



2022 Scientific Consensus Statement

Question 2.2 What are the current and predicted impacts of climate change on Great Barrier Reef ecosystems (including spatial and temporal distribution impacts)

Question 2.2.1 How is climate change currently influencing water quality in coastal and marine areas of the Great Barrier Reef, and how is this predicted to change over time?

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Citation

Fabricius K, Brown A, Songcuan A, Collier C, Uthicke S, Robson B (2024) Question 2.2 What are the current and predicted impacts of climate change on Great Barrier Reef ecosystems (including spatial and temporal distribution of impacts)? In Waterhouse J, Pineda M-C, Sambrook K (Eds) 2022 Scientific Consensus Statement on land-based impacts on Great Barrier Reef water quality and ecosystem condition. Commonwealth of Australia and Queensland Government.

The 2022 Scientific Consensus Statement was led and coordinated by C2O Consulting coasts | climate | oceans.

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The 2022 Scientific Consensus Statement is funded by the Australian Government's Reef Trust and Queensland Government's Queensland Reef Water Quality Program.

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Explanatory Notes for readers of the 2022 SCS Syntheses of Evidence

These explanatory notes were produced by the SCS Coordination Team and apply to all evidence syntheses in the 2022 SCS.

What is the Scientific Consensus Statement?

The Scientific Consensus Statement (SCS) on land use impacts on Great Barrier Reef (GBR) water quality and ecosystem condition brings together scientific evidence to understand how land-based activities can influence water quality in the GBR, and how these influences can be managed. The SCS is used as a key evidence-based document by policymakers when they are making decisions about managing GBR water quality. In particular, the SCS provides supporting information for the design, delivery and implementation of the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP) which is a joint commitment of the Australian and Queensland governments. The Reef 2050 WQIP describes actions for improving the quality of the water that enters the GBR from the adjacent catchments. The SCS is updated periodically with the latest peer reviewed science.

C₂O Consulting was contracted by the Australian and Queensland governments to coordinate and deliver the 2022 SCS. The team at C₂O Consulting has many years of experience working on the water quality of the GBR and its catchment area and has been involved in the coordination and production of multiple iterations of the SCS since 2008.

The 2022 SCS addresses 30 priority questions that examine the influence of land-based runoff on the water quality of the GBR. The questions were developed in consultation with scientific experts, policy and management teams and other key stakeholders (e.g., representatives from agricultural, tourism, conservation, research and Traditional Owner groups). Authors were then appointed to each question via a formal Expression of Interest and a rigorous selection process. The 30 questions are organised into eight themes: values and threats, sediments and particulate nutrients, dissolved nutrients, pesticides, other pollutants, human dimensions, and future directions, that cover topics ranging from ecological processes, delivery and source, through to management options. Some questions are closely related, and as such Readers are directed to Section 1.3 (Links to other questions) in this synthesis of evidence which identifies other 2022 SCS questions that might be of interest.

The geographic scope of interest is the GBR and its adjacent catchment area which contains 35 major river basins and six Natural Resource Management regions. The GBR ecosystems included in the scope of the reviews include coral reefs, seagrass meadows, pelagic, benthic and plankton communities, estuaries, mangroves, saltmarshes, freshwater wetlands and floodplain wetlands. In terms of marine extent, while the greatest areas of influence of land-based runoff are largely in the inshore and to a lesser extent, the midshelf areas of the GBR, the reviews have not been spatially constrained and scientific evidence from anywhere in the GBR is included where relevant for answering the question.

Method used to address the 2022 SCS Questions

Formal evidence review and synthesis methodologies are increasingly being used where science is needed to inform decision making, and have become a recognised international standard for accessing, appraising and synthesising scientific information. More specifically, 'evidence synthesis' is the process of identifying, compiling and combining relevant knowledge from multiple sources so it is readily available for decision makers¹. The world's highest standard of evidence synthesis is a Systematic Review, which uses a highly prescriptive methodology to define the question and evidence needs, search for and appraise the quality of the evidence, and draw conclusions from the synthesis of this evidence.

In recent years there has been an emergence of evidence synthesis methods that involve some modifications of Systematic Reviews so that they can be conducted in a more timely and cost-effective

¹ Pullin A, Frampton G, Jongman R, Kohl C, Livoreil B, Lux A, ... & Wittmer, H. (2016). Selecting appropriate methods of knowledge synthesis to inform biodiversity policy. *Biodiversity and Conservation*, 25: 1285-1300. <https://doi.org/10.1007/s10531-016-1131-9>

manner. This suite of evidence synthesis products are referred to as '**Rapid Reviews**'². These methods typically involve a reduced number of steps such as constraining the search effort, adjusting the extent of the quality assessment, and/or modifying the detail for data extraction, while still applying methods to minimise author bias in the searches, evidence appraisal and synthesis methods.

To accommodate the needs of GBR water quality policy and management, tailor-made methods based on Rapid Review approaches were developed for the 2022 SCS by an independent expert in evidence-based syntheses for decision-making. The methods were initially reviewed by a small expert group with experience in GBR water quality science, then externally peer reviewed by three independent evidence synthesis experts.

Two methods were developed for the 2022 SCS:

- The **SCS Evidence Review** was used for questions that policy and management indicated were high priority and needed the highest confidence in the conclusions drawn from the evidence. The method includes an assessment of the reliability of all individual evidence items as an additional quality assurance step.
- The **SCS Evidence Summary** was used for all other questions, and while still providing a high level of confidence in the conclusions drawn, the method involves a less comprehensive quality assessment of individual evidence items.

Authors were asked to follow the methods, complete a standard template (this 'Synthesis of Evidence'), and extract data from literature in a standardised way to maximise transparency and ensure that a consistent approach was applied to all questions. Authors were provided with a Methods document, '*2022 Scientific Consensus Statement: Methods for the synthesis of evidence*'³, containing detailed guidance and requirements for every step of the synthesis process. This was complemented by support from the SCS Coordination Team (led by C₂O Consulting) and the evidence synthesis expert to provide guidance throughout the drafting process including provision of step-by-step online training sessions for Authors, regular meetings to coordinate Authors within the Themes, and fortnightly or monthly question and answer sessions to clarify methods, discuss and address common issues.

The major steps of the Method are described below to assist Readers in understanding the process used, structure and outputs of the synthesis of evidence:

1. **Describe the final interpretation of the question.** A description of the interpretation of the scope and intent of the question, including consultation with policy and management representatives where necessary, to ensure alignment with policy intentions. The description is supported by a conceptual diagram representing the major relationships relevant to the question, and definitions.
2. **Develop a search strategy.** The Method recommended that Authors used a S/PICO framework (Subject/Population, Exposure/Intervention, Comparator, Outcome), which could be used to break down the different elements of the question and helps to define and refine the search process. The S/PICO structure is the most commonly used structure in formal evidence synthesis methods⁴.
3. **Define the criteria for the eligibility of evidence for the synthesis and conduct searches.** Authors were asked to establish **inclusion and exclusion criteria to define the eligibility of evidence** prior to starting the literature search. The Method recommended conducting a **systematic literature search** in at least **two online academic databases**. Searches were typically restricted to 1990 onwards (unless specified otherwise) following a review of the evidence for the previous (2017) SCS which indicated that this would encompass the majority of the evidence

² Collins A, Coughlin D, Miller J, & Kirk S (2015) The production of quick scoping reviews and rapid evidence assessments: A how to guide. UK Government. <https://www.gov.uk/government/publications/the-production-of-quick-scoping-reviews-and-rapid-evidence-assessments>

³ Richards R, Pineda MC, Sambrook K, Waterhouse J (2023) 2022 Scientific Consensus Statement: Methods for the synthesis of evidence. C₂O Consulting, Townsville, pp. 59.

⁴ <https://libguides.jcu.edu.au/systematic-review/define>

base, and due to available resources. In addition, the geographic **scope of the search for evidence** depended on the nature of the question. For some questions, it was more appropriate only to focus on studies derived from the GBR region (e.g., the GBR context was essential to answer the question); for other questions, it was important to search for studies outside of the GBR (e.g., the question related to a research theme where there was little information available from the GBR). Authors were asked to provide a rationale for that decision in the synthesis. Results from the literature searches were screened against **inclusion and exclusion** criteria at the title and abstract review stage (**initial screening**). Literature that passed this initial screening was then read in full to determine the eligibility for use in the synthesis of evidence (**second screening**). Importantly, all literature had to be **peer reviewed and publicly available**. As well as journal articles, this meant that grey literature (e.g., technical reports) that had been externally peer reviewed (e.g., outside of organisation) and was publicly available, could be assessed as part of the synthesis of evidence.

4. **Extract data and information from the literature.** To compile the data and information that were used to address the question, **Authors were asked to complete a standard data extraction and appraisal spreadsheet**. Authors were assisted in tailoring this spreadsheet to meet the needs of their specific question.
5. **Undertake systematic appraisal of the evidence base.** Appraisal of the evidence is an important aspect of the synthesis of evidence as it provides the reader and/or decision-makers with valuable insights about the underlying evidence base. Each evidence item was assessed for its spatial, temporal and overall relevance to the question being addressed, and allocated a relative score. The body of evidence was then evaluated for overall relevance, the size of the evidence base (i.e., is it a well-researched topic or not), the diversity of studies (e.g., does it contain a mix of experimental, observational, reviews and modelling studies), and consistency of the findings (e.g., is there agreement or debate within the scientific literature). Collectively, these assessments were used to obtain an overall measure of the level of confidence of the evidence base, specifically using the overall relevance and consistency ratings. For example, a high confidence rating was allocated where there was high overall relevance and high consistency in the findings across a range of study types (e.g., modelling, observational and experimental). Questions using the **SCS Evidence Review Method** had an **additional quality assurance step**, through the assessment of reliability of all individual studies. This allowed Authors to identify where potential biases in the study design or the process used to draw conclusions might exist and offer insight into how reliable the scientific findings are for answering the priority SCS questions. This assessment considered the reliability of the study itself and enabled authors to place more or less emphasis on selected studies.
6. **Undertake a synthesis of the evidence and complete the evidence synthesis template** to address the question. Based on the previous steps, a narrative synthesis approach was used by authors to derive and summarise findings from the evidence.

Guidance for using the synthesis of evidence

Each synthesis of evidence contains three different levels of detail to present the process used and the findings of the evidence:

1. **Executive Summary:** This section brings together the evidence and findings reported in the main body of the document to provide a high-level overview of the question.
2. **Synthesis of Evidence:** This section contains the detailed identification, extraction and examination of evidence used to address the question.
 - **Background:** Provides the context about why this question is important and explains how the Lead Author interpreted the question.
 - **Method:** Outlines the search terms used by Authors to find relevant literature (evidence items), which databases were used, and the inclusion and exclusion criteria.
 - **Search Results:** Contains details about the number of evidence items identified, sources, screening and the final number of evidence items used in the synthesis of evidence.

- **Key Findings:** The **main body of the synthesis**. It includes a summary of the study characteristics (e.g., how many, when, where, how), a deep dive into the body of evidence covering key findings, trends or patterns, consistency of findings among studies, uncertainties and limitations of the evidence, significance of the findings to policy, practice and research, knowledge gaps, Indigenous engagement, conclusions and the evidence appraisal.
3. **Evidence Statement:** Provides a succinct, high-level overview of the main findings for the question with supporting points. The Evidence Statement for each Question was provided as input to the 2022 Scientific Consensus Statement Summary and Conclusions.

While the Executive Summary and Evidence Statement provide a high-level overview of the question, it is **critical that any policy or management decisions are based on consideration of the full synthesis of evidence**. The GBR and its catchment area is large, with many different land uses, climates and habitats which result in considerable heterogeneity across its extent. Regional differences can be significant, and from a management perspective will therefore often need to be treated as separate entities to make the most effective decisions to support and protect GBR ecosystems. Evidence from this spatial variability is captured in the reviews as much as possible to enable this level of management decision to occur. Areas where there is high agreement or disagreement of findings in the body of evidence are also highlighted by authors in describing the consistency of the evidence. In many cases authors also offer an explanation for this consistency.

Peer Review and Quality Assurance

Each synthesis of evidence was peer reviewed, following a similar process to indexed scientific journals. An Editorial Board, endorsed by the Australian Chief Scientist, managed the process. The Australian Chief Scientist also provided oversight and assurance about the design of the peer review process. The Editorial Board consisted of an Editor-in-Chief and six Editors with editorial expertise in indexed scientific journals. Each question had a Lead and Second Editor. Reviewers were approached based on skills and knowledge relevant to each question and appointed following a strict conflict of interest process. Each question had a minimum of two reviewers, one with GBR-relevant expertise, and a second 'external' reviewer (i.e., international or from elsewhere in Australia). Reviewers completed a peer review template which included a series of standard questions about the quality, rigour and content of the synthesis, and provided a recommendation (i.e., accept, minor revisions, major revisions). Authors were required to respond to all comments made by reviewers and Editors, revise the synthesis and provide evidence of changes. The Lead and Second Editors had the authority to endorse the synthesis following peer review or request further review/iterations.

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Acknowledgements

Many thanks to Mari-Carmen Pineda (C₂O Consulting), Jane Waterhouse (C₂O Consulting), and Rob Richards (Evidentiary) for guidance in the Evidence Synthesis process, formatting edits and early review comments, Bianca Molinari (C₂O Consulting) for wetlands expertise and support with searches and data extraction, and to the two anonymous reviewers of this work.

Executive Summary

Questions

Primary Question 2.2 What are the current and predicted impacts of climate change on Great Barrier Reef ecosystems (including spatial and temporal distribution of impacts)?

Secondary Question 2.2.1 How is climate change currently influencing water quality in coastal and marine areas of the Great Barrier Reef, and how is this predicted to change over time?

Background

The cumulative pressures from climate change and water quality are considered a key threat to the health of the Great Barrier Reef (GBR). Climate change is the most significant threat to the long-term outlook of many GBR ecosystems, and climate change-related disturbances over increasingly short time intervals are reducing the ability of GBR ecosystems to recover. Because of these cumulative disturbances, the overall outlook for GBR ecosystems is currently classified as ‘poor to very poor’. As climate change intensifies, local management actions to improve water quality will become increasingly important, as poor water quality delays the recovery of key habitats, species and ecosystem processes. This Evidence Summary summarises what is known about how the climate is changing in the GBR, how climate change impacts GBR ecosystems and organisms, and how it is affecting GBR water quality. It aims to contribute to guiding management initiatives to reduce threats to the GBR and improve resilience, by addressing climate change, improving water quality and strengthening effective on-ground management actions.

Methods

- A formal Rapid Review approach was used for the 2022 Scientific Consensus Statement (SCS) synthesis of evidence. Rapid reviews are a systematic review with a simplification or omission of some steps to accommodate the time and resources available⁵. For the SCS, this applies to the search effort, quality appraisal of evidence and the amount of data extracted. The process has well-defined steps enabling fit-for-purpose evidence to be searched, retrieved, assessed and synthesised into final products to inform policy. For this question, an Evidence Summary method was used.
- Search locations included Web of Science and Scopus.
- Main source of evidence: The search was limited to sources specifically relating to the GBR to keep the review manageable, given the very large number of publications that might otherwise fit the search criteria.
- Of 3,823 evidence items returned from the initial search results, 458 passed initial screening (i.e., were found to be potentially relevant) and 317 were used in the final evidence appraisal. This included 21 studies providing evidence relating to climate change in the GBR, 273 relating to the effects of climate change on GBR ecosystems, and 31 relating to the effects of climate change on GBR water quality.
- Studies before and after the 2017 Scientific Consensus Statement were jointly assessed. There seemed no substantial change in broad research directions and findings between these periods, except for greater recognition of damage from bleaching and cumulative impacts.

⁵ Cook CN, Nichols SJ, Webb JA, Fuller RA, Richards RM (2017) Simplifying the selection of evidence synthesis methods to inform environmental decisions: A guide for decision makers and scientists. *Biological Conservation* 213: 135-145 <https://doi.org/10.1016/j.biocon.2017.07.004>

Method limitations and caveats to using this Evidence Summary

For this Evidence Summary, the following caveats or limitations should be noted when applying the findings for policy or management purposes:

- Only studies written in English were included.
- Studies were mainly GBR derived (with a few exceptions).
- Studies were retrieved from either of two academic databases.
- Studies were published from 1990 onwards, and before October 2022.

Key Findings

Summary of evidence to 2022

The key research findings to 2022 for the questions ‘how is the climate of the GBR changing’ and ‘how does climate change affect GBR ecosystems and organisms’, were based on 21 and 273 studies, respectively, and are summarised here:

Rising temperatures: GBR seawater temperature has increased by ~1.0°C since pre-development times, which has led to increasing frequencies of marine heatwaves (Conceptual diagram Figure 1, Section 4.1.1.1, Tables 8 and 9).

- These marine heatwaves can lead to coral mortality, and other selective impacts in aquatic marine ecosystems (Tables 8 to 11). The link between climate change and large-scale bleaching of corals is now undeniable.
- GBR annual mean seawater temperatures are projected to increase by a further 1.0 to 3.5°C by 2090, leading to four- to eight-fold increases in the frequency of marine heatwaves towards the end of this century, depending on emissions pathways. At the present business-as-usual rate of warming, conditions that lead to heat-induced coral bleaching will become almost annual by 2040.
- The IUCN threat status of some threatened species may further deteriorate due to climate change, for example for sea turtles because of their unique temperature-controlled hatchling sex determination, and nests being flooded due to sea level rise.
- Of crucial importance here is the exceedance of regional evolutionary adapted temperature thresholds. Of the six mass bleaching events recorded since monitoring started in 1985, four have occurred in the last eight years (2016, 2017, 2020, 2022).
- Little quantitative evidence exists about rates of evolutionary adaptation and acclimatisation of tropical benthic species and shifts in their geographic ranges.
- Some water quality guidelines will need to be revised because temperature rises can alter organism sensitivities to pollutants.
- As expected for broad Evidence Summaries, literature searches on any specific topic would have yielded numerous additional references. However, the agreement with known literature from other regions is an additional confirmation that the broad conclusion would not change if more specific search phrases had been used; namely, that rapid warming leads to profound physiological and ecological changes and widespread adverse impacts to coral reefs, seagrass meadows, mangroves and wetlands in the GBR.

Ocean acidification, the change in seawater chemistry resulting from the uptake of the additional atmospheric CO₂ into the seawater, represents an additional pervasive threat for coral reefs. Ocean acidification adversely affects biotic calcification and coral recruitment, and acts as a nutrient for marine plants, shifting the ecological balance from corals to algae. Relevant study findings for the GBR are summarised in Tables 8 to 11. Globally, a mean aragonite saturation state (a unitless measure of the seawater carbonate content) of 3.0 is considered to be the absolute minimum critical level for coral reef formation. However, 99.9% of coral reefs are located in areas where

seawater aragonite exceeded 3.5 in pre-industrial times, confirming this value as one of the most well-defined climate change related thresholds for coral reefs.

- For the GBR, the aragonite saturation state of 3.5 has been confirmed as an ecologically relevant threshold. Data from the National Reference Station off Townsville, and Heron Island reported a decline in aragonite saturation state of -0.0673 per decade, confirming that this ecologically relevant threshold of 3.5 will be reached by 2030 in parts of the GBR.
- Climate model intercomparisons also show that under a business-as-usual scenario (RCP 8.5), all open-water coral reefs in the world will be exposed to an aragonite saturation state <3.0 by 2100. To ensure the majority of GBR coral reefs are surrounded by seawater with an aragonite saturation state >3.5 at the end of the century will require very aggressive reductions in CO₂ emissions.
- Effects of ocean acidification on coral reefs include the dissolution of reef sediments, the proliferation of fleshy macroalgae, greater reef bioerosion, negative effects on coral recruitment, negative effects on crustose coralline algae, and a multitude of other adverse changes to the physiology, behaviour and ecology of tropical marine organisms and ecosystems.
- Although some regions with elevated CO₂ variability may provide scope for adaptation, to date no specific ocean acidification refugia have been identified in the GBR. Unlike with temperature, there is no possibility of latitudinal escape through southward migration, and little evidence for organism adaptation to acidification exists.

The prediction of increases in intense rainfall events in the GBR has high confidence, paralleling similar conclusions from many regions around the world (IPCC, 2021).

- For the GBR, the magnitude of the increase in intense rainfall cannot be confidently projected yet, neither for the near future nor for later this century.
- The relationship between extreme rainfall events, river loads, floods and inshore water quality is known conceptually but difficult to quantify as long as magnitudes of changes are unknown.
- GBR catchments south of 20°S (near Bowen) may additionally experience increasing periods of drought over the course of the century. This may impact GBR water quality, as drought-stricken vegetation retains less soil, leading to disproportionately high loads of sediments, nutrients and pesticides in drought-breaking floods (refer to SCS Questions in Themes 3 to 5).
- The strength of the causal associations between increasing rainfall extremes and inshore water quality suggest implications for future river loads of sediments and nutrients especially for the southern GBR region, with likely longer-term implications for its water quality targets.

Tropical cyclones may become less frequent, but the proportion of cyclones in the most intense storm categories may increase along the northern and central GBR.

- For the GBR region north of latitude 20°S, tropical cyclones are projected with medium confidence to become less frequent with increases in the proportion of the most intense storms. South of latitude 20°S (where cyclones are rare), the models predict no changes in cyclone frequency or intensity.
- Estimates of past and future changes in cyclone damage to the GBR under water are still uncertain, as they also depend on wave generation, which in turn also depends on cyclone size, forward movement speed, and the track of the cyclone relative to the reef. Not all of these parameters have been measured or included in models.

Organism and ecosystem responses to climate change are highly variable (Section 4.1.1.2).

- Coral reefs are highly threatened by warming temperatures, with their near-future ecosystem integrity and persistence depending on global carbon emission pathways.
- Over 100 studies have documented that warming temperatures and marine heatwaves affect the physiology, survival and populations of a multitude of other marine organisms and marine ecosystems, with the severity of changes typically increasing as temperature levels rise. A specialist literature search on the topic for specific GBR taxonomic groups (but with searches not regionally restricted to the GBR) would have yielded numerous additional references but was outside the scope of this review.
- Many studies show the significant effects of climate change especially of warming and ocean acidification on the marine ecosystems in the GBR.
- Coastal GBR ecosystems also appear highly vulnerable to sea level rise, El Niño-Southern Oscillation (ENSO) related sea level variability and rainfall variability, as well as to warming and increasing storm activity.
- The review showed that for many GBR ecosystems (including mesophotic reefs, *Halimeda* mounds, soft bottom habitats, sea fan fields, etc.) data on climate change impacts are still sparse (Tables 8 to 11). Hence, their responses to climate change, and the interactions of climate change in combination with water quality, remain largely unknown.

The review found a number of links between **climate change and GBR water quality** and water quality effects (Table 14). Some examples are:

- Intensifying rainfall variability affecting runoff is supported mostly indirectly to date, through causal chains of evidence (Conceptual diagram Figure 2, Section 4.1.1.3).
- Ocean acidification, warming temperatures, changes in wind speed and direction, upwelling regimes, resuspension regimes from cyclones, all alter marine productivity which affects water quality.
- Warming temperatures will accelerate metabolic rates and affect food and energy demands of organisms.
- Warming temperatures accelerate nutrient cycling and therefore energy supply.
- Warming temperatures or temperature stress change the sensitivity of some organisms to pollutants such as diuron. Therefore, water quality guideline values may need to be adjusted as the climate changes.
- The numerous other interactions between temperature and water quality are reviewed in Question 2.4 (Uthicke et al., this SCS).
- Few studies were found that predict the timing when critical thresholds will be crossed, as predictions on the magnitude of change in rainfall variability do not yet exist. An exception is ocean acidification which is highly predictable.
- It appears likely that water quality improvement strategies and targets will have to be constantly monitored and their management adapted in a reactive fashion, to deal with the rapidly changing environmental conditions.
- Research priorities should be the role and direction of change in marine nitrogen sources such as upwelling and nitrogen fixation, the regionally specific consequences of increasing variability in rainfall events for GBR runoff, and the apparent altered sensitivity of some organisms to pollutants at higher temperatures.

Recent findings 2016-2022

Chapter 1 of the 2017 Scientific Consensus Statement summarised the main points of observed and predicted climate change and observed severe weather events prior to 2017. Since then, the GBR has been subject to further climate impacts, but the findings are still largely current. The 2017 SCS did not include in-depth coverage of questions equivalent to the impacts of climate change on GBR water quality, organisms and ecosystems (Q2.2 and Q2.2.1, Sections 4.1.1.2 and 4.1.1.3). Therefore, this Evidence Summary jointly assessed the retrieved 207 studies before and 113 studies after 2017,

rather than splitting the assessment by the 2017 date. Overall, there seemed no substantial change in broad research directions and findings around that year, instead the new studies provided additional and confirmatory evidence.

Two exceptions to this general statement apply. First, the last five years have documented the increasing role of coral bleaching as major cause of coral mortality. Models for 2020 estimated bleaching to now contribute 48% to simulated GBR-wide annual model rates of coral mortality, ahead of cyclones (41%) and crown-of-thorns starfish (COTS) predation (11%), and is up from the previous estimate of 10% of coral loss attributed to bleaching from 1985 to 2012). The Great Barrier Reef Marine Park Authority's (GBRMPA) Outlook Report (2019) assessed the outlook for GBR ecosystems as 'poor to very poor' and identified climate change now as the most significant threat to the Region's long-term outlook. Second, there has been rising awareness of the role of cumulative impacts from climate change and water quality. Studies now show that recovery times for coral cover have slowed, and that water quality co-determines coral recovery times. These new findings have important implications for GBR management, for the urgency to address carbon emissions and the need to meet GBR water quality targets, before climate impacts overwhelm reef recovery potential.

Significance for policy, practice, and research

This Evidence Summary builds upon earlier key studies on the same topic, in particular the 24-chapter peer reviewed GBRMPA book 'Climate Change Vulnerability Assessment' (Johnson and Marshall 2007). The Evidence Summary documents significant scientific progress in GBR climate science since completion of the Vulnerability Assessment, with many findings that are relevant to GBR policy or management action. For example, the Evidence Summary documented that:

- Climate change is now widely accepted as the most significant threat to the long-term outlook for GBR coral reefs.
- At the present business-as-usual rate of warming, conditions that lead to heat-induced coral bleaching will become almost annual by 2040, severely threatening ecosystem integrity. Coral bleaching is now the most important cause of coral mortality, with models for 2020 estimating coral bleaching to contribute 48% to simulated GBR-wide annual model rates of coral mortality. Threat reduction requires aggressive reductions in CO₂ emissions globally and nationally.
- Climate change disturbances of GBR ecosystems, due to heatwaves and ocean acidification will increase along the whole GBR. This further increases the relevance of water quality improvement by 2030 to facilitate ecosystem recovery from these disturbances, before bleaching events become near annual and ocean acidification starts leading to a negative carbonate balance in some reef habitats.
- For the majority of GBR reefs to be surrounded by seawater with an aragonite saturation state >3.5 at the end of the century, very aggressive reductions in CO₂ emissions globally and nationally will be required.
- Some threatened species may become critically endangered due to additional pressure from climate change (e.g., sea turtles due to their temperature-controlled hatchling sex determination), confirming the need for climate change specific endangered species management plans.
- There is documented altered sensitivity of some organisms to pollutants under warming temperatures, highlighting that water quality guideline values may need to be adjusted as the climate changes.
- Increasingly extreme rainfall events along the whole GBR suggest significant greater challenges to meet GBR water quality targets, as severe rainfall leads to more severe terrestrial runoff of sediments, nutrients and pesticides.

- Frequency of droughts may increase over the course of the century in southern GBR catchments, adding to challenges to meet water quality targets, as sediments loads tend to be highest in drought-breaking floods.
- Ocean acidification, like poor water quality, leads to the proliferation of algae, greater bioerosion, reduced coral recruitment and lower cover of crustose coralline algae. The additivity in these responses suggests water quality improvement may mitigate some of the effects of ocean acidification on reefs.

There is still insufficient knowledge about how climate change impacts differ across GBR regions, and when they will reach critical levels throughout this century. However, this Evidence Summary has identified some broad evidence for regional differences in exposure and vulnerability, suggesting that there will need to be region-specific management responses to changing climate. For example:

- Climate models predict overall greater regional warming 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.
- Reduced cyclone frequency and increasing intensity applies to the GBR north of about latitude 20°S, not to the southern GBR.
- Increasing drought intensity is only affecting the GBR south of about latitude 20°S.
- Changes in upwelling affect nutrient supply predominantly on offshore reefs.
- More severe episodic runoff from intensifying rainfall extremes is predominantly affecting the inshore GBR, although the offshore areas may also be affected due to the links between floods and outbreaks of COTS, and offshore transport of pollutants in the narrower GBR north of about latitude 18°S.
- Ocean acidification is affecting the whole GBR, however, saturation state declines with temperatures and there are indications for coastal acidification, making the southern inshore reefs potentially the most vulnerable to ocean acidification. It is likely that water quality improvements may be especially beneficial in these areas.

These findings are not new and do not fundamentally change previous understandings of management and policy needs; however, they do communicate a sense of urgency. Efforts to rapidly reduce and then halt further atmospheric carbon dioxide pollution globally and nationally are critical. Furthermore, the Evidence Summary suggests that local management tools are rapidly becoming more important to mitigate these climate change impacts. They will make the greatest difference *before* mass coral bleaching conditions occur almost annually and ocean acidification starts leading to a negative carbonate balance in some reefs in the GBR.

Key uncertainties and/or limitations

Many key knowledge gaps remain, some of which are listed in Table 17. For example:

- Of the dozens of ecosystems and hundreds of thousands of species inhabiting the GBR, the responses of only few have been studied to some of the climate change agents, and even fewer to the interactive effects of climate change and other threats.
- There is still little quantitative data to address the questions about how climate change impacts differ across regions and habitats, and when they will reach critical levels throughout this century.
- It is important to obtain region-specific estimates about the cumulative damage from the various forms of disturbances.
- For the question on climate change effects on GBR water quality, few direct study approaches exist. The synthesis on the links between rainfall variability and water quality was based on a causal evidence chain (climate change affects extreme rainfall, which in turn affects runoff, which in turn predominantly affects inshore water quality).

- It is well known that studies that show ‘no effects’ are severely underrepresented in the scientific literature.

Evidence appraisal

Overall, the confidence in the body of evidence used to answer the primary question, and the secondary question, using the evidence appraisal results is High (Table 16). There was a large number of relevant studies, a High diversity of study approaches, and multiple lines of evidence to explain how the climate is changing, how climate change is impacting GBR organisms and ecosystems, and how climate change is currently influencing water quality in coastal and marine areas of the GBR. Due to the vast size of the GBR and the diversity of ecosystems along multiple environmental gradients, there is presently Moderate confidence in the spatial component of the question, namely the spatial distribution of impacts. Due to the episodic nature of extreme events, the many ecosystems and species involved, and unknown rates of evolutionary adaptation, there is presently only Moderate confidence in the temporal component of the question, namely estimating timelines for predicted impacts of climate change on GBR ecosystems and on water quality.

1. Background

The Great Barrier Reef (GBR) is Australia’s largest World Heritage Area (WHA), housing a diverse range of ecosystems with numerous outstanding universal values, and have significant economic values for Queensland’s communities and industries (2022 Scientific Consensus Statement (SCS) Question 1.1, Newlands et al.). Increasing disturbances from climate change threaten to rapidly deteriorate the GBR and its values. Climate change affects the GBR through both a change in the frequency and magnitude of pulse disturbances (extreme weather events), and through increasing chronic pressures. The following climate change agents are known to affect coastal marine ecosystems: Warming temperatures, short-term marine heatwaves, ocean acidification, sea level rise, changes in extreme rainfall events, the frequency of droughts and drought-breaking floods, changes in the intensity of tropical cyclones, and changes in wind speed or direction.

The cumulative pressures from climate change and poor water quality further threaten the health of the GBR (Question 2.4, Uthicke et al., this SCS). The term poor water quality is used here to reflect concentrations of nutrients, sediments, pesticides and other pollutants exceeding the region-specific GBR Water Quality Guidelines (GBRMPA, 2010), see SCS Questions in Themes 3 to 6). With intensifying climate change, water quality increases in importance, as poor water quality delays the recovery of key habitats, species and ecosystem processes (see SCS Questions in Themes 3 to 6). Climate change disturbances over increasingly short time intervals are reducing the ability of GBR ecosystems to recover. Because of these cumulative disturbances, the overall outlook for the GBR is presently classified as ‘poor to very poor’ (GBRMPA, 2019).

This Evidence Summary summarises what is known about how the climate is changing in the GBR, how these changes impact GBR ecosystems and organisms, and how it is currently affecting GBR water quality. The study incorporates and builds upon findings from the IPCC Sixth Assessment Report (2021), the Outlook Report by the Great Barrier Reef Marine Park Authority (GBRMPA, 2019), a special report on the GBR by the National Climate Change Adaptation Research Facility (Morrison and Hughes 2016), and the Reef 2050 Long-term Sustainability Plan 2021 (Commonwealth of Australia, 2021). These Reports were not included in the literature evidence extraction and appraisal nor included in the counts of studies, as they are considered as ‘background materials’. By synthesising this information and informing governments, industries and the community, this Evidence Summary aims to provide guidance for management initiatives aimed at reducing threats to the GBR and improving resilience, by addressing climate change, improving water quality and strengthening effective on-ground management actions.

1.1 Questions

Primary question	Q2.2 What are the current and predicted impacts of climate change on Great Barrier Reef ecosystems (including spatial and temporal distribution of impacts)?
Secondary question	Q2.2.1 How is climate change currently influencing water quality in coastal and marine areas of the Great Barrier Reef, and how is this predicted to change over time?

Authors’ interpretation:

“How is the climate in the GBR changing? What are the responses of GBR ecosystem functions and biota (predominantly coral reefs, seagrass meadows, mangroves and wetlands, but also any other benthic and pelagic ecosystems) to these varying types of climate change (warming trend, marine heatwaves, altered rainfall, tropical cyclone frequency and intensity, ocean acidification, wind speed and direction, sea level rise)? How do exposure, vulnerability and impacts differ across regions and

habitats, and how are impacts predicted to change throughout this century, and when will they reach critical levels?”

“How are the above climate change variables, and their interactions, currently influencing water quality (rainfall and drought patterns altering runoff frequency and sediment and nutrient loads entering the GBR lagoon, water clarity, in relation to water quality guideline values) in coastal and marine areas of the GBR? How are these effects predicted to change throughout this century, and when will they reach critical levels?”

1.2 Conceptual diagrams

Two conceptual diagrams were developed to add structure to the questions. Figure 1 shows how Question 2.2 was broken into three components: Box 1 (blue) summarises the main observed and predicted changes in GBR climate separately for the main climate change agents in section 4.1.1.1. Box 2 (green) provides an overview of the main impacts of these climate change agents on the main ecosystems and organisms of concern (section 4.1.1.2), while Box 3 (tan) indicates that climate change is also an important issue affecting GBR water quality. There are important spatial and temporal considerations to this question, as outlined in the orange elements.

Figure 2 breaks down Question 2.2.1 into its main components and summarises the main pathways for how the various climate change agents (blue) affect various chemical GBR water quality attributes, properties, and agents (tan), and these in turn affect biotic GBR water quality agents, and threshold values (green). It emphasises the connectedness, and indeed the importance of the connections, between all components of the GBR World Heritage Area (GBRWHA).

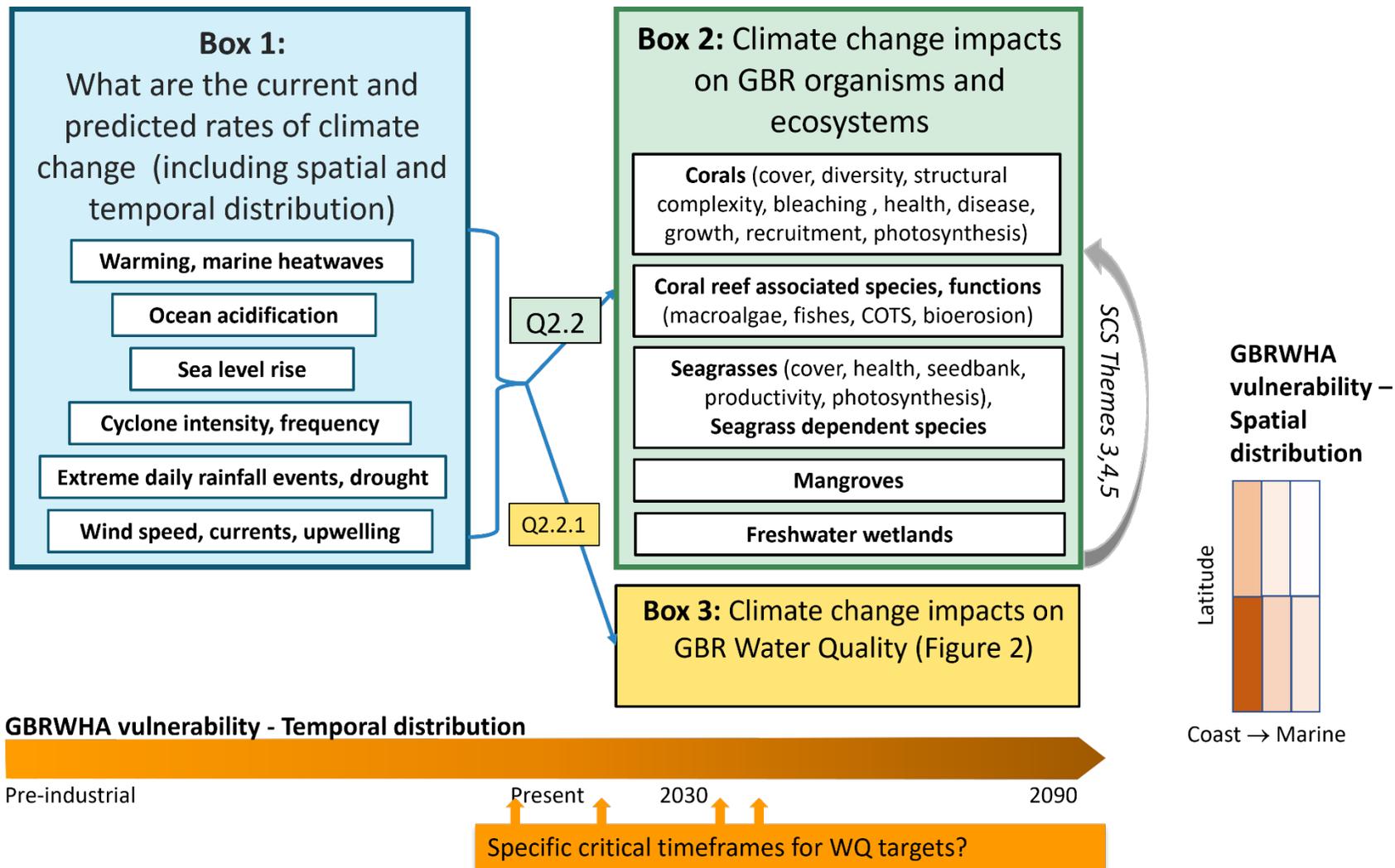


Figure 1. Conceptual diagram for Question 2.2: What are the current and predicted impacts of climate change on Great Barrier Reef ecosystems (including spatial and temporal distribution of impacts)? Darker shades in the spatial and temporal distribution grids represent greater pressure, and potential critical time frames for water quality targets are symbolised below in exemplary way.

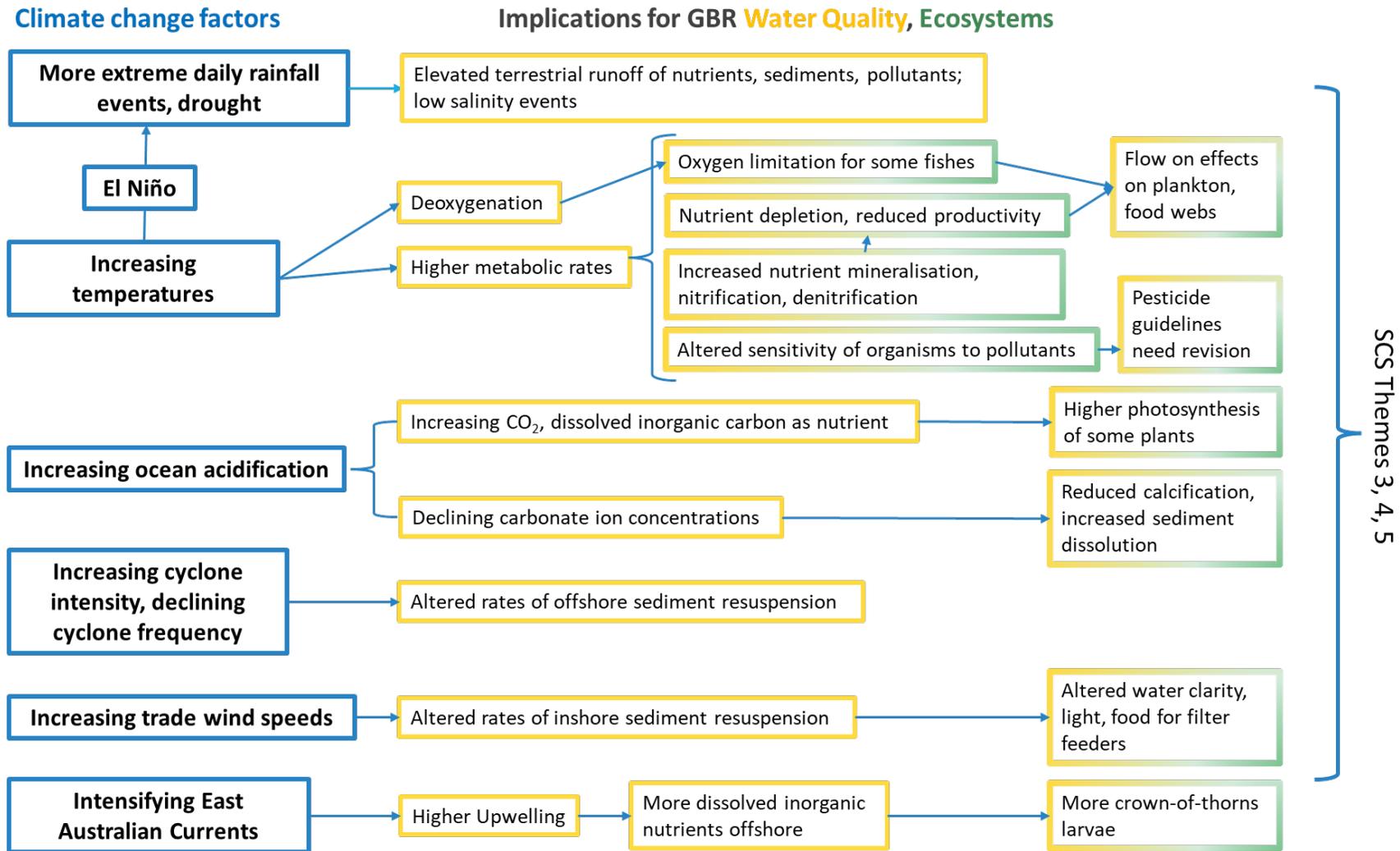


Figure 2. Conceptual diagram for Question 2.2.1: How is climate change currently influencing water quality in coastal and marine areas of the Great Barrier Reef, and how is this predicted to change over time?

1.3 Links to other questions

This synthesis of evidence addresses one of 30 questions that are being addressed as part of the 2022 SCS. The questions are organised into eight themes: values and threats, sediments and particulate nutrients, dissolved nutrients, pesticides, other pollutants, human dimensions, and future directions, that cover topics ranging from ecological processes, delivery and source, through to management options. As a result, many questions are closely linked, and the evidence presented may be directly relevant to parts of other questions. The relevant linkages for this question are identified in the text where applicable. The broad nature of this question links it to many other questions within the SCS but the primary question linkages are listed below.

Links to other related questions	<p>Q1.2/1.3/2.1 What is the extent and condition of Great Barrier Reef ecosystems and what are the primary threats to their health?</p> <p>Q2.3 What evidence is there for changes in land-based runoff from predevelopment estimates in the Great Barrier Reef?</p> <p>Q2.4 How do water quality and climate change interact to influence the health and resilience of Great Barrier Reef ecosystems?</p> <p>Q3.1 What are the spatial and temporal distributions of terrigenous sediments and associated indicators within the Great Barrier Reef?</p> <p>Q3.2 What are the measured impacts of increased sediment and particulate nutrient loads on Great Barrier Reef ecosystems, what are the mechanism(s) for those impacts and where is there evidence of this occurring in the Great Barrier Reef?</p> <p>Q4.1 What is the spatial and temporal distribution of nutrients and associated indicators within the Great Barrier Reef?</p> <p>Q4.2 What are the measured impacts of nutrients on Great Barrier Reef ecosystems, what are the mechanism(s) for those impacts and where is there evidence of this occurring in the Great Barrier Reef?</p> <p>Q5.1 What is the spatial and temporal distribution of pesticides across Great Barrier Reef ecosystems, what are the (potential or observed) ecological impacts in these ecosystems and what evidence is there for pesticide risk?</p>
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2. Method

A formal Rapid Review approach was used for the 2022 Scientific Consensus Statement (SCS) synthesis of evidence. Rapid reviews are a systematic review with a simplification or omission of some steps to accommodate the time and resources available⁶. For the SCS, this applies to the search effort, quality appraisal of evidence and the amount of data extracted. The process has well-defined steps enabling fit-for-purpose evidence to be searched, retrieved, assessed and synthesised into final products to inform policy. For this question, an Evidence Summary method was used.

2.1 Primary question elements and description

The primary question is: ***What are the current and predicted impacts of climate change on Great Barrier Reef ecosystems (including spatial and temporal distribution of impacts)?***

The secondary question is: ***How is climate change currently influencing water quality in coastal and marine areas of the Great Barrier Reef, and how is this predicted to change over time?***

S/PICO frameworks (Subject/Population, Exposure/Intervention, Comparator, Outcome) can be used to break down the different elements of a question and help to define and refine the search process. The S/PICO structure is the most commonly used structure in formal evidence synthesis methods⁷ but other variations are also available.

- **Subject/Population:** Who or what is being studied or what is the problem?
- **Intervention/exposure:** Proposed management regime, policy, action or the environmental variable to which the subject populations are exposed.
- **Comparator:** What is the intervention/exposure compared to (e.g., other interventions, no intervention, etc.)? This could also include a time comparator as in ‘before or after’ treatment or exposure. If no comparison was applicable, this component did not need to be addressed.
- **Outcome:** What are the outcomes relevant to the question resulting from the intervention or exposure?

Table 1. Description of question elements for Questions 2.2 and 2.2.1.

Question S/PICO elements	Question term	Description
Subject/ Population	GBR ecosystems Water quality in coastal and marine areas of the GBR	GBR , Great Barrier Reef World Heritage Area, coral reefs, seagrass meadows, <i>Halimeda</i> mounds, soft bottom intertidal, physical hydrodynamics, mangroves, pelagic, fish, freshwater wetlands will be included if searches result in sufficient information. Water quality: Australian & New Zealand Guidelines for Fresh & Marine Water Quality definition: the physical, chemical and biological characteristics of water and the measure of its condition relative to the requirements for one or more biotic species. Components may include volumes, variability in river discharges of nutrients and sediments, concentrations in flood plumes, regionally resolved annual mean water clarity, nutrient concentrations.

⁶ Cook CN, Nichols SJ, Webb JA, Fuller RA, Richards RM (2017) Simplifying the selection of evidence synthesis methods to inform environmental decisions: A guide for decision makers and scientists. *Biological Conservation* 213: 135-145 <https://doi.org/10.1016/j.biocon.2017.07.004>

⁷ <https://libguides.jcu.edu.au/systematic-review/define> and <https://guides.library.cornell.edu/evidence-synthesis/research-question>

Question S/PICO elements	Question term	Description
		Coastal and marine areas of the GBR: enclosed and open coastal and inshore Natural Resource Management regions (NRMs), midshelf, offshore NRMs.
Intervention, exposure & qualifiers	Climate change	Climate change: both pulse events (frequency, magnitude, direction of extreme events), and increasing chronic pressure in the factors.
Comparator	Currently, and how is this predicted to change over time? Including spatial and temporal distribution of impacts	Currently: as observed in the last few decades or modelled as present-day baseline. Predicted change over time: within the coming decades to end of century. Spatial and temporal distribution of impacts: Spatial distribution: regionally varying (inshore to offshore, north to south, along exposure gradients). Temporal distribution: specific information on expected timeframes: e.g., “bleaching will occur annually by year xx in region yy”. When is the critical time period in next few decades, how much time is ‘won’ in spatial refugia, what are rates of adaptation, what are knowledge gaps?
Outcome & outcome qualifiers	Impact	Impact: alter, affect, change, influence (via intensity/concentration, and/or frequency) Coral bleaching, mortality, calcification, health, disease Seagrass growth, cover, health Freshwater wetland and other ecosystem health outcomes Floods: Possible consequence: water quality change through more runoff, freshwater lenses (unfavourable for marine flora and fauna) Tropical cyclones: frequency, intensity (consequence: physical destruction of reefs, selection towards robust species) Connectivity Timeframes of climate impacts for the GBR, expected increase frequency of disturbance events etc., to align with the urgency for reaching the water quality targets.

Table 2. Definitions for terms used in Questions 2.2 and 2.2.1.

Definitions	
GBR ecosystems	<p>Great Barrier Reef World Heritage Area (including ports).</p> <p>Marine ecosystems: Coral reefs, seagrass, deepwater seagrass, pelagic, benthic, plankton communities</p> <p>Coastal ecosystems: Estuaries mangroves, freshwater wetlands, floodplains, freshwater (freshwater wetlands – see specific wetland types below, floodplain wetlands).</p> <p>Map source: Extracted from the 2017 Scientific Consensus Statement</p>
Coastal and marine areas	<p>Waterbodies will be used to define geographic extent i.e., Coastal = enclosed coastal and open coastal, Marine = midshelf and offshore.</p>
Climate change	<p>Climate change refers to long-term shifts in temperatures and weather patterns, mostly driven by human activities (i.e., burning fossil fuels like coal, oil and gas) since the 1800s (UN). Climate change-related potential threats in the context of the SCS include increasing temperature, intensity and frequency of heatwaves, ocean acidification, altered extreme rainfall events (drought / floods), rising sea levels, and frequency and strength of tropical cyclones.</p>
Water quality	<p>Australian & New Zealand Guidelines for Fresh & Marine Water Quality definition (https://www.waterquality.gov.au/anz-guidelines/resources/glossary): the physical, chemical and biological characteristics of water and the measure of its condition relative to the requirements for one or more biotic species and/or to any human need or purpose.</p>

2.2 Search and eligibility

The Method includes a systematic literature search with well-defined inclusion and exclusion criteria.

Identifying eligible literature for use in the synthesis was a two-step process:

1. Results from the literature searches were screened against strict inclusion and exclusion criteria at the title and abstract review stage (initial screening). Literature that passed this initial screening step were then read in full to determine their eligibility for use in the synthesis of evidence.
2. Information was extracted from each of the eligible papers using a data extraction spreadsheet template. This included information that would enable the relevance (including spatial and temporal), consistency, quantity, and diversity of the studies to be assessed.

a) Search locations

Searches were performed in:

- Web of Science, searching 'Topic' fields
- Scopus, searching Title/Abstract/Keyword fields

b) Search terms

Table 3 shows a list of the search terms used to conduct the online searches.

Table 3. Search terms for S/PICO elements of Questions 2.2 and 2.2.1.

Question element	Search terms
Subject/ Population	2.2: "Great Barrier Reef", GBR 2.2.1: Queensland, "North-Eastern Australia", "Great Barrier Reef"
Exposure or Intervention	2.2: "climate change", "sea surface temperature", "seawater temperature", "water temperature", SST, heat*, warming, cyclone, "acidification", "sea level rise", storm 2.2.1: "climate change" "water quality", sediment, nutrient, pesticide, rainfall, drought, ENSO, cyclone, "ocean current", productivity, acidification
Comparator	n/a
Outcome	2.2 coral*, seagrass*, mangrove*, macroalga*, fish*, "freshwater wetland", population, abundance, diversity, cover, complexity, productivity, photosynthesis, mortality, bleaching, health, disease, growth, recruitment, bioerosion, "crown of thorns", "crown-of-thorns" 2.2.1 drought, flood, upwelling, connectivity, wind, rainfall, "water quality", nutrient*, chlorophyll, turbidity, salinity, irradiance, "water clarity", plume, freshwater, runoff

c) Search strings

Table 4 shows a list of the search strings used to conduct the online searches.

Table 4. Search strings used for electronic searches for Questions 2.2 and 2.2.1.

Search strings
<p>2.2 and 2.2.1 (Search 1)</p> <p>((“Great Barrier Reef” OR GBR) AND (“climate change” OR “sea surface temperature” OR “seawater temperature” OR “water temperature” OR SST OR heat* OR warming OR cyclone OR “acidification” OR “sea level rise” OR storm))</p>
<p>2.2.1 (Search 2)</p> <p>(“Climate change”)</p> <p>AND (Queensland OR “North-Eastern Australia” or “Great Barrier Reef”)</p> <p>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)</p>

d) Inclusion and exclusion criteria

Table 5. Inclusion and exclusion criteria for Questions 2.2 and 2.2.1 applied to the search returns.

Question element	Inclusion	Exclusion
Subject/Population	<p>2.2: Within GBR</p> <p>2.2.1: Enclosed and open coastal and inshore NRMs, midshelf, offshore NRMs within the GBR</p>	<ul style="list-style-type: none"> • Not specifically addressing the question • Australia but not GBR, not GBR • Management or risk assessment study
Exposure or Intervention		<ul style="list-style-type: none"> • Insufficient spatial relevance • Insufficient temporal relevance
Comparator (if relevant)	n/a	n/a
Outcome	n/a	n/a
Language	English	Non-English studies
Study type	<ul style="list-style-type: none"> • Observational • Experimental • Modelled • Review/Meta-analysis 	<ul style="list-style-type: none"> • Studies published before 1990 or after October 2022 • Purely Theoretical/Method study

3. Search Results

A total of 382 studies were identified through online searches for peer reviewed and published literature following the initial screening. A further 73 studies were identified manually through personal collection (missed by the literature search mostly because they did not mention the GBR) and through expert contact during the review process, which represented 16% of the total evidence. Following the secondary screening, 317 studies were eligible for inclusion in the synthesis of evidence (Table 6) (Figure 3). No studies were unobtainable.

Table 6. Search results table, separated by A) Academic databases, B) Search engines and C) Manual searches. The search results for A and B are provided in the format X (Z) of Y, where: X (number of relevant evidence items retained); Y (total number of search returns or hits); and Z (number of relevant returns that had already been found in previous searches).

Date (d/m/y)	Search strings	Sources	
A) Academic databases		Scopus	Web of Science
12/10/2022	((“Great Barrier Reef” OR GBR) AND (“climate change” OR “sea surface temperature” OR “seawater temperature” OR “water temperature” OR SST OR heat* OR warming OR cyclone OR “acidification” OR “sea level rise” OR storm))	317 of 1,202	312 (287) of 1,341
26/01/2023	(“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)	25 of 124	33 (15) of 1,083
B) Search engines (e.g., Google Scholar)			
	n/a		
Total items online searches		382 (84 %)	
C) Manual search			
Date	Source	Number of items added	
	Author personal collection	73	
Total items manual searches		73 (16 %)	

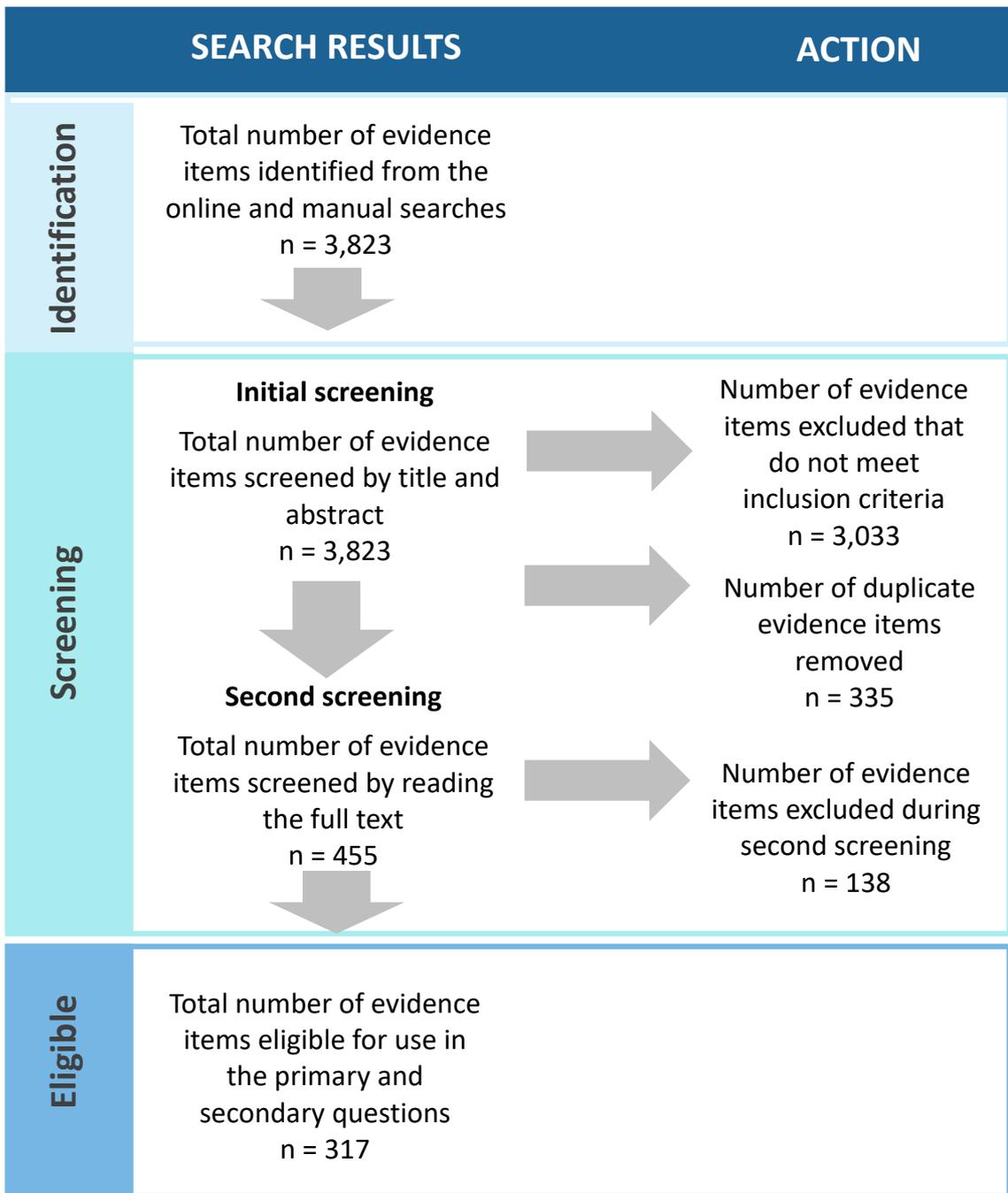


Figure 3. Flow chart of results of screening and assessing all search results for Question 2.2.

4. Key Findings

4.1 Narrative synthesis

4.1.0 Summary of study characteristics

The literature searches recovered 2,424 publications through Web of Science, and 1,326 publications through Scopus. Of these, 3,033 publications were excluded in the initial screening along with 335 duplicates, and an additional 138 publications were excluded in the secondary screening for not meeting the eligibility criteria (Table 5). Seventy-three publications were added manually, especially on the topics:

- Rates of climate change in the GBR (11 manual additions)
- Question 2.2 especially for seagrasses, wetlands and mangroves responding to climate change, which often did not mention the term ‘Great Barrier Reef’ in the title, abstract or key words (49 manual additions)
- Effects of climate change on water quality (13 manual additions).

In total, 317 publications were considered to assess evidence for the various agents of climate change, and their impacts on GBR ecosystems, organisms, ecological functions and water quality (Table 7).

Studies were classified as experimental, observational, modelled, or reviews (Table 7). Most field studies were observational in nature, often investigating unimpacted sites in comparable settings as control sites, but there were also a limited number of field experiments. Laboratory experiments were retained if they included some elements of spatial or temporal relevance for the GBR. There are numerous additional publications on the effects of climate change on tropical marine ecosystems (e.g., experiments that did not score high on spatial or temporal relevance, global reviews or meta-analyses that did not mention ‘Great Barrier Reef’). Many of these would have included additional relevant information for GBR species or ecological processes. However, the amount of studies would have been unmanageable for such a broad Evidence Summary, so they were filtered out by adding the search term (AND ‘Great Barrier Reef’ OR GBR).

This Evidence Summary builds upon earlier key studies. A study that is particularly relevant here is the landmark **GBRMPA ‘Climate Change Vulnerability Assessment’** (Johnson & Marshall, 2007), a peer reviewed, 24-chapter book on the same topic, published in 2007. The 800-page book summarised literature from around the world, since GBR-specific studies and laboratory experiments were still only starting to emerge. The literature search yielded only 43 climate change GBR-specific studies that were published before or in 2007, whereas the number of studies post-2007 retrieved by the search was 277 (Figure 4). This shows significant scientific progress within the GBR since the Vulnerability Assessment was completed, but also reflected the strict and structured exclusion criteria which narrowed down the literature considerably. GBR-specific summaries of changes in the physical and chemical conditions of the GBR are also provided by the GBRMPA Outlook Report (2019) (GBRMPA, 2019).

Furthermore, Chapter 1 of the **2017 Scientific Consensus Statement** summarised the main points of observed and predicted climate change and observed severe weather events prior to 2017 (Schaffelke et al., 2017). Since then, the GBR has been subject to further mass coral bleaching events and some severe regional flooding but little cyclone activity. Overall, the findings of the Climate Chapter in the 2017 SCS (Schaffelke et al., 2017) are still largely current. The 2017 SCS did not include in-depth coverage of questions equivalent to the impacts on climate change on GBR water quality, organisms and ecosystems (Q2.2 and Q2.2.1, Sections 4.1.1.2 and 4.1.1.3).

Therefore, this Evidence Summary jointly assessed the retrieved 207 studies before and 113 studies after 2017, rather than splitting the assessment by the 2017 date. Overall, there seemed no substantial change in broad research directions and findings around that year, instead the new studies provided additional and confirmatory evidence (Tables 10 to 13).

Table 7. Number of studies classified as experimental, observational, modelled, or reviews/meta-analyses. Studies with multiple study types or relevant to both Questions 2.2 and 2.2.1 were tallied more than once.

Study Type	Q2.2 Climate change in GBR	Q2.2 Effects of climate change on GBR ecosystems	Q2.2.1 Effects of climate change on GBR water quality
Observational	10	119	14
Experimental	0	123	3
Modelled	13	65	10
Review/Meta-analysis	6	17	11
Total	21	273	31

This Evidence Summary is presented in three sections, following the structure of the Conceptual Diagrams (Figure 1 and Figure 2):

- Section 4.1.1.1 provides information on the currently observed rates of climate change, and best model estimates about near-future climate change in the GBR. Although this specific question was not an explicit component of the SCS Q2.2 scope, this information provides the necessary context for the consecutive sections. The findings from this synthesis are summarised in Tables 8 and 9.
- Section 4.1.1.2 summarises the existing evidence about how climate change affects GBR organisms and ecosystems, as summarised in Tables 10 to 13.
- Section 4.1.1.3 summarises the existing evidence about how climate change has and will affect GBR water quality (Figure 2). The characteristics of these studies are summarised in Table 14.

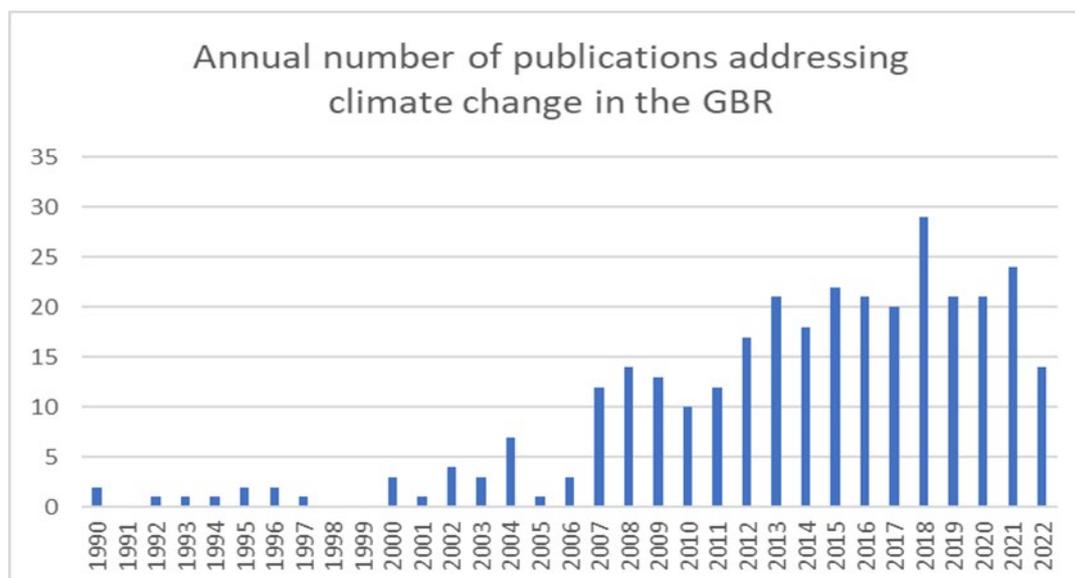


Figure 4. Total number of publications (post-secondary screening) returned by the searches for Questions 2.2 and 2.2.1 (up to October 2022 when the search was conducted, hence the lower bar for 2022).

4.1.1 Summary of evidence to 2022

4.1.1.1 Summary of evidence to 2022 for Q2.2: What are the current and predicted rates of climate change (including spatial and temporal distribution) (Figure 1. Conceptual diagram, Box 1)

This section summarises publications that addressed observations and predictions of climate change for the GBR region and subregions. Since most climate models and observational and predictive climate change data were not GBR specific and hence were not retrieved by the literature search, relevant additional studies were added manually to the database (Table 8).

Table 8. Studies documenting climate change in the GBR incorporated in this assessment. Studies marked with asterisks () are larger than the GBR scope (all of Australia, broader Pacific, or global) but contain GBR relevant data.*

Impact type Response type (water quality variable)	Number of studies	References
Region-specific climate forecasting tools	3	Dowdy, 2015; McInnes, 2015b; Moise, 2015
Temperature (air, sea surface)	8	Dowdy, 2015; Hughes, 2003*; IPCC, 2021*; Lough, 2000; MacKellar et al., 2013; McInnes, 2015b; 2015c; Moise, 2015
Rainfall (rainfall variability, changes in precipitation distribution, frequency of flood events)	9	Dowdy, 2015; IPCC, 2021*; Lough et al., 2015; Lough, 2000; McInnes, 2015b; Moise, 2015; Mullen, 2009; Rodriguez-Ramirez et al., 2014; Ward et al., 2016
Drought frequency and extent	5	Dowdy, 2015; IPCC, 2021*; Kirono et al., 2011; McInnes, 2015b; Moise, 2015;
ENSO related climate variability and interactions with climate change (increased sea surface temperatures (SST), altered rainfall, river flow, heat budget, storm variability, surface winds, wave height, currents)	3	Lough, 1994; Karnauskas, 2020; Redondo-Rodriguez et al., 2012
Ocean acidification (seawater pH, aragonite saturation state, pCO ₂ , dissolved inorganic carbon)	8	Doney et al., 2009*; 2020*; Fabricius et al., 2020; IPCC, 2021*; Lenton et al., 2016*; Mongin et al., 2016; Ricke et al., 2013*; Wu et al., 2018
Cyclones (intensity, frequency, wave climate, cyclones damage prediction)	8	Callaghan & Power, 2011; Callaghan et al., 2020*; Dixon et al., 2022; Holmes, 2020; IPCC, 2021*; Knutson et al., 2020*; McInnes, 2015c; Parker et al., 2018

Most data of the currently predicted rates of climate change presented here (Table 9) originate from the Climate Change in Australia Tool (CCIA) by CSIRO and the CSIRO and Bureau of Meteorology <https://www.climatechangeinaustralia.gov.au/en/> (2015). The region-specific climate forecasting tools (Dowdy, 2015; McInnes, 2015b; Moise, 2015) published in 2015 are still considered the most comprehensive and relevant regionally resolved climate models available to date. These models have been continuously updated as represented on the website, reviewed and incorporate a large body of data and literature, and are therefore found to be the most up to date predictions for the GBR. The CCIA predictions are presented as ranges of change compared to the average of a reference period, 1986–2005. They are presented for two future time periods: the ‘near future years’ 2020–2039 (referred to as 2030) and ‘late in the century’ 2080–2099 (referred to as 2090). The models present separate predictions for three subregions that encompass the GBR, namely:

- The “Wet Tropics” subregion includes the Cape York, Wet Tropics and Mackay Whitsunday NRM regions; <https://www.climatechangeinaustralia.gov.au/en/projections-tools/regional-climate-change-explorer/sub-clusters/?current=WTC&tooltip=true&popup=true> (accessed 20 February 2023), (McInnes, 2015b);
- The “Monsoonal North East” subregion includes the Burdekin NRM; <https://www.climatechangeinaustralia.gov.au/en/projections-tools/regional-climate-change-explorer/sub-clusters/?current=MNEC&tooltip=true&popup=true> (accessed 20 February 2023), (Moise, 2015);
- The “East Coast North” subregion includes the Fitzroy and Burnett Mary NRM regions; <https://www.climatechangeinaustralia.gov.au/en/projections-tools/regional-climate-change-explorer/sub-clusters/?current=ECNC&tooltip=true&popup=true> (accessed 20 February 2023), (Dowdy, 2015).

The following key summary climate projections by the CCIA apply to all three subregions:

- Average temperatures will continue to increase in all seasons (with very high confidence).
- More hot days and warm spells are projected (with very high confidence).
- Changes to rainfall are possible but unclear.
- Increased intensity of extreme rainfall events is projected (with high confidence).
- Mean sea level will continue to rise, and height of extreme sea level events will also increase (with very high confidence).

For the Wet Tropics and Monsoonal North East subregions, additional projections by the CCIA are:

- Fewer but more intense tropical cyclones are projected (with medium confidence).
- On an annual and decadal basis, natural variability in the climate system can act to either mask or enhance any long-term human induced trend, particularly in the next 20 years and for rainfall.

For the “East Coast North” subregion, an additional projection by the CCIA is a harsher fire-weather climate in the future (with high confidence).

Some of the main rates of subregion specific observed and predicted rates of change are summarised in Table 9 and in the following paragraphs, for the five main groups of climate change agents, namely temperature, ocean acidification, sea level rise, rainfall, and winds.

Table 9. Observed and predicted changes in climate and extreme weather events for the three subregions for the GBR. WT = Wet Tropics, MNE = Monsoonal North East, ECN = East Coast North. 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).

	Subregions	Observed (time range in brackets)	Predicted for 2030 (compared to reference years 1986-2005)	Predicted for 2090 (RCP4.5) (compared to reference years 1986-2005)	Predicted for 2090 (RCP8.5) (compared to reference years 1986-2005)	References
Surface air temperature (change in °C)	WT**	+1.1 (1910 to 2013)	+0.3 to 1.1	+1.0 to 2.0	+2.3 to 3.9	McInnes, 2015b
	MNE**	+1.0 (1910 to 2013)	+0.5 to 1.3	+1.3 to 2.7	+2.8 to 5.1	Moise, 2015
	ECN	+1.0 (1910 to 2013)	+0.4 to 1.3*	+1.2 to 2.6*	+2.5 to 4.7*	Dowdy, 2015
Sea surface temperature (change in °C)	WT: Cairns, Mackay	+1.0°C (+0.8°C in 1910 to 2013; +0.1 to 0.2°C in 2013-2022)	+0.3 to 1.0*	+1.0 to 1.8*	+2.2 to 3.5*	McInnes, 2015b
	MNE (Townsville)		+0.4 to 1.0*	+1.1 to 1.8*	+2.3 to 3.4*	Moise, 2015
	ECN (Gladstone)		+0.3 to 1.0*	+1.1 to 1.9*	+ 2.1 to 3.5*	Dowdy, 2015
Temperature extremes (number of days)	WT ** MNE** ECN**	Average temperatures will continue to increase in all seasons (very high confidence), currently by 0.1 to 0.2°C per decade. A substantial increase in the temperature on the hottest days, the frequency of hot days and the duration of warm spells is projected (with very high confidence).				Dowdy, 2015; McInnes, 2015b; Moise, 2015
Marine heatwaves (days >99 th percentile of local sea surface temperatures observed in 1982 to 2016)	Global (IPCC, 2021, Box 9.2 maps show GBR rates are approximately average to global observations)			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)	WT (Cairns, Mackay) MNE (Townsville) ECN (Gladstone)		-0.06 to -0.08*	-0.14 to -0.15*	-0.31 to -0.32*	Dowdy, 2015; McInnes, 2015b; Moise, 2015

	Subregions	Observed (time range in brackets)	Predicted for 2030 (compared to reference years 1986-2005)	Predicted for 2090 (RCP4.5) (compared to reference years 1986-2005)	Predicted for 2090 (RCP8.5) (compared to reference years 1986-2005)	References
	GBR	-0.08 to -0.09 (1870 to 2015)				Lenton et al., 2016
	Central GBR	-0.07 (8.13 in 1960 to 8.06 in 2009)				Fabricius et al., 2020
Ocean acidification (change in aragonite saturation state, Ω_{ar})	WT (Cairns, Mackay) MNE (Townsville) ECN (Gladstone)		-0.29 to -0.45*	-0.73 to -0.78*	-1.49 to -1.61*	Dowdy, 2015; McInnes, 2015b; Moise, 2015
	Central GBR	-0.33 (3.92 in 1960 to 3.59 in 2009)				Fabricius et al., 2020
	GBR	-0.55 to -0.6 (1870 to 2015)				Lenton et al., 2016
			Some reefs will be exposed to aragonite saturation state <3.5.	Most reefs will be exposed to aragonite saturation state <3.2.	All open-water reefs will be exposed to aragonite saturation state <3.0.	McInnes, 2015b; Ricke et al., 2013
Sea level rise (m)	WT (Cairns, Mackay)	+1.4 mm/yr (1966 to 2009) (+3.1 mm/yr in 1993 to 2009, after corrections)	+0.09 to 0.18*	+0.31 to 0.64*	+0.44 to 0.87*	McInnes, 2015b
	MNE**		+0.06 to 0.17	+0.28 to 0.64	+0.38 to 0.85	Moise, 2015
	ECN (Gladstone)		+0.08 to 0.18*	+0.30 to 0.64*	+0.44 to 0.86*	Dowdy, 2015
Mean rainfall (%)	WT**	No significant long-term trend	-12 to +6*	-12 to +8*	-26 to +21*	McInnes, 2015b
	MNE**	Linear trend suggests	-11 to +8*	-15 to +7*	-24 to +24*	Moise, 2015

	Subregions	Observed (time range in brackets)	Predicted for 2030 (compared to reference years 1986-2005)	Predicted for 2090 (RCP4.5) (compared to reference years 1986-2005)	Predicted for 2090 (RCP8.5) (compared to reference years 1986-2005)	References
		slight rise of +10 mm/decade (1900 to 2012)				
	ECN	No significant long-term trend	-17 to +12*	-21 to +7*	-32 to +17*	Dowdy, 2015
Intense rainfall	WT** MNE** ECN**	NA	Increased intensity of extreme daily rainfall events is projected, with high confidence. However, the magnitude of the increases cannot be confidently projected.			Dowdy, 2015; McInnes, 2015b; Moise, 2015
Drought	WT**	NA	Drought will continue to be a feature of the regional climate variability, but projected changes are uncertain.			McInnes, 2015b
	MNE**	NA	Drought will continue to be a feature of the regional climate variability, but there is low confidence in projections of how the frequency and duration of extreme drought may change.			Moise, 2015
	ECN**	NA	Time spent in drought is projected, with medium confidence, to increase over the course of the century. An increase in the frequency and duration of extreme drought is projected with low confidence.			Dowdy, 2015
Tropical cyclones	WT** MNE** ECN**	NA	Less frequent cyclones, but the proportion of the most intense storms is projected to increase (medium confidence)			Dowdy, 2015; McInnes, 2015b; Moise, 2015
Changes in seasonal surface wind speed (% ranges are max and min across the four seasons)	WT**	NA	-3.7 to +10.2*	-2.8 to +12.9*	-5.2 to +11.8*	McInnes, 2015b
	MNE**	NA	-4.2 to +3.3*	-5 to +4.9*	-7.6 to +8.4*	Moise, 2015
	ECN	NA	-3.8 to +4.4*	-4.8 to +4.4*	-4.5 to +9.9*	Dowdy, 2015

* Predictions data sourced from appendix of report (to ensure predictions are from sites within GBR)

**Data/prediction for entire region, which includes locations outside of the GBR (subregion/site data not available)

Temperature

Annual mean surface air temperature has increased by 1.1°C between 1910 and 2013 in the Wet Tropics subregion (McInnes, 2015b), and by 1.0°C in the Monsoonal North East and the East Coast North (Dowdy, 2015; Moise, 2015). Further warming will be a direct response to the realised increase in global greenhouse gases and are extracted here from the CCIA for the Representative Concentration Pathways (RCP) 4.5 and 8.5. For air temperature, temperatures in the 2030 period compared to the 1986-2005 period are predicted to be again substantially higher, from 0.3 to 1.1°C (10th to 90th percentile) for the Wet Tropics, 0.5 to 1.3°C for the Monsoonal North East, and 0.4 to 1.3°C for the East Coast North, with only minor differences between the emission scenarios (Dowdy, 2015; McInnes, 2015b; Moise, 2015). The same studies predict for RCP4.5 further air temperature increases for 2090 compared to 1986-2005 in the Wet Tropics as 1.0 to 2.0°C (2.3 to 3.9°C for RCP8.5), in the Monsoonal North East 1.3 to 2.7°C (2.8 to 5.1°C for RCP8.5), and in the East Coast North 1.2 to 2.6°C (2.5 to 4.7°C for RCP8.5).

The occurrence of **surface air temperature extremes** is also predicted to increase in all regions, including increases in the temperature reached on the hottest days, the frequency of hot days and the duration of warmer periods (Dowdy, 2015; McInnes, 2015b; Moise, 2015). For example, Cairns currently experiences three days per year with temperatures above 35°C, however under RCP4.5 this is predicted to increase to 11 days in 2090 (McInnes, 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). There is very high confidence that SST around Australia will continue to rise, with the magnitude of the warming dependent on the RCP scenario. Note the large, predicted temperature rise between 1990 and 2030: Near-coastal SSTs around Australia currently increase by 0.1 to 0.2°C per decade, and will have substantially risen again by 2030 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, 2015; McInnes, 2015b; Moise, 2015), and related websites <https://www.climatechangeinaustralia.gov.au/en/projections-tools/coastal-marine-projections/>).

Marine heatwaves (defined as days exceeding the 99th percentile in sea surface temperature from 1982 to 2016) 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) more frequently under the business-as-usual pathway SSP5-8.5. Marine heatwaves in the GBR are often associated with doldrum conditions during times of surface air temperature extremes, or the onshore transport of heated surface waters from the Coral Sea. Marine heatwaves are of specific concern for the GBR as these events lead to coral bleaching and mortality (Section 4.1.1.2). For the GBR, the marine heatwaves in 2016 and 2017, 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 and 2022 which also led to a widespread mass bleaching in the GBR.

Ocean acidification

Like global warming and climate change, ocean acidification is caused by the additional atmospheric CO₂ emitted from human activities. To re-establish equilibrium, the additional atmospheric CO₂ is taken up into the surface seawater, altering the seawater carbon chemistry. About 30% of the anthropogenic CO₂ emitted into the atmosphere over the past 200 years has been absorbed by the global oceans. Rates of ocean acidification in most Australian regions are at a rate that is commensurate with the rate of atmospheric increase in CO₂ and similar to rates observed in open oceans (Lenton et al., 2016). 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 CO₂ dissolved in seawater have increased by an estimated 6% in the decade 2009 and 2019 alone, and by ~28% since atmospheric CO₂ measurements started in 1958 (Fabricius et al., 2020). 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). 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, 2015c).

Annual mean aragonite saturation state (Ω_{ar}) in the GBR is likely to have averaged over 4.0 in pre-industrial times (Lenton et al., 2016). A value greater than 3.0 is a threshold for reef development (see Section 4.1.1.2), but steep changes in reef biota are observed as Ω_{ar} drops to below 3.5 (Smith et al., 2020). Between 1960 and 2009, the GBR aragonite saturation state 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, 2015; McInnes, 2015b; 2015c; Moise, 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 CO₂ such as salinity and alkalinity will not change much).

Sea level rise

Sea level rise is caused primarily by the melting of polar ice sheets and glaciers, and the thermal expansion due to 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 (ENSO) 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 from 0.06 to 0.18 m above the 1986–2005 level, with only minor differences between emission scenarios. Later projections are sensitive to concentration pathways. By 2090, the RCP4.5 scenario is associated with a projected rise of 0.28 to 0.65 m along the GBR, and for RCP8.5, a rise of 0.38 to 0.87 m. Sea level will continue rising beyond 2100 for many centuries proportionally to the degree of warming. Extreme **short-term inundations** above and beyond mean sea level rise are caused by combinations of extreme astronomical tides, storm surges and wind-waves, and affect coastal GBR ecosystems depending on latitude (<https://www.climatechangeinaustralia.gov.au/en/projections-tools/coastal-marine-projections/>).

Presently, one-in-a-hundred-year inundation heights in the GBR are 2 to 3 m north of the 20 °S latitude, but as much as 3.5 to 4.0 m south of 20 °S latitude (Figure 8.2.1 in McInnes, 2015c).

Rainfall

Inter-annual variability in rainfall and river flow in coastal Queensland is strongly influenced by 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, whereas El Niño conditions are associated with higher temperatures and drought in GBR catchments, than during neutral ENSO times. In a 30-year study period (1958–1987), the ‘La Niña’ phase was associated with greatly increased freshwater inputs, reduced surface radiation (and thus light levels) and enhanced tropical cyclone activity, while El Niño events had less effect on climate of the GBR (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 (Rodríguez-Ramírez 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).

For annual mean rainfall, there has been no significant trends in the Wet Tropics nor the East Coast North throughout the 20th century. In contrast, the Monsoonal North East experienced an overall slight increase in rainfall during the 20th century, including prolonged periods of drying as well as above average rainfall. Predictions of changes in mean rainfall for the 21st century are highly uncertain for all GBR subregions, with both dryer and wetter conditions a possibility (McInnes, 2015b). For example, under RCP8.5 rainfall across the GBR region is predicted to change by 2090 from anywhere between -32% to +24% (Dowdy, 2015; McInnes, 2015b; Moise, 2015).

Intensity of extreme rainfall events: Paleoclimate records provide evidence for an increased frequency in extreme rainfall and river flows into the GBR (Lough et al., 2015). There is high confidence of increasing intensity of extreme rainfall events projected for all GBR subregions. However, the magnitude of future increases cannot be confidently projected. For the East Coast North under RCP8.5, a greater time in drought is projected with medium confidence by late in the 21st century, and greater frequency and duration of extreme drought is projected with low confidence (Dowdy, 2015). 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, consistently with a total rainfall decrease, indicating changes in the position of the precipitation distribution rather than its shape.

Predictions of rainfall and extreme rainfall events leading to terrestrial runoff of nutrients and sediments into the GBR are especially relevant for SCS Q2.2.1 due to its implications for GBR water quality. Drought-breaking floods tend to yield particularly high nutrient and sediment discharges into the GBR, as there is little vegetation to hold back the soil during floods, and are hence particularly relevant climate change effects on the GBR water quality (Section 4.1.1.3).

Wind

Mean wind speeds averaged for each season along the GBR are similar for 2030 compared to values observed in the reference period. Under RCP8.5, median wind speed is predicted to increase slightly by 4 to 6% in all three GBR regions in spring, and by 2 to 4% between latitude 10°S and 20°S in winter (McInnes, 2015a). However, the prediction for slightly stronger trade winds has a low confidence. The models project similar summer and autumn wind speeds along the whole GBR for 2090 compared to 1986-2005. A potential strengthening in ENSO patterns can also affect inter-annual variability in wind fields and sea surface temperature, albeit to a lesser extent than the ENSO effect on rainfall (Lough, 1994).

Tropical cyclone damage to the GBR is a function of cyclone frequency, intensity, diameter, and speed of forward movement of the system, at a sub-basin scale (Dixon et al., 2022). Globally, climate change is expected to reduce the frequency, but increase the intensity and alter the behaviour of tropical cyclones (Knutson et al., 2020). For the GBR, the CClA synthesis concluded for both the Wet Tropics and the Monsoonal North East that tropical cyclones are projected to become less frequent, but the proportion of the most intense storms is projected to increase (medium confidence) (McInnes, 2015b; Moise, 2015). For the East Coast North, the CClA forecasts no changes to cyclone intensities and frequencies (Dowdy et al., 2015).

For Queensland, several studies suggest that long term trends in cyclone frequency and intensity are already observable. For example, Callaghan and Power (2011) find a statistically significant decline in severe cyclones making landfall at centennial scales along the Queensland coastline. Holmes (2020) reviewed the numbers of tropical cyclones in Queensland since 1969 and suggests the emergence of an apparent trend of increasing strength, consistent with numerical climate and weather models, and with other recent studies. A synthetic cyclone model at 600 m resolution, comparing averages of

key forcing parameters between 1950 to 1999 and 2050 to 2099, also found that average maximum wind speed will increase by about 17% (from 24 to 28 m/s), but also that cyclone arrival rate will increase by about 7% (from 2.25 to 2.41 cyclones/year), while the radius of maximum winds (the cyclone eye) will remain on average relatively unchanged 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. This is significant since a 1.5 to 2-fold wave height attenuation is a key ecosystem service provided by GBR reefs to Queensland's coastline.

Holmes (2020) proposed revisions to the Australian Standard for Wind Actions, AS/NZS 1170.2, including a 'climate change multiplier', as increasing wind speeds alone are an indicator for damage to above water infrastructure, e.g., islands, mangroves etc. on the GBR. Changes in cyclone damage below water, which depends on all factors that influence wave generation, remain largely unresolved. Dixon et al. (2022) showed that to date 20+ papers concluded that in the GBR region cyclones will become less frequent or stay the same, but climate models are typically unable to resolve all four cyclone damage predictors in direction and degree for specific reef regions around Australia. In particular, little work has been done to model how cyclone overall sizes (mean diameter of gale force winds), forward movement (translation) speed, and the track's spatial configuration relative to the reef will change in the future. They concluded that it seems still too uncertain to conclude whether the damage caused by tropical cyclones on the GBR has or will change.

[4.1.1.2 Summary of evidence to 2022 for Q2.2: What are the current and predicted impacts of climate change on GBR ecosystems \(including spatial and temporal distribution of impacts\) \(Figure 1. Conceptual diagram, Box 2\)](#)

The direct effects of climate change on GBR species or ecosystems is a field of active research (Table 10). Of the 273 publications retained after the secondary screening, the impact types most commonly assessed were temperature, coral bleaching events, heat budgets and El Niño (187 studies); ocean acidification (50 studies), storms (31 studies), rainfall variability (13), and sea level rise (7 studies) (Table 10). Multiple and cumulative climate change impacts were also included (23 studies) but are dealt with elsewhere (Question 2.4, Uthicke et al., this SCS). The study types included 119 field observations, 123 experimental, 65 model predictions and 17 reviews.

Not surprisingly, the types of responses most commonly addressed were corals and coral reefs (Table 10, 140 studies). Far fewer studies were retrieved on coral associated macro-organisms (macroalgae, fishes, crown-of-thorns starfish, and non-coral invertebrates), viruses and microbial assemblages on corals or sea anemones, as well as on sea turtles and seabirds (often only one study, typically less than five studies; Table 10). The search also yielded only seven, and nine studies, respectively, on the responses of mangroves and wetlands to climate change in the GBR. Many of the latter studies referred to Queensland or Northern Australia instead of the GBR, hence the list of publications retrieved by the search terms was incomplete. Additional search terms and manual additions of publications were used to complement the general search for these three important ecosystems. The combined results of the online and manual searches are presented in Tables 12 and 13 to synthesise the directions of change and spatially explicit effects of the different climate change agents on GBR seagrasses, mangroves and wetlands.

The response types included molecular (gene expression and physiological), ecological processes (life histories, reproduction, population dynamics, symbiotic associations, recovery rates, shifts in communities, shifts from corals to algae), and geomorphological changes (rates of reef framework erosion, carbonate sediment dissolution, persistence of seagrass and mangrove ecosystems).

The findings of this Evidence Summary are summarised in the following paragraphs. Three key elements of the question are: what are the rates and direction of change, what are critical thresholds or tipping points for specific impact and response types, and are there regional differences in responses? This information is needed to know when the predicted levels of climate

change will reach critical levels for the GBR ecosystems and taxa, including which of these critical values are already being experienced in this decade or will occur in the coming decades.

A total of 71 of the studies provided various forms of quantitative information about rates and direction of change, thresholds or tipping points for specific impact types, ecosystems, organisms or ecological processes in the GBR (Table 11). As outlined also in the paragraphs below, Table 11 shows some limited evidence about spatial variability in responses. For example, model forecasts predict greater increases in bleaching events in the southern and central compared with the northern and far northern GBRMP zones (McWhorter et al., 2022b). Little information was retrieved about the temporal variability in responses (Table 11).

Table 10. Summary of the included 273 studies, separated by primary types of climate impacts on the GBR ecosystems or species. Studies that presented results on several main impact and/or response types were listed more than once. Studies marked with asterisks are broader than Australia (e.g., Pacific, or global), but contain GBR relevant data or findings.

Impact type Response (ecosystem, species)	Number of studies	References
Temperature	187	
Heat budget	12	Bainbridge, 2017; Crabbe, 2008; Cropp et al., 2018; DeCarlo & Harrison, 2019; Heidemann & Ribbe, 2019; Karnauskas, 2020; MacKellar et al., 2013; McWhorter et al., 2022a; 2022b; Redondo-Rodriguez et al., 2012; Wolanski et al., 2017; Zhu et al., 2014
Coral reefs	12	Baird et al., 2018c; Berkelmans et al., 2004; Cropp et al., 2018; Dalton & Roff, 2013; DeCarlo & Harrison, 2019; Dietzel et al., 2021; Isern et al., 1996; Lantz et al., 2022; MacKellar et al., 2013; McGowan et al., 2022; Smith et al., 2022; Stuart-Smith et al., 2018
Coral	80	Ainsworth et al., 2016; Álvarez-Noriega et al., 2018; Anderson et al., 2017; 2018; Anthony & Kerswell, 2007; Anthony et al., 2007; 2008; Attrill & Foster, 2016; Baird & Marshall, 2002; Baird et al., 2018b; Berkelmans, 2002; Berkelmans et al., 2010; Boyett et al., 2007; Brodnicke et al., 2019; Bruno et al., 2007; Cantin & Lough, 2014; Cheung et al., 2021; Chollett et al., 2010*; Chua et al., 2013b; Cooper et al., 2008; 2011; 2015; Dalton & Carroll, 2011; Diaz-Pulido et al., 2009; D'Olivo et al., 2019; Done et al., 2010; Dove, 2004; Dove et al., 2020; Edmunds, 2005; Figueiredo et al., 2022; Fitt et al., 2009; Flores et al., 2021; Franklin et al., 2004; Haapkylä et al., 2013; Howells et al., 2013; Hughes et al., 2017; 2018; 2019; 2021; Hutchings et al., 2013; Jackson et al., 2018; 2022; Jones & Berkelmans, 2010; Jones et al., 1997; 2000; 2004; 2007; 2008; 2018; Jones, 2008; Jurriaans & Hoogenboom, 2019; Kamenos & Hennige, 2018; Kennedy et al., 2018; Lantz et al., 2017; Lesser et al., 1990; Littman et al., 2011; Lough & Barnes, 2000; Madin et al., 2018; Maynard et al., 2008; McClanahan et al., 2004; McGowan & Theobald, 2017; McMahan et al., 2019; Nielsen et al., 2020; Nolan et al., 2021; Osborne et al., 2017; Randall et al., 2020*; Razak et al., 2019; 2020; Rölfer et al., 2021; Rosic et al., 2020; Sato et al., 2009; Spalding & Brown, 2015; Tebbett et al., 2022; Thompson et al., 2022; Torda et al., 2018; Vercelloni et al., 2020; Wei et al., 2009; Wooldridge, 2009; Wu et al., 2017; Zhao et al., 2021
Coralline algae	2	Anthony et al., 2008; Diaz-Pulido et al., 2012
Coral microbial assemblages	2	Ainsworth & Hoegh-Guldberg, 2008; Bourne et al., 2008
Crown-of-thorns starfish	5	Caballes et al., 2021; Lamare et al., 2014; Lang et al., 2022; Uthicke et al., 2015; Sparks et al., 2017

Impact type Response (ecosystem, species)	Number of studies	References
Echinodermata	1	Buccheri et al., 2019
Fish	24	Bernal et al., 2020; Booth & Beretta, 2002; Gardiner et al., 2010; Johansen et al., 2014; Lönnstedt & Frisch, 2014; McCormick & Molony, 1995; McLeod et al., 2015a; 2015b; Messmer et al., 2017; Monaco et al., 2021; Munday et al., 2008a*; 2008b; 2009; Nilsson et al., 2009; Nilsson et al., 2010; Pratchett et al., 2006; 2008*; Richardson et al., 2018; Scott et al., 2017; Sikkel et al., 2019; Takahashi et al., 2012; Triki & Bshary, 2019; Triki et al., 2018; Wismer et al., 2019
Foraminifera	7	Prazeres, 2018; Prazeres & Pandolfi, 2016; Prazeres et al., 2016; Schmidt et al., 2011; 2014; Sinutok et al., 2014; Uthicke et al., 2012
Invertebrates (non-coral)	1	Przeslawski et al., 2008
Jellyfish	1	Courtney et al., 2016
Macroalgae	3	Diaz-Pulido et al., 2009; Ho et al., 2021; Rölfer et al., 2021
Mangrove	1	Duarte de Paula Costa et al., 2021
Mollusca	2	Lefevre et al., 2015; Mies, 2019
Sea anemone associated bacteria	1	Hartman et al., 2020
Sea turtle	7	Blechs Schmidt et al., 2020; Booth & Astill, 2001; Booth & Freeman, 2006; Fuentes et al., 2010b; Fuentes & Porter, 2013; Jensen et al., 2018; Staines et al., 2020
Seabird	5	Erwin & Congdon, 2007; Devney et al., 2009; Peck et al., 2004; Smithers et al., 2003; Weeks et al., 2013
Seagrass	13	Campbell et al., 2006; Carter et al., 2021; Chartrand et al., 2018; Collier et al., 2011; 2017; 2018; Collier & Waycott, 2014; Duarte de Paula Costa et al., 2021; Lee et al., 2007; McKenzie et al., 2022; Pedersen et al., 2016; Rasheed & Unsworth, 2011; Wilkinson et al., 2017
Sediment	1	Trnovsky et al., 2016
Sponge	12	Abdul Wahab et al., 2014; Achlatis et al., 2017; Bennett et al., 2017; Fang et al., 2013; 2018; Laffy et al., 2019; Mary et al., 2018; Massaro et al., 2012; Ramsby et al., 2018; Simister et al., 2012; Whalan et al., 2008; Wisshak et al., 2013
Wetlands	3	Canning & Waltham, 2021; Duarte de Paula Costa et al., 2021; Leigh et al., 2015
Ocean acidification	50	
Coral reefs	5	Albright et al., 2016; Anthony et al., 2011; Shaw et al., 2012; 2015; Stoltenberg et al., 2021
Corals	16	Albright et al., 2016; Anthony et al., 2008; Brien et al., 2016; Chua et al., 2013a; 2013b; De'ath et al., 2013; D'Olivo et al., 2019; Dove et al., 2020; Guan et al., 2015*; Guo et al., 2020; Lough 2016; Meyer et al., 2016; Rölfer et al., 2021; Smith et al., 2020; Wei et al., 2009; Wu et al., 2017
Coralline algae	3	Anthony et al., 2008; Diaz-Pulido et al., 2012; Smith et al., 2020
Crown-of-thorns starfish	2	Sparks et al., 2017; Uthicke et al., 2013
Crustacea	1	Boco et al., 2021
Fish	3	Miller et al., 2013; Munday et al., 2009; Rummer et al., 2013
Foraminifera	5	Prazeres et al., 2015; Reymond et al., 2013; Schmidt et al., 2014; Sinutok et al., 2014; Uthicke & Fabricius, 2012

Impact type Response (ecosystem, species)	Number of studies	References
Invertebrates (non-coral)	1	Przeslawski et al., 2008
Macroalgae	4	Ho et al., 2021; Meyer et al., 2015; Smith et al., 2020; Rölfer et al., 2021
Mollusca	1	Lefevre et al., 2015
Seagrass	4	Collier et al., 2018; Ow et al., 2015; 2016a; 2016b
Sediment	4	Cyronak et al., 2013; Eyre et al., 2018*; Fink et al., 2017; Trnovsky et al., 2016
Sponge	6	Achlatis et al., 2017; Bennett et al., 2017; Fang et al., 2013; 2018; Wisshak et al., 2012; 2013
Turf algae	1	Ober et al., 2016
Storms	31	
Coral reefs	1	Dietzel et al., 2021
Coral	19	Baird et al., 2018a; Beeden et al., 2015; Bongaerts et al., 2013; Cheal et al., 2002; 2017; Dixon et al., 2022; Done, 1992; Fabricius et al., 2008; Haapkylä et al., 2013; Madin et al., 2018; Massel & Done, 1993; Perry et al., 2014; Torda et al., 2018; Turton, 2019; van Woesik et al., 1995; Vercelloni et al., 2020; Walker et al., 2008; Wolff et al., 2016; Woolsey et al., 2012
Fish	5	Ceccarelli et al., 2016; Cheal et al., 2002; Gerlach et al., 2021; Triki & Bshary, 2019; Triki et al., 2018
Mangroves	2	Chamberlain et al., 2021; Turton, 2019
Seagrass	4	Carter et al., 2022; Rasheed et al., 2014; Pollard & Greenway, 2013; Turton, 2019
Sediment	1	Carter et al., 2009
Wetlands	2	Leigh et al., 2015; Wolanski & Hopper, 2022
Sea level rise	7	
Coral reefs	1	Morgan et al., 2020
Coral	3	Hamylton et al., 2014; Saunders et al., 2014; Scopéltis et al., 2011
Estuarine	1	Wolanski & Chappell, 1996
Mangrove	1	Duarte de Paula Costa et al., 2021
Sea turtle	1	Fuentes et al., 2010a
Seagrass	2	Duarte de Paula Costa et al., 2021; Saunders et al., 2014
Wetland	1	Duarte de Paula Costa et al., 2021
Rainfall variability/ flood plume related low salinity or high turbidity	13	
Coral	1	Berkelmans et al., 2012
Mangrove	1	Duarte de Paula Costa et al., 2021
Sea turtle	1	Staines et al., 2020
Seagrass	8	Chartrand et al., 2018; Collier et al., 2014; Duarte de Paula Costa et al., 2021; Lambert et al., 2021; McKenna et al., 2015; Petus et al., 2014; Pollard & Greenway, 2013; Rasheed & Unsworth, 2011
Sponges	1	Abdul Wahab et al., 2014
Wetlands	3	Canning & Waltham, 2021; Croke et al., 2013; Duarte de Paula Costa et al., 2021

Impact type Response (ecosystem, species)	Number of studies	References
Cumulative impacts from climate factors and other disturbances	23	
Coral reefs	5	Castro-Sanguino et al., 2021; Davis et al., 2019; Hughes, 2011; Mellin et al., 2019; Wolff et al., 2018
Corals	10	Bozec et al., 2022; Brodie & Waterhouse, 2018; De'ath et al., 2012; Fine et al., 2019; Fontoura et al., 2020; Foster & Attrill, 2021; Hughes, 2003; Ortiz et al., 2018; Poloczanska et al., 2007; Thompson & Dolman, 2010
Fish	3	Fontoura et al., 2020; Gordon et al., 2018; Poloczanska et al., 2007
Mangroves	5	Alongi, 2015; Gilman et al., 2008; Lovelock & Ellison, 2007
Seagrass	1	Brodie & Waterhouse, 2018
Wetlands	4	Adame et al., 2019; Angly et al., 2016; Haynes et al., 2007
Multiple ecosystems	1	Pratchett et al., 2011

Effects of sea surface temperatures and temperature anomalies on GBR ecosystems and taxa

Studies on the responses of corals to elevated temperatures show that periods of sea surface temperatures that exceed the long-term maximum summer monthly means by several weeks are causing mass coral bleaching events, as well as stress and damage to numerous other marine organisms (Foster & Attrill, 2021; Hughes et al., 2017). Other stressors such as extremely low temperatures or salinity, or sedimentation, can also trigger coral bleaching and mortality, but such events are local rather than regional in extent (Anthony & Kerswell, 2007). The number of case studies on this topic is beyond what can be summarised in this narrative, so instead some key examples and findings of critical climate thresholds are tabulated in Table 11. For example, bleaching severity and the fate of corals (recovery within a season, slow recovery with 1 – 2 years of impaired growth and fecundity, or mortality) 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). A study of the 2016 bleaching event showed that sensitive corals began to die above a critical threshold of 3-4 Degree Heating Weeks, and at or above 6 Degree Heating Weeks, coral assemblages had shifted to a new composition within 9 months (Hughes et al., 2018).

On the GBR, the severity of coral bleaching on individual reefs is tightly correlated with the level of local heat exposure, but the realised local extent of bleaching in any one year is further modulated by factors such as wind, solar irradiance, humidity and cloud cover (McGowan & Theobald, 2017). Cloud cover can have partially mitigating effects (Bainbridge, 2017; Zhao et al., 2021). The upwelling of nutrient rich waters from the edge of the continental shelf has been shown to lead to or be a proxy for worse bleaching outcomes in the central GBR (Berkelmans et al., 2010; DeCarlo & Harrison, 2019). Water quality and fishing pressure had minimal effect on bleaching severity during severe heat anomalies, suggesting that local reef management afforded little protection against impacts by extreme heat (Hughes et al., 2017). However, turbidity may reduce the effects of heat stress on corals on the GBR, potentially by reducing irradiance (Morgan et al., 2020).

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 & Theobald, 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, 2017 (causing an estimated 30% loss; Hughes et al., 2018), and for 2020 and 2022 which was widespread

but caused relatively lower mortality (Thompson et al., 2022). Field observations confirm increases in the frequency, severity and/or spatial extent of mass coral bleaching since 1998 (Hughes et al., 2021). 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 & Hennige, 2018).

Some studies suggest the existence of climate change refugia at the present level of 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 some local reef communities, but they concluded that such potential climate refugia only persist until global warming exceeds ~3°C. Models suggest that overall, the northern and far northern GBRMP zones (GBRMPA 2004) 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). On high latitude reefs south of the GBR, recent temporal stability in coral assemblages has been attributed to high thermal stress resistance (Dalton & Roff, 2013), although their dominant taxa bleached extensively during thermal stress in 2010 (Dalton & Carroll, 2011).

Temperature effects on other GBR taxa and ecosystems are also addressed through numerous studies (Tables 10, 11, 12, 13). For numerous widely distributed organism groups such as seabirds or sea turtles, the literature retrieved through the online search is almost certainly incomplete, and specialist searches without the search term “Great Barrier Reef” is warranted but was beyond the scope of this Evidence Summary. Some findings on the thresholds for seabirds, sea turtles, fishes, sponges, macroalgae, microbes are highlighted in Table 11, while effects on seagrasses, mangroves and wetlands are summarised in Table 12 and Table 13. Many of these studies show severe impacts from high seawater temperatures on GBR organisms and ecosystems.

Three studies showed links between warming temperatures and reproductive success in the coral eating **crown-of-thorns starfish** (COTS) *Acanthaster sp.* Optimum all-at-once gametogenesis and spawning occurred above 28°C seawater temperature (Caballes et al., 2021). While food availability was the main driver of larval development, an experiment and model suggest that an increase in global temperatures by 2°C may increase the probability of COTS larval survival by 240%, with the higher temperature predominantly accelerating development (Uthicke et al., 2015). Given the additional role of chlorophyll in promoting larval survival (Question 4.3, Caballes et al., this SCS), this reinforces the importance of water quality management under rising temperatures.

Sea turtles are particularly vulnerable to rising temperatures, as sex determination of hatchlings is dependent on temperature. Warmer sand temperatures during incubation result 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 & Porter, 2013; Fuentes et al., 2010b; Jensen et al., 2018).

Reef associated fish are vulnerable to both direct physiological and indirect (altered habitat and food webs) effects of warming oceans (Munday et al., 2008a; Pratchett et al., 2008). Field studies showed that fish assemblages are more homogenised after coral mortality from bleaching (Richardson et al., 2018). Sites that experienced extensive coral bleaching had reduced recruitment of damselfish (Booth & Beretta, 2002) and fewer coral feeding butterflyfishes (Pratchett et al., 2006) but there were also some signs that habitat plasticity and migration may have protected some fish

assemblages in the short term from coral loss (Wismer et al., 2019). Similarly, bleaching of anemones leads to reduced anemonefish abundance (Lönstedt & Frisch, 2014). There are numerous physiological experimental studies, often focusing on small fish that are easily kept in laboratory settings in larger numbers. For example, increased temperatures have been associated with reduced pelagic larval duration (McLeod et al., 2015b), and changes to species- and location specific thermal reaction norms which can affect larval duration and pre-settlement growth rates (Takahashi et al., 2012), and growth of juvenile and adult reef fishes (Munday et al., 2008b). Furthermore, a 3°C rise in temperature has been found to increase oxygen consumption of cardinalfish (*Ostorhinchus doederleini*) and damselfish (*Pomacentrus moluccensis*) (Nilsson et al., 2010). This increased oxygen need is likely to reduce aerobic scope (capacity to perform aerobically), thus impacting performance (Nilsson et al., 2010). The aerobic scope of cardinalfish has been found to be very sensitive to temperature increases, with an increase of 2°C (from 29 to 31°C) resulting in a reduction of aerobic scope by almost 50%, with a threshold of capacity at 33°C (Nilsson et al., 2009). In contrast, damselfish were able to maintain half their aerobic scope at 33°C, displaying varied thermal tolerance between species, which may lead to a shift in community assemblages as temperatures continue to rise (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 suggested likely future climate-induced reductions in body size, with important ramifications for fisheries productivity and for ecosystem functions.

Studies of **sponges** under elevated temperatures 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).

On the topic of temperature effects on **seagrasses**, 13 relevant publications were found (Table 10 and Table 12). The thermal tolerance of seagrasses is influenced by how temperature affects the rates of photosynthesis and respiration and the consequence of changes in these for the plant energy balances (Collier et al., 2017). Seagrass species differ in their thermal tolerance (Campbell et al., 2006; Collier et al., 2017; Collier & Waycott, 2014) and their distributional ranges. For example, water temperature was one of the environmental predictors of species composition of seagrass communities across the GBR (Carter et al., 2021). Experimental studies showed species-specific sensitivities to temperature stress. For example, Collier et al. (2011) showed that the seagrass species *Halodule uninervis* had optimum growth over four weeks at 33°C and Collier et al. (2017) showed that thermal optima of 33°C modelled from measured metabolic rates in short-term incubations (hours) was consistent for a northern and southern population of this species. By contrast, *Cymodocea serrulata* had a predicted optimum temperature for metabolism of 35°C for a northern and southern population. By contrast, *Zostera muelleri* went into energy deficit at 33°C and stopped growing after four weeks (Collier et al., 2011). The predicted optimum temperatures of *Z. muelleri* were affected by morphology and the relative mass of photosynthetic and non-photosynthetic (rhizomes/roots) plant components and so optimum temperature may be highly variable and much lower in some populations. Therefore, there may be future retractions in its distributional range away from the northern GBR (Collier et al., 2011). However, a population of this species from Midge Point survived (albeit at reduced density) at 35°C for seven weeks (and was more tolerant in that experiment than *H. uninervis* or *C. serrulata*) indicating that there may be acclimation or local adaptation possible in this species (Collier et al., 2018) but this remains largely untested in the GBR.

Extensive areas of seagrass grow in shallow and intertidal habitat where short-term exposure to extreme temperatures above 35°C occurs at low tide and may also rise above 40°C for a couple of days a year (McKenzie et al., 2022). An experimental study showed that short-term (few days) temperature spikes of 40°C for just four hours per day (simulating low water level rises in temperature) did not affect the photosystem II efficiency of some species of seagrass, but was detrimental to others, in particular *Halophila ovalis* and *Syringodium isoetifolium*. The thermal optimum for photosystem II efficiency, was later found to be 31°C for *H. ovalis* over 24-48 hours (Wilkinson et al., 2017). Exposure to 40°C had minimal effect on photosystem II efficiency in other species including *C. serrulata*, *Cymodocea rotundata* and *Thalassia hemprichii* (Campbell et al., 2006). Despite maintaining photosystem II efficiency, growth rates of these species were reduced by more than half in this exposure regime when maintained over six days for four hours per day and this is likely to be due to the energetic costs of rising respiration at higher temperatures (Collier & Waycott, 2014). Two to three days of exposure to 43°C for four hours per day led to complete mortality, indicating extended thermal events in shallow habitats above 40°C are likely to affect the ecological function of tropical seagrass meadows (Campbell et al., 2006; Collier & Waycott, 2014).

Temperature effects on **mangroves and wetlands** are poorly represented in the literature. No GBR specific reference was found for temperature effects on wetlands, and an Australia-wide review also returned little information (Leigh et al., 2015). Among climate change studies on mangroves, temperature is one of the lesser studied stressors. Productivity of mangroves, along with all plants, 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 & Ellison, 2007). In contrast, southern GBR mangroves may experience an increase in productivity as they are limited by low temperatures (Lovelock & Ellison, 2007). Furthermore, warmer winter temperatures may also result in the expansion of mangroves further south (Lovelock & Ellison, 2007).

Effects of ocean acidification (OA) on GBR ecosystems and taxa

The literature search retrieved 50 studies on the effects of ocean acidification (OA) in the GBR (Tables 10, 11, 12 and 13), some of which covered ocean acidification in combination with temperature, salinity or dissolved inorganic or organic carbon as additional stressors. Ocean acidification is a relatively recent field of research, with 2009 being the earliest date of retrieved publications for the GBR (Doney et al., 2009; Munday et al., 2009; Wei et al., 2009). GBR studies were based on manipulative field experiments, space-by-time substituting field observations, or models, complemented by some key laboratory experiments. Many additional laboratory experiments exist that were excluded by the criteria of limited spatial or temporal relevance for the GBR.

Five studies provide observational evidence and predictions that **reef calcium carbonate production** in GBR coral reefs has already declined due to ocean acidification and will continue to decline (Table 11). Albright et al. (2016) showed that experimental restoration of the seawater carbon chemistry to pre-industrial conditions through alkalinity enrichment increased net community calcification of a natural coral reef community. This provides strong evidence that ocean acidification is already impairing coral reef growth. Shaw et al. (2012) estimated that the GBR reef net community calcification will decline by 55% of its pre-industrial value by the end of the century. These estimates were refined by Shaw et al. (2015) who used observational data to predict that community net calcification of the One Tree Island reef flat is expected to reach zero at an aragonite saturation state (Ω_{ar}) of ~2.5. Estimates of the global threshold for coral reef existence range from an aragonite saturation state of <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 ocean acidification 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 an aragonite saturation of 2.92 ± 0.16 ,

which is expected for the second half of this century depending on emissions pathways. Fink et al. (2017) showed that GBR midshelf reef sediments changed from net precipitating ($-0.8 \text{ g CaCO}_3 \text{ m}^{-2} \text{ d}^{-1}$) under ambient CO_2 to net dissolving ($1 \text{ g CaCO}_3 \text{ m}^{-2} \text{ d}^{-1}$) under ocean acidification conditions of $+170$ to $+900 \text{ } \mu\text{atm CO}_2$ (-0.1 to $-0.4 \text{ } \Delta\text{pH}$). Enhanced sediment dissolution could diminish sediment accumulation rates in the lagoon by up to 31% ($2\text{--}4 \text{ mm decade}^{-1}$), but will affect net ecosystem calcification of the Davies Reef reef flat by $<4\%$. Stoltenberg et al. (2021) found evidence for net carbonate dissolution on Heron Island reef flat during summer afternoons, when respiration rates were high and Ω_{ar} was low. They concluded that the reefs that are most vulnerable to overall net dissolution under future ocean acidification are those already experiencing low calcification rates, have low coral and high sediments that are most easily dissolved, and have high rates of respiration (heterotrophy).

Responses of specific organisms to ocean acidification were investigated in 46 studies. After filtering out less spatially and temporally relevant studies, studies retained included those on corals, crustose coralline algae, seagrasses, mangroves, macroalgae, crown-of-thorns starfish, crustaceans, molluscs, foraminifera, sponges and fish behaviour (Tables 10 to 13). A field study showed that spatial differences in the cover of crustose coralline algae and macroalgae and the density of coral juveniles, were strongly associated with spatial differences in seawater carbon chemistry, when statistically controlling for the effects of turbidity and dissolved nutrients (Smith et al., 2020). This study concluded that ocean acidification will likely diminish the capacity of coral reefs to recover after disturbance, by promoting fleshy macroalgae and impairing crustose coralline algae and coral recruitment. Importantly, these associations with ocean acidification (proliferation of fleshy macroalgae, negative effects on coral recruitment and on crustose coralline algae) are similar to the responses to poor water quality, suggesting water quality improvement may mitigate some of the effects of ocean acidification.

Some seagrasses were found to benefit from the additional CO_2 in the seawater through additional productivity (as higher concentration of dissolved inorganic carbon (DIC) can release plants from carbon limitation), however responses were not consistent, and benefits may be offset by the negative effects of marine heatwaves on seagrasses as CO_2 rises (Collier et al., 2018) (Table 12). Mangroves may also benefit with increasing growth from elevated CO_2 , with responses depending on many additional variables (Hughes, 2003; Lovelock & Ellison, 2007). Most ocean acidification 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). For mangroves, elevated CO_2 was found to promote plant growth, with unknown implications for mangrove ecosystems and their ranges (Hughes, 2003; Lovelock & Ellison, 2007). Overall, the responses of many GBR organism groups and ecosystems to ocean acidification are still poorly understood, although global reviews tended to find detrimental or no effects on many calcifying organisms, and promotion or no effects on many photosynthetic organisms.

Effects of storms on GBR ecosystems and taxa

Tropical cyclones are among the most destructive forces impacting GBR ecosystems, with 48% of coral losses attributed to tropical cyclones between 1985 and 2012 (De'ath et al., 2012), and 41% of losses from 2008 to 2020 (Bozec et al., 2022). A total of 31 studies covered the impacts of storms on corals, coral reefs, coral reef fishes, seagrasses, mangroves and wetlands (Tables 10, 11, 12, 13). However, a critical knowledge gap that needs to be resolved is whether cyclone damage above and below water has or will increase in the GBR.

On land, wind damage is controlled by wind speed and duration, with damage increasing exponentially with wind speed. Faster-moving cyclones can generate higher wind speeds in the front left quadrant of the storm (where the forward motion of the storm is additive with the wind speed)

and thus storms like Cyclone Larry (2006) that moved very fast at high intensity created very high winds on land, but this did not translate into persistent damaging sea states. Underwater, cyclone damage depends on wave generation, with large, slow-moving intense cyclones causing the most damage because this maximises wave height, and wave barriers such as upwind reefs reduce damage (Dixon et al., 2022).

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). The extent of damage to corals is species-specific, with branching and plate corals (e.g., *Acropora* and *Pocillopora*) more vulnerable than massive and encrusting morphologies (e.g., *Porites*) (Baird et al., 2018a; Fabricius et al., 2008; van Woerik et al., 1995). While damage is greatest closest to the track, it can be widespread, with Beeden et al. (2015) recording coral damage from Cyclones Yasi extending up to 250 km from the cyclone track. Following Cyclone Nathan in March 2015, Baird et al. (2018a) noted a 90% reduction in live coral cover on Trimodal Reef, Lizard Island, with dislodgment of corals the primary cause. This reduction in coral cover has been documented to have complex interactions with reef fish communities. In a study by Ceccarelli et al. (2016), although there was no significant decline in total fish density, biomass and species richness following Cyclone Ita, there did appear to be high species-level turnover with decreased damselfish densities and increased grazer density. Tropical cyclones also cause major disturbances to soft bottom habitats, redistributing otherwise undisturbed sediments and impacting the 90% of the GBR that lies between the coral reefs yet are poorly studied (Carter et al., 2009; Gagan et al., 1990; Larcombe & Carter, 2004).

The intertidal biodiversity of sessile invertebrates such as ascidians, sponges and bryozoans were found to follow strong wave exposure and temperature gradients, suggesting this fauna is also highly sensitive to climate change, with more intense storms leading to a decrease in the diversity of cryptic sessile assemblages that perform critical but often poorly understood ecosystem functions (Walker et al., 2008). The recent loss of 2.3% of mangroves in parts of the Mackay Whitsunday NRM, Central Queensland, have been attributed to storms and precipitation variation (Chamberlain et al., 2021).

Seagrass meadows in coastal areas are vulnerable to severe storms and cyclones, but most studies that describe impacts from storms and cyclones (e.g., Cyclone Yasi) also refer to protracted impacts caused by declines in water quality from rainfall and discharge (Lambert et al., 2021; McKenna et al., 2015; Petus et al., 2014; Pollard & Greenway, 2013). Flooding and strong winds associated with climate change have also been found to enhance coastal erosion (Wolanski & Hopper, 2022) and surface elevation of wetlands (Lovelock & Ellison, 2007).

The effects of climate extremes (droughts, fires, floods, heatwaves, storm surges and tropical cyclones) on riverine ecosystems in Australia were reviewed in Leigh et al. (2015). Although not GBR-specific, the review demonstrated that tropical cyclones and post-cyclonic floods damage riparian vegetation, erode stream banks and alter water quality. While cyclone-induced delivery of large woody debris provides important instream habitat, the wider ecological consequences of more intense tropical cyclones on riverine ecosystems remain uncertain.

Effects of sea level rise on GBR ecosystems and taxa

Sea level rise is a growing economic challenge since housing and infrastructure development has involved many low-lying and swampland areas along the Queensland coast in recent years. Mangroves, saltmarshes and other coastal marine ecosystems are sensitive to sea level rise (Table 11) (Duarte de Paula Costa et al., 2021). Landward migration of mangroves into saltmarshes and freshwater wetlands is predicted with future sea level rise, resulting in significant changes in ecosystem function (Hughes, 2003; Lovelock & Ellison, 2007; Wolanski & Chappell, 1996). The extent of this landward migration is dependent on numerous factors, including rate of sediment deposition and soil elevation (Lovelock & Ellison, 2007), however is predicted to increase mangrove area by 2800 ha under RCP4.5 (Duarte de Paula Costa et al., 2021).

As sea levels rise, coral reefs are predicted to increase in spatial extent, although these areas are expected to have low coral cover and generic diversity (Morgan et al., 2020). However, under sea level rise at RCP8.5 scenarios, the rate of vertical accretion of reefs is expected to be insufficient, resulting in completely submerged reef flats and move reef slope communities below the euphotic zone (Morgan et al., 2020). Modelling has also demonstrated the potentially negative effects of sea level rise on reef seagrasses as the vertical accretion of reefs will no longer shelter them (Saunders et al., 2014). In addition, models by Fuentes et al. (2010a) predict a 38% reduction of available nesting areas within sea turtle rookeries on low lying islands with limited capacity for beach expansion due to inundation by rising sea levels.

Effects of rainfall variability on GBR ecosystems and taxa

Intensifying rainfall variability can have direct physiological or population effects on submarine ecosystems including coral reefs and subtidal seagrasses. Intense rainfall can lead to the formation of a freshwater lens in surface waters, potentially causing mortality of sensitive organisms on reef flats or intertidal or shallow subtidal marine ecosystems during low tides, such as in the Keppel Islands (Berkelmans et al., 2012). The numerous indirect and flow-on effects on coral reefs from increasing terrestrial runoff of nutrients, sediments and pesticides through flood plumes are covered in Section 4.1.1.3 (this question) and in Question 3.2 (Collier et al., this SCS), Question 4.2 (Diaz-Pulido et al., this SCS) and Question 5.1 (Negri et al., this SCS).

Seagrasses showed high tolerance (i.e., maintaining shoot density and growth) after 10 weeks of exposure to salinity as low as 15 PSU in three species, which is an unlikely level of exposure in the GBR (Collier et al., 2014). At lower salinities there was stress-induced morphological change (shoot proliferation), that preceded mortality with complete mortality only occurring in *Halodule uninervis* at 3 PSU and in *Halophila ovalis* at 6 PSU, while *Zostera muelleri* did not suffer mortality at any salinity from 36 to 3 PSU (Collier et al., 2014). Subtidal communities are also particularly sensitive and lose cover due to increased turbidity and light loss caused by runoff (Table 12). Recovery times from such severe salinity changes can be a decade for intertidal seagrasses, and even longer for subtidal and estuarine communities (Carter et al., 2022).

For mangroves and coastal wetlands, intensifying rainfall variability is important. For mangroves, prolonged drought has been identified as one of the causes of widespread mangrove die-backs (Chamberlain et al., 2021). Additionally, regions with decreased rainfall are more susceptible to the landward migration of mangroves due to altered sedimentation rates (Lovelock & Ellison, 2007). Wetland connectivity between habitats and the flushing of accumulated materials is also influenced by the amount of rainfall (Croke et al., 2013). Similarly, a review and conceptual diagrams by Leigh et al. (2015) outlined a strong dependency of Australia's riverine systems on rainfall variability: droughts alter water quality and reduce habitat availability, while extreme floods can trigger booms in productivity and improve connectivity, but also alter channel morphology and cause hypoxic blackwater events and fish kills.

Effects of cumulative impacts and GBR recovery rates

Climate change and water quality do not act in isolation. A number of key studies have addressed the cumulative effects of multiple impacts. This paragraph outlines a few of the aspects at an ecosystem level, whereas the broader question addressing both species and ecosystems is reviewed in Question 2.4 (Fabricius et al., this SCS).

Overall, several studies have shown that recovery rates of coral cover after disturbances appear to be slowing significantly, by as much as 84% (Ortiz et al., 2018), or even halving (Osborne et al., 2017). The causes of this slowing reef recovery were attributed to residual effects of acute heat stress plus other chronic stressors. Indeed, other studies have shown that water quality improvement may help mitigate such slowing in recovery. A modelling study by Bozec et al. (2022) estimated that suspended sediments delay recovery on at least 25% of inshore reefs. Another

modelling study indicated up to 66% of reef performance loss is attributable to local stressors (Wolff et al., 2018), and that management strategies to alleviate cumulative impacts have the potential to reduce the vulnerability of all inshore reefs and some midshelf reefs in the central and southern GBR by 83%, if combined with strong mitigation of carbon emissions. During the 2016 extreme heatwave, water quality and fishing pressure had minimal effect on bleaching severity, suggesting that local protection of reefs affords little or no physiological protection once heatwaves are intense and prolonged (Hughes et al., 2017), but this does not diminish the benefit of accelerating recovery (Wolff et al., 2018).

Table 11. Examples of predictions about potential magnitude and timing of impacts from climate change, and potential threshold levels.

Impact type	Thresholds/ Indicators/ Predictions	Reference
Temperature		
Effect of temperature on GBR heat budget	Projections indicate more regional warming and heatwaves in the central and southern than the far north and northern GBRMP zones , due to changing cloud cover. By 2080, adherence to SSP1-2.6 (2°C warming) predict five bleaching events per decade . At SSP1-1.9 (1.5°C), three bleaching events predicted per decade, but crucially, the thermal heat budget would stabilise below the critical threshold of 8 Degree Heating Weeks. Under SSP3-7.0 and SSP5-8.5, thermal stress is 3- to 4-fold higher than present day. Annual severe bleaching events are predicted for SSP5-8.5.	McWhorter et al., 2022b
	Climate refugia are local areas where tides and wind transports warm water away from the sea surface, providing relief from warming. These climate refugia will fail as global warming exceeds 3°C.	McWhorter et al., 2022a
Effects of temperature on coral reefs	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 Degree Heating Weeks . At or above 6 Degree Heating Weeks, coral assemblages shifted to new composition.	Hughes et al., 2018
	During extreme heatwaves, water quality and fishing pressure had minimal effect on bleaching severity, suggesting that local protection of reefs affords little or no resistance to extreme heat . Past exposure to bleaching in 1998 and 2002 did not lessen the severity of bleaching in 2016 .	Hughes et al., 2017
	A sublethal SST stress period prior to a main bleaching event can reduce coral bleaching severity. Temperature increases of >0.5°C will remove this protective sublethal SST stress period.	Ainsworth et al., 2016
	Modelling predicts that a 1°C increase in SST would increase the occurrence of bleaching by 50-82%. A 2°C increase would increase the occurrence to 97%, and 3°C increase to 100% .	Berkelmans et al., 2004
	Modelled SST projections predict the frequency of coral bleaching in the GBR will rise rapidly, with bleaching set to occur annual in most oceans by 2040 .	Crabbe, 2008
	Following bleaching, a change in dominant coral symbiont was observed. Symbiont change, in conjunction with acute thermal stress,	Jones & Berkelmans, 2010

Impact type	Thresholds/ Indicators/ Predictions	Reference
	likely results in reduced coral growth, with implications for future reef recovery rates.	
	Cumulative bleaching in 2016, 2017, and 2020 is predicted to have reduced coral larval supply by 26%, 50%, and 71%, respectively. But 13% of the GBR are potential thermal refugia (14% of which are in highly protected areas) which may deliver larvae to 58% of the GBR, providing pockets of systemic resilience in the near-term.	Cheung et al., 2021
	A 2°C warming accelerates larval development and alters coral dispersal patterns, increasing local larval retention and decreasing connectivity to distant places.	Figueiredo et al., 2022
	Long-term model projections suggest that moderate future warming (~2°C) led to corals being replaced by sponges, gorgonians and other taxa, whereas under extreme future warming (>2°C) algal dominance was projected.	Cooper et al., 2015
	Mean annual temperatures of 24°C or higher are needed for adequate coral growth to prevent reef drowning.	Isern et al., 1996
	For <i>Acropora hyacinthus</i> on Beaver Reef, heat stress at 8.3 Degrees Heating Weeks coincided with the highest prevalence (48% of colonies) of the coral disease White Syndrome, and led to whole-colony mortality in 68% of colonies after 8 months; with only 4% of colonies not displaying signs of bleaching or disease. A threshold of 50% colony bleaching was a good indicator that substantial mortality at both the colony and population level is likely to follow a heat stress event.	Brodnicke et al., 2019
Temperature effects on high-latitude coral reefs	In high latitude reefs (30-31.5°S), the bleaching threshold was 26.5-26.8°C. Patterns of subtropical coral family bleaching susceptibility differed to those in the central GBR.	Dalton & Carroll, 2011
	Observed recent 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 & Roff, 2013
Effect of temperature on coral species	The skeletal density of <i>Porites</i> increased with increasing SST up to an optimum of 26.5°C. At temperatures beyond this threshold, skeletal density decreased with increasing temperature.	Razak et al., 2020
	The optimum temperature for <i>Acropora millepora</i> is 27°C. When exposed to mild cold (23°C) and ambient (27°C) temperatures, physiological condition improved, however when exposed to mild heat (29.5°C) coral condition declined.	Nielsen et al., 2020
	A 3°C warming will alter community composition in pocilloporid coral populations (<i>Seriatopora hystrix</i> , <i>S. caliendrum</i> and <i>Pocillopora damicornis</i>) in the southern GBR: (1) annualised colony growth rates increased by 24-39% in all species; and (2) intrinsic rate of population growth (λ) for <i>S. hystrix</i> decreased by 26%, for <i>S. caliendrum</i> increased by 5%, and did not change for <i>P. damicornis</i> .	Edmunds, 2005
Effects on temperature on	Aerosol concentration over reefs increased with irradiance up to a SST of ~1°C below the mean monthly maximum, at which point the trend reversed/correlation strength weakens.	Jackson et al., 2018

Impact type	Thresholds/ Indicators/ Predictions	Reference
aerosol emissions	At >30°C SST, corals shut down production of atmospheric dimethylsulphide (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 photosynthetic active radiation (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
Effects of temperature on foraminifera	After being exposed to 32°C for 7 days, <i>Marginopora vertebralis</i> physiological parameters were compromised. Exposure to 34°C (5°C above the current summer maxima) for 7 days resulted in mortality for most individuals.	Uthicke et al., 2012
Effects of temperature on crown-of-thorns starfish (COTS) (<i>Acanthaster sp.</i>)	A 2°C temperature increase may increase the probability of COTS larval survival by 240% , by shortening developmental times.	Uthicke et al., 2015
	For <i>Acanthaster cf. solaris</i> , optimum all-at-once gametogenesis and spawning occurred at >28°C seawater temperature.	Caballes et al., 2021
	For <i>Acanthaster planci</i> , normal larval development and larval size occurred between 28.7 to 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
Effects of temperature on sponges	Above 31°C for >48 hours was lethal for the reef sponge <i>Rhopaloeides odorabile</i> .	Massaro et al., 2012
	At 32°C (3°C above maximum monthly mean temperature), the sponge <i>Cliona orientalis</i> bleached and photosynthesis of their <i>Symbiodinium</i> symbionts was compromised, consistent with responses of sympatric corals.	Ramsby et al., 2018
	At 32°C, certain viruses appear to be replicating under thermal stress in the sponge <i>Rhopaloeides odorabile</i> , and may contribute to rapid decline in host health.	Laffy et al., 2019
Effects of temperature on fish	Aerobic scope of the two cardinalfishes (<i>Ostorhinchus cyanosoma</i> and <i>O. doederleini</i>) was reduced by nearly half at 31°C compared with 29°C, and virtually all capacity for additional oxygen uptake was exhausted by 33°C. In contrast, three damselfishes (<i>Dascyllus aruanus</i> , <i>Chromis atripectoralis</i> and <i>Acanthochromis polyacanthus</i>) retained over half their aerobic scope at 33°C. Suggests fish community structure might change significantly as ocean 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 <i>Acanthochromis polyacanthus</i> : Growth rate declined with increasing temperature. At 31°C, the growth of juveniles and adults on the high food ration was nearly identical to growth on the low food ration. Capacity for growth is severely limited at temperatures predicted to become the average at that site (Orpheus Island) within the next 100 years.	Munday et al., 2008b
Effects of temperature on sea turtles	Model projections suggest a near complete feminisation of hatchling output for green turtle (<i>Chelonia mydas</i>) by 2070 under A1T emission scenario.	Fuentes et al., 2010b
	The seagrass <i>Halodule uninervis</i> had optimum growth at 33°C, while the seagrass <i>Zostera muelleri</i> exhibited critical metabolic imbalances at	Collier et al., 2011

Impact type	Thresholds/ Indicators/ Predictions	Reference
Effects of temperature on seagrass	33°C. <i>Zostera muelleri</i> may contract in its distributional range away from the northern GBR.	
	<i>Halodule uninervis</i> had a predicted optimum temperature for metabolism of 33°C, for <i>Cymodocea serrulata</i> it was 35°C and for <i>Zostera muelleri</i> it was 31°C; however, the relative proportion of photosynthetic vs non photosynthetic components affected the predicted optimum temperature.	Collier et al., 2017
	Short-term (six days) temperature spikes (four hours) of 40°C represented a critical threshold for growth and mortality in tropical seagrass meadows, with species-specific difference in tolerance.	Collier & Waycott, 2014
Effects of temperature and herbicide on seagrass	The thermal optimum for photosynthetic efficiency in <i>Halophila ovalis</i> was 31°C while lower and higher temperatures reduced efficiency, as did all elevated concentrations of the herbicide diuron.	Wilkinson et al., 2017
Ocean acidification		
Effects of OA on coral reefs	Predict that reef net community calcification will decline by 55% of its pre-industrial value by the end of the century.	Shaw et al., 2012
	Community net calcification of One Tree Island reef flat is expected to reach zero at an aragonite saturation state (Ω_{ar}) of ~2.5.	Shaw et al., 2015
	A manipulation experiment restoring carbon chemistry over a natural coral reef community through alkalinity enrichment to pre-industrial conditions, showed a 7% increase in net community calcification. Showed that ocean acidification is already impairing coral reef growth.	Albright et al., 2016
	Showed sensitive response of reef sediments to OA, with some reefs already experiencing net sediment dissolution. Global transition from net precipitation to net dissolution at aragonite saturation of 2.92 ± 0.16 expected for the second half of this century.	Eyre et al., 2018
	Midshelf reef sediments changed from net precipitating ($-0.8 \text{ g CaCO}_3 \text{ m}^{-2} \text{ d}^{-1}$) under ambient CO_2 to net dissolving ($1 \text{ g CaCO}_3 \text{ m}^{-2} \text{ d}^{-1}$) under OA conditions ($\Delta p\text{CO}_2$: +170 to +900 μatm , ΔpH : -0.1 to -0.4). Enhanced sediment dissolution could diminish sediment accumulation rates in the lagoon by up to 31% ($2\text{--}4 \text{ mm decade}^{-1}$) but will affect net ecosystem calcification of Davies Reef reef flat by <4%.	Fink et al., 2017
	Observed decline in aragonite saturation state of -0.0673 per decade in the central GBR. The ecologically critical level of aragonite saturation state for reef formation of 3.5 will be crossed by 2030 in parts of the GBR.	Fabricius et al., 2020
	Data suggest a tipping point at Ω_{ar} 3.5–3.6 for crustose coralline algae cover, coral juvenile densities, and non-calcifying macroalgal cover. NB: Several of the documented effects of ocean acidification on reefs (proliferation of fleshy macroalgae, negative effects on coral recruitment, negative effects on crustose coralline algae), are similar in their direction to the effects of poor water quality, which suggests that water quality improvement may mitigate some of the effects of ocean acidification on reefs.	Smith et al., 2020
Effects of OA on foraminifera	At a pH of 7.6, <i>Marginopora rossi</i> suffered a significant decline in calcification and growth, irrespective of eutrophication.	Reymond et al., 2013

Impact type	Thresholds/ Indicators/ Predictions	Reference
Effects of OA on 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 ocean acidification		
Temperature, CO ₂ and diuron effects on coral	An increase in ~1°C from ambient (28.1°C, pCO ₂ = 397 ppm) to RCP8.5 2050 (29.1°C, pCO ₂ = 680 ppm) and 2100 (30.2°C, pCO ₂ = 858 ppm) sensitised <i>Acropora millepora</i> 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 OA and temperature on coral and crustose coralline algae	For 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 coral reef fish	33°C was close to the lethal thermal limit for two species, <i>Ostorhinchus doederleini</i> and <i>O. cyanosoma</i> . The declines in aerobic scope in acidified water were similar to those from a 3°C temperature increase. Acidification could significantly reduce their aerobic capacity by 2100.	Munday et al., 2009
Effects of temperature and OA on coral	A 2°C rise in temperature accelerated rates of coral larval development in <i>Acropora millepora</i> and <i>A. tenuis</i> , altering connectivity . No consistent effects of pCO ₂ alone nor in combination with temperature.	Chua et al., 2013b
Effects of temperature and OA on a photosynthetic bioeroding sponge	Prolonged warming (to +2.7°C above the local maximum monthly mean) caused extensive bleaching, lowered bioerosion, and increased mortality in <i>Cliona orientalis</i> . Acidification alone did not have a strong effect on total bioerosion or survival rates. Their bioerosion capacity could be substantially reduced rather than increased by the end of the century under "business-as-usual" emissions.	Achlatis et al., 2017
Effects of temperature, OA and eutrophication on sponge	The bioeroding sponge <i>Cliona orientalis</i> will likely grow faster and have higher bioerosion rates in a high OA future than at present, even with significant bleaching. Assuming that findings hold for excavating sponges in general, 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	<i>Zostera muelleri</i> was the most thermally tolerant as it maintained positive net production to 35°C. In contrast, <i>Cymodocea serrulata</i> and <i>Halodule uninervis</i> showed a sharp decline in productivity, growth, and shoot density at 35°C, which was exacerbated by elevated pCO ₂ . Results challenge the hypothesis that tropical seagrass will be 'winners' under future climate change conditions as thermal stress will not be offset by ocean acidification.	Collier et al., 2018
Effects of temperature and OA on macroalgae	The growth of bicarbonate (HCO ₃ ⁻)-using fleshy macroalgae (<i>Lobophora</i> sp., <i>Amansia rhodantha</i>) decreased with rising temperatures under ambient pCO ₂ conditions, however this negative effect of temperature was alleviated under by OA at 30°C. These findings suggest that HCO ₃ ⁻ using fleshy macroalgae benefit from future CO ₂ increases.	Ho et al., 2021
Tropical cyclones		

Impact type	Thresholds/ Indicators/ Predictions	Reference
Effects of cyclones on coral reefs	Prediction of modest to moderate (0-20%) increases in average and maximum cyclone intensities by the end of the century.	Hughes, 2003
	No clear evidence for more cyclone damage to Australian coral reef regions in the future, with some models projecting increases and others decreases in cyclone damage.	Dixon et al., 2022
	For cyclones ≤ 965 hPa that cross GBR in a day, serious damage to coral reefs would not be expected greater than 50 km from the path to the south, 30 km to the north.	Done, 1992
	Under RCP8.5, cyclone frequency is expected to increase from the observed rate (1950-1999) of 2.25 cyclones per year to 2.41 cyclones per year by 2050-2099. The maximum wind speed is also predicted to increase from 24 to 28 m/s , however the radius of maximum winds remains constant.	Callaghan et al., 2020
	Predictions for 2071-2100 under RCP8.5 show increased cyclone intensity, characterised by a reduction in central pressure up to 11hPa, increased wind speeds (by 5-10%) and increased rainfall (by up to 27% for average hourly rainfall rates).	Parker et al., 2018
	Future projections of reduced frequency, increased intensity and altered behaviour of tropical cyclones.	Knutson et al., 2020
	Maximum winds $< 28 \text{ m s}^{-1}$ for < 12 h inflicted only minor damage on any reef, but winds $> 33 \text{ m s}^{-1}$ and $> 40 \text{ m s}^{-1}$ caused catastrophic damage on inshore and offshore reefs, respectively. Offshore reefs had the deepest depth of damage, inshore reefs had the greatest rates of coral breakage and dislodgement.	Fabricius et al., 2008
Sea level rise		
Effects of sea level rise on mangroves, seagrasses and wetlands	With predicted sea level rise, landward migrations would add ~2,800 ha mangrove and tidal marshes under RCP4.5 and 4,194 ha under RCP8.5.	Duarte de Paula Costa et al., 2021
Effects of sea level rise on coral reefs	Depending on scenarios, sea levels are projected to increase by 0.5 m to 1.2 m above 1990 levels by 2100. All reef sites can keep up with 0.5 m rise, and with 1.2 m rise for the first 30 years. Only fast-growing reef sites can keep up with 1.2 m rise, while leeward and lagoonal sites with a low accretion rate maintain a similar profile but slowly gain depth relative to sea level.	Hamylton et al., 2014
	For turbid water reefs, sea level rise 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
Effects of sea level rise on sea turtles	Up to 38% of available green turtle nesting area across all northern GBR rookeries may be inundated as a result of sea level rise. Flooding, as a result of higher wave run-up during storms, will increase egg mortality at these rookeries.	Fuentes et al., 2010a
Effects of sea level rise on 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

Impact type	Thresholds/ Indicators/ Predictions	Reference
Flood plumes		
Effects of flood plumes on seagrass	<i>Halophila ovalis</i> and <i>Halodule uninervis</i> suffered severe mortality at salinities less than 9 PSU, however <i>Zostera muelleri</i> survived salinities as low as 3 PSU for 10 weeks.	Collier et al., 2014
Multiple types of climate impacts and reef recovery		
Effects of climate change on reef recovery	Coral recovery rates across the GBR have declined by an average of 84% between 1992 and 2010.	Ortiz et al., 2018
	Compared with the 7-year period before 2002, the recovery of fast-growing Acroporidae and of “Other” slower growing hard corals slowed after the bleaching in 2002, doubling the time taken for modest levels of recovery . From 2003 to 2009, there were few acute disturbances in the region, allowing us to attribute the observed shortfall in coral recovery rates to residual effects of acute heat stress plus other chronic stressors. If present trend persists, recovery times will be increasing at a time when acute disturbances are predicted to become more frequent and intense.	Osborne et al., 2017
	Tropical cyclones, coral predation by crown-of-thorns starfish (COTS), and coral bleaching accounted for 48%, 42%, and 10% of coral losses, amounting to 3.38% y ⁻¹ mortality rate in the GBR in 1985-2012. However, the estimated rate of increase in coral cover in the absence of cyclones, COTS, and bleaching was 2.85%y⁻¹, demonstrating substantial capacity for recovery of GBR reefs to date.	De'ath et al., 2012
	By 2020, simulated GBR-wide annual model rates of coral mortality were bleaching (48%) ahead of cyclones (41%) and COTS predation (11%). Water quality (eReefs models of the suspended sediment concentrations for each reef) was estimated to delay recovery for at least 25% of inshore reefs. The metric ‘equilibrium cover for each reef’, combined with maps of impacts, recovery potential, water quality thresholds, and reef state metrics, facilitates strategic spatial planning and resilience-based management across the GBR.	Bozec et al., 2022
	Model projections (2017–2050) indicate significant potential for coral recovery in the near-term, relative to current state, followed by climate-driven decline. Under unmitigated emissions (RCP8.5) and business-as-usual management of local stressors, mean coral cover on the GBR is predicted to recover over the next decade and then rapidly decline to only 3% by 2050. Up to 66% of reef performance loss is attributable to local stressors. Management strategies to alleviate cumulative impacts have the potential to reduce the vulnerability of some midshelf reefs in the central GBR by 83%, but only if combined with strong mitigation of carbon emissions.	Wolff et al., 2018

Table 12. Published observed and predicted effects of climate change on GBR seagrasses.

	Effect type	Spatial distribution	Temporal distribution	Predicted impacts: Time thresholds	Strength of Evidence (1 to 10)	Adaptation	Knowledge gaps	Comments	References
Temperature	Affects plant energetics: increase in respiration, non-linear changes in net productivity, and growth. Acute extreme temperature also causes 'burning' and increased mortality. Average temperature affects probability of seagrass presence and composition,	Thermal optima at different latitudes \cong for two of two species tested.	Seasonal variability in thermal optima for one of two species tested. Consecutive days of low tide heat stress and prolonged heat stress (weeks-months) have impacts.	Threshold temperature ranges from 30°C to 40°C depending on species, indicator, plant morphology/energy budget, time of exposure. Below 30°C temperature may affect response to other stressors e.g., higher temperature enhances low light stress.	8 Studies on 9 of 12 GBR species.	Some species are more heat tolerant than others. Signs of acclimation/adaptation in <i>Zostera</i> , broad distribution of other species in tropics/sub-tropics/temperate rate especially <i>H. ovalis</i> implies acclimation/adaptation but unclear in other species.	Thermal optima and thresholds for most species. Interactive/cumulative effects. Spatial and temporal impacts extremes. Factors increasing resilience to thermal stress (e.g., pre-exposure conditions) Acclimation. Adaptive/genetic differences in tolerance.	Most studies were lab experiments or conducted in incubation chambers on site. Long-term monitoring data from the Marine Monitoring Program (MMP) provides <i>in situ</i> temperature exposure regimes (site-specific). Spatial information needed.	7 Campbell et al., 2006; Carter et al., 2021; Collier et al., 2011; 2017; 2018; Collier & Waycott, 2014; Pedersen et al., 2016; Wilkinson et al., 2017

	Effect type	Spatial distribution	Temporal distribution	Predicted impacts: Time thresholds	Strength of Evidence (1 to 10)	Adaptation	Knowledge gaps	Comments	References
Ocean acidification	Increased productivity with OA is possible. Higher concentration of DIC can release plants from carbon limitation. The response is not consistent and depends on many variables.	n/a	Increased productivity in short-term exposure (days to weeks) but not in the longer-term (1 month or more) studies suggesting down-acclimation.	No 'impacts' identified.	4 Contrasting results among studies (because of differences among species, exposure times, interactive effects).	Species differ in their carbon concentration mechanisms.	Long-term effects of OA and acclimation/adaptation. Spatial and temporal analysis of effect of ocean acidification on seagrass. Joint temperature and ocean acidification study.	Only short-medium term laboratory studies.	4 Collier et al., 2018; Ow et al., 2015; 2016a; 2016b
Sea level rise	Increased exposure to wave action.	Seagrass habitats in reef lagoons where sediment stability is mediated by surrounding reef.		Vertical carbonate accretion of reef flats will not be sufficient to maintain suitable conditions for reef top seagrass under moderate to high greenhouse	1 One modelling study from one location relevant to reef seagrass. Limited global literature.		Interdependency among ecosystems is difficult to predict. Cumulative impacts. Possibility for contraction in suitable habitat: light limitation at depth limit, unsuitable	Only one modelling study.	1 Saunders et al., 2014

	Effect type	Spatial distribution	Temporal distribution	Predicted impacts: Time thresholds	Strength of Evidence (1 to 10)	Adaptation	Knowledge gaps	Comments	References
				gas (GHG) emission scenarios by 2100.			habitat in shallow areas.		
Extreme rainfall (drought, flood event)	Decrease in cover due to increased turbidity caused by runoff. Hypo-salinity causes impact only at very low salinities and prolonged exposure.	Degree of impact on seagrass depends on distance from tropical cyclone or flood plume. Shallow/intertidal habitats have slower impact times/reduced impacts. Deep habitats highly sensitive.	The impact depends on duration of exposure, repeated exposure (multiple big wet seasons).	Depends on species: days to weeks for <i>Halophila</i> spp., weeks to months for most species. Also depends on how extreme the flood event is.	7 Long-term monitoring programs measured impacts at numerous locations. Experiments tested some mechanisms (especially light).	Life history strategy affects susceptibility.	Recovery processes and time needed between events to increase resilience. Acclimation/adaptation. Local factors affecting impact e.g., sediment composition and recovery.	Impacts of extreme rainfall events are conflated with storms (physical disturbance) and low incoming solar radiation (light). See also Q3.2 and Q5.2.	6 Brodie & Waterhouse, 2018; Collier & Waycott, 2014; Lambert et al., 2021; McKenna et al., 2015; Petus et al., 2014; Pollard & Greenway, 2013
Storm intensity, frequency	Mortality and decrease in abundance.	Greater recovery at deeper sites compared to shallow post tropical cyclone.	Rapid recovery in deepwater habitats (with a seedbank). Protracted recovery in shallow habitats with low seedbank and relying on vegetative	Immediate impacts caused by physical uprooting of plants.	5 Long-term monitoring programs measured many locations and examples of flood events, experiments tested some mechanisms	Life history traits are an important characteristic affecting the longer-term effects of storms. Colonising species (<i>Halophila</i> spp.) can	Recovery processes, including factors influencing seed production, seed longevity and germination of seeds. Effect of storms on	Only 3 studies. Effects of storms are conflated with those of floods. Recovery capacity is critical to understanding medium and long-term	3 Carter et al., 2022; Rasheed et al., 2014; Turton, 2019

	Effect type	Spatial distribution	Temporal distribution	Predicted impacts: Time thresholds	Strength of Evidence (1 to 10)	Adaptation	Knowledge gaps	Comments	References
			growth from fragments.		(especially light).	recover quickly if there is a seed bank.	benthic substrate.	impacts of storms	

Table 13. Published observed and predicted effects of climate change on GBR mangroves and wetlands.

	Effect type	Spatial distribution	Temporal distribution	Predicted impacts: Time thresholds	Strength of Evidence (1 to 10)	Adaptation	Knowledge gaps	Comments	References
Temperature	Temperature was the strongest predictor for soil organic carbon (SOC) stocks in mangroves, together with rainfall and irradiance. Reduced mangrove productivity.	n/a	n/a	SOC stocks increased with temperature up to 23.8°C, where there was a decline followed by a two-fold increase in stocks at 26°C.	3		Limited number of studies		3 Duarte de Paula Costa et al., 2021; Leigh et al., 2015; Lovelock & Ellison, 2007
Ocean acidification	Elevated CO ₂ promotes growth of mangroves, potentially increasing	n/a	n/a		2		Limited number of studies, direct effects of ocean acidification		2 Hughes, 2003; Lovelock & Ellison, 2007

	Effect type	Spatial distribution	Temporal distribution	Predicted impacts: Time thresholds	Strength of Evidence (1 to 10)	Adaptation	Knowledge gaps	Comments	References
	expansion of mangroves.						not demonstrated.		
Sea level rise	Landward migration and reduced growth or mortality due to increased salinity. Reduction in mangrove areas if vertical accretion cannot keep up with sea level rise.	Greatest landward migration is predicted to occur in Cape York (up to 2,732 ha by 2100) and Fitzroy (837 ha)	n/a	Landward migration was estimated between 2,800 ha to 4,194 ha by 2100.	7	Maintaining vertical accretion rates, however outcome depends on the rate of sea level rise.			3 Duarte de Paula Costa et al., 2021; Hughes, 2003; Lovelock & Ellison, 2007
Extreme rainfall (drought, flood event)	Alters wetland sediment budget (erosion and accretion). Increased rainfall is also directly correlated to increased SOC stock in	n/a	n/a	SOC stock in mangroves is positively correlated with rainfall up to 2,000 mm/year, followed by another peak at 3,000 mm/year.	2		Limited direct correlation of extreme rainfall (drought and flood event) and mangroves.		2 Duarte de Paula Costa et al., 2021; Lovelock & Ellison, 2007

	Effect type	Spatial distribution	Temporal distribution	Predicted impacts: Time thresholds	Strength of Evidence (1 to 10)	Adaptation	Knowledge gaps	Comments	References
	wetlands and mangrove area.								
Storm intensity, frequency	Alters wetland sediment budget (erosion and accretion). Increased storm intensity and frequency may damage mangroves (defoliation, mortality), reducing cover.	n/a	n/a	Model predictions indicate increased intensity of cyclones up to 20% by 2050 associated with increased frequency of one in 100-year floods.	2		Limited direct correlation of storm intensity and frequency and mangroves. Limited data on ecological damage and recovery of mangroves from tropical cyclones.		2 Lovelock & Ellison, 2007; Turton, 2019

4.1.1.3 Summary of evidence to 2022 for Q2.2.1: How is climate change currently influencing water quality in coastal and marine areas of the Great Barrier Reef, and how is this influence predicted to change over time? (Figure 1. Conceptual diagram, Box 3)

Together with rising temperature and ocean acidification, the terrestrial runoff of nutrients and sediments represent the highest-ranking forms of threats that are impacting the broader GBR (GBRMPA, 2019). The question is of key relevance since there are strong causal links between intense rainfall (and especially intense drought-breaking rainfall) and terrestrial runoff of sediments, nutrients, pesticides and other pollutants into the GBR (SCS Themes 3 to 6). Other climate factors, e.g., temperature, salinity, rainfall, wind waves, are strong predictors for marine productivity, water quality and GBR ecosystem functions (Angly et al., 2016).

The literature review yielded 31 studies that addressed directly or indirectly selected aspects and predictions of the likely effects of climate change on GBR water quality (Table 14). The presentation of these studies follows the conceptual model presented in Figure 2. Haynes et al. (2007) also developed a conceptual model that included longer-term threats to GBR water quality from climate change, through processes such as changes in monsoonal wind direction, rainfall intensity, and flood plume residence times. The studies present evidence that GBR inshore water quality will be further challenged by climate change, in ways similar to those reported from other regions globally (e.g., Li et al., 2020). The studies included in this Evidence Summary include observational and experimental studies, models and reviews (Table 7), as outlined in the paragraphs below.

Evidence of climate change effects on terrestrial runoff

Terrestrial runoff supplies new terrigenous sediments, nutrients and pesticides to the inshore GBR, and is a key factor determining GBR inshore water quality (SCS Themes 3 to 5). Question 4.1 (Robson et al., this SCS) reviews evidence regarding spatial and temporal water quality variability, establishing that there is a strong link between large flood events and reduced inshore water quality. Question 2.2 – 4.1.1.1 above has summarised the projections of climate change induced increases in more extreme daily rainfall events along the whole GBR (with high confidence), in agreement with global climate models (Dowdy, 2015; McInnes, 2015b; Moise, 2015). Some studies also show that rising temperatures magnify the magnitude of surface climate anomalies associated with ENSO events (Power et al., 2017). Hydrological modelling suggests that runoff is likely to increase, with a greater percentage of rainfall converted to runoff during these high-intensity events (Alluvium, 2019).

For the southern GBR (Fitzroy and Burnett Mary NRM regions), projections suggest (with medium confidence) that time in drought will increase over the course of the century, and that extreme drought may potentially also increase in frequency and duration (low confidence) (Dowdy, 2015), with unknown consequences for net loads of sediment and nutrient runoff. In the Burdekin and Wet Tropics regions, projections regarding drought are unclear, but it is projected with high confidence that heavy rainfall events will become more intense (McInnes et al., 2015b; Moise et al., 2015).

The projection of more extreme daily rainfall events, greater time in drought in the southern GBR, and greater ENSO anomalies suggests likely negative implications for land erosion and river runoff into the GBR. Increased runoff would expose the inshore GBR to greater river loads of nutrients and sediments (especially after drought-breaking floods). Depending on wind mixing, it could also lead to more frequent periods of low salinity which can be fatal for marine organisms (Berkelmans et al., 2012). The effects of exposure of GBR mangroves, seagrasses, and corals to such elevated levels of nutrients, sediments and pesticides are the subject of SCS Themes 3, 4, and 5.

However, the magnitude of these increases in rainfall, extreme rainfall events, droughts and proportion of rainfall converted to runoff cannot yet be projected with confidence (Dowdy, 2015) and this is further complicated by non-stationarity in parameters used in hydrological models in climate change scenarios (e.g., Alluvium, 2019). Hence the magnitude of these predicted changes in terrestrial runoff to the GBR has not yet been quantified in the published literature.

Table 14. Examples of studies documenting climate change or 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	Number of studies	References
Review of modelling to link climate change to runoff, rainfall variability, flood risk, water availability.	1	Alluvium, 2019
Reviews of links between climate change and water quality or marine biogeochemistry.	3	Ani & Robson, 2021; Haynes et al., 2007; Li et al., 2020*
Review of influence of climate change on Australian marine systems, including upwelling, nutrients, pH, runoff, suspended sediments.	1	Poloczanska et al., 2007
Long-term variations in runoff, estimated from coral skeletal luminescence in Keppel Islands are influenced by climatic variations predicted by ENSO and PDO indices.	1	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 very likely to be more intense with climate change).	6	See literature reviewed for Q4.1 Robson et al., this SCS, and: Angly et al., 2016; Berkelmans et al., 2012; Hughes, 2003; Jones & Berkelmans, 2014; Roche et al., 2014; Schaffelke et al., 2012
Temperature, rainfall, and sea level rise are altering soil organic carbon stock, nutrients and hence potential runoff and coastal wetland water quality.	1	Duarte de Paula Costa et al., 2021
Climatic variability affects stratification, upwelling and hence primary productivity and chlorophyll <i>a</i> . Surface warming is accompanied by reduced primary productivity.	2	Behrenfeld, 2006; Hoegh-Guldberg & Bruno, 2010
Nitrogen fixation via <i>Trichodesmium</i> blooms may be increasing with climate change.	1	Blondeau-Patissier et al., 2018
Strength of the East Australian Current and upwelling varies in response to climate and ENSO variability.	2	Berkelmans et al., 2010; Weeks et al., 2010
Upwelling amplifies ocean acidification on the outer and midshelf GBR.	1	Schulz et al., 2019
Ocean acidification, pH, aragonite saturation state, dissolved inorganic carbon, acting as water quality parameters.	3	Fabricius et al., 2020; Mongin et al., 2016; Wu et al., 2018
Ocean acidification altering carbon and nutrient cycling.	2	Doney et al., 2009; 2020
Ocean acidification altering primary productivity.	1	Gao, 2012
Climate disturbance affects reef primary production and calcification, in turn altering seawater carbon chemistry signal over the reef.	1	Pisapia et al., 2019

Response type (water quality variable) and summary	Number of studies	References
Temperature affects the sensitivity of organisms to pollutants such as diuron.	1	Flores et al., 2021; Negri et al., 2020
Cyclones are key factors for inshore and midshelf sediment transport and mixing.	3	Carter et al., 2009; Larcombe & Carter, 2004; Orpin 1999

Evidence of increasing temperatures on oxygen, productivity, and critical pollutant thresholds

Many water quality parameters are temperature sensitive, and either directly or indirectly affected by warming temperatures (reviewed in Ani & Robson, 2021). An example of direct effects is that oxygen concentrations in the seawater decline with increasing temperatures (deoxygenation). An example of indirect effects is that metabolic rates and hence oxygen demand of biota that cannot regulate their body temperature (e.g., microbes, plankton, plants, invertebrates, fishes) increase with increasing temperatures. Both direct and indirect effects have flow-on effects on almost every ecosystem function in the GBR.

Several studies have shown how temperature affects metabolic rates of GBR organisms (Tables 10, 11, 14). Increasing temperatures typically accelerate metabolic rates (and hence photosynthesis, growth and respiration) up to a tipping point, beyond which organisms start being temperature-stressed and productivity declines steeply. With higher metabolic rates, food and oxygen demands increase. Oxygen may become limiting for actively mobile animals such as some fishes, as oxygen demand increases with increasing metabolic rates, while seawater oxygen concentrations decline with increasing temperatures (Table 11, Nilsson et al., 2009). Similarly, food may become limiting, since nutrient and energy requirements increase with increasing metabolic rates, leading to trophic shifts, and implications for the concentrations for dissolved nutrients and the standing stock (biomass) and all trophic levels dependent on phytoplankton at the bottom of the food chain (Behrenfeld, 2006; Hoegh-Guldberg & Bruno, 2010).

Several studies have concluded that seawater productivity is declining globally with warming temperatures or increasing CO₂ (Behrenfeld, 2006; Gao, 2012; Hoegh-Guldberg & Bruno, 2010). Planktonic community composition is expected to change as a result of these metabolic rate changes, which could have flow-on effects on food web and fisheries productivity (Ani & Robson, 2021). For example, temperature variation leads to altered seawater productivity, with consequences for sea bird populations (Devney et al., 2009; Weeks et al., 2013). Increasing temperatures may also lead to increased rates of 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 & Robson, 2021).

To date it is unclear how GBR productivity will change, and whether there will be regional. Seawater in the cooler southern end of the GBR is more productive (higher concentrations of chlorophyll, higher standing biomass of macroalgae inshore) than in lower latitudes nearer the equator (Question 4.1, Robson et al., this SCS). A predicted strengthening of the East Australian Current (EAC) may lead to increased upwelling and hence increased production in some offshore sections of the GBR (Weeks et al., 2010). Higher terrestrial runoff of nutrients may provide episodic boosts to productivity in some inshore parts of the GBR. All these factors complicate predictions of net changes for the GBR.

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). Concentrations that lead to ecologically significant effects or mortality today may be beyond threshold levels at higher temperatures. Negri et al. (2020) describe and demonstrate an approach to adjust pesticide guidelines to account for this interactive effect.

Evidence of climate change effects on dissolved inorganic carbon - ocean acidification

Ocean acidification is typically considered a 'climate change' factor (i.e., caused by increased CO₂ in the atmosphere), hence it is covered in detail in Question 2.2 Section 4.1.1.1. However, ocean acidification is also a water quality factor, as CO₂ and bicarbonate ions are important and at times limiting nutrient

for marine photosynthetic organisms, and pH is a chemical seawater property that alters calcification potential. When the additional CO₂ enters the surface seawater, it combines with water molecules to form carbonic acid, reducing pH and carbonate saturation state, and elevating the concentrations of total dissolved organic carbon, bicarbonate ions and CO₂ (Doney et al., 2009; 2020). Carbonate saturation increases with warmer temperatures, however this increase is insufficient to offset the large losses in carbonate saturation state due to ocean acidification (Doney et al., 2020).

GBR ocean acidification has increased directly proportional to atmospheric CO₂ emissions to date, both in an inshore and an offshore station (Fabricius et al., 2020). Observations show that CO₂ has already increased by about 28% since pre-industrial times. This is likely a far greater change than that in the mean concentrations in any other dissolved inorganic nutrient in the GBR (nitrogen dioxide, nitrate, ammonia, silicate and phosphate). For seagrasses and many algae, CO₂ is a limiting nutrient, suggesting rising CO₂ will lead to productivity gains (Gao, 2012) (Tables 10 to 13) and altered carbon and nutrient cycling (Doney et al., 2009; 2020). Rising CO₂ will make little difference for photosynthetic organisms that have carbon concentrating mechanisms.

Superimposed on this trend of rising CO₂ are fluctuations in CO₂ both at diurnal and seasonal 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 CO₂ is temperature dependent. Diurnal fluctuations are predominantly attributable to the metabolism of photosynthetic and calcifying organisms. Photosynthesis leads to CO₂ uptake during the day, and respiration releases CO₂ at night. Calcification removes carbonate ions, which also leads to the release of CO₂, by shifting the carbonate chemistry balance (Doney et al., 2020; Fabricius et al., 2020). If reef communities shift due to climate change towards fewer calcifying algae and corals and more fleshy seaweed (Cooper et al., 2015), the sea water carbonate chemistry organisms are experiencing near the benthos and around reefs will likely display altered magnitudes of diurnal and seasonal fluctuations (Anthony et al., 2011; Pisapia et al., 2019).

Evidence of climate change effects on currents, upwelling, and the resuspension of bottom sediments

The upwelling of deeper water onto the continental shelf onto the outer and midshelf of the GBR can cool waters by up to 5°C, and is an important source of dissolved inorganic nutrients, but it is also elevating CO₂ and hence worsening ocean acidification (Schulz et al., 2019). Due to their coarse spatial resolution of ~1° latitude/longitude, published global climate models do not yet accurately represent the details of ocean currents such as the EAC, 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, 2015c). Downscaled modelling of GBR climate change projections at resolutions that do resolve these effects is underway, but not yet published.

Few studies exist that address how climate change will affect long-shore and cross-shelf transport of seawater through potentially altered wind directions and current strengths. Weeks et al. (2010) and Berkelmans et al. (2010) suggest on the basis of satellite observations that climate change is producing an intensification of the EAC, leading to increased nutrient supply and hence increased ocean productivity adjacent to the Capricorn Eddy. However, some observational and modelling evidence suggests that El Niño periods may be associated with a weaker EAC leading to reduced eddy and upwelling activity and reduced supply of nutrients to the surface (Poloczanska et al., 2007).

The resuspension of bottom sediments is a key factor involved in determining GBR water clarity (SCS Theme 3). Intensifying trade winds should lead to changes in resuspension regimes; however due to the high natural variability and the small effect size attributable to climate change in this parameter (2–4% change; Table 9), the expected change in winter and spring resuspension regime are likely to be minor. In the midshelf region, resuspension events are associated primarily with cyclone activity (Orpin, 1999). As cyclones are predicted to increase in intensity with climate change, but decline in frequency (McInnes, 2015c), the resultant effects on midshelf sediment redistributions remain unknown.

Summary of findings regarding the effects of climate change effects on water quality in the GBR

The evidence reviewed above shows:

- It is very likely that cyclones and extreme rainfall events will become more intense, and this is likely to increase river loads and resuspension of nutrients, sediments and other pollutants, thus reducing water quality in the inshore GBR.
- There is strong evidence that oceanographic processes such as upwelling and the EAC respond to climatic variability. Although the implications of this are not entirely clear, it is likely that the influence of climate change on these processes is resulting in reduced primary productivity. It may also be driving increased *Trichodesmium* blooms.
- Increased CO₂ concentrations are also driving ocean acidification, reducing pH and increasing dissolved inorganic carbon.

Changes in temperature mediate a range of metabolic and biogeochemical effects. The implications of these for water quality are difficult to predict but may include reduced oxygen concentrations.

4.1.2 Recent findings 2016-2022 (since the 2017 SCS)

Chapter 1 of the 2017 SCS summarised the main points of observed and predicted climate change and observed severe weather events prior to 2017. Since then, the GBR has been subject to further climate impacts, but the findings of this question are still largely current. The 2017 SCS did not include in-depth coverage of questions equivalent to the impacts on climate change on GBR water quality, organisms and ecosystems (Q2.2 and Q2.2.1, Sections 4.1.1.2 and 4.1.1.3). Therefore, this Evidence Summary jointly assessed the retrieved 207 studies before and 113 studies after 2017, rather than splitting the assessment by the 2017 date. Overall there seemed no substantial change in broad research directions and findings around that year, instead the new studies provided additional and confirmatory evidence.

Two exceptions to this general statement apply. First, the last five years have documented the increasing role of coral bleaching as a major cause of coral mortality; models for 2020 estimated bleaching to now contribute 48% to simulated GBR-wide annual model rates of coral mortality, ahead of cyclones (41%) and COTS predation (11%) (Bozec et al., 2022), and up from the previous estimate of 10% of coral loss attributed to bleaching in 1985 to 2012 (De'ath et al., 2012). Second, there has been rising awareness of the role of cumulative impacts from climate change and water quality. Studies now show that recovery times for coral cover have slowed (Ortiz et al., 2018; Osborne et al., 2017), and that water quality (e.g., suspended solids) co-determines coral recovery times on some inshore reefs (Bozec et al., 2022). These new findings have important implications for GBR management, for the urgency to address carbon emissions, and the need to meet GBR water quality targets by 2030, before climate impacts overwhelm reef recovery potential.

4.1.3 Key conclusions

This Evidence Summary summarises the existing data on rates of climate change in the GBR, and its impact on GBR ecosystems, organisms and water quality. The synthesised regional observational and modelling studies showed, with high confidence, that the GBR along its entire length is rapidly warming, becoming less alkaline, and that sea level is rising. GBR region-specific or regionally relevant observational and modelling studies are confirmed by many global models and observations. The prediction of increasing rainfall variability, with more frequent intense rainfall events in the GBR also has high confidence, albeit the magnitude of the increases cannot be confidently projected. These predictions parallel similar conclusions from many regions around the world.

The conclusion is that climate change has already started to significantly alter the environmental settings for tropical marine organisms and ecosystems like the GBR. Climate change pressures will continue to increase in the GBR, with the intensity of changes experienced towards the middle, and even more towards the end of the century depending on CO₂ emissions pathways (IPCC, 2021), although climate feedback loops (clouds, currents etc.) are still poorly resolved and understood.

Of particular concern is the rapid rate of change. For example, the 2015 model estimates⁸ suggest that near-coastal sea surface temperature will have increased again by 0.3 to 1.1°C between the reference

⁸ <https://www.climatechangeinaustralia.gov.au/en/>

period (1986 to 2005) and the year 2030, on top of the ~1.0°C warming observed in 1910-2022 (Section 4.1.1.1).

This Evidence Summary also synthesised the multiple lines of evidence about how and by how much climate change is affecting GBR organisms and ecosystems (Sections 4.1.1.2), and GBR water quality (4.1.1.3). Intensifying extreme rainfall variability is increasingly contributing to challenge GBR water quality. Of great concern is the prediction that conditions that lead to heat-induced coral bleaching will become almost annual by 2040. Of additional great concern is that by 2030, some reefs will already start experiencing a carbonate saturation state below the ecologically critical level of 3.5, with likely implications for reef recovery rates.

4.1.4 Significance of findings for policy, management and practice

This Evidence Summary confirms the importance of meeting all GBR water quality targets by 2030, before conditions that lead to heat-induced coral bleaching become near-annual and ocean acidification starts leading to a negative carbonate balance in some reefs. The cumulative effects of how GBR water quality improvement may help the GBR dealing with climate change have been outlined through multiple pathways:

- More extreme rainfall events and rainfall variability suggest significant greater challenges to meet GBR water quality targets, since the association between severe rainfall and terrestrial runoff of sediments, nutrients and pesticides is firmly established (SCS Themes 3 to 5).
- More frequent droughts in the southern GBR over the course of the century also suggest significant greater challenges to meet GBR water quality targets, as sediments loads tend to be highest in drought-breaking floods (SCS Theme 3).
- The many diverse and often nuanced effect of water quality on reef health and reef recovery rates from disturbances are firmly established (SCS Themes 3 to 5). Rapidly intensifying climate change increases the frequency and severity of disturbances to GBR ecosystems, due to heatwaves, more intense cyclones, and sea level rise. This increases the relevance of maintaining high water quality to facilitate ecosystem recovery from these disturbances.
- Several effects of ocean acidification on reefs (proliferation of fleshy macroalgae, greater bioerosion, negative effects on coral recruitment, negative effects on crustose coralline algae) are similar in their direction to the effects of poor water quality, suggesting water quality improvement may mitigate some of the effects of ocean acidification on reefs.
- The dual links between warming temperatures and reproductive success in the coral eating crown-of thorns starfish., and between chlorophyll and the survival of their larvae reinforces the importance of water quality management under rising temperatures.
- The Evidence Summary has identified some regional differences in exposure and vulnerability, suggesting that there will need to be region-specific management responses to changing climate. For example:
 - Climate models predict overall less bleaching inducing temperature stress in the northern GBR compared to the central and southern GBR.
 - Changes in cyclone frequency and intensity applies to the GBR north of about latitude 20°S.
 - Changes in drought intensity is affecting the GBR south of about latitude 20°S.
 - Changes in upwelling affect nutrient supply to offshore reefs.
 - More severe episodic runoff from intensifying rainfall extremes is predominantly affecting the inshore GBR, although the offshore may also be affected due to the links between floods and outbreaks of crown-of-thorns starfish, and offshore transport of pollutants in the narrower GBR north of about latitude 18°S.
 - Ocean acidification is affecting the whole GBR, however, saturation state declines with temperatures and there are indications for coastal acidification, making the southern inshore reefs potentially the most vulnerable to ocean acidification. It is likely that water quality improvements may be especially beneficial in these areas.

- For scientists conducting climate change experiments, it would be advisable to standardise and adhere to treatment values in line with those predicted for the GBR (Table 9).

Together with urgent efforts to prevent further atmospheric carbon dioxide pollution globally and nationally, the Evidence Summary suggests that local management tools are rapidly becoming more important to mitigate these climate change impacts, before mass coral bleaching becomes almost an annual occurrence in the GBR.

4.1.5 Uncertainties and/or limitations of the evidence

The following uncertainties or limitations of the body of evidence need to be considered (together with those listed in Table 17):

- There is still little evidence on quantitative answers to the questions about how the climate change impacts on ecosystems and water quality differ across regions and habitats, and when they will reach critical levels throughout this century.
- For the question on climate change effects on GBR water quality, few direct study approaches exist. The synthesis on the links between rainfall variability and water quality was based on a causal evidence chain (climate change affects extreme rainfall, which in turn affects runoff, which in turn affects inshore water quality).
- It is well known that studies that show ‘no effects’ are severely underrepresented in the scientific literature.
- Of the dozens of ecosystems and hundreds of thousands of species inhabiting the GBR, the responses of only a few have been studied to some of the climate change agents, and even fewer to the interactive effects of climate change and other threats.

4.2 Contextual variables influencing outcomes

Table 15 provides key points summarising the influence of the main contextual variables on the question outcomes or causal relationships.

Table 15. Summary of contextual variables for Questions 2.2 and 2.2.1.

Contextual variables	Influence on question outcome or relationships
El Niño / La Niña	See Section 4.1.1. In brief, ENSO may become more intense, effects from ENSO on precipitation and heatwaves occur superimposed on warming, hence extreme rainfall and heatwave events may get more severe (Table 9).
Hydrodynamics, connectivity	See Sections 4.1.1.3. In brief, GBR sections within reach of flood plumes will have impaired recovery from climate related disturbances (SCS Themes 3 and 4). Well-flushed and well-connected areas will experience reduced impact and recover more quickly.
Land use change	See SCS Themes 3, 4, 5. Greater river loads of nutrients and sediments impair reef recovery from climate related disturbances, and climate change related effects on water quality (Section 4.1.1.3).
Fishing pressure	Altered fish communities (e.g., fewer top predators, fewer herbivores etc.) impair reef recovery from climate related disturbances (Mellin et al., 2016).
Adaptation and Acclimatisation	Understanding rates and limits of ecological acclimatisation and evolutionary adaptation to warming temperatures, more severe temperature anomalies, and ocean acidification, is a key knowledge gap. The topic ecological adaptation for the GBR was reviewed by Evans et al. (2012), who summarised existing evidence for each of the three processes of acclimatisation and adaptation: (a) shifts in geographic distribution (latitude, landward, depths), (b) shifts in physiology, and/or (c) genetic changes at the population level. This important review warrants an update, as the topic is a key priority for climate change research. Studies are typically presented with a

Contextual variables	Influence on question outcome or relationships
	<p>global readership in mind, so would fail to populate literature searches with a regional focus, for example, seasonal acclimatisation to temperature in GBR corals. Ainsworth et al. (2016) found that if a sublethal temperature stress period preceded a severe temperature anomaly, then coral bleaching severity may be diminished. However, they also reported that a global temperature increase of as little as 0.5°C removes this protective sublethal SST stress period. On the other hand, (Hughes et al., 2017) found that the extent of exposure to previous bleaching events in 1998 and 2002 did not lessen the severity of bleaching in 2016, suggesting limited scope for acclimatisation or adaptation.</p> <p>The knowledge about marine ecosystems to adapt to acidifying seas is particularly sparse, despite the predictable and universal distribution of this rising stressor, and geological evidence that suggests that past acidification events led to global hiatuses in the existence of coral reefs (Veron et al., 2009).</p>
Interactions between different types of impacts	See Question 2.4, Uthicke et al., this SCS.

4.3 Evidence appraisal

Relevance

The overall relevance of the overall body of evidence for Q2.2 was High. The individual indicators scored High for overall relevance to the question, Moderate for spatial relevance, and Moderate for temporal relevance. Of the 273 articles included in the synthesis of Q2.2, 165 were given a High score for overall relevance to the question, while 93 and 15 studies had a Moderate or Limited score for overall relevance. Spatial relevance scores were overall slightly lower, with 70 and 151 studies with High and Moderate spatial scores, respectively. Fifty-four studies scored High for temporal relevance, and 126 scored Moderate for temporal relevance.

In the context of this question, the High overall relevance reflects efficient filtering of unrelated studies. The Moderate rating for spatial relevance is not surprising given the large spatial extent of the GBR and its many spatial gradients in its biota and ecosystems. Similarly, the Moderate rating for temporal relevance reflects the experimental and observational limitations in testing the effects of climate change, with limited scope to introduce acclimatisation, and few studies on evolutionary adaptation. It also reflects the many temporal horizons over which climate change will play out, with critical levels of temperature, ocean acidification, sea level rise etc. varying between taxa.

Consistency, Quantity and Diversity

There was High consistency in the prediction of changes by 2030 and 2090 across the various climate change agents. There was also High consistency across the studies in reporting that climate change is significantly impacting many of the tested organisms and ecosystems, although the response types, the severity of impacts and thresholds varied across organisms and ecosystems. The combined body of evidence that climate change has already started to affect the GBR was strong. The evidence that this threat on ecosystem health will continue to intensify throughout this century can also be considered as High. The consistency of findings with studies conducted outside of the GBR was also high albeit not quantitatively assessed here.

The overall quantity of studies was High (317 studies). A Moderate number of quantitative studies (21) were available for the summary of estimates of rates of climate changes by 2030 and 2090 across the various climate change agents. There was an overall High quantity of studies (273) assessing the impacts on organisms and ecosystems, however studies were unevenly distributed and for most individual

ecosystems and response types, the number of studies was Limited within the GBR. The number of studies used as evidence for the effects of climate change on GBR water quality was Moderate (31). However, when combining the lines of evidence from different types of studies ('experimental', 'observational', 'modelling' and 'reviews'), the overall evidence is considered as High.

The Diversity of studies was considered as High, reflecting the numerous ecosystems and climate change impact types, and the spread of the studies across study types (main question: 119 observational, 123 experimental, 65 modelled and 17 reviews or meta-analyses).

Confidence

Overall, the confidence in the body of evidence used to answer the primary question, and the secondary question, using the evidence appraisal results is High (Table 16). There was a large number of relevant studies, a High diversity of study approaches, and multiple lines of evidence to explain how the climate is changing, how climate change is impacting GBR organisms and ecosystems, and how climate change is currently influencing water quality in coastal and marine areas of the GBR. There is presently Moderate confidence in the temporal component of the question, namely estimating timelines for predicted impacts of climate change on GBR ecosystems and on water quality. There is presently Moderate confidence in the spatial component of the question, namely the spatial distribution of impacts.

Table 16. Summary of results for the evidence appraisal of the whole body of evidence used in addressing Questions 2.2 and 2.2.1. The overall measure of Confidence (i.e., Limited, Moderate and High) is represented by a matrix encompassing overall relevance and consistency.

Indicator	Rating	Overall measure of Confidence
Relevance (overall)	High	
-To the Question	High	
-Spatial	Moderate	
-Temporal	Moderate	
Consistency	High	
Quantity	High (317 studies in total).	
Diversity	High (37% observational, 32% experimental, 22% modelled and 9% reviews)	

4.4 Indigenous engagement/participation within the body of evidence

No significant Indigenous engagement and/or direct participation was recorded in the studies within the body of evidence.

4.5 Knowledge gaps

There are numerous key research gaps, with implications for policy and management. Some of the many knowledge gaps are listed in Table 17.

Table 17. Summary of knowledge gaps for Questions 2.2 and 2.2.1.

Gap in knowledge (based on what is presented in Section 4.1)	Possible research or Monitoring & Evaluation (M&E) question to be addressed	Potential outcome or Impact for management if addressed
2.2		
Winners and losers in GBR ecosystems under climate change.	What are the temperature optima, and what is the acclimatisation potential, for keystone taxa, functional groups, and threatened species? How is their thermal tolerance influenced by environmental factors such as OA, nutrients, light, turbidity, etc.?	Better predictions of future ecosystem states and species performances.
Rates of evolutionary adaptation to warming and acidification for key taxa.	What are the rates of evolutionary adaptation for key taxa to warming and ocean acidification, identified through literature reviews from other ecosystems, field genetic studies and multi-generational experimental studies?	Better understanding of GBR adaptation potential and future ecosystem states.
Role of far northern GBR in providing temperature tolerance.	What is the difference in temperature tolerance between organisms in the far northern GBR compared to those living further south? Are there connectivity bottlenecks between the far northern and the northern reefs?	Potential for moving corals further south to assist adaptation. Better understanding of GBR connectivity and natural regions.
Rates of range shifts for many key taxa.	What is the scope for latitudinal range extension for the far northern genotypes, would they face other limitations (e.g., light) further south?	Better understanding of GBR connectivity and natural limitations to ecological adaptation.
Responses of mesophotic reefs, deeper seagrass meadows	How do mesophotic reefs, deeper seagrass meadows and other deeper water communities respond to climate change? How can we cost-effectively improve deepwater monitoring through new RUV oceanographic and ecological surveys, physiological studies?	Better understanding of the existence of potential climate refugia in deeper waters.

Gap in knowledge (based on what is presented in Section 4.1)	Possible research or Monitoring & Evaluation (M&E) question to be addressed	Potential outcome or Impact for management if addressed
Natural rates of reef recovery in different environments.	When and where will disturbance frequencies be too high to overwhelm recovery potential, and how can good water quality help?	Better understanding of the potential for natural adaptation in the GBR, improved predictions of the future of the GBR, of the merits of water quality improvement
2.2.1		
Effects of climate change on GBR water quality: Spatial differences in impacts.	Modelling study combining climate predictions with ecosystem response studies.	Better understanding of potentially growing water quality challenges in the different NRM regions.
Systematic numerical study linking GBR water quality to climate change.	Can we quantify region-specific GBR water quality responses to different climate change scenarios, using modelling and prediction?	Better informed water quality management.
Cumulative effects of climate change on water quality.	What are the region-specific responses of numerous ecosystem processes (and organisms, from microbes to invertebrates and key marine plants), to the cumulative effects of climate change and water quality?	Better understanding of the future health of the GBR.
Effects of climate change on GBR water quality: Temporal considerations.	For how long will water quality be beneficial for reef recovery times under increasing frequency of marine heatwaves, identified through modelling study, combining climate predictions with ecosystem response studies?	Better understanding of potentially growing water quality challenges in the different NRM regions.

5. Evidence Statement

The summary of the evidence for **Question 2.2 and 2.2.1** was based on 317 studies, primarily undertaken in the Great Barrier Reef and published between 1990 and 2022. The synthesis includes a *High* diversity of study types (37% observational, 32% experimental, 22% modelled and 9% reviews), and has a *High* confidence rating (based on *High* consistency and *High* overall relevance of studies).

Summary of findings relevant to policy or management action

Studies over the last three decades confirm that the climate of the Great Barrier Reef is changing rapidly and in multiple ways, with some changes already significantly impacting Great Barrier Reef ecosystems and selected organisms. These studies also clearly show that impacts are predicted to intensify rapidly throughout this century, with severity depending on CO₂ emissions pathways. Climate change is now widely accepted as the most significant threat to the long-term outlook of Great Barrier Reef coral reef ecosystems. The main climate change agents known to affect coastal and marine ecosystems include: warming temperatures, increasing frequencies of marine heatwaves, increasing ocean acidification, extreme rainfall events, changes to the frequency and intensity of droughts and drought-breaking floods, sea level rise, and a potential reduction in the frequency but increasing intensity of tropical cyclones. Of great concern is the prediction that conditions that lead to heat-induced coral bleaching will become almost annual by 2040, depleting sensitive species and severely threatening the ecosystem integrity of coral reefs. By 2030, the evidence consistently indicates that some reefs will already start experiencing a seawater carbonate saturation state below ecologically critical levels, diminishing reef accretion and reef recovery rates. The strong link between rainfall extremes and terrestrial runoff of pollutants into the Great Barrier Reef show that climate change is already impacting Great Barrier Reef water quality, and these impacts will continue to intensify. The evidence also demonstrates the cumulative impacts from climate change and water quality, with the latter adversely affecting recovery times and community composition as climate disturbances are becoming more frequent and intense. The evidence confirms the urgency of meeting all Great Barrier Reef ecologically relevant water quality targets within the next decade before climate impacts exceed the capacity for reef ecosystems to persist.

Supporting points

- Studies verify that periods of extreme sea surface temperatures (exceeding the long-term maximum summer monthly means by six or more 'degree heating weeks' i.e., the product of temperature exceedance and duration) are causing mass coral bleaching and can lead to mortality.
- Thermal extremes also cause stress and damage to numerous other marine organisms including some species of fish, sponges, and seagrasses.
- Effects of ocean acidification on reefs (proliferation of fleshy macroalgae, greater bioerosion, negative effects on coral recruitment, negative effects on crustose coralline algae) are similar in their direction to the effects of poor water quality, suggesting water quality improvement may mitigate some of the effects of ocean acidification on inshore reefs.
- Modelling studies attribute substantial loss of reef performance to local stressors, in addition to the losses from climate change. They conclude that management strategies to alleviate cumulative impacts have the potential to reduce the vulnerability of some reefs, but only if combined with strong emissions mitigation.
- 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 Great Barrier Reef ecosystems and functions that are less immediately threatened by climate change.
- Increasingly extreme rainfall events along the whole Great Barrier Reef suggests significantly greater challenges to meet Great Barrier Reef water quality targets, as severe rainfall leads to more severe terrestrial runoff of sediments, nutrients and pesticides.

- The review demonstrated regional differences in exposure and vulnerability to climate change:
 - 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 zones compared to the Northern and Far Northern zones where cloud cover may increase.
 - Predictions of reduced cyclone frequency and increasing intensity applies to the Great Barrier Reef north of about Latitude 20°S (Bowen), not to the southern Great Barrier Reef.
 - More severe episodic runoff from intensifying rainfall extremes will predominantly affect the inshore Great Barrier Reef, although the offshore may also be affected due to the links between floods and outbreaks of crown-of-thorns starfish, and offshore transport of pollutants in the narrower Great Barrier Reef north of about Latitude 18°S.
 - Predictions about increasing drought intensity mostly relate to the Great Barrier Reef south of about Latitude 20°S.
 - Frequency of droughts may increase during this century in southern Great Barrier Reef basins, adding to challenges to meet water quality targets, as sediment loads tend to be highest in drought-breaking floods.
 - Predicted increase in upwelling due to a strengthening East Australian Current (EAC) would increase offshore nutrient supply in the central Great Barrier Reef.
 - Ocean acidification is affecting the whole Great Barrier Reef, however, carbonate saturation state is temperature dependent (increases with warmer temperatures) and there are indications of coastal acidification, making the southern inshore reefs potentially the most vulnerable to ocean acidification.

These points suggest region-specific differences in management responses to changing climate, including greater challenges to meet Great Barrier Reef water quality targets in some locations.

- Altered sensitivity of some organisms to pollutants under warming temperatures highlights that water quality guideline values may need to be adjusted as the climate changes.
- Some threatened species may become critically endangered due to additional pressure from climate change (e.g., sea turtles due to their temperature-controlled hatchling sex determination), confirming the need for climate change specific threatened species management plans.

6. References

The 'Body of Evidence' reference list contains all the references that met the eligibility criteria and were counted in the total number of evidence items included in the review, although in some cases, not all of them were explicitly cited in the synthesis. In some instances, additional references were included by the authors, either as background or to provide context, and those are included in the 'Supporting References' list.

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Appendix 1: 2022 Scientific Consensus Statement author contributions to Question 2.2

Themes 1 and 2: Values, condition and drivers of health of the Great Barrier Reef

Primary Question 2.2 What are the current and predicted impacts of climate change on Great Barrier Reef ecosystems (including spatial and temporal distribution of impacts)?

Secondary question 2.2.1 How is climate change currently influencing water quality in coastal and marine areas of the Great Barrier Reef, and how is this predicted to change over time?

Author team

Name	Organisation	Expertise	Role in addressing the Question	Sections/Topics involved
1. Katharina Fabricius	Australian Institute of Marine Science	Tropical marine ecologist	Lead Author	All Sections
2. Aimee Brown	Private Consultant	Marine scientist	Contributor	Searches and data extraction, co-writing of all sections
3. Barbara Robson	Australian Institute of Marine Science	Oceanographer	Contributor	Co-writing of 4.1.1.1, and final revision of overall report
4. Al Songcuan	Private Consultant	Marine scientist	Contributor	Searches and data extraction
5. Catherine Collier	James Cook University	Tropical marine ecologist	Contributor, Expert advice (seagrasses, mangroves)	Section 4.1.1.2 (seagrasses), final revision of overall report
6. Sven Uthicke	Australian Institute of Marine Science	Tropical marine ecologist	Contributor	Final revision of overall report