causes unprecedented regional mass bleaching of thermally resistant corals in northwestern Australia. *Scientific Reports*, 7(1), 14999. https://doi.org/10.1038/s41598-017-14794-y

Loneragan, N., Kangas, M., Haywood, M., Kenyon, R., Caputi, N. & Sporer, E. (2013) Impact of cyclones and aquatic macrophytes on recruitment and landings of tiger prawns *Penaeus esculentus* in Exmouth Gulf, Western Australia. *Estuarine, Coastal and Shelf Science*, 127, 46–58.

Lotze, H.K., Tittensor, D.P., Bryndum-Buchholz, A., Eddy, T.D., Cheung, W.W.L., Galbraith, E.D., Barange, M., Barrier, N., Bianchi, D., Blanchard, J.L., Bopp, L., Büchner, M., Bulman, C.M., Carozza, D.A., Christensen, V., Coll, M., Dunne, J.P., Fulton, E.A., Jennings, S., Jones, M.C., Mackinson, S., Maury, O., Niiranen, S., Oliveros-Ramos, R., Roy, T., Fernandes, J.A., Schewe, J., Shin, Y.-J., Silva, T.A.M., Steenbeek, J., Stock, C.A., Verley, P., Volkholz, J., Walker, N.D. & Worm, B. (2019) Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. *Proceedings of the National Academy of Sciences*, 116(26), 12907–12912. https://doi.org/10.1073/pnas.1900194116

Lovelock, C.E., Grinham, A., Adame, M.F. & Penrose, H.M. (2010) Elemental composition and productivity of cyanobacterial mats in an arid zone estuary in north Western Australia. *Wetlands Ecology and Management*, 18(1), 37–47.

Lowe, M.L., Morrison, M.A. & Taylor, R.B. (2015) Harmful effects of sediment-induced turbidity on juvenile fish in estuaries. *Marine Ecology Progress Series*, 539, 241–254. https://www.int-res.com/abstracts/meps/v539/p241-254/

Lowe, R.J., Cuttler, M.V. & Hansen, J.E. (2021a) Climatic drivers of extreme sea level events along the coastline of Western Australia. *Earth's Future*, 9, e2020EF001620.

Lowe, R.J., Cuttler, M.V. & Hansen, J.E. (2021b) Climatic drivers of extreme sea level events along the coastline of Western Australia. *Earth's Future*, 9(4), e2020EF001620.

Lu, Y., Yuan, J., Lu, X., Su, C., Zhang, Y., Wang, C., Cao, X., Li, Q., Su, J., Ittekkot, V., Garbutt, R.A., Bush, S., Fletcher, S., Wagey, T., Kachur, A. & Sweijd, N. (2018) Major threats of pollution and climate change to global coastal ecosystems and enhanced management for sustainability. *Environmental Pollution*, 239, 670–680. https://doi.org/10.1016/j.envpol.2018.04.016

McCook, L., Klumpp, D. & McKinnon, A. (1995) Seagrass communities in Exmouth Gulf, Western Australia: a preliminary survey. *Journal of the Royal Society of Western Australia*, 78, 81–87.

McTainsh, G., O'Loingsigh, T. & Strong, C. (2011) *Update of Dust Storm Index (DSI) maps for 2005 to 2010*. https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=596a03a7864abf000c60b9f2ecca75944d1547ae [Accessed 5th February 2022].

McTainsh, G. & Strong, C. (2007) The role of aeolian dust in ecosystems. *Geomorphology*, 89(1-2), 39–54.

Milne, G.A., Gehrels, W.R., Hughes, C.W. & Tamisiea, M.E. (2009) Identifying the causes of sea-level change. *Nature Geoscience*, 2(7), 471–478. https://doi.org/10.1038/ngeo544

Moore, J.A., Bellchambers, L.M., Depczynski, M.R., Evans, R.D., Evans, S.N., Field, S.N., Friedman, K.J., Gilmour, J.P., Holmes, T.H. & Middlebrook, R. (2012) Unprecedented mass bleaching and loss of coral across 12 of latitude in Western Australia in 2010–11. *PLoS ONE*, 7(12), e51807.

Morgan, K.M., Perry, C.T., Arthur, R., Williams, H.T.P. & Smithers, S.G. (2020) Projections of coral cover and habitat change on turbid reefs under future sea-level rise. *Proceedings of the Royal Society B: Biological Sciences*, 287(1929), 20200541. https://doi.org/10.1098/rspb.2020.0541

Morgan, K.M., Perry, C.T., Johnson, J.A. & Smithers, S.G. (2017) Nearshore turbid-zone corals exhibit high bleaching tolerance on the Great Barrier Reef following the 2016 ocean warming event. *Frontiers in Marine Science*, 4, 224.

Morim, J., Hemer, M., Wang, X.L., Cartwright, N., Trenham, C., Semedo, A., Young, I., Bricheno, L., Camus, P., Casas-Prat, M., Erikson, L., Mentaschi, L., Mori, N., Shimura, T., Timmermans, B., Aarnes, O., Breivik, Ø., Behrens, A., Dobrynin, M., Menendez, M., Staneva, J., Wehner, M., Wolf, J., Kamranzad, B., Webb, A., Stopa, J. & Andutta, F. (2019) Robustness and uncertainties in global multivariate wind-wave climate projections. *Nature Climate Change*, 9(9), 711–718. https://doi.org/10.1038/s41558-019-0542-5

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., Van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M. & Kram, T. (2010) The next generation of scenarios for climate change research and assessment. *Nature*, 463(7282), 747–756.

NASA. (2018) *NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group. Moderate-resolution Imaging Spectroradiometer (MODIS) Aqua Data; NASA OB.DAAC, Greenbelt, MD, USA*. Available at: https://oceancolor.gsfc.nasa.gov/ [Accessed 11th February 2019].

Nerem, R.S., Beckley, B.D., Fasullo, J.T., Hamlington, B.D., Masters, D. & Mitchum, G.T. (2018) Climate-change–driven accelerated sea-level rise detected in the altimeter era. *Proceedings of the National Academy of Sciences*, 115(9), 2022–2025. https://doi.org/10.1073/pnas.1717312115

Norström, A.V., Nyström, M., Lokrantz, J. & Folke, C. (2009) Alternative states on coral reefs: beyond coral–macroalgal phase shifts. *Marine Ecology Progress Series*, 376, 295–306. https://www.int-res.com/abstracts/meps/v376/p295-306/

O'Neill, B.C., Tebaldi, C., van Vuuren, D.P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.F., Lowe, J., Meehl, G.A., Moss, R., Riahi, K. & Sanderson, B.M. (2016) The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6.

Geoscientific Model Development, 9(9), 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016

Oceanica. (2006) *Marine and coastal environment of the eastern Exmouth Gulf*. Available at: https://www.epa.wa.gov.au/sites/default/files/PER_documentation/1295-ERMP-Appendix%207-Marine%20and%20coastal%20environment%20V1-2.pdf

Oliver, E.C.J., Donat, M.G., Burrows, M.T., Moore, P.J., Smale, D.A., Alexander, L.V., Benthuysen, J.A., Feng, M., Sen Gupta, A., Hobday, A.J., Holbrook, N.J., Perkins-Kirkpatrick, S.E., Scannell, H.A., Straub, S.C. & Wernberg, T. (2018) Longer and more frequent marine heatwaves over the past century. *Nature Communications*, 9(1), 1324. https://doi.org/10.1038/s41467-018-03732-9

Paling, E., Kobryn, H. & Humphreys, G. (2008) Assessing the extent of mangrove change caused by Cyclone Vance in the eastern Exmouth Gulf, northwestern Australia. *Estuarine, Coastal and Shelf Science*, 77(4), 603–613.

Palter, J.B., Frölicher, T.L., Paynter, D. & John, J.G. (2018) Climate, ocean circulation, and sea level changes under stabilization and overshoot pathways to 1.5K warming. *Earth System Dynamics*, 9(2), 817–828. https://doi.org/10.5194/esd-9-817-2018

Pickering, M.D., Horsburgh, K.J., Blundell, J.R., Hirschi, J.J.M., Nicholls, R.J., Verlaan, M. & Wells, N.C. (2017) The impact of future sea-level rise on the global tides. *Continental Shelf Research*, 142, 50–68. https://doi.org/10.1016/j.csr.2017.02.004

Preen, A., Marsh, H., Lawler, I., Prince, R. & Shepherd, R. (1997) Distribution and abundance of dugongs, turtles, dolphins and other megafauna in Shark Bay, Ningaloo Reef and Exmouth Gulf, Western Australia. *Wildlife Research*, 24(2), 185–208.

Puotinen, M., Drost, E., Lowe, R., Depczynski, M., Radford, B., Heyward, A. & Gilmour, J. (2020) Towards modelling the future risk of cyclone wave damage to the world's coral reefs. *Global Change Biology*, 26(8), 4302–4315. https://doi.org/10.1111/gcb.15136

Reguero, B.G., Losada, I.J. & Méndez, F.J. (2019) A recent increase in global wave power as a consequence of oceanic warming. *Nature Communications*, 10(1), 205. https://doi.org/10.1038/s41467-018-08066-0

Ridder, N.N., Pitman, A.J. & Ukkola, A.M. (2021) Do CMIP6 climate models simulate global or regional compound events skillfully? *Geophysical Research Letters*, 48(2), e2020GL091152. https://doi.org/10.1029/2020GL091152

RStudio. (2020) *Integrated development for R*. Available at: http://www.rstudio.com/

Sato, M., Nanami, A., Bayne, C.J., Makino, M. & Hori, M. (2020) Changes in the potential stocks of coral reef ecosystem services following coral bleaching in Sekisei Lagoon, southern Japan: implications for the future under global warming. *Sustainability Science*, 15(3), 863–883. https://doi.org/10.1007/s11625-019-00778-6

Scott, J.D., Alexander, M.A., Murray, D.R., Swales, D. & Eischeid, J. (2016) The climate change web portal: a system to access and display climate and Earth system model output from the CMIP5 archive. *Bulletin of the American Meteorological Society*, 97(4), 523–530.

Smale, D.A., Wernberg, T., Oliver, E.C.J., Thomsen, M., Harvey, B.P., Straub, S.C., Burrows, M.T., Alexander, L.V., Benthuysen, J.A., Donat, M.G., Feng, M., Hobday, A.J., Holbrook, N.J., Perkins-Kirkpatrick, S.E., Scannell, H.A., Sen Gupta, A., Payne, B.L. & Moore, P.J. (2019) Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nature Climate Change*, 9(4), 306–312. https://doi.org/10.1038/s41558-019-0412-1

Song, H., Kemp, D.B., Tian, L., Chu, D., Song, H. & Dai, X. (2021) Thresholds of temperature change for mass extinctions. *Nature Communications*, 12(1), 1–8.

Tebbett, S.B. & Bellwood, D.R. (2019) Algal turf sediments on coral reefs: what's known and what's next. *Marine Pollution Bulletin*, 149, 110542. https://doi.org/10.1016/j.marpolbul.2019.110542

The CMIP6 landscape. (2019) The CMIP6 landscape. *Nature Climate Change*, 9(10), 727–727. https://doi.org/10.1038/s41558-019-0599-1

Thirukanthan, C.S., Azra, M.N., Lananan, F., Sara', G., Grinfelde, I., Rudovica, V., Vincevica-Gaile, Z. & Burlakovs, J. (2023) The evolution of coral reef under changing climate: a scientometric review. *Animals*, 13(5), 949.

Ullah, H., Nagelkerken, I., Goldenberg, S.U. & Fordham, D.A. (2018) Climate change could drive marine food web collapse through altered trophic flows and cyanobacterial proliferation. *PLoS Biology*, 16(1), e2003446. https://doi.org/10.1371/journal.pbio.2003446

Van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V. & Lamarque, J.F. (2011) The representative concentration pathways: an overview. *Climatic Change*, 109(1), 5–31.

Wang, G., Cai, W., Yang, K., Santoso, A. & Yamagata, T. (2020) A unique feature of the 2019 extreme positive Indian Ocean Dipole event. *Geophysical Research Letters*, 47(18), e2020GL088615.

Wang, H., Kumar, A., Murtugudde, R., Narapusetty, B. & Seip, K.L. (2019) Covariations between the Indian Ocean dipole and ENSO: a modeling study. *Climate Dynamics*, 53(9–10), 5743–5761.

Wooldridge, S.A. (2009) Water quality and coral bleaching thresholds: formalising the linkage for the inshore reefs of the Great Barrier Reef, Australia. *Marine Pollution Bulletin*, 58(5), 745–751. https://doi.org/10.1016/j.marpolbul.2008.12.013

Zvifler, A., O'Leary, M., Morgan, K. & Browne, N.K. (2021) Turbid coral reefs: past, present and future—a review. *Diversity*, 13(6), 251.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Cartwright, P., Browne, N., Fearns, P., O'Leary, M. & Lowe, R. (2024) Applying ensemble climate models to predict the fate of marginal coral reefs already existing at thermal and turbidity limits in arid tropical Australia. *Climate Resilience and Sustainability*, 3, e66. https://doi.org/10.1002/cli2.66