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Review

The seven sins of climate change: A review of rates of change, and quantitative impacts on ecosystems and water quality in the Great Barrier Reef

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ABSTRACT

The term climate change encompasses many types of impacts and threats to the long-term outlook of coastal marine ecosystems. Based on a structured Evidence Summary methodology, this review synthesises the peer-reviewed knowledge on climate change impacts on the Great Barrier Reef (GBR). We summarise the observed and predicted region-specific rates of change for seven climate change factors; three representing episodic extreme weather events (heatwaves, tropical storms, and extreme rainfall events), and four chronic progressive climate change factors (rising temperatures, ocean acidification and sea level, and altered cloudiness/windiness). We extract key quantitative findings on their impacts on GBR ecosystems and associated organisms, especially coral reefs, seagrasses, mangroves and wetlands, and on GBR water quality. Quantifying GBR-wide effects requires data on their four dimensions: intensity, duration, spatial extent, and frequency. The review shows that to date, most damage to GBR ecosystems is inflicted by extreme weather events. Of the progressive climate change factors, ocean acidification is already altering some GBR ecosystem functions, potentially reaching a critical threshold within decades. The progressive climate change factors are already causing selective mortality and changes in communities. We document regional differences, and we outline the evidence of climate change impacts on GBR water quality, suggesting further cumulative effects. This review provides an overview of empirical data for modellers and ecologists, and for experimentalists to choose environmentally relevant treatment levels. Intensifying climate change disturbances increase the urgency of climate change mitigation, as well as effective local management to accelerate ecosystem recovery.

1. Introduction

It is now unequivocal that greenhouse gas emissions from human activities have warmed the Earth's atmosphere, ocean and land (IPCC, 2021). Increasing greenhouse gas concentrations and temperatures are directly or indirectly causing changes in other climate-related factors, such as sea level, ocean acidification and storm intensity. Many studies have investigated climate change impacts on tropical marine ecosystems and their functions, on the performance and fitness of their resident organisms, and on ecosystem values. Coral reefs are considered particularly sensitive to climate change, and both existential ecological losses and economic losses are forecasted, diminishing their present-day global value of US$35 billion annually (Gaines et al., 2023). Other tropical marine ecosystems including seagrass, mangroves and wetlands are also highly sensitive to climate change. However, it is difficult to obtain a comprehensive, evidence-based quantitative understanding of the various types and magnitudes of climate change impacts (direct and indirect, negative and positive) on key tropical marine ecosystems, organisms and specific functions. This is due to the multifactorial nature of climate change, the complexity of tropical ecosystems, significant regional differences in magnitudes of change, and important interactions with other forms of disturbances such as water quality.

This review synthesises and consolidates key findings from the large volume of peer-reviewed publications on documented and predicted

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region-specific rates and effects of climate change on the Great Barrier Reef (GBR), its ecosystems and its water quality. The GBR is a vast World Heritage Area with numerous outstanding universal values and significant economic benefits to coastal communities and industries. Although mostly known for its over 3000 individual coral reefs, it also encompasses a diverse range of other ecosystems including inter-reef soft-bottom communities, seagrass meadows, islands and cays, mangroves, salt marshes and coastal freshwater wetlands. Compared to many other tropical marine systems (which are predominantly located in low-income countries), the GBR has benefitted from a relatively large number of scientific studies. Climate change has been ranked the greatest threat to the GBR for the last decade, however the terrestrial runoff of nutrients and sediments into the GBR also represents a significant threat (GBRMPA, 2019, 2024; Waterhouse et al., 2024a, 2024b). With intensifying climate change, water quality increases in importance, as poor water quality delays the recovery of key habitats, species and ecosystem processes (Wolff et al., 2018). Because of these cumulative disturbances, the overall outlook for these GBR ecosystems is presently classified as ‘very poor’ (GBRMPA, 2024).

The structure of this review is outlined in Fig. 1. We consider seven main environmental change factors attributable to climate change, namely: 1) warming temperatures, 2) heatwaves (marine and air), 3) ocean acidification, 4) sea level rise, 5) rainfall, 6) tropical cyclones, and 7) cloudiness/windiness. Three of these factors reflect changes in the frequency and intensity of weather extremes (marine heatwaves, tropical cyclones, and extreme rainfall events) representing pulse disturbances linked to global warming, while the remaining four factors represent increasing pressures from gradual changes. We review the literature through three lenses, in three sections. Section 1 summarises what is known about observed and modelled projected region-specific rates of change in the seven climate change factors in the GBR. In Section 2 we review what has been published to date about their impacts on GBR ecosystems and organisms. The plethora of these studies were interrogated and subset especially focusing on quantitative answers on rates and directions of key biological responses, and on evidence for critical thresholds or tipping points for specific response types. Finally, in Section 3 we review existing evidence on how these climate change factors may also affect water quality in the GBR, either directly or indirectly, via biological pathways. The term “water quality” is used here to refer to concentrations of nutrients, sediments and pesticides exceeding the region-specific GBR Water Quality Guidelines (GBRMPA, 2010; Waterhouse et al., 2024a, 2024b). Ocean acidification and deoxygenation were also included as climate change-related water quality issues. The numerous direct impacts of altered water quality on marine ecosystems are beyond the scope of this work and have been covered elsewhere (e.g., Waterhouse et al., 2024a, 2024b). By providing structured access to the complex body of quantitative evidence, this review aims to support management, scientific and regulatory efforts towards mitigation and preparation for these rapidly encroaching changes on tropical marine ecosystems in the Indo-Pacific.

2. Methods

A Rapid Review approach was used to develop the synthesis of evidence, using an Evidence Summary method (Fabricius et al., 2024; Richards et al., 2023). Rapid Review approaches involve a reduction in or omission of some steps compared to full systematic reviews during the search, quality assessment and data extraction steps, whilst applying methods to minimise author bias. The Evidence Summary method used here involved a systematic literature search with well-defined inclusion and exclusion criteria, followed by an initial screening to determine potential relevance based on the title and abstract of each item, and a secondary screening to determine eligibility after reading the item in full. An appraisal of the evidence was completed for each evidence item to ensure the relevance, quantity, diversity and consistency of the evidence base.

The literature searches were performed based on the following approach: peer-reviewed studies written in English and published between January 1990 and October 2022 were included, discovered through a combination of two online academic databases. Web of Science was searched through the ‘Topic’ field, and Scopus was searched through the ‘Title/Abstract/Keyword’ field. Two search strings were used: Sections 1 and 2: ((“Great Barrier Reef” OR GBR) AND (“climate change” OR “sea surface temperature” OR “seawater temperature” OR

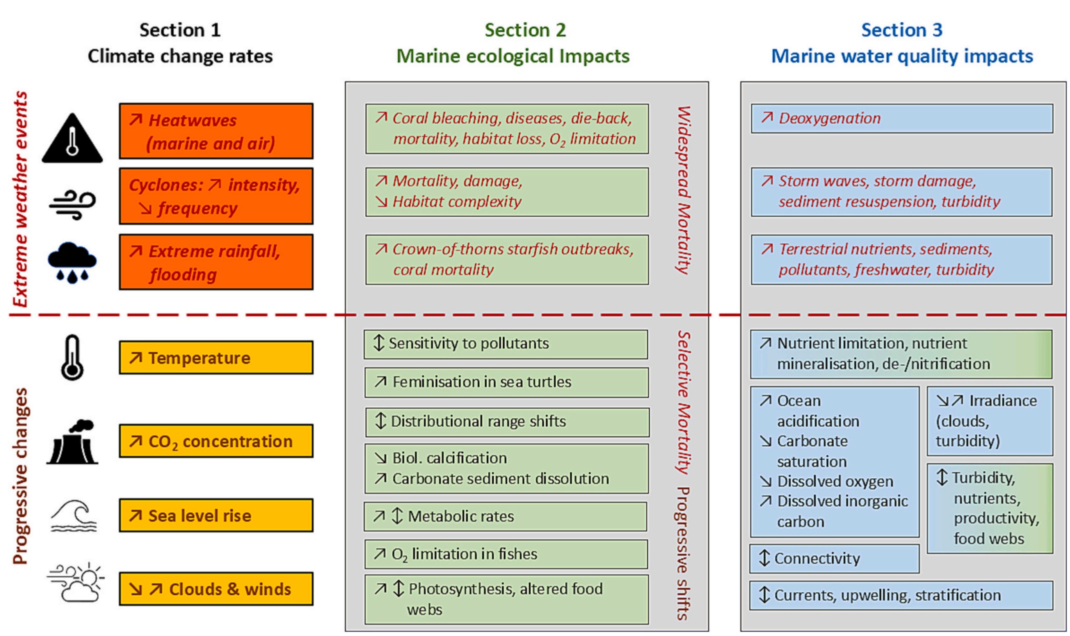

Fig. 1. Conceptual diagram of this review: Section 1: A review of the currently observed and model-predicted near-future rates of change in extreme weather (red, italics) and progressive climate change agents (orange) in the Great Barrier Reef (GBR). Section 2: Evidence how these seven climate change agents affect important GBR eco-system functions and organisms of concern (green). Section 3: Evidence how climate change is affecting the marine environment and water quality in the GBR and its subregions (blue). Arrows indicated the presumed directions of change. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

"water temperature" OR SST OR heat* OR warming OR cyclone OR "acidification" OR "sea level rise" OR storm)). Section 3: ("Climate change") AND (Queensland OR "North-Eastern Australia" or "Great Barrier Reef") AND ("water quality" OR sediment OR nutrient OR pesticide OR rainfall OR drought OR El Nino OR ENSO OR cyclone or "ocean current" OR productivity OR acidification). Reports and non-peer-reviewed literature were excluded. Supplementary Tables 1, 2, and 3 list the search terms and their definitions. Searches were limited to sources specifically relating to the Great Barrier Reef (including enclosed and open coastal and inshore, mid-shelf and offshore regions within the GBR; for Section 3 also including the terms Queensland and North-Eastern Australia) to keep the review manageable, given the very large number of publications that might otherwise fit the search criteria. All retrieved evidence items were screened based on eligibility criteria including observational, experimental, modelled or review/meta-analysis, while purely theoretical or methods studies were excluded. Laboratory experiments were retained only if they included some elements of spatial or temporal relevance for the GBR, i.e., environmentally realistic treatment levels for key taxa or processes (Richards et al., 2023). Additional studies were identified through personal collections and expert contacts (missed by the literature search mostly because they didn't mention the 'Great Barrier Reef', e.g., global reviews or meta-analyses), and added manually.

3. Results

The literature searches returned 3750 evidence items, of which 244 passed the screening by meeting the eligibility criteria. Additionally, 76 studies were added manually, which represented 24 % of the total evidence. As a result, 320 studies were eligible for inclusion in the synthesis of evidence (Supplementary Table 4, Supplementary Fig. 1). Overall, the diversity of study types was high, with 37 % of studies being observational, 32 % experimental, 22 % modelling and 9 % reviews (Supplementary Table 5).

3.1. Section 1: Current and predicted rates of climate change in the GBR, including spatial and temporal distributions

A total of 22 publications were considered that specifically addressed rates of climate change in the GBR region and its subregions (Supplementary Table 6). They included 11 observational, 13 modelling, and 6 review or meta-analysis studies (multiple study types counted more than once). Additional regionally relevant studies that did not use the term 'Great Barrier Reef' were added manually to the database (12 of 22 publications).

Table 1 provides an overview of some observed and predicted rates of change; the referenced original literature provides a wealth of additional important aspects and nuances. Most data originated from the Climate Change in Australia Tool (CCIA, https://www.climatechangeinaustralia.gov.au/en/, accessed 20 February 2024), reviewing and incorporating a large body of data and literature. The models present separate predictions for three subregions that span land and sea along the GBR coast, namely (i) a northern subregion that also includes the Whitsundays ("Wet Tropics": about latitudes 10.5–18.6°°S and 20–21.7°°S; (McInnes et al., 2015b); a central subregion covering the "Dry Tropics" between about latitudes 18.6–20°S ("Monsoonal North East"; (Moise et al., 2015); and the subregion south of about latitude 21.7°S ("East Coast North"; (Dowdy et al., 2015) (outlines see Fig. 2). The CCIA predictions are presented as change compared to the reference period 1986–2005, for 'near future years' (2020–2039, labelled 2030) and 'late in the century' (2080–2099, labelled 2090).

In summary and as outlined in the following pages, the CCIA projects the following five trends for the whole GBR: average temperatures will continue to increase in all seasons (very high confidence); more hot days and warm spells are projected (very high confidence); changes to the total rainfall amount are possible but unclear while the intensity of extreme rainfall events will increase (high confidence); and mean sea level and height of extreme sea-level events will also continue to increase (very high confidence). Additionally, for the northern and central subregions, the CCIA projects fewer but more intense tropical cyclones (medium confidence), although, on an annual to decadal basis, natural variability in the climate system can either mask or enhance any long-term human-induced trend, particularly in the next 20 years and for rainfall. For the southern subregion, a further projection is a future harsher fire-weather climate (high confidence).

3.1.1. Warming temperatures and marine heatwaves

Annual mean surface air temperature has increased by 1.0 to 1.1 °C between 1910 and 2013, and is predicted to rise further by 0.3 to 1.3 °C (10th to 90th percentile) in the 2030 period compared to 1986–2005, with only a minor difference between regions and the emission scenarios (Dowdy et al., 2015; McInnes et al., 2015b; Moise et al., 2015). Further warming will directly depend on global emissions, but importantly will be lower in the northern compared to the other subregions (Table 1). **Extremes in surface air temperature** (the maximum temperature reached on the hottest days, the frequency of hot days and the duration of warmer periods) will increase in all regions (Dowdy et al., 2015; McInnes et al., 2015b; Moise et al., 2015). For example, the coastal city of Cairns (~17°° S) currently experiences three days per year with temperatures above 35 °C, compared to 11 days in 2090 under RCP4.5 (McInnes et al., 2015b).

Annual mean sea surface temperature (SST) in the GBR has increased by around 1.0 °C (0.8 °C between 1910 and 2013, and a further 0.1 to 0.2 °C to 2022). Near-coastal SST around Australia presently increases by 0.1 to 0.2° per decade, and by 2030 will have again risen by as much as 0.3 to 1.0 °C compared to the period 1986–2005. Warming by 2090 is estimated to be 1.0 to 1.8 °C under RCP4.5, and 2.2 to 3.5 °C under RCP8.5 (Dowdy et al., 2015; McInnes et al., 2015b; Moise et al., 2015), (Table 1). Associated with warming temperatures are greater temperature variability and **heatwaves (marine and air)** which are of specific concern for the GBR as these events lead to coral bleaching (Section 2). Although the definition of marine heatwaves varies regionally (IPCC, 2021), Hobday et al. (2016) proposed a standardised definition as 'five or more days exceeding the 90th percentile of temperatures at the same time of the year in a 30-year period'. Marine heatwaves have very likely doubled in frequency globally between 1982 and 2016 (high confidence), and become more intense and longer (IPCC, 2021). Globally, the frequency of marine heatwaves is predicted to increase four times (5–95 % range: 2–9 times) in 2081–2100 compared to 1995–2014 under the optimistic SSP1–2.6 pathway, and eight times (3–15 times) under SSP5–8.5. In the GBR, the 2016–2017 marine heatwaves, with 1.03 °C above the 1961–1990 average, led to extensive mass coral bleaching and mortality (Hughes et al., 2018), closely followed by heatwaves in 2020, 2022 and 2024. Bleaching events are often associated with low windiness and low cloud cover (doldrum conditions) during times of heat waves (also damaging mangroves and intertidal seagrass, see Section 2), or the onshore transport of heated surface waters from the Coral Sea. Climate models predict overall greater regional warming, reduced cloud cover, and more frequent bleaching events in the southern and central Great Barrier Reef Marine Park (GBRMP) compared to the northern and far northern GBRMP zones where cloud cover may increase. These are important trends as low cloud cover is highly negatively correlated to lagged regional sea surface temperature and hence coral bleaching extent (Zhao et al., 2021).

3.1.2. Ocean acidification

Like global warming and the other climate change factors, ocean acidification is caused by the additional atmospheric CO_2 emitted by human activities. To re-establish equilibrium, the additional atmospheric CO_2 is taken up into the surface seawater, reducing pH and carbonate saturation state, and elevating the concentrations of total dissolved carbon, bicarbonate ions and CO_2 (Doney et al., 2020; Doney

Table 1
Published, observed and predicted changes in climate conditions and extreme weather events for the three GBR subregions (outlined in Fig. 2). WT = "Wet Tropics" (northern subregion), MNE = "Monsoonal North-East" (central subregion), ECN = "East Coast North" (southern subregion). Observed rates vary in their reference period as indicated in the cells. Predictions are compared to the reference period 1986–2005, and are given as 10th and 90th percentiles for the near future years 2020–2039 (referred to as 2030) and 2080–2099 (referred to as 2090). * Data/predictions from sites within GBR were sourced from an appendix of the reference; **Data/predictions are for the entire region, including locations outside the GBR (subregion/site data not available).

	Sub-regions	Observed (time range in brackets)	Predicted for 2030 (compared to 1986–2005)	Predicted for 2090 (RCP4.5) (compared to 1986–2005)	Predicted for 2090 (RCP8.5) (compared to 1986–2005)	References
Surface air temperature (means, seasonal minima, maxima; °C)	WT**	+1.1 (1910–2013)	+0.3 to 1.1	+1.0 to 2.0	+2.3 to 3.9	(McInnes et al., 2015b)
	MNE**	+1.0 (1910–2013)	+0.5 to 1.3	+1.3 to 2.7	+2.8 to 5.1	(Moise et al., 2015)
	ECN	+1.0 (1910–2013)	+0.4 to 1.3*	+1.2 to 2.6*	+2.5 to 4.7*	(Dowdy et al., 2015)
Sea surface temperature (SST) (°C)	WT: Cairns, Mackay	+1.0 °C (+0.8 °C in 1910–2013; +0.1 to 0.2 °C in 2013–2022).	+0.3 to 1.0* +0.4 to 1.0*	+1.0 to 1.8* +1.1 to 1.8*	+2.2 to 3.5* +2.3 to 3.4*	(McInnes et al., 2015b)
	MNE (Townsville)	Average temperatures will continue to increase in all seasons (very high confidence), presently by 0.1 to 0.2 °C per decade.	+04 to 1.0*	+1.0 to 1.8*	+2.2 to 3.4*	(Moise et al., 2015)
	ECN (Gladstone)		+0.3 to 1.0*	+1.1 to 1.9*	+ 2.1 to 3.5*	(Dowdy et al., 2015)
Air temperature extremes	WT ** MNE** ECN**	Substantially increasing temperatures on the hottest days, the frequency of hot days, and duration of warm spells (very high confidence).				(Dowdy et al., 2015; McInnes et al., 2015b; Moise et al., 2015)
Marine heatwaves	GBR	Projections indicate more frequent heatwaves in the central and southern than the far north and northern GBRMP regions, due to changing cloud cover.				(McWhorter et al., 2022b)
	Global (IPCC, 2021, Box 9.2 show GBR rates to be about average vs global)			Four times (5–95 % range: 2–9 times) more frequent in 2081–2100 compared to 1995–2014 under SSP1–2.6	Eight times (3–15 times) more frequent under SSP5–8.5	(IPCC, 2021)
Ocean acidification: Change in pH, in aragonite saturation state (Ωar)	GBR		pH: −0.06 to −0.08* Ωar: Some reefs will be exposed to Ωar <3.5.	pH: −0.14 to −0.15* Ωar: Most reefs will be exposed to Ωar <3.2.	pH: −0.31 to −0.32* Ωar: All open-water reefs will be exposed to Ωar <3.0.	(Dowdy et al., 2015; McInnes et al., 2015b; Moise et al., 2015)
	GBR	pH: −0.08 to −0.09 (1870–2015) Ωar: −0.55 to -0.6 (1870–2015)				(Lenton et al., 2016)
	Central GBR	pH: −0.07 (8.13 in 1960 to 8.06 in 2009) Ωar: −0.33 (3.92 in 1960 to 3.59 in 2009)				(Fabricius et al., 2020)
Sea level rise (m)	WT (Cairns, Mackay)	+1.4 mm yr^{-1} (1966 to 2009) (+3.1 mm yr^{-1} in 1993–2009, after corrections)	+0.09 to 0.18*	+0.31 to 0.64*	+0.44 to 0.87*	(McInnes et al., 2015b)
	MNE**		+0.06 to 0.17	+0.28 to 0.64	+0.38 to 0.85	(Moise et al., 2015)
	ECN (Gladstone)		+0.08 to 0.18*	+0.30 to 0.64*	+0.44 to 0.86*	(Dowdy et al., 2015)
Mean rainfall (%)	WT**	No significant long-term trend	-12 to +6*	-12 to +8*	-26 to +21*	(McInnes et al., 2015b)
	MNE**	Linear trend suggests slight rise of +10 mm per decade (1900–2012)	−11 to +8 *	−15 to +7*	−24 to +24*	(Moise et al., 2015)
	ECN	No significant long-term trend	−17 to +12*	−21 to +7*	−32 to +17*	(Dowdy et al., 2015)
Intense rainfall	WT** MNE** ECN**		Increasing intensity of extreme daily rainfall events (high confidence). The magnitude of increases cannot be confidently projected.			(Dowdy et al., 2015; McInnes et al., 2015b; Moise et al., 2015)
Drought	WT**		Projected changes in the frequency and duration of drought are uncertain.			(McInnes et al., 2015b)
	MNE**		Low confidence in projections of how the frequency and duration of extreme drought may change.			(Moise et al., 2015)
	ECN**		Time spent in drought is projected to increase (medium confidence). Frequency and duration of extreme drought is projected to increase (low confidence).			(Dowdy et al., 2015)
Tropical cyclone	WT** MNE**		Less frequent cyclones, but the proportion of the most intense storms is projected to increase (medium confidence).			(Dowdy et al., 2015; McInnes et al., 2015b; Moise et al., 2015)
	ECN**		No changes in cyclone intensities and frequencies.			(Dowdy et al., 2015)
	GBR		Prediction of modest to moderate (0–20 %) increases in average and maximum cyclone intensities by the end of the century.			(Hughes, 2003)

(continued on next page)

Table 1 (*continued*)

	Sub-regions	Observed (time range in brackets)	Predicted for 2030 (compared to 1986–2005)	Predicted for 2090 (RCP4.5) (compared to 1986–2005)	Predicted for 2090 (RCP8.5) (compared to 1986–2005)	References
	Australia		No clear evidence for more cyclone damage to Australian coral reef regions in the future.			(Dixon et al., 2022)
Changes in cloudiness	WT		Predicted intensification of the summer monsoon, leading to more clouds in the far north and northern GBR			(McWhorter et al., 2022b)
	MNE, ECN		Reduced clouds in the central and southern GBR, due to poleward shift in the subtropical ridge			(McWhorter et al., 2022b)
Changes in seasonal surface wind speed (%, ranges: max, min across seasons)	WT**		−3.7 to +10.2*	−2.8 to +12.9*	−5.2 to +11.8*	(McInnes et al., 2015b)
	MNE**		−4.2 to +3.3*	−5 to +4.9*	−7.6 to +8.4*	(Moise et al., 2015)
	ECN		−3.8 to +4.4*	−4.8 to +4.4*	−4.5 to +9.9*	(Dowdy et al., 2015)

et al., 2009). Rates of surface ocean acidification in most Australian regions are commensurate with the rate of atmospheric CO_2 increase and similar to rates observed in open oceans (Lenton et al., 2016). Currently, the rate of pH change in open ocean surface waters is about ten times greater than observed at any other time in the previous 65 million years, and rates of acidification have been accelerating in recent decades. On the GBR continental shelf, ocean acidification is also progressing fast, with long-term acidification trends predominantly driven by atmospheric forcing, superimposed by high diurnal and annual fluctuations from biotic metabolism and temperature (Fabricius et al., 2020; Lenton et al., 2016). Concentrations of CO_2 dissolved in GBR seawater have increased by ~6 % in 2009–2019, and by an estimated ~28 % since atmospheric CO_2 measurements started in 1958, showing that the carbonate GBR seafloor has been unable to buffer the seawater against atmospheric changes (Fabricius et al., 2020).

Annual mean surface seawater pH has already declined by 0.1 units globally (a 26 % rise in acidity) (Doney et al., 2009; IPCC, 2021). Some GBR reefs are now experiencing conditions outside the pH envelope experienced before 1850, i.e., pre-industrial times (Fabricius et al., 2020). For the coastal waters of the GBR, mean annual seawater pH is projected to decrease by 2090 compared to 1986–2005 by an additional 0.15 units under RCP4.5, and up to 0.33 units under RCP8.5 - a 40 and 100 % rise in acidity, respectively (McInnes et al., 2015c); Table 1).

Annual mean aragonite saturation state (Ωar) in the GBR is likely to have averaged >4.0 in pre-industrial times (Lenton et al., 2016). Although carbonate saturation increases with increasing temperature, this increase is insufficient to offset the large losses in carbonate saturation state due to increasing CO_2 (Doney et al., 2020). A value >3.0 is a threshold for reef development, but steep changes in reef biota are observed as Ωar drops to <3.5 (Section 2). Between 1960 and 2009, GBR Ωar has likely decreased by 0.33 units (Fabricius et al., 2020). Compared to the reference period 1986–2005, further declines are predicted to be up to 0.45 units by 2030, and 0.73 to 0.78 by 2090 under RCP4.5 (1.49 to 1.61 under RCP8.5) (Dowdy et al., 2015; McInnes et al., 2015c; McInnes et al., 2015b; Moise et al., 2015). This means the critical threshold value of an annual mean of 3.0 would be crossed before the end of this century throughout the GBR (Ricke et al., 2013), and the threshold of ecological concern of 3.5 will already be reached in some parts of the GBR before the year 2030 (assuming relevant factors other than CO_2 such as salinity and alkalinity won't change much).

3.1.3. Sea level rise

Sea level rise is caused primarily by the melting of polar ice sheets and glaciers, and changes in ocean density from warming. Globally, mean sea level has increased by 0.20 [0.15 to 0.25] m between 1901 and 2018 (IPCC, 2021). The CCIA reports that, consistent with global average values, sea levels have risen around the Australian coastline at an average rate of 1.4 mm yr^{-1} (or 2.1 mm yr^{-1} over 1966–2009 and 3.1 mm yr^{-1} over 1993–2009, after correcting for the influence of the El Niño Southern Oscillation on sea level, vertical land movements, natural climate variability, and changes in atmospheric pressure). For all three GBR subregions, there is very high confidence in future and accelerating sea-level rise in line with global mean sea level. By 2030, the projected range of sea-level rise ranges (0.06 to 0.18 m above the 1986–2005 level) shows only minor differences between emission scenarios, while later projections are sensitive to CO_2 concentration pathways (Table 1). Sea levels will continue rising beyond 2100 for many centuries proportionally to the degree of warming. A higher sea level worsens the impacts of storms and heavy rainfall. Extreme **short-term inundations** above and beyond mean sea level are caused by combinations of extreme astronomical tides, storm surges and wind waves, and affect coastal GBR ecosystems depending on latitude: presently, one-in-a hundred-year storm tide heights in the GBR are 2–3 m above mean sea level north of about latitude 20°S, but as much as 3–4 m between 20 and 23°S (McInnes et al., 2015c).

3.1.4. Rainfall

Inter-annual variability in rainfall and river flow in coastal Queensland is strongly influenced by the El Niño Southern Oscillation (ENSO) together with the Pacific Decadal Oscillation (PDO) (Lough, 1994; Redondo-Rodriguez et al., 2012; Rodriguez-Ramirez et al., 2014). La Niña conditions are typically associated with more intense rainfall in GBR catchments, whereas El Niño conditions are associated with higher temperatures and drought than neutral ENSO times. In a 30-year study period (1958–1987), the 'La Niña' phase was associated with greatly increased freshwater discharges, reduced surface radiation (and thus benthic irradiance) and enhanced tropical cyclone activity, while El Niño events had less effect on the GBR climate (Lough, 1994). In the Southern GBR, rainfall variability was significantly explained by PDO, with reduced runoff associated with El Niño years during positive PDO phases, while increased runoff coincided with La Niña years during negative PDO phases (Rodriguez-Ramirez et al., 2014). Some studies suggest that globally rising temperatures may magnify the magnitude of surface climate anomalies associated with ENSO (Power et al., 2017).

Annual mean rainfall showed no significant trends throughout the 20th Century along most of the GBR, but it slightly increased in the central subregion. Predictions of changes in mean rainfall for the 21st Century are highly uncertain for all GBR subregions, with both drier and wetter conditions a possibility (Table 1).

Intensity of extreme rainfall events: Paleoclimate records provide evidence for an increased frequency of extreme rainfall and river flows into the GBR (Lough et al., 2015). There is high confidence in increasing intensity of extreme rainfall events projected for all GBR subregions. However, the magnitude of future increases cannot be confidently projected. A greater time in drought is projected with medium confidence for the southern subregion under RCP8.5, by late in the 21st century, and a greater frequency and duration of extreme drought is projected with low confidence (Dowdy et al., 2015). Hydrological modelling also

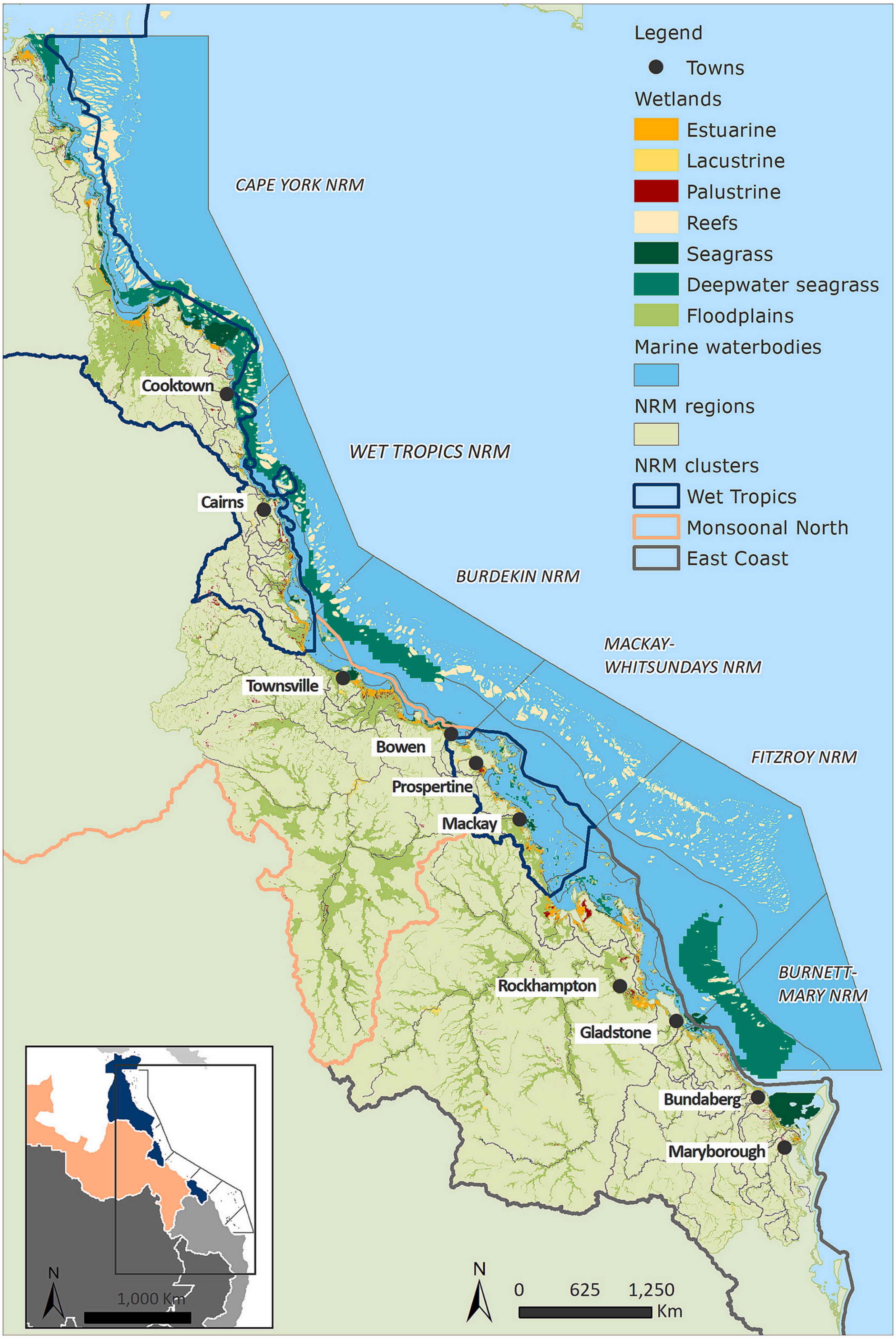

Fig. 2. Map of the Great Barrier Reef World Heritage area, and the three climatic regions differentiated by Climate Change in Australia Tool (CCIA, https://www.climatechangeinaustralia.gov.au/en/): Blue shapes: northern subregion ("Wet Tropics"), orange shape: central subregion within the Burdekin NRM (part of the "Monsoonal North East subregion in the CCIA), light grey shape: Southern subregion ("East Coast North"). Insert: map of NE Australia, with the regional CCIA boundaries. Map data sourced from the Queensland spatial catalogue http://qldspatial.information.qld.gov.au/catalogue// © State of Queensland (Queensland Reconstruction Authority) 2023, under a Creative Commons - Attribution 4.0 International license. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

suggests that runoff is likely to increase in the coming decades, with a greater percentage of rainfall converted to runoff during high-intensity events (Alluvium, 2019). On the other hand, Taschetto and England (2009) found that the frequency of extreme rainfall events along the Queensland coast has declined during summer and autumn, consistent with a total rainfall decrease, indicating changes in the position of the precipitation distribution rather than its shape. Predictions of more frequent extreme rainfall events leading to flooding and the terrestrial runoff of nutrients and sediments have implications for GBR water quality (Section 3).

3.1.5. Windiness and tropical cyclones

Mean wind speed predictions averaged for each season along the GBR are similar for 2030 compared to the reference period (but see evidence of intensification in the Central region in Wolanski and Hopper, 2022). Under RCP8.5, median wind speed may increase slightly in all three GBR regions in spring and winter (low confidence) (McInnes et al., 2015a). Few studies exist that address how climate change through potentially altered wind directions, surface mixing and current strengths will affect long-shore and cross-shelf transport of seawater. Weeks et al. (2010) and Berkelmans et al. (2010) suggest based on satellite observations that climate change is producing an intensification of the East Australian Current (EAC), leading to increased nutrient supply and hence increased ocean productivity adjacent to the Capricorn Eddy. Other observational and modelling evidence suggests that times of El Niño may be associated with a weaker EAC leading to reduced eddy and upwelling activity and a reduced supply of nutrients to the surface (Poloczanska et al., 2007). A potential strengthening in ENSO oscillations affects inter-annual variability in wind fields, cloudiness and sea surface temperature, albeit to a lesser extent than the ENSO effect on rainfall (Lough, 1994).

For tropical cyclones, the CCIA projects for both the northern and central subregions less frequent tropical cyclones, but the proportion of intense storms increases (medium confidence) (McInnes et al., 2015b; Moise et al., 2015), similar to global predictions (Knutson et al., 2020). For the southern subregion, the CCIA forecasts no changes in cyclone frequencies and intensities (Dowdy et al., 2015). Several studies suggest that long-term trends in cyclone frequency and intensity are already observable. Callaghan and Power (2011) report a statistically significant decline in landfalling severe cyclones along the Queensland coastline at centennial scales, and Dixon et al. (2022) showed that to date 20+ papers concluded that cyclone frequency will reduce or stay the same in the GBR region. A review by Holmes (2020) suggests the emergence of an apparent trend of increasing strength of tropical cyclones in Queensland since 1969, consistent with numerical models and other recent studies. Another model demonstrated consistently reduced central pressure (greater intensity), on average 5–10 % increased wind speeds, and up to 27 % increased average hourly rainfall (Parker et al., 2018). Due to predicted cyclone intensification, Holmes (2020) proposed revisions to the Australian Standard for Wind Actions, including a 'climate change multiplier', to accommodate increasing damage to above-water infrastructure, including GBR islands and mangroves. A synthetic cyclone model, comparing averages of key forcing parameters between 1950 and 1999 and 2050–2099 at 600 m resolution, also found average maximum wind speeds to increase by about 17 % (from 24 to 28 m s^{-1}), cyclone arrival rates to increase by 7 % (from 2.25 to 2.41 cyclones/year; cyclone radius remained set at 51 km) (Callaghan et al., 2020). They also showed that a 1 m sea level rise will not cause a significant reduction in wave attenuation by the reef if coral cover remains healthy: a significant finding since GBR reefs provide a 1.5 to 2-fold wave height attenuation to Queensland's coastline.

To resolve whether cyclone damage has or will increase remains a critical knowledge gap. On land, wind damage increases exponentially with wind speed and is also controlled by duration. Faster, forward-moving cyclones can generate higher wind speeds in the front left storm quadrant, where the forward motion is additive with the wind speed of the storm. Cyclone damage below water depends on all factors that influence wave generation. Large, slow-moving intense cyclones cause the most damage because this maximises wave height, while wave barriers such as upwind reefs reduce damage (Dixon et al., 2022). Dixon et al. (2022) showed that climate models are typically unable to resolve all four cyclone damage predictors in direction and degree for specific reef regions. In particular, few models address how cyclone diameter, forward movement (translation) speed and the track's spatial configuration relative to the reef will change in future around Australia. They concluded that it seems still too uncertain to conclude whether the damage caused by tropical cyclones on the GBR has or will change.

In summary, the reviewed studies show that GBR seawater temperature has increased by ~1.0 °C since pre-industrial times to date, which has led to increasing frequencies of marine heatwaves. The frequency of marine heatwaves is predicted to increase four- to eight-fold towards the end of this century, depending on emissions pathways. Aragonite saturation state is presently declining by 0.067 units per decade, and an ecologically relevant threshold of 3.5 will be reached by 2030 in parts of the GBR, and the critical threshold of 3.0 for reef formation will be crossed before 2090 throughout the GBR. Intense rainfall events are becoming more frequent along the whole GBR, but the magnitude of this increase cannot currently be confidently projected. GBR catchments south of 20°S may additionally experience increasing times of drought throughout the century. There is medium confidence in evidence that north of latitude 20°S, tropical cyclones are becoming less frequent while the proportion of the most intense storms is predicted to increase, so estimates of future changes in cyclone damage to the GBR underwater are still uncertain.

3.2. Section 2: Current and predicted impacts of climate change on GBR organisms and ecosystems

A total of 275 studies on the effects of climate change on ecosystems and organisms met the inclusion criteria (Supplementary Tables 7–9). They included 121 field observations, 123 experimental, 65 modelling, and 17 review and meta-analysis studies, of which 51 were added manually, especially on seagrasses, wetlands, and mangroves. The most assessed impact types were temperature, coral bleaching events, heat budgets, and El Niño (189 studies); far fewer assessed ocean acidification (50), storms (31), rainfall variability (13), and sea level rise (7) or multiple and cumulative impacts (23). Compared to corals and coral reefs, far fewer studies focused on responses of mangroves and wetlands, and specific organism groups (sea turtles, seabirds, macroalgae, fishes, non-coral invertebrates, viruses, microbial assemblages). For many GBR ecosystems, their responses to climate change, also in combination with water quality, remain largely unknown. Response types that were assessed included molecular (gene expression and physiological), ecological (life histories, reproduction, population dynamics, symbiotic associations, recovery rates, communities, species interactions), and geomorphological changes (reef framework erosion, carbonate sediment dissolution, persistence of mangrove ecosystems). A total of 71 of the studies provided various levels of quantitative evidence about rates and direction of change, thresholds, or tipping points for specific impact types, ecosystems or organisms in the GBR (Table 2, and outlined below).

3.2.1. Effects of rising sea surface temperatures and marine heatwaves

Studies on corals and coral reefs show unequivocally that periods of sea surface temperatures that exceed the regional long-term maximum summer monthly means by several weeks are causing mass bleaching and mortality to corals and numerous other marine organisms (Foster and Attrill, 2021; Hughes et al., 2017). Mass bleaching events in the GBR have been documented for 1998, 2002 (each causing ~5 % loss of shallow-water corals in the GBR (Berkelmans et al., 2004; De'ath et al., 2012), for 2016 (causing an estimated 30 % loss; Hughes et al., 2018), for 2017 (poorly quantified as the intense surveys in 2016

Table 2
Examples of predictions about the potential magnitude and timing of impacts from climate change, and management-relevant suggestions of thresholds (in bold).

Impact type	Thresholds/ Indicators/ Predictions	Reference
TEMPERATURE – MARINE HEATWAVES		
Coral reefs, reef resilience	Predictions for 2080: Under SSP1–1.9 (1.5 °C warming), three coral bleaching events per decade, thermal heat budget would stabilise below a critical threshold of 8 Degree Heating Weeks (DHW). SSP1–2.6 (2 °C) predict 5 bleaching events per decade. SSP3–7.0 and SSP5–8.5: thermal stress is 3–4-fold higher than presently. SSP5–8.5 leads to annual severe bleaching events.	(McWhorter et al., 2022b)
	For 2020, simulated GBR-wide annual coral mortality was from bleaching (48 %) ahead of cyclones (41 %) and crown-of-thorns seastar (COTS) predation (11 %). Water quality (simulated suspended sediment concentrations) delayed recovery for at least 25 % of inshore reefs.	(Bozec et al., 2022)
	Tropical cyclones, COTS predation, and coral bleaching accounted for 48 %, 42 %, and 10 % of coral losses, amounting to 3.38 % yr^{-1} absolute coral cover loss in the GBR in 1985–2012. The estimated rate of increase in absolute coral cover in the absence of cyclones, COTS, and bleaching was 2.85 % yr^{-1}, demonstrating substantial capacity for recovery of GBR reefs up to 2012.	(De'ath et al., 2012)
	Models indicate significant coral recovery in the near-term, but rapid declines by 2050 under business-as-usual management of local stressors and emissions (RCP8.5). Up to 66 % of reef performance loss is attributable to local stressors. Management strategies to alleviate cumulative impacts can reduce the vulnerability of some central GBR mid-shelf reefs by 83 %, but only if combined with strong emissions mitigation.	(Wolff et al., 2018)
	Modelled SST projections predict the frequency of coral bleaching in the GBR will rise rapidly, with bleaching set to occur annually in most oceans by 2040.	(Crabbe, 2008)
	Predicted that a 1 °C increase in SST would increase bleaching occurrence by 50–82 %; 2 and 3 °C warming would increase the occurrence to 97 % and 100 %, respectively.	(Berkelmans et al., 2004)
	Cumulative bleaching in 2016, 2017, and 2020 is predicted to have reduced coral larval supply by 26 %, 50 %, and 71 %, respectively. 13 % of the GBR are potential thermal refugia, delivering larvae to 58 % of the GBR in the near-term.	(Cheung et al., 2021)
	Severity of coral bleaching on individual reefs in 2016 was tightly correlated with the level of local heat exposure. Sensitive corals began to die above a critical threshold of 3–4 DHW. At ≥6 DHW, coral assemblages shifted to new composition.	(Hughes et al., 2018).
	Bleaching severity in 2016 was not lessened by past (1998 and 2002) bleaching exposure. Water quality and fishing pressure had minimal effect on bleaching severity, i.e., local reef protection afforded little or no protection against extreme heat.	(Hughes et al., 2017)
	Coral recovery rates declined on average 84 % across the GBR from 1992 to 2010, partly explained by chronic pressures (water quality, warming), and acute disturbances (sublethal effects of cyclones, COTS, and bleaching).	(Ortiz et al., 2018)
	Coral recovery (both of fast-growing Acroporidae and slower growing corals) slowed after the 2002 bleaching compared to 1995–2002, doubling the time for modest recovery.	(Osborne et al., 2017)
	For Acropora hyacinthus on Beaver Reef, heat stress at 8.3 DHW coincided with highest 'White Syndrome' disease prevalence (48 % of coral colonies). Whole-colony mortality in 68 % of colonies after 8 months; only 4 % of colonies had not displayed signs of bleaching or disease. A threshold of 50 % colony bleaching indicates that substantial mortality is likely to follow a heat stress event.	(Brodnicke et al., 2019)
Reef foraminifera	Exposure to 32 °C for 7 days compromised physiological parameters in Marginopora vertebralis; exposure to 34 °C for 7 days results in mortality for most individuals.	(Uthicke et al., 2012)
Reef sponges	Above 31 °C for >48 h was lethal for reef sponge Rhopaloeides odorabile	(Massaro et al., 2012)
High-latitude coral reefs	In high latitude reefs (30–31.5°S), bleaching threshold was 26.5–26.8 °C. Patterns of subtropical coral family bleaching susceptibility differed to those in the central GBR.	(Dalton and Carroll, 2011)
	Observed temporal stability of coral cover and assemblages on high-latitude reefs was used to suggest they may provide a limited refuge for tropical coral populations in the future. However recent severe bleaching events on these reefs qualify this finding.	(Dalton and Roff, 2013)
TEMPERATURE – PROGRESSIVE WARMING		
Coral reefs, coral physiology	A 2 °C warming accelerates larval development, increasing local larval retention and decreasing connectivity to distant places.	(Figueiredo et al., 2022)
	Models project that future global warming of ~2 °C will lead to corals being replaced by sponges,	(Cooper et al., 2015)

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Table 2 (*continued*)

Impact type	Thresholds/ Indicators/ Predictions	Reference
	gorgonians and other taxa, >2 °C will lead to algal dominance.	
	Mean annual temperatures of 24 °C or higher are needed for adequate coral growth to prevent reef drowning.	(Isern et al., 1996)
	Climate refugia, defined as local areas where tidal and wind transports warm water away from the sea surface, will fail as global warming exceeds 3 °C.	(McWhorter et al., 2022a)
	The skeletal density of Porites increases with increasing SST up to an optimum of 26.5 °C, and decreases with increasing temperature beyond this threshold.	(Razak et al., 2020)
	A 3 °C warming will alter community composition in pocilloporid corals in the southern GBR, leading to species-specific declines in intrinsic rates of population growth.	(Edmunds, 2005)
Reef aerosol emissions	Aerosol concentration over reefs increases with irradiance up to SST of ~1 °C below the mean monthly maximum, at which point the trend reverses/ correlation strength weakens.	(Jackson et al., 2018)
	At >30 °C SST, corals shut down production of atmospheric DMS and DMS flux, with potential (minor) implications for local aerosol-cloud processes.	(Jones et al., 2018)
	A 1.5 to 3.0 °C rise in annual mean SST and a 1.1 to 1.7 mol m^{-2} d^{-1} increase in PAR could increase atmospheric DMS concentration in the GBR by 9.2–14.5 %, with potential implications for local aerosol-cloud processes.	(Jackson et al., 2022)
Crown-of-thorns seastar (COTS, Acanthaster cf. solaris)	A 2 °C warming may increase the probability of COTS larval survival by 240 %, by shortening developmental times.	(Uthicke et al., 2015)
	Optimum all-at-once gametogenesis and spawning occurred at >28 °C seawater temperature.	(Caballes et al., 2021)
	Normal larval development and larval size occurred between 28.7 and 31.6 °C. Below 28.7 °C development rates slowed with decreasing temperature, ceasing at ~20 °C. Above 31.6 °C, abnormality rates increased, to 100 % at 33 °C.	(Lamare et al., 2014)
Reef sponges	At 32 °C (3 °C above maximum monthly mean temperature), the bioeroding reef sponge Cliona orientalis bleached and photosynthesis of their Symbiodinium symbionts was compromised, consistent with responses of sympatric corals.	(Ramsby et al., 2018)
	At 32 °C, certain viruses appear to be replicating due to thermal stress in the sponge Rhopaloiedes odorabile, and may contribute to rapid decline in host health.	(Laffy et al., 2019)
Reef fish	At 31 °C compared with 29 °C, aerobic scope of two cardinalfishes was reduced by nearly half; at 33 °C, their capacity for additional oxygen uptake was exhausted. In contrast, three damselfishes retained over half their aerobic scope at 33 °C. Suggests fish community structure might change significantly as temperatures increase.	(Nilsson et al., 2009)
	At 32 °C compared to 29 °C, critical oxygen levels increased by 71 % in a cardinalfish and by 23 % in a damselfish.	(Nilsson et al., 2010)
	Damselfish growth declined with increasing temperature. At 31 °C, the growth of juveniles and adults on a high food ration was nearly identical to growth on low food ration. Capacity for growth was severely limited at temperatures predicted to become the average at that site within the next 100 years.	(Munday et al., 2008b)
Sea turtles	Model projections suggest a near complete feminization of hatchling output for green sea turtle (Chelonia mydas) by 2070 under A1T emission scenario.	(Fuentes et al., 2010b)
Seagrass	The seagrass Halodule uninervis had optimum growth at 33 °C. Zostera muelleri exhibited critical metabolic imbalances at 33 °C, potentially contracting its distribution away from the northern GBR.	(Collier et al., 2011)
	Predicted optimum temperature for seagrass metabolism: 33 °C for Halodule uninervis, 35 °C for Cymodocea serrulate, 31 °C for Zostera muelleri.	(Collier et al., 2017)
	Six days with four hours temperature spikes of 40 °C represented a critical threshold for growth and mortality in tropical seagrass meadows, with species-specific tolerance differences.	(Collier and Waycott, 2014)
Effects of temperature and herbicide on seagrass	The thermal optimum for photosynthetic efficiency in Halophila ovalis was 31 °C. Lower and higher temperatures, and all elevated concentrations of the herbicide diuron reduced efficiency.	(Wilkinson et al., 2017)
OCEAN ACIDIFICATION (OA)		
Coral reefs	Predict that reef net community calcification will decline by 55 % of its preindustrial value by the end of the century under business-as-usual emissions.	(Shaw et al., 2012)
	Community net calcification of One Tree Island reef flat is expected to reach zero at an aragonite saturation state (Ωar) of ~ 2.5.	(Shaw et al., 2015)
	Restoring carbon chemistry over a natural coral reef community through alkalinity enrichment to pre-industrial conditions led to 7 % higher net community calcification, showing OA is already impairing reef growth.	(Albright et al., 2016)
	Show sensitive response of reef sediments to OA, with some reefs	(Eyre et al., 2018)

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Table 2 (*continued*)

Impact type	Thresholds/ Indicators/ Predictions	Reference
	already experiencing net sediment dissolution. Global transition from net precipitation to net dissolution at Ωar 2.92 ± 0.16, expected for the second half of this century.	
	Midshelf reef sediments changed from presently net precipitating (+0.8 g $CaCO_3$ m^{-2} d^{-1}) to net dissolving (−1 g $CaCO_3$ m^{-2} d^{-1}) at ΔpCO_2 + 170 to +900 µatm, ΔpH: −0.1 to −0.4. Sediment accumulation rates in the lagoon may diminish by up to 31 % (2–4 mm $decade^{-1}$), compared to <4 % reductions in net ecosystem calcification on the reef.	(Fink et al., 2017)
	Ωar presently declines −0.0673 per decade in the central GBR. The ecologically critical Ωar level of 3.5 will be crossed by 2030 in parts of the GBR.	(Fabricius et al., 2020);
	Rising coralline algae and coral juveniles, declining non-calcifying macroalgal cover with Ωar, steep changes around 3.5–3.6 Ωar. These OA effects are similar to effects from poor water quality, suggesting water quality improvement may partially mitigate some OA effects.	(Smith et al., 2020)
Effects of OA and water quality on foraminifera	At a pH of 7.6, Marginopora rossi suffered decline in calcification and growth, irrespective of eutrophication	(Reymond et al., 2013)
Rock lobster larvae	Metabolic effects at as little as −0.1 pH, survival and behavioural effects at − 0.3 pH.	(Boco et al., 2021)
COMBINED EFFECTS OF TEMPERATURE AND OTHER STRESSORS		
Effects of temperature, CO_2 and diuron on coral	An increase in ~1 °C from ambient (28.1 °C, pCO2 = 397 ppm) to RCP8.5 2050 (29.1 °C, pCO_2 = 680 ppm) and 2100 (30.2 °C, pCO_2 = 858 ppm) sensitized Acropora millepora to diuron, with EC50 values declining from 19.4 to 10.6 and 2.6 µg L − 1 diuron. These results highlight that water quality guideline values may need to be adjusted as the climate changes.	(Flores et al., 2021)
Effects of temperature and OA on coral, crustose coralline algae	In CCA, >520 ppm CO_2 lead to negative productivity and high rates of net dissolution. CCA may be pushed beyond their thresholds for growth and survival within the next few decades, whereas corals will show delayed and mixed responses.	(Anthony et al., 2008)
Effects of temperature and OA on two coral reef fish	33 °C was close to the lethal thermal limit, and declines in aerobic scope due to OA were similar to those from +3 °C in both species. Acidification could significantly reduce aerobic capacity by 2100.	(Munday et al., 2009)
Effects of temperature and OA on coral	Shows that OA alone has caused a 13 % ± 3 % decline in the skeletal density of massive Porites corals on the GBR since 1950, with warming temperatures and hence faster linear extension also contributing to skeletal thinning. .	Guo et al. (2020)
Effects of temperature and OA on coral	A 2 °C rise in temperature accelerated rates of coral larval development in Acropora millepora and A. tenuis, altering connectivity. No consistent effects of pCO_2 alone nor in combination with temperature	(Chua et al., 2013)
Effects of temperature and OA on a bioeroding sponge	Prolonged warming (+2.7 °C above local maximum monthly mean) caused extensive bleaching, lowered bioerosion, and increased mortality in the photosynthetic boring sponge Cliona orientalis. Acidification alone did not affect bioerosion or survival. Sponge bioerosion could be substantially reduced rather than increased by end-of-the-century under business-as-usual emissions.	(Achlatis et al., 2017)
	The bioeroding sponge Cliona orientalis will likely grow faster and have higher bioerosion rates in a high OA future than at present, even with significant bleaching. Increased sponge biomass coupled with accelerated bioerosion may push coral reefs towards net erosion and negative carbonate budgets in the future.	(Fang et al., 2013)
Effects of temperature and OA on seagrasses	Responses to warming temperatures were far greater than responses to pCO_2 in 3 seagrass species, which sharply declined in productivity, growth, and shoot density from 30 vs. 35 °C. Tropical seagrass are unlikely to be 'winners' under climate change as thermal stress won't be offset by future pCO_2 increases.	(Collier et al., 2018)
Effects of temperature and OA on macroalgae	The growth of HCO_3^- -using fleshy macroalgae (Lobophora sp., Amansia rhodantha) decreased with rising temperature under ambient pCO_2, however the negative effect of temperature was alleviated by OA at 30 °C. These findings suggest that some HCO_3^- -using fleshy macroalgae may benefit from future CO_2 increases.	(Ho et al., 2021)
TROPICAL CYCLONES		
Coral reefs	Observational data show maximum winds <28 m s^{-1} for <12 h inflicted only minor coral damage, but winds > 33 m s^{-1} and > 40 m s^{-1} caused catastrophic damage on inshore and offshore reefs, respectively. Offshore reefs had the deepest depth of damage (>15 m), inshore reefs had the greatest rates of coral breakage and dislodgement.	(Fabricius et al., 2008)
Riparian vegetation, mangroves	Riparian vegetation and mangroves affected by increases in wind and wave energy, higher storm surges, higher intensity	(Turton, 2019)

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Table 2 (*continued*)

Impact type	Thresholds/ Indicators/ Predictions	Reference
	rainfall, and larger river plume events.	
Seagrass	Seagrass communities progressively change along temperature gradients, but experienced catastrophic destruction after a cyclone.	(Pollard and Greenway, 2013)
SEA LEVEL RISE (SLR)		
Mangroves, seagrasses, wetlands	With predicted SLR, landward migrations would add ~ 2800 ha mangrove and tidal marshes under RCP 4.5 and 4194 ha under RCP 8.5.	(Duarte de Paula Costa et al., 2021)
Coral and seagrass	Rates of vertical reef carbonate accretion typical of modern reef flats (up to 3 mm yr^{-1}) will probably be insufficient to maintain suitable conditions for reef lagoon seagrass under moderate to high greenhouse gas emissions scenarios by 2100	(Saunders et al., 2014)
Coral reefs	SLR are projected as 0.5 m to 1.2 m above 1990 levels by 2100, depending on scenario. All reefs can keep up with 0.5 m rise. All reef sites can keep up with 1.2 m rise for the next 30 years. After that, only fast-growing reef sites keep up with 1.2 m rise, while leeward and lagoonal sites with low accretion rates maintain a similar profile but slowly gain depth relative to sea-level.	(Hamylton et al., 2014)
	For turbid-water reefs, SLR at RCP4.5 will increase the spatial extent of habitats with low coral cover and generic diversity over the next 100 years. More severe SLR (RCP8.5) will move some reef slope coral communities below the euphotic depth.	(Morgan et al., 2020)
Sea turtles	Up to 38 % of available green turtle nesting area across all northern GBR rookeries may get inundated and experience egg mortality from higher wave run-ups during storms because of SLR.	(Fuentes et al., 2010a)
RAINFALL VARIABILITY		
Coral	Salinity thresholds in sensitive corals are a dose-time combination, ranging from 22 to 28 PSU at an exposure time of 3–16 days	(Berkelmans et al., 2012)
Seagrass	Halophila ovalis and Halodule uninervis suffered severe morality at salinities <9 PSU, however Zostera muelleri survived salinities as low as 3 PSU for 10 weeks.	(Collier et al., 2014)
Wetlands	Rainfall (in the wettest seasonal quarter) was a strong predictor for assemblage turnover in all groups of vertebrates	(Canning and Waltham, 2021)

depleted researchers and resources, and coinciding with other cumulative impacts), and for 2020 and 2022 which were wide-spread but caused relatively lower mortality (Thompson et al., 2022).

Bleaching severity is predictable by the cumulative heat energy in the system, which can be quantified through remote sensing data as 'Degree Heating Weeks' (Berkelmans et al., 2004; Hughes et al., 2017). Degree Heating Weeks is also a good predictor of the fate of bleached corals (recovery within 1–2 years, often with impaired growth and fecundity, or mortality). During the 2016 bleaching event, sensitive corals began to die above a critical threshold of 3–4 Degree Heating Weeks, and coral communities had changed (lost their sensitive taxa) after 6 or more Degree Heating Weeks (Hughes et al., 2018). The trajectory of extreme events such as the shape of heat wave curves, e.g., the rate of evolution, its steepness and monotonicity of ramping and decline, contribute to predicting organism responses (Ainsworth et al., 2016; Hobday et al., 2016). Furthermore, prolonged hot periods below the threshold of the above heat wave definitions can also impact organisms.

Evidence of temporal trends and regional differences is emerging. For example, historical records from Porites coral skeletons suggest that coral bleaching has occurred in the past during times of temperature anomalies, but that the frequency of coral bleaching has been increasing from 1821 to 2001 when the study ended (Kamenos and Hennige, 2018). Field observations also confirm increases in the frequency, severity and/or spatial extent of mass coral bleaching since 1998 (Hughes et al., 2021). Models suggest that overall, the northern and far northern GBRMP zones are predicted to be less affected by warming temperatures than the central and southern GBRMP zones, due to projected intensification in the summer monsoon leading to more clouds in the far north and northern GBR, and a poleward shift in the subtropical ridge reducing clouds in the central and southern GBR (McWhorter et al., 2022b). Spatial differences in coral bleaching severity are tightly correlated with the spatial extent of marine heatwaves and other thermal anomalies, and are further modulated by factors such as wind, solar irradiance, humidity, and cloud cover (McGowan and Theobald, 2017). Cloud cover can have partially mitigating effects (Bainbridge, 2017; Zhao et al., 2021). Weather patterns during El Niño events with doldrum conditions of light winds, high surface air temperatures, and clear skies over the GBR are predictors of bleaching extent, however El Niño events themselves, without superimposed weather anomalies of high pressure, high temperatures and low clouds, do not elevate SST enough to cause coral bleaching (McGowan and Theobald, 2017).

Other environmental factors can further modulate coral bleaching severity, and some studies suggest the existence of climate refugia for coral reefs at present levels of global warming. For example, cool-water upwelling has been shown to reduce heat exposure hence improve bleaching outcomes in regions other than the GBR, but only if the timing of upwelling coincides with that of the marine heatwaves (Chollett et al., 2010; Randall et al., 2020). McWhorter et al. (2022a) showed that tidal and wind mixing of warm water away from the sea surface provided relief from warming for local reef communities, but that such potential refugia only persist until warming exceeds ~3 °C. Coral taxa also vary in their bleaching susceptibility and their abundance varies along environmental gradients. For high-latitude reefs south of the GBR, initially observed temporal stability in coral assemblages suggested the potential for thermal refugia (Dalton and Roff, 2013), however repeated extensive bleaching has now documented high thermal sensitivity also of many dominant taxa on high latitude reefs (Dalton and Carroll, 2011; Moriarty et al., 2023). Extremely low temperatures, low salinity, or high sedimentation can also trigger coral bleaching and mortality, but such events are local rather than regional in extent (Anthony and Kerswell, 2007).

Climate change and water quality impacts do not act in isolation on reefs. Some studies show that turbidity can reduce the effects of heat stress on corals on the GBR, potentially by reducing irradiance (Morgan et al., 2020). In contrast, water quality and fishing pressure had minimal effect on bleaching severity during a severe heatwave in 2016, suggesting that local reef management afforded little protection against impacts once heatwaves are intense and prolonged (Hughes et al., 2017). There is strong evidence that recovery rates of coral cover after disturbances are affected by poor water quality. Modelling studies suggest that water quality improvement may help mitigate such slowing recovery. In particular, Bozec et al. (2022) estimated that suspended sediments delay recovery on at least 25 % of inshore reefs. A modelling study by Wolff et al. (2018) based on a different set of heat stress estimates suggested that up to 66 % of reef performance loss is attributable to local stressors, and that management strategies to alleviate cumulative impacts have the potential to reduce the vulnerability of all inshore and some mid-shelf reefs in the central and southern GBR by 83 %, but only if combined with strong mitigation of carbon emissions. Empirical data have also documented that recovery rates have halved (Osborne et al., 2017) or slowed by as much as 84 % (Ortiz et al., 2018), with causes attributed to the residual effects of heat stress in combination with other chronic stressors. Although (Hughes et al., 2017) concluded that water quality and fishing pressure had minimal effect on bleaching severity in 2016, this does not diminish the benefit of local protection in accelerating recovery (Wolff et al., 2018).

For seagrasses, 13 relevant publications on temperature effects were found, documenting strong species-specific differences in temperature optima and maxima, temperature-dependent rates of photosynthesis and respiration, energy balances, and distributional ranges (Table 2, Supplementary Table 8). For example, both a northern and southern population of the seagrass species Halodule uninervis and Cymodocea serrulata had a predicted optimum growth at 33 °C and 35 °C, respectively (Collier et al., 2011; Collier et al., 2017). By contrast, Zostera muelleri went into energy deficit and stopped growing after four weeks at 33 °C. This suggests future retractions in their distributional ranges away from the northern GBR (Collier et al., 2011), although one Zostera muelleri population survived (albeit at reduced density) at 35 °C for seven weeks, possibly suggesting an acclimation or local adaptation potential in this species (Collier et al., 2018). Extensive areas of intertidal and shallow subtidal seagrasses experience short-term exposures to >35 °C temperature at low tides, and even >40 °C for a couple of days a year probably due to high air temperatures and radiative heat absorption in shallow water (McKenzie et al., 2022). Four-hour spikes to 40 °C affect photosystem II efficiency in some but not other seagrass species, and slow growth rates to less than half due to high respiration (Collier and Waycott, 2014). Two to three days of exposure to 43 °C or above for four hours per day severely affect photosystem II efficiency in all species and led to nearly complete mortality in most species (Collier and Waycott, 2014). Therefore, extended heatwaves of 40 °C or above are likely to affect the ecological function of tropical seagrass meadows in shallow habitats (Collier and Waycott, 2014).

For mangroves and wetlands, temperature effects are poorly represented in the literature (Table 2, Supplementary Table 9**)**. However, studies show that like for all plants, mangrove productivity is highly sensitive to temperature. Photosynthesis in northern GBR mangroves is limited by high midday temperatures because of stomatal closure, therefore increased temperatures may decrease productivity in these areas (Lovelock and Ellison, 2007). In contrast, southern GBR mangroves may experience an increase in productivity as they are presently limited by low temperatures (Lovelock and Ellison, 2007). Warmer winter temperatures may also result in a southward expansion of mangroves (Lovelock and Ellison, 2007). For wetlands, no GBR-specific reference was found, and an Australia-wide review also returned little information (Leigh et al., 2015).

Other reef-associated organisms also display many temperature-related physiological changes and severe impacts from marine heatwaves, although the literature retrieved by the searches was incomplete, especially for widely distributed organism groups such as seabirds or sea turtles (Table 2, Supplementary Tables 6–7). For example, for the coral-eating **crown-of-thorns seastar** Acanthaster cf. solaris that is responsible for wide-spread coral mortality, three studies show links between warming temperatures and reproductive success. Optimum all-at-once gametogenesis and spawning occurred above 28 °C seawater temperature (Caballes et al., 2021). An experiment and model suggest that an increase in temperatures by 2 °C may increase larval survival probability by 240 %, predominantly through faster development, although food availability was the main driver of larval development (Uthicke et al., 2015). The study reinforces the importance of water quality management under rising temperatures. **Sea turtles** are particularly vulnerable to rising temperatures, as the sex determination of hatchlings is dependent on temperature, with warmer sand temperatures during incubating resulting in a greater proportion of female hatchlings (Fuentes et al., 2010b; Jensen et al., 2018). Under current conditions, turtle rookeries in the northern GBR are already producing an unbalanced sex ratio, with more females than males (Jensen et al., 2018). Under extreme scenarios of climate change, model projections suggest near-complete feminisation of hatchlings by 2070, compromising the viability of future sea turtle populations (Fuentes et al., 2010b; Fuentes and Porter, 2013; Jensen et al., 2018). Studies of **sponges** under heat stress demonstrate depressed reproductive output (Abdul Wahab et al., 2014), decreased feeding behaviour (Massaro et al., 2012) and bleaching (Ramsby et al., 2018). Temperatures of 32 °C and greater were found to be lethal to many sponge species, with little capacity to recover from thermal stress after exposure (Massaro et al., 2012; Ramsby et al., 2018).

Reef associated fish are vulnerable to both direct physiological effects of high temperatures, and indirect effects through altered habitats and food webs (Munday et al., 2008a; Pratchett et al., 2008). Field studies show that fish assemblages are more homogenised after coral mortality from bleaching (Richardson et al., 2018). Sites damaged by coral bleaching had reduced recruitment of damselfish (Booth and Beretta, 2002) and fewer coral feeding butterflyfishes (Pratchett et al., 2006). Bleaching of anemones leads to reduced anemonefish abundance (Lönnstedt and Frisch, 2014). Physiological experimental studies often focus on small fish that are easily kept in laboratories. They show, e.g., that increased temperatures lead to shorter pelagic larval duration (McLeod et al., 2015), species- and location specific changes in larval duration and pre-settlement growth rates (Takahashi et al., 2012) and effects on growth rates of juvenile and adult reef fishes (Munday et al., 2008b). Warming also increases oxygen consumption in some fish, likely reducing aerobic scope (capacity to perform aerobically), thus impacting performance (Nilsson et al., 2010). Cardinalfish (Ostorhinchus doederleini) were particularly sensitive, with temperature increases from 29 °C to 31 °C reducing aerobic scope by almost 50 % and 33 °C representing capacity threshold (Nilsson et al., 2009). Damselfish maintained half their aerobic scope at 33 °C but displayed species-specific thermal tolerance, potentially indicating future shifts in assemblages (Nilsson et al., 2009). For larger fish, Messmer et al. (2017) showed increasing energetic limitations in the commercially important leopard coral grouper (Plectropomus leopardus), with larger adult individuals being more thermally sensitive than smaller conspecifics. They suggest likely future climate-induced reductions in body size, with important ramifications for fisheries productivity and for ecosystem functions.

3.2.2. *Effects of ocean acidification (OA)*

The literature search retrieved 50 studies on the effects of ocean acidification (OA) in the GBR, some in combination with additional stressors (Table 2, Supplementary Tables 6–9). OA is a relatively recent field of research, with the earliest retrieved GBR publications from 2009 (Munday et al., 2009; Wei et al., 2009); (Doney et al., 2009). Studies were based on manipulative field experiments, field observations along spatial seawater carbon gradients as proxy for temporal changes under climate change, or models, complemented by few key laboratory experiments with spatial or temporal relevance.

Reef calcium carbonate production in GBR coral reefs has already declined due to OA, and it will continue to decline, with strong evidence provided by five studies (Table 2). Experimental restoration of the seawater carbon chemistry through alkalinity enrichment to pre-industrial conditions increased net community calcification of a natural coral reef community, showing that ocean acidification is already impairing coral reef growth (Albright et al., 2016). Shaw et al. (2012) estimated that GBR reef net community calcification will decline by 55 % of its preindustrial value by the end of the century. Shaw et al. (2015)

used observational data to predict that community net calcification of One Tree Island reef flat is expected to reach zero at an aragonite saturation state (Ωar) of ~2.5. Estimates of the global threshold for coral reef existence range from a more conservative value of Ωar <3.5 (Ricke et al., 2013) to <2.8 (Guan et al., 2015). Eyre et al. (2018) showed that reef sediments, including those from the GBR, are more sensitive to OA than coral calcification, and that some reefs are already experiencing net sediment dissolution. They predicted a global transition from net precipitation to net dissolution at Ωar 2.92 ± 0.16, which is expected for the second half of this century depending on emissions pathways. Fink et al. (2017) showed that on the mid-shelf Davies Reef, reef flat sediments changed from net precipitating under ambient CO_2 to net dissolving under +170 to +900 µatm CO_2. They concluded OA could diminish sediment accumulation rates in the lagoon by up to 31 % (2–4 mm decade^{-1}), but would affect net ecosystem calcification by only <4 % on this reef. Stoltenberg et al. (2021) documented net carbonate dissolution on Heron Island reef flat during summer afternoons, when respiration rates were high and Ωar was low. They concluded that reefs are most vulnerable to overall net dissolution under OA if they already have low rates of calcification, low coral cover, high sediments, and high net rates of respiration (heterotrophy).

Responses of specific organisms to ocean acidification were considered based on 46 studies (Table 2, Supplementary Tables 7–9). Global reviews have documented many detrimental or no effects on calcifying organisms, and many forms of benefits or no effects on photosynthetic organisms, findings that are likely relevant for the GBR. Two independent data sets showed spatial associations between declining seawater Ωar and increasing cover of macroalgae while crustose coralline algae and coral juvenile densities declined (Smith et al., 2020). This study concluded that OA will likely diminish the capacity of coral reefs to recover from disturbances, and showed pathways for how water quality improvement may mitigate some of the effects of ocean acidification. For seagrasses, some species showed additional productivity under elevated CO_2 that released carbon limitation, however responses were inconsistent, and benefits may be offset by the negative effects of marine heatwaves on seagrasses (Collier et al., 2018) (Supplementary Table 8). For mangroves, elevated CO_2 was found to promote plant growth, with unknown implications for mangrove ecosystems and their ranges as responses depend on many additional variables (Hughes, 2003; Lovelock and Ellison, 2007). Most OA studies on fishes and non-calcareous invertebrates have focused on the investigation of behavioural changes to date, typically documenting detrimental outcomes such as impaired prey detection or loss of natural responses to odours or sound, but some also showed positive effects on physiological (aerobic scope; (Rummer et al., 2013) or population parameters (stimulating reproductive attributes; (Miller et al., 2013).

3.2.3. Effects of changes in tropical storms and in windiness

A total of 31 studies covered the impacts of storms on GBR organisms and ecosystems (Table 2, Supplementary Tables 7–9). Tropical cyclones are amongst the most destructive forces impacting GBR ecosystems. The primary impact of tropical cyclones to coral reefs is structural damage via coral breakage and dislodgement, therefore reducing live coral cover (Beeden et al., 2015; Done, 1992; Turton, 2019). Overall, a massive 48 % of annual mean coral losses between 1985 and 2012 have been attributed to tropical cyclones (De'ath et al., 2012), and 41 % of losses between 2008 and 2020 (Bozec et al., 2022). Branching and plate corals (e.g. Acropora and Pocillopora) are more vulnerable than massive and encrusting morphologies (e.g. Porites) (Baird et al., 2018; Fabricius et al., 2008; van Woesik et al., 1995). While damage is greatest closest to the cyclone track, it can be widespread, with Beeden et al. (2015) recording coral damage extending up to 250 km from the track. Winds >33 m s^{-1} and > 40 m s^{-1} caused catastrophic damage on inshore and offshore reefs, respectively. At comparable wind speeds, offshore reefs had the deepest depth of damage (>15 m), while the inshore reefs had the greatest rates of coral breakage and dislodgement (Fabricius et al., 2008). Ceccarelli et al. (2016) showed that a cyclone led to high fish species-level turnover with decreased damselfish and increased grazer densities, whilst total fish density, biomass and species richness did not change.

Seagrass meadows in coastal areas are vulnerable to severe storms, but protracted impacts are additionally caused by declines in water quality from rainfall and discharges (Lambert et al., 2021; McKenna et al., 2015; Petus et al., 2014; Pollard and Greenway, 2013). Flooding and strong winds enhance coastal erosion (Wolanski and Hopper, 2022) and surface elevation of wetlands (Lovelock and Ellison, 2007). A regional loss of 2.3 % of mangroves was attributed to storms and precipitation (Chamberlain et al., 2021). Tropical cyclones also cause major disturbances to soft bottom habitats, redistributing sediments and impacting their benthos (Carter et al., 2009; Gagan et al., 1990; Larcombe and Carter, 2004). Intertidal sessile invertebrates such as ascidians, sponges and bryozoans follow wave exposure and temperature gradients, making them sensitive to climate change, with more intense storms potentially reducing the diversity of these assemblages (Walker et al., 2008).

For wetlands, little GBR-specific work exists. A review by Leigh et al. (2015) of the effects of weather extremes (tropical cyclones, droughts, floods, heatwaves, storm surges and fires) on riverine ecosystems in Australia demonstrated that tropical cyclones and post-cyclonic floods are the major agents damaging riparian vegetation, eroding stream banks and altering water quality. While cyclone-induced delivery of large woody debris provides important instream habitat, the wider ecological consequences of more intense tropical cyclones remain uncertain.

3.2.4. Effects of sea level rise (SLR)

Sea level rise is a growing economic challenge since housing and infrastructure development involves many low-lying areas along the Queensland coast. Mangroves, salt marshes, and other coastal marine ecosystems are sensitive to SLR (Table 2); (Duarte de Paula Costa et al., 2021). Landward migration of mangroves into salt marshes and freshwater wetlands is predicted, resulting in significant changes to ecosystem functions (Hughes, 2003; Lovelock and Ellison, 2007; Wolanski and Chappell, 1996). The extent of this landward migration depends on numerous factors, including rates of sediment deposition and soil elevation (Lovelock and Ellison, 2007), however, the mangrove area is predicted to increase by 4194 ha under RCP 8.5 (Duarte de Paula Costa et al., 2021).

Coastal coral reefs are predicted to increase in spatial extent with SLR, although these additional areas are expected to have low coral cover and generic diversity (Morgan et al., 2020). However, at RCP8.5 scenarios, the rate of vertical accretion of reefs is expected to be insufficient to compensate for predicted SLR, resulting in completely submerged reef flats. Modelling has also demonstrated the potentially negative effects of SLR on coral reef-inhabiting seagrasses, as vertical reef accretion becomes insufficient to keep pace (Saunders et al., 2014). Lower reef slope communities may move below the euphotic zone (Morgan et al., 2020), especially in turbid waters. For sea turtles, models by Fuentes et al. (2010a) predict a reduction by 38 % of available nesting area in sea turtle rookeries on low-lying islands with limited capacity for beach expansion.

3.2.5. Effects of rainfall variability

Intensifying rainfall variability can have direct physiological or population effects, directly through damage from low salinity, or indirectly through impairing marine water quality (Section 3). A freshwater lens which can be fatal for marine organisms (Berkelmans et al., 2012) can form in surface waters from intense rainfall directly onto the sea surface and from river plumes in regions near river mouths. At risk of low-salinity induced mortality are sensitive reef flat, intertidal and shallow subtidal reef organisms during low tide (Berkelmans et al., 2012). Seagrasses are highly freshwater tolerant, maintaining shoot density and growth even after 10 weeks of exposure to 15 PSU salinity, an unlikely exposure level in the GBR (Collier et al., 2014). Mortality occurred in Halodule uninervis only at 3 PSU and in Halophila ovalis at 6 PSU, while Zostera muelleri did not suffer mortality at reduced salinity (Collier et al., 2014). However, recovery times from severe freshwater exposure can be a decade for intertidal seagrasses, and even longer for subtidal and estuarine seagrass and reef communities (Carter et al., 2022). For mangroves and coastal wetlands, intensifying rainfall variability is significantly important. Prolonged drought has been identified as one of the causes of widespread mangrove die-backs (Chamberlain et al., 2021). Wetland connectivity between habitats and the flushing of accumulated materials is also influenced by rainfall (Croke et al., 2013).

By far the most pervasive impacts from increasing rainfall variability are attributable to increasing terrestrial runoff of nutrients, sediments and pesticides. Their numerous direct and flow-on effects on subtidal ecosystems and organisms have been reviewed in (Waterhouse et al., 2024a, 2024b), and are beyond the scope of this study. In brief, both coral reefs and seagrass communities are highly sensitive and lose cover due to increased turbidity and light loss from runoff (Supplementary Tables 7–8). There is also strong evidence for a link between severe floods and initiation of outbreaks waves of crown-of-thorns seastar, which cause wide-spread damage to coral reefs throughout the GBR (Bozec et al., 2022). Regions with decreased rainfall are more susceptible to the landward migration of mangroves due to altered sedimentation rates (Lovelock and Ellison, 2007). Conceptual diagrams proposed in a review (Croke et al., 2013) outlined a strong dependency of Australia's riverine systems (and GBR wetlands) on rainfall variability: droughts alter their water quality and reduce habitat availability, while extreme floods trigger booms in productivity and improve connectivity, but can also alter channel morphology and cause hypoxic blackwater events and fish kills in these systems.

In summary, the reviewed studies demonstrate highly variable responses by organisms and ecosystems to the seven climate change factors. In combination, they show that marine heatwaves cause widespread but often selective impact and mortality, and that the link between climate change and large-scale bleaching of corals is now undeniable. Some species may become critically endangered due to additional pressure from climate change (e.g., sea turtles due to their unique temperature-controlled hatchling sex determination). Little evidence exists about rates of evolutionary adaptation, acclimatisation and shifts in geographic ranges. Some water quality guidelines will need revision as temperature rise can alter organism sensitivities to pollutants. The literature provided some evidence about spatial differences in responses, yet little information about the timing when critical thresholds will be crossed. Exceptions are studies that included predictions of near-annual bleaching by 2040, and ocean acidification crossing ecologically relevant thresholds in parts of the GBR by 2030, and for all reefs before 2100.

3.3. *Section 3: Current and predicted effects of climate change on GBR water quality*

The literature screening yielded a total of 32 relevant studies on climate change effects on coastal and marine water quality, of which 14 were added manually (including two studies from outside the GBR) (Table 3). They included 15 observational, 3 experimental, 10 modelling and 11 review studies. None of the retrieved studies addressed the topic directly and comprehensively, however, in combination with Section 1 they supported the creation of indirect conceptual causal chains of evidence (see below). The most important climate change related responses are outlined in Fig. 1, and in the paragraphs below.

3.3.1. *Terrestrial runoff of nutrients, sediments, freshwater and pesticides*

There are firmly established causal links between rainfall extremes, terrestrial runoff of sediments, nutrients and pesticides (Lewis et al., 2024; Robson et al., 2024), and elevated turbidity and dissolved and

Table 3
Examples of studies documenting climate change or extreme weather impacts on GBR water quality. Asterisks mark studies that are either global or conducted outside of the GBR/Australia.

Response type (water quality variable) and summary of findings	References
Review of modelling to link climate change to runoff, rainfall variability, flood risk, water availability.	(Alluvium, 2019)
Reviews of links between climate change and water quality or marine biogeochemistry.	(Haynes et al., 2007) (Ani and Robson, 2021) (Li et al., 2020)*
Review of influence of climate change on Australian marine systems, including upwelling, nutrients, pH, run off, suspended sediments.	(Poloczanska et al., 2007)
Long-term variations in runoff, estimated from coral skeletal luminescence in Keppel Islands are influenced by climatic variations from ENSO and Pacific Decadal Oscillation indices (which are likely to intensify with climate change).	(Rodriguez-Ramirez et al., 2014)
Inshore GBR water quality parameters (nutrients, turbidity, salinity, herbicides, pesticides, microbes) are influenced by river floods: inshore water quality is poorer following large floods and cyclones (which are likely to intensify with climate change).	(Angly et al., 2016; Berkelmans et al., 2012; Jones and Berkelmans, 2014; Lewis et al., 2024; Robson et al., 2024; Roche et al., 2014; Schaffelke et al., 2012) (Hughes, 2003)*
Marine photosynthetically active irradiance (PAR) is a function of depth, clouds and turbidity. All three factors are affected by climate change, sea level rise, increasing rainfall intensity affecting water clarity, intensifying monsoons and intensifying La Niña phases, altered windiness, cloudiness and seawater productivity affecting water clarity.	(McInnes et al., 2015b, Moise et al., 2015, Dowdy et al., 2015, McWhorter et al., 2022b, Fabricius et al., 2016, Zhao et al., 2021)
Temperature, rainfall, and sea level rise are altering soil organic carbon stock, nutrients and hence potential runoff and coastal wetland water quality.	(Duarte de Paula Costa et al., 2021)
Climatic variability affects stratification, upwelling and hence primary productivity and chlorophyll a. Surface warming is accompanied by reduced primary productivity.	(Behrenfeld et al., 2006; Hoegh-Guldberg and Bruno, 2010)
Nitrogen fixation via Trichodesmium blooms may be increasing with climate change.	(Blondeau-Patissier et al., 2018)
Strength of the East Australian Current and hence upwelling varies in response to climate and ENSO variability.	(Berkelmans et al., 2010; Weeks et al., 2010)
Upwelling amplifies ocean acidification on the outer and mid-shelf GBR.	(Schulz et al., 2019)
Ocean acidification, dissolved inorganic carbon, aragonite saturation state and pH acting as water quality parameters, differ in their long-term means and seasonal and diurnal variations along and across the continental shelf.	(Fabricius et al., 2020; Mongin et al., 2016; Wu et al., 2018)
Ocean acidification altering carbon and nutrient cycling.	(Doney et al., 2020; Doney et al., 2009)
Ocean acidification altering primary productivity.	(Gao et al., 2012)
Climate disturbance affects reef primary production and calcification, in turn altering seawater carbon chemistry signal over the reef.	(Pisapia et al., 2019)
Temperature affects the sensitivity of organisms to pollutants such as diuron.	(Flores et al., 2021; Negri et al., 2020)
Cyclones are key factors for inshore and midshelf sediment transport and mixing.	(Carter et al., 2009; Orpin et al., 1999); (Larcombe and Carter, 2004)

particulate nutrients, which have severe consequences for GBR ecosystems and organisms (reviewed in Waterhouse et al., 2024a, 2024b). For example, each of the three most extreme floods in the last 60 years have been followed by a population outbreak wave of coral-destroying crown-of-thorns seastar Acanthaster cf. solaris, affecting reefs way beyond the reach of the initial flood plumes over a decade or more. Drought-breaking floods yield particularly high nutrient and sediment discharges, as parched vegetation is less effective in holding back soils during intense rainfall. Thus, projections of greater probability for droughts in the southern GBR have severe implications for increased exposure of the southern inshore GBR to river loads of nutrients and sediments. More frequent low salinity events could also result from a greater percentage of rainfall being converted to runoff (Alluvium, 2019) depending on soil compaction and wind mixing. However, the magnitude of these increases in rainfall, extreme rainfall events, droughts and the proportion of rainfall converted to runoff cannot yet be projected for this region with confidence (Alluvium, 2019; Dowdy et al., 2015).

3.3.2. Irradiance

Photosynthetically active irradiance (PAR) is a key factor for ecosystem health, fuelling primary productivity, and co-determining the thermal tolerance in corals (Bainbridge, 2017; Zhao et al., 2021). In marine systems, irradiance is a direct function of water depth, water clarity and cloud cover. Climate change has direct and indirect effects on GBR irradiance in several ways, including through rising sea level, intensifying rainfall variability and hence turbidity, altered windiness and cloudiness. After major floods, water clarity and hence irradiance is significantly reduced for up to six months on GBR inshore to mid-shelf reefs (Fabricius et al., 2016). Altered primary production from warmer temperatures, altered windiness, sediment resuspension and upwelling regimes also impact water clarity (Table 3). In particular, intensifying La Niña phases lead to increased freshwater discharges and greater cloudiness, hence reduced benthic irradiance. Climate models predict increasing cloud cover in the northern GBR, and reduced cloud cover in the central and southern GBR (Section 1), with altered windiness and even DMSA production potentially further impacting cloudiness. However, the joint net effects of these climate impacts on marine irradiance are not yet quantitatively understood and will likely vary regionally and with depth.

3.3.3. Oxygen, productivity, and critical pollutant thresholds

Many water quality parameters are temperature sensitive, and either directly or indirectly affected by warming temperatures (Ani and Robson, 2021). An example of a direct effect is that oxygen saturation concentrations in seawater decline with increasing temperatures. An example of an indirect effect is that metabolic rates (oxygen demand, photosynthesis, respiration, feeding rates, growth) increase with increasing temperatures in the majority of marine organisms that cannot control their body temperature. These physiological changes alter water concentrations of CO_2, O_2 and protons, with particularly large changes possible in areas of still water, on shallow reef flats and in boundary layers. Both have flow-on effects on almost every ecosystem function in the GBR. Increasing temperatures typically accelerate metabolic rates up to a tipping point, beyond which organisms become temperature-stressed and productivity declines steeply. Oxygen may become limiting for actively mobile animals such as some fishes (Table 2), (Nilsson et al., 2009). Similarly, food demand may increase, with implications for the concentrations of dissolved nutrients, phytoplankton biomass and productivity, and trophic levels dependent on phytoplankton (Behrenfeld et al., 2006; Hoegh-Guldberg and Bruno, 2010).

Several studies have concluded that seawater productivity is declining globally with warming temperatures (Behrenfeld et al., 2006; Gao et al., 2012; Hoegh-Guldberg and Bruno, 2010). Plankton community composition is expected to change because of metabolic rate changes, which could have flow-on effects on food webs, fisheries productivity and seabird populations (Ani and Robson, 2021; Devney et al., 2009; Weeks et al., 2013). Increasing temperatures may also lead to increased rates of nutrient mineralisation, nitrification and denitrification (Bell et al., 1999). The implications of these various changes are likely to be complex and have not yet been explored in detail for the GBR (Ani and Robson, 2021). However, it is unclear to date how productivity will change in different GBR regions. Seawater in the subtropical southern GBR is more productive (higher chlorophyll concentrations and inshore macroalgal biomass than in the tropics (Fabricius et al., 2023; Robson et al., 2024). Higher terrestrial runoff of nutrients will also boost productivity in some inshore regions of the GBR, while a strengthening East Australian Current would trigger upwelling and hence increase production in some offshore regions (Weeks et al., 2010). All these factors complicate predictions of net changes for the GBR.

There is evidence from ocean colour observations in the GBR that the frequency of Trichodesmium blooms, a nitrogen-fixing cyanobacterium and a major nitrogen source for the GBR, has been increasing over time (Blondeau-Patissier et al., 2018) which may be due to climate change (Ani et al., 2023).

Two studies showed that temperature may also affect the sensitivity of organisms to pollutants such as diuron (Flores et al., 2021; Negri et al., 2020), with ecologically significant effects or mortality observed at lower concentrations when the temperature is higher. Negri et al. (2020) describe and demonstrate an approach to adjust pesticide guidelines to account for this interactive effect, extending the application of a method (multisubstance-Potentially Affected Fraction, or ms-PAF) that was initially developed to facilitate adjusting guideline values for toxicants to account for the interacting effects of multiple substances (e.g., the combined effects of two or more pesticides).

3.3.4. Seawater inorganic carbon

Ocean acidification is typically considered a ‘climate change’ factor, caused by increased CO_2 in the atmosphere, as summarised in Section 1. However, ocean acidification is also a water quality factor, with dissolved inorganic carbon being an important plant nutrient. Seawater CO_2 has already increased by ~28 % since preindustrial times - a greater proportional change than anthropogenic changes in other dissolved inorganic nutrients (NO_2, NO_3, NH_4, SiO_2, and PO_4). For seagrasses and those algae that don’t have carbon-concentrating mechanisms, CO_2 is a limiting nutrient, suggesting rising CO_2 will lead to productivity gains in these taxa (Gao et al., 2012) and altered carbon and nutrient cycling (Doney et al., 2020; Doney et al., 2009).

Superimposed on this trend of rising CO_2 are fluctuations in CO_2 both at diurnal, seasonal, and interannual time scales (Fabricius et al., 2020; Lenton et al., 2016; Mongin et al., 2016; Wu et al., 2018). Seasonal fluctuations are partly temperature-related, as the partial pressure of CO_2 is temperature-dependent. Diurnal fluctuations are predominantly attributable to the metabolism of photosynthetic and calcifying organisms: photosynthesis leads to CO_2 uptake during the day, and respiration releases CO_2 at night. Calcification removes carbonate ions, which also leads to the release of CO_2 by shifting the carbonate chemistry balance. Climate change related shifts in reef communities to fewer calcifying corals and more fleshy algae (Cooper et al., 2015) will further alter the magnitudes of diurnal and seasonal fluctuations in the seawater carbonate chemistry that organisms are experiencing (Anthony et al., 2011); (Pisapia et al., 2019).

3.3.5. Currents, windiness, upwelling, and the resuspension of bottom sediments

The upwelling of deeper water onto the continental shelf is an important source of dissolved inorganic nutrients hence increasing primary production, but also elevating CO_2 and hence worsening ocean acidification (Schulz et al., 2019). There is evidence that the East Australian Current (EAC) is linked to increased upwelling and responds to inter-annual climatic variability (Weeks et al. (2010) including ENSO (Section 1). However, little quantitative information exists as published global climate models do not yet accurately represent the details of ocean currents such as the EAC. This is because due to their coarse spatial resolution of ~1° latitude/longitude, they are not eddy-resolving and do not completely represent deep ocean and continental shelf interactions; changes in currents and upwelling are therefore not resolved (McInnes et al., 2015c).

The resuspension of bottom sediments from wind waves also reduces GBR water clarity (Fabricius et al., 2016). Intensifying trade winds would lead to more resuspension, however due to high natural variability and the small predicted changes effect size in this parameter (2–4 % change; Table 1), the expected change in winter and spring resuspension regimes attributable to climate change are likely to be minor. In the midshelf region, resuspension events are associated primarily with cyclone activity (Orpin et al., 1999). As cyclones are predicted to decline in frequency but potentially increase in intensity in the northern and central sections (Section 1), the resultant effects on midshelf sediment resuspension and redistribution remain unknown.

In summary, the reviewed studies show that climate change is already affecting many aspects of GBR water quality.

4. Discussion

This review of existing peer-reviewed published evidence is documenting rapid and profound changes in the GBR. The body of studies shows, with high confidence, that the GBR along its entire length is rapidly warming, that heatwave frequencies are increasing, seawater is becoming less alkaline, and the sea level is rising. These impacts will continue to intensify throughout this century, with severity depending on CO_2 emissions pathways. The prediction of increasing rainfall variability also has high confidence, although the magnitude of change cannot be confidently projected. Coastal GBR ecosystems are also highly vulnerable to warming and increasing storm activity, as well as to sea level rise and ENSO related rainfall variability. There is also growing evidence that climate change is already impacting GBR water quality. Empirical data and models demonstrate increase in rainfall extremes and hence increased sediment and nutrient runoff and turbidity, increased CO_2 and reduced O_2, altered productivity and resuspension regimes, and numerous other pathways. Little quantitative information exists to date, however some regional differences are becoming evident. Each of the seven investigated climate change factors inflicts a multitude of direct and indirect impacts on its ecosystems and organisms, on their own and through their cumulative impacts and interactions.

Overall, the three main climate factors representing weather extremes, namely marine heatwaves, tropical cyclones, and rainfall extremes, nowadays inflict the greatest damage on coral reefs, seagrasses, mangroves and riparian vegetation. Of great concern is the observed increase in frequency of marine heatwaves, and the prediction that conditions that lead to heat-induced mass coral bleaching will become almost annual by 2040, severely threatening the ecosystem integrity, and also causing stress and mortality in numerous other marine organisms. Storm effects are often underappreciated, having inflicted over 40 % of mean annual coral loss on the GBR in the last decades (Bozec et al., 2022; De'ath et al., 2012), so any changes in cyclone damage would profoundly impact GBR ecosystems. Flood plumes directly impact inshore ecosystems and GBR water quality.

For the progressive climate change factors, some thresholds appear imminent within the coming decades (e.g., ocean acidification lowering the carbonate saturation state below critical levels, temperature-related feminisation in sea turtles, hypoxia stress in some fish). All progressive factors will increase in their ecological relevance in the coming decades, with their relative impacts often more taxon-specific than the extreme weather events, but importantly, with pressure being reef-wide and all year round.

The 1990–2022 review period displayed three noticeable trends in the literature. Firstly, the last few years have documented a rapid increase in coral bleaching damage as a major cause of coral mortality; models for 2020 estimated bleaching to contribute 48 % to GBR-wide annual coral mortality (ahead of cyclones and seastar predation with 41 % and 11 %, respectively (Bozec et al., 2022). This is a steep change from the previous estimate of 10 % of coral loss attributed to bleaching in 1985 to 2012 (De'ath et al., 2012). Second, ocean acidification has only started being scientifically addressed from the early 2000s onwards, mostly in the last decade. Third, there has been rising awareness of the role of cumulative impacts of climate change and water quality. Studies now show that recovery times for coral cover have slowed, and that water quality (e.g., suspended solids) co-determines coral recovery times on some inshore reefs (Ortiz et al., 2018; Power et al., 2017; Wolff et al., 2018). These trends have important implications for GBR management, for the urgency to address carbon emissions, and for the need to improve GBR water quality, before climate impacts overwhelm reef recovery potential.

Models are needed to quantify the cumulative impacts of the seven climate change impacts on GBR ecosystems (Bozec et al., 2022). Importantly, the overall damage inflicted by tropical storms is a function of their frequency, intensity, diameter and forward translation speed (Dixon et al., 2022). The same equations should apply to assessing the ecosystem impacts of the other climate factors, i.e., their overall impact depending on four dimensions: frequency, intensity, duration, and spatial extent (Fig. 3). Spatial extent includes the horizontal and vertical footprint of the disturbance, with cyclone, heatwave and salinity impacts not only varying across and along the continental shelf but also with depth. These four dimensions are also relevant for protective factors such as cloudiness and windiness. Their specific impacts depend on the sensitivity of taxa, i.e., taxon-dependent total 'dose' functions, representing exposure intensity (e.g., heat maxima, salinity minima), duration and frequency. Furthermore, the steepness of onset and decline and other metrics of variability of the climate pressure contribute to predicting organism responses (Ainsworth et al., 2016; Hobday et al., 2016).

The review also documented several links between climate change and GBR water quality, through causal chains of evidence. Haynes et al. (2007) developed a conceptual model of longer-term threats to GBR water quality that included global climate change, through processes such as changes in rainfall intensity, monsoonal wind direction, and flood plume residence times. The present study reviewed, for the first time, many more aspects of the earlier assessment. There is high confidence in the prediction of intensifying rainfall variability, and that drought-breaking floods are a major contributor of pollutants for the GBR (Waterhouse et al., 2024a, 2024b). Increasingly extreme rainfall events along the whole GBR suggest significantly greater challenges to meet GBR water quality targets, as severe rainfall leads to more severe terrestrial runoff of sediments, nutrients and pesticides. Also, ocean acidification, warming temperatures, changes in wind speed and direction, upwelling regimes, and resuspension regimes from wind waves and cyclones all alter marine productivity, and hence water quality. In combination, these studies present some evidence that GBR water

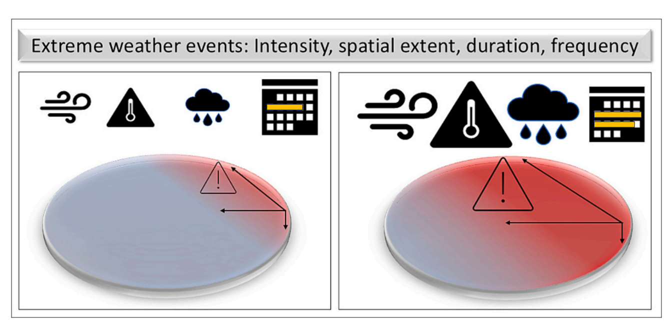

Fig. 3. Schematic of the four dimensions determining the ecosystem impacts (red) of the climate change factors considered here: Intensity, spatial extent, duration, and frequency.

quality will likely be further challenged by climate change, in ways similar to those reported for freshwater bodies and from other regions globally (e.g., Li et al. (2020). However, while rates of ocean acidification are highly predictable, predictions on the magnitude of change in rainfall variability do not yet exist, impeding quantitative estimates of regional changes in water quality and ecosystem impacts.

The review demonstrated important regional differences in the rates of climate change, suggesting management responses to changing climate need to be region-specific. In particular, the presently available climate models predict slower rates of warming in the northern compared to the central and southern GBR, and greater cyclone intensities for the centre and north but not for south of about latitude 20°S. Increasing drought intensity is predicted for the GBR south of 20°S. Terrestrial runoff from intensifying rainfall extremes predominantly affects the inshore GBR, although the offshore region may also be affected by larger floods in the narrower GBR north of about latitude 18°S. Changes in upwelling primarily affect nutrient supply to offshore reefs. Lastly, although acidification affects the whole GBR, carbonate saturation state declines with declining temperatures and there are indications for coastal acidification, making the southern inshore reefs potentially the most vulnerable to ocean acidification. Despite these regional differences in magnitude and prominence of specific changes, many of our findings should be transferrable to other tropical coastal and marine Indo-Pacific ecosystems.

Many knowledge gaps remain, due to the vast size and immense biological, geographical and physical diversity and complexity of the GBR and its many ecosystems. For many GBR ecosystems (including mesophotic reefs, Halimeda mounds, soft bottom habitats, sea fan fields) data on their responses to climate change remain largely unknown. Similarly, of the hundreds of thousands of species inhabiting the GBR, only a small percentage has been studied, and even fewer have been investigated for the cumulative effects of multiple stressors. Also, studies that show 'no effects' are severely underrepresented in the scientific literature. Nevertheless, the overall confidence in the body of evidence is high: a large number and high diversity of relevant studies exists, and multiple lines of evidence document how the GBR climate is changing, and how these seven climate change factors are impacting GBR water quality, organisms and ecosystems.

The review outlines several important implications for GBR policy, management and science. It reconfirms that to prevent near-annual build-up of marine heat waves and to maintain a majority of GBR reefs surrounded by seawater with aragonite saturation state >3.5 to the end of the century will require very aggressive reductions in CO_2 emissions at a global scale. During extreme heatwaves, and once bleaching conditions occur near-annually (predicted to be around 2040), water quality management in conjunction with other local management are insufficient tools for coral reef protection. However, they will remain relevant for other GBR ecosystems and functions less immediately threatened by climate change. Some ocean acidification effects on reefs are additive to the effects of poor water quality, suggesting scope for some mitigation through water quality improvement. Importantly, warming temperatures or temperature stress change the sensitivity of some organisms to pollutants such as diuron, suggesting that water quality guideline values may need to be adjusted as the climate changes. Some threatened species may become critically endangered due to climate change (e.g., sea turtles due to their temperature-controlled hatchling sex determination), confirming the need for climate change adjusted endangered species management plans. For scientists conducting climate change experiments, it is advisable to standardise and adhere to treatment values in line with those predicted for the GBR (Table 1).

The findings from this review are not fundamentally changing previous understandings of management and policy needs; however, they do communicate a sense of urgency. Efforts to rapidly reduce and then halt and reverse further atmospheric greenhouse gas pollution globally and nationally are critical. Overall, intensifying climate change disturbances of GBR ecosystems along the whole GBR increases rather than diminishes the relevance of local management tools, especially to facilitate ecosystem recovery from these disturbances. The findings emphasise the importance of having met all GBR water quality targets by 2030, before bleaching conditions occur almost annually and bleaching together with ocean acidification will start leading to a negative carbonate balance in some reefs in the GBR.

CRediT authorship contribution statement

Katharina E. Fabricius: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Investigation, Conceptualization. **Aimee Brown:** Writing – review & editing, Validation, Data curation. **Catherine Collier:** Writing – review & editing, Investigation. **Mari-Carmen Pineda:** Writing – review & editing, Resources, Project administration, Methodology. **Barbara Robson:** Writing – review & editing, Writing – original draft, Investigation. **Sven Uthicke:** Writing – review & editing, Investigation. **Jane Waterhouse:** Writing – review & editing, Resources, Project administration, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2025.118267.

Data availability

No data was used for the research described in the article.

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