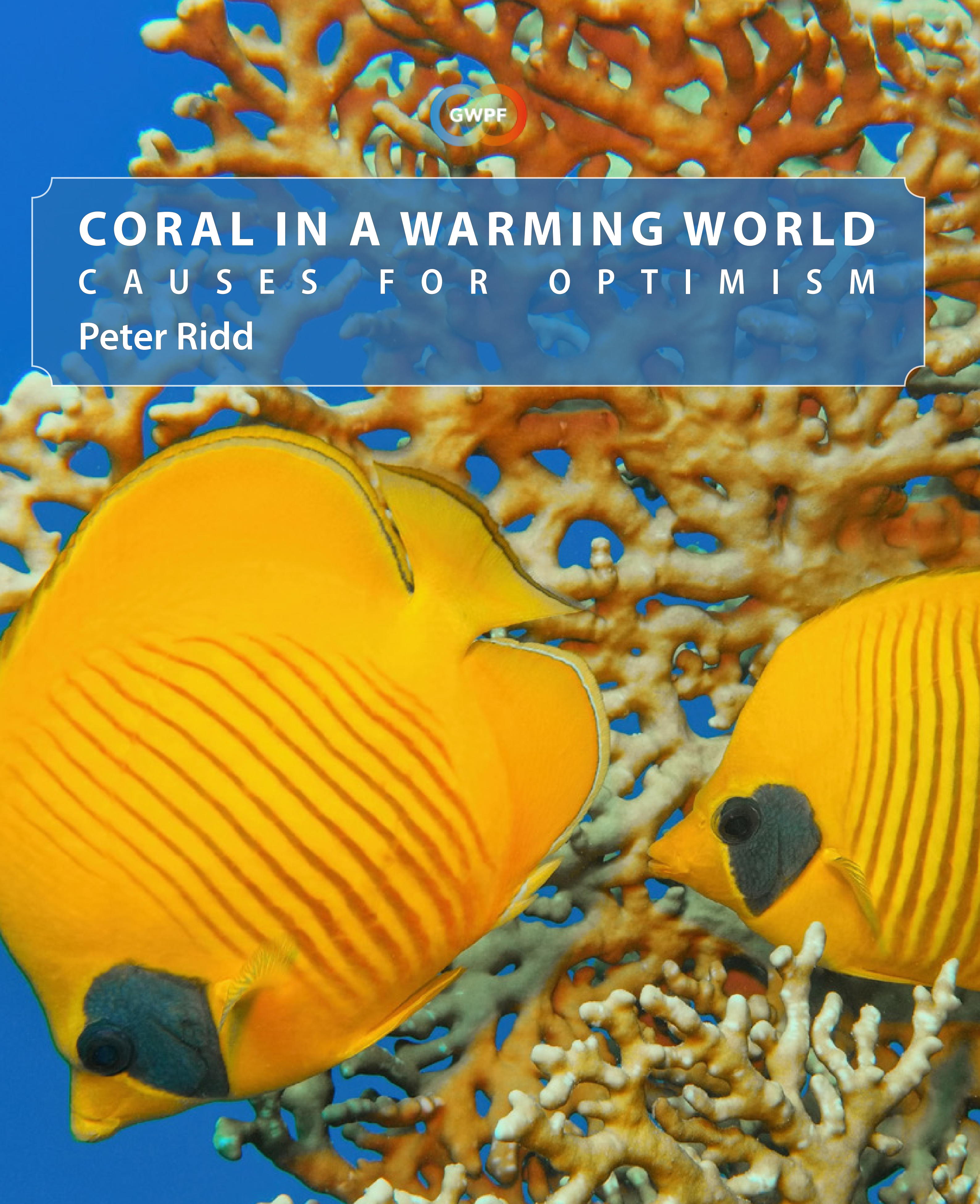
CORAL IN A WARMING WORLD

CAUSES FOR OPTIMISM

Peter Ridd



The Global Warming Policy Foundation
Report 55

Coral in a Warming World: Causes for Optimism
Peter Ridd
Report 55, The Global Warming Policy Foundation

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About the author

Peter Ridd is a physicist. He has researched the Great Barrier Reef since 1984, and has published over 100 scientific publications. A former head of the Marine Geophysical Laboratory at James Cook University, Townsville, Australia, he was fired in 2018 for pointing out quality assurance deficiencies in reef-science institutions. He presently works, without payment, on science quality assurance issues. He is an adjunct fellow of the Institute of Public Affairs and a member of the Academic Advisory Council of the Global Warming Policy Foundation.

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Dissenting response

In accordance with our policies, GWPF invited a response to this paper from authors likely to dissent from its conclusions. None of the authors who were contacted accepted this invitation.

Executive summary

Coral data

- The most reliable long-term record of coral cover of a large area is from the Great Barrier Reef. Its cover varies greatly from year to year, but in 2022 was at the highest level since records began in 1985, and double the level in 2011.
- Of the 3000 individual reefs of the Great Barrier Reef, none have been lost, and all have excellent coral, although there are large fluctuations in cover from year to year, mostly as a result of cyclones and starfish predation.
- Data for other parts of the world is less reliable, and is only useful for the last two decades.
- Aggregated over the whole world, the data does not support the proposition that there has been a major drop in coral cover. At worst, there might have been a reduction of 7% from 2000–19, but the stated error margin is of similar size to the difference. In addition, natural variability of the data is also around 10% – higher than the difference between 2000 and 2019.
- Data for the East Asia Seas coral bioregion, with 30% of the world's coral reefs, and containing the particularly diverse 'Coral Triangle', show no statistically significant net coral loss since records began.
- Outside Australia, there is a need to improve standardisation and randomisation of data sets.

Coral bleaching

- The most comprehensive data, by far, on coral bleaching due to high water temperatures comes from the Great Barrier Reef. This indicates that the overall impacts are very minor. Current record coral cover comes despite four supposedly catastrophic bleaching events in the six years prior to 2022.
- Coral usually takes at least 5–10 years to regrow from a major mortality event, so the record high coral levels in 2022 suggests reports of massive mortality events were erroneous. This raises serious questions about integrity in science institutions and in the media.
- Coral bleaching occurs when corals expel the symbiotic algae (zooxanthellae) that live inside them, often subsequently replacing them with a different species when they recover. The process makes them highly adaptable to changing temperatures.
- Most corals that bleach do not die.

In conclusion, the future of the world's reefs is much less discouraging than is often thought, at least from the impacts of climatic temperature variations. It is now clear that many of the institutional claims of massive permanent coral loss have been greatly exaggerated. It seems probable that a pessimistic groupthink has taken hold of large sections of the coral reef science community, affecting the clarity with which some in that community observe the world's reefs.


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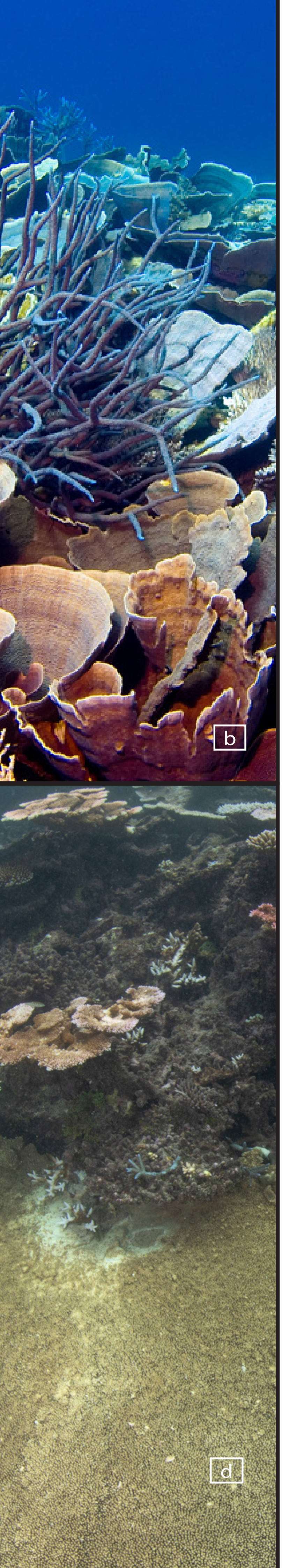


1. Introduction

It is often claimed that coral reef ecosystems are particularly sensitive to anthropogenic climate change,[1] and have been badly damaged in recent decades.[2] They are supposedly the 'canary in the coal mine',[3] and have become the frontline of the climate debate. In 2018, the Intergovernmental Panel on Climate Change (IPCC) stated that

> Coral reefs, for example, are projected to decline by a further 70–90% at 1.5°C (high confidence) with larger losses (>99%) at 2°C (very high confidence).[4]

This report has three major sections. Sections 2 and 3 review data on the condition of the coral reefs of the world, and attempt to determine whether the trajectories of reefs are as dire as is often portrayed. They also review the data on how much coral has been lost due to thermal 'bleaching'. Section 4 reviews the remarkable ability of corals to adapt to rising temperatures by changing the symbiotic algae that reside inside them. Research in recent decades has shown that bleaching is part of a remarkable adaptive mechanism that makes coral potentially one of the organisms that is least susceptible to rising temperatures.

This report will not consider in any detail the many non-climate related threats that coral reefs face, especially in parts of the world where there is very little protection or useful management. These threats include over-fishing, invasive species, and pollution.

Corals and coral reefs

It is worth considering the biology of corals before delving deeply into the data. Hard coral colonies are made up of thousands to millions of polyps – small animals that are from millimetres to a centimetre across. Their colonies can range from a few centimetres to meters in size (Figure 1). The polyp of hard corals (Figure 1a) is an animal that makes its pot-shaped home from calcium carbonate, which is as hard as concrete. Unlike woody plants, coral skeletons do not decompose, and can last millions of years after the death of the animal.

Figure 1: (opposite) Corals

(a) Individual coral polyps. (b) corals come in a myriad of forms and sizes. These are fast growing and delicate 'plate' and 'staghorn' corals that are extremely susceptible to damage by storms and starfish plagues. They are also the most susceptible to thermal bleaching. (c) An example of a 'massive' coral. These are slow growing but can live for centuries. They are relatively unsusceptible to bleaching. (d) Coral cover on top of this 'bommie' is 100% (1.0). In the deeper water in the bottom left corner, the coral cover is considerably less than 50% (0.5) – there is considerable dead coral, and sand.

Over time, the dead coral skeleton builds up to form 'coral reefs', which often rise 100m above the seabed, up to the water's surface (Figure 2). A coral reef[5] is therefore a thin veneer of live coral sitting on top of a pile of dead coral. Corals usually grow on coral graveyards.

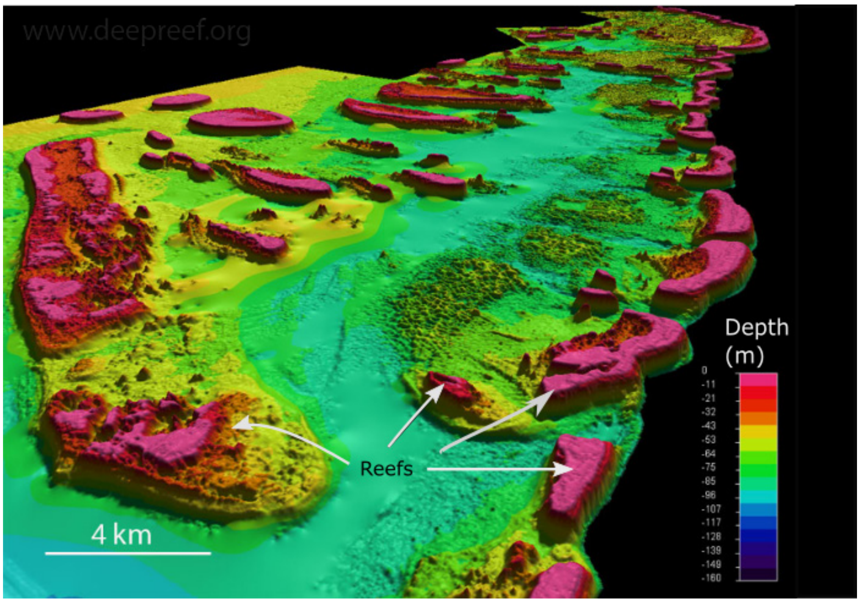


Figure 2: Reef structure

Coral reefs are a thin veneer of living coral residing on a pile of coral rubble or thick beds of consolidated coral rubble. These reefs from the Great Barrier Reef are flat–topped underwater hills around 50–100 metres high sitting on a relatively flat continental shelf. Coral reefs require continuous coral death to grow to the sea-surface. (Courtesy R. Beaman, deepreef.org)

Corals can grow in a wide variety of climates, but are far more abundant in tropical waters than in temperate regions. The area of most coral diversity, the 'Coral Triangle',[6] in the seas around Indonesia, Papua New Guinea and the Philippines, is located at the centre of the Indo-Pacific Warm Pool – the hottest large water body on earth. This is not a coincidence. For every 1°C reduction in water temperature, there is a roughly 15% reduction in growth rate.[7]

Corals are also found in colder water, such as Scotland and Alaska, but their growth rate in these places is so slow that they are unable to form reefs.

2. Coral abundance on the world's reefs

Barely a month goes by without a major media report of the loss of coral somewhere in the world due to climate change. Examples of these claims are that the Great Barrier Reef (GBR) lost half its coral after 1995,[8] and that the world has lost 14% of its coral since 2009.[9]

This report will consider available data to determine the trajectory of coral reefs. Two datasets will be considered:

- the Australian Institute of Marine Science Long Term Monitoring program for the GBR
- the Global Coral Reef Monitoring Network (GCRMN) data for reefs around the world.

Using this information to determine the long-term trajectory of the amount of coral on reefs is made difficult because data collection on reef condition only started a few decades ago, and even today is relatively sparse. There are no century-long records such as exist for meteorological observations. The GBR, which has about 13% of the world's coral reefs, has by far the most reliable and longest record (37 years) for a large-scale system. GCRMN data is generally only useful since the late 1990s because of insufficient data collection before that time.

Unlike Australia, which has a huge amount of coral within a marine national park that has been well-monitored and protected since the 1970s, most other countries have much smaller amounts of coral, monitoring of which was almost non-existent until the end of the 1990s. Even today, monitoring by the GCRMN is generally sporadic, and uses inconsistent sampling methodologies.

Of primary interest in this report are the recorded changes in the amount of (hard) coral. However, reefs also contain many other organisms: soft corals, and algae, including the crustose coralline algae that are the 'cement' that binds together the broken bits of coral. Reefs often have large areas of bare sand and sediment. There should be no expectation that they should all have 100% hard coral cover. The main concern of the effect of increasing global temperature is whether the amount of coral has decreased and been replaced by other habitat types, such as algae.[10]

Because most of a reef is underwater, determining long-term changes in condition is difficult; historical archives of aerial photographs cannot be used.[11] This is in contrast to monitoring the decline of the world's tropical rainforests, where clearing of rainforests has been documented for about a century. The reduction in rainforest extent in Africa, Asia, and South America can be easily inferred from old maps and modern aerial photographs. For example, Google Earth images can be used to infer a 50% loss of Australian tropical rainforest, and almost total loss of lowland rainforest, since the European settlement, due to clearing for agriculture. Farms are now located where rainforest would once have been. However, for the GBR, all that can be said is that there has been no physical destruction of any reef on the scale of clearing for agriculture. All 3000 of GBR's reefs still exist, and all have coral on them.

Physical destruction of some reefs around the world *has* occurred: for development of ports and airports, and quarrying for cement. This much can be easily observed from satellite. China's recent destruction of entire reef tops for military bases in the South China Sea is an obvious example.[12] But generally, the changes to reefs are far more subtle than the wholesale environmental destruction that has occurred on land. In addition, reefs often have considerable variability in the amount of coral and other organisms, and comparison of a reef from one period to another is not necessarily useful in determining long-term trends. Thus, in looking for changes in coral cover on reefs, we are looking for quite subtle shifts, over long periods of time. Is there less coral on a reef and more of other species, such as coralline algae or macroalgae?

Monitoring coral reefs is not easy

Even today, monitoring of reef condition is very limited, due to the wide areas that have to be covered, and the extreme cost involved. Even to monitor a small subset of a reef system involves many divers and is therefore highly labour-intensive.

Large tracts of reefs can be surveyed using 'Manta-tows' (Figure 3), a kind of visual census, which involves a diver, towed behind a small boat along a transect, estimating the percentage cover, type and condition of the coral over 100 meters or so. Manta-tows give a quick – broad-brush – estimate of total coral over a very large area. The diver is trained, but there is a degree of subjectivity to these estimates.[13] Each reef is many kilometres/miles long around its perimeter, so there could be roughly 50 to 100 individual estimates for each reef.

Figure 3: Manta tow

A scientist from the Australian Institute of Marine Science surveying a reef using the manta-tow method (Image: AIMS).

Shorter transects of reefs can be sampled more accurately, but far more slowly, using benthic surveys, which involve taking photos roughly every 1 meter. These give a more detailed picture of a very small area – transects are typically less than 100 m long.

In order to appreciate the magnitude and difficulty of the task of monitoring reef systems, it is useful to consider the GBR, which has, by far, the most comprehensive monitoring program in the world. Carried out by the Australian Institute of Marine Science (AIMS), the 'Long Term Monitoring Program' (LTMP) only started in the mid-1980s – sporadic data exists for earlier periods, but is too limited for determining long-term trends. The GBR is huge – larger than Germany and as long as California – and has 3000 individual reefs, each a few kilometres across. AIMS surveys roughly 100 of the reefs each year using Manta tows, which means they cover roughly 1000 km each year. Despite this huge distance, the area surveyed represents only roughly 0.003% of the total area of the marine national park. In addition, AIMS covers around 100 small set transects with benthic surveys.

The data available from the AIMS LTMP is therefore severely limited by the inherent difficulty of manually monitoring coral reefs. Artificial intelligence methods and underwater drones are currently being developed in the hope that these will enable far more cost-effective, and therefore far more comprehensive, surveys. However, this is for the future.

As well as limitations in the monitoring of reefs because of scale and cost, another common problem with media and scientific reports on reefs is that not enough consideration is given to:

- the short time periods for which data are available
- measurement uncertainties in the data
- the different methods used for collecting data.

These factors are all very important for interpretation of a dataset. Much of the data has a high uncertainty margin, so small variations in coral can be impossible to resolve. In addition, natural variability must be considered. As shown later in this paper, coral reefs often go through major cycles of death and regrowth completely naturally. A periodic major 'loss' of coral may be normal. Only if there is a failure to regenerate is there a real problem.

Data sources, quality, and comparability

Surveys of reefs usually include some measure of 'coral cover', which is the fraction of the seafloor on a reef covered by hard coral. In most of this report a normalised coral cover unit will be used. 1.0 represents complete cover by hard corals, and 0 represents no coral.

Unlike this report, coral cover is often stated in the scientific literature as a percentage, with 100% representing full coral cover. The use of a percentage has inadvertently caused confusion, mostly in media reports, where changes in coral cover are also reported as percentages, an approach that sometimes makes it difficult to determine if absolute or relative changes are being considered. So, for example, a change from 10% to 15% coral cover could be represented as a 5% absolute increase ($15 - 10 = 5$), or a 50% relative increase in coral ($(15 - 10)/10 \times 100 = 50\%$). In normalised units, this example would be a change from 0.1 to 0.15, which is an absolute increase of 0.05, or a relative increase of 50%. This approach therefore avoids considering percentage changes of a quantity that is itself a percentage.

Data Source 1: GCMRN

The Global Coral Reef Monitoring Network (GCRMN) coordinates scientists, managers and organisations that monitor the condition of coral reefs throughout the world, operating through 10 regional nodes. Its 2020 report contains considerable data about reefs of the world, [14] primarily on coral cover, but also on coral taxa and water depth. The data is entirely for coral living in the 'photic' zone – the uppermost layers of the sea where light reaches, down to about 40 m depth. It does not include the almost totally unstudied deep-water 'rariphotic' zone coral.[15] The data only covers corals living in depths of generally less than about 10 m, despite many coral reefs having abundant coral throughout the photic zone. This bias toward very shallow water is a consequence of extreme costs and difficulty associated with surveying deeper waters. It also demonstrates that, presently, the data on coral coverage is extremely limited.

GCRMN divides the world into ten major regions and provides a standardised report on each, plus a compilation for the whole world. It says that 83% of coral reefs[16] are found in just four of the ten regions – East Asia (30%), Pacific (27%), Australia (16%), and the Caribbean (10%). Although data from all ten regions will be shown here, in the interests of brevity, the four regions with the most corals are considered in greater detail.

GCRMN data quality and methodology is highly variable, in large part due to input coming from a large number of science organisations and government jurisdictions. This variability is also understandable when considering the difficulty and cost of monitoring underwater systems.

It is interesting to consider the difference in data collection methodology between the East Asia and Australian regions. For East Asia, only 5% of the GCMRN data is taken from sites with more than 15 years of data and less than 12% from sites with more than 10 years. Over 75% of sites have only a single year of data. By contrast, for Australia, for benthic surveys, over 35% of sites have more than 15 years of data, and more than 60% have more than 10 years. However, even the Australian benthic data reported by GCRMN only started in the mid-1990s, limiting the historical value of the data. GCRMN does not include the manta-tow data for the GBR (see next section), which covers roughly 50–100 times the area of the benthic surveys which are reported.

The main methodology for the benthic surveys for the East Asia region was 'a visual census' (65% of data), which, although not described in the GCRMN report, seems to be an estimate by a trained expert. This makes them directly equivalent to the manta tow surveys conducted on the GBR. However, GCRMN chose to include only benthic survey data for the GBR, although only roughly 25% of the surveys it included for the rest of the world used these more detailed methods. There is therefore an inconsistency in the methodology used in the GCRMN data.

Data Source 2: LTMP

Aside from the GCRMN data, this report will consider the AIMS Long-term Monitoring Programme (LTMP) data for the GBR. The GBR also has special place in the debate about the future of coral reefs, as it is by far the largest single reef system, and is regularly cited in political debates as having being greatly damaged by climate change.[17] Long-term monitoring of the GBR started in 1985 because of grave concern about the impact of crown-of-thorns starfish, which were being observed in plague numbers, and were eating large amounts of coral. The complete loss of the entire GBR was predicted as a likely possibility, especially in the media.[18] This was long before concern over the climate became prevalent; it was therefore the precursor 'alarm' about the GBR.

As noted above, the dataset has two major components: photographic benthic surveys and manta-tow (visual census) data. The manta-tow data is considered in this section. It is the oldest and most consistent in terms of methodology.

Data limitations, uncertainty and margins of error

Changes in coral cover are often subtle and localised. As a result, it is important to consider what magnitude of change is meaningful. Uncertainties in coral-cover measurements are generally quite high. AIMS quotes uncertainties of around 0.10–0.19 for surveys of an individual reef,[19] and the figure is often higher for the benthic surveys of the GCRMN. Averaging over many reefs reduces the uncertainty, but only if it can be assumed that the distribution of errors is random; that is, that there is a quasi-Gaussian[20] distribution of errors. As a result, there is a typical uncertainty margin of roughly 0.04 when considering the average of coral cover over roughly 100 reefs.[21,22] The error in the difference between two years is thus 0.08, so any difference less than 0.08 cannot be interpreted as significant. The data from the two years are effectively the same unless the difference exceeds about 0.08.

However, averaging larger data sets will not help reduce the uncertainty if errors are not random. One source of such systematic error is the inconsistent methodologies used by the GCRMN from region to region, as mentioned above. Methodologies have also changed in an unknown way over time; much of the data from coral-rich regions is haphazard and ad hoc. The GCRMN quotes uncertainty margins of up to 25% for the world-aggregated data for periods prior to 2000. This is probably an underestimate. Unlike the LTMP data for the GBR, almost all of the GCRMN data for before 2000, and a significant proportion for later periods, was not collected with the express intention of looking at long-term trends. Thus, for many regions, methodologies changed from year to year. In most regions, there was a roughly tenfold increase in the quantity of data collected after about 2000, so a spurious change in the coral cover average would result unless great effort was taken to randomise the sampling locations before and afterwards; there can be a huge difference in the amount of coral at different locations of a reef – some parts may have almost none, while others have 100% cover. It seems certain that careful randomisation did not occur in most regions[23] before 2000, and the GCRMN reports that the uncertainty due to non-randomisation in the data can be as high as 30%.[24] However, this figure is not reflected in the uncertainty estimates of their graphs.

It is useful to consider an analogy in political opinion polling. Consider changes over time in response to a hypothetical yearly opinion poll on the question, ‘Do you think socialism is a good thing?’ Let us presume that up to 2000, this opinion poll was only asked in a left-wing voting electorate of the country. After 2000, ten times more polls were taken each year, and most of the polls were taken in other parts of the country – including many centre/right wing voting areas that were not polled before 2000. The data would probably show an apparent dramatic drop in support for socialism after 2000. However, this may not be a true reflection of opinion. The sampling was biased before 2000. Considerable care would be needed in interpreting the results. A similar situation exists with much of the GCRMN data. The biggest problem with lack of randomisation of sampling is that uncertainty estimates are almost impossible. The GCRMN need to publish a full analysis of how their samples were randomised to determine to what extent any failings increase the uncertainty margins.

3. Results

LTMP data for the GBR

Data for the GBR LTMP will be considered first, as it has used the same methodology since its inception in the mid-1980s. It is also the longest time series available, and disaggregated figures are available, so that temporal variability of the system can be examined at scales from individual reefs to the entire GBR system. This information on temporal variability will be useful when later considering the GCRMN data.

In 2022, the LTMP found record high coral cover on the GBR (Figure 4) of 0.34 ± 0.04 (i.e. 34% of the seabed on the coral reefs monitored are covered with coral).[25] Over the past 36 years, cover has varied dramatically, and reached a low point in 2011 of 0.12 ± 0.03. There is about twice[26] as much coral on the GBR in 2022 as in 2011. Since 2016 there has been a rapid rise in cover, despite four bleaching events occurring between 2016 and 2022. These were reported to have killed a large amount of coral.[27] However, the data in Figure 4 shows that the actual impact of these bleaching events was very limited. It must be remembered that most corals that bleach do not die – although this point is rarely made by science institutions or the media.[28] Some can lose

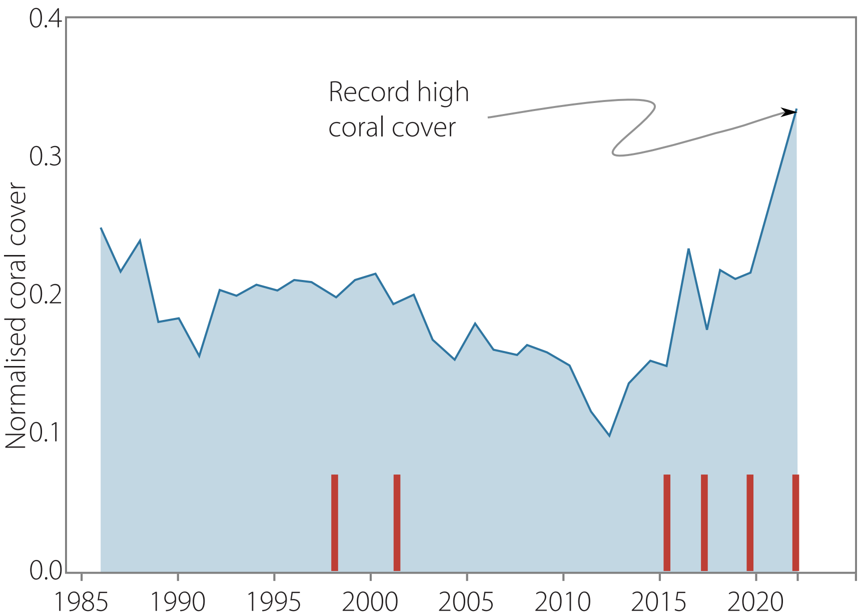


Figure 4: Coral cover for the Great Barrier Reef

As measured by the AIMS Long Term Monitoring Program. Coral is a slow growing organism,[92] so this graph is proof that institutions claiming major coral loss due to bleaching grossly exaggerated. Margin of uncertainty ~0.04.

Major bleaching event announced

almost all living tissue, but still regrow the alga-covered dead coral skeleton, restoring coral cover within 12 months.[29] The other major bleaching events on the GBR occurred in 1998 and 2002, but neither caused major coral loss, as seen from Figure 4.[30] The low point in 2011 came after two major cyclone/hurricanes and concurrent crown-of-thorns starfish events affected much of the GBR.[31]

Breaking the GBR data into its three major regions (Northern, Central and Southern; Figure 5) shows that coral cover varies greatly, both temporally and spatially:

- The Northern region experienced a major decline around 2016 'caused by two severe cyclones, an ongoing crown-of-thorns starfish outbreak and severe coral bleaching in 2016'.[32] However, it has since completely recovered, with coral cover now at double the 2016 level, equalling the previous record.
- The Central region is also at record-equalling high coral cover, and has experienced a greater degree of fluctuation.
- The Southern region was severely affected by Tropical Cyclone Hamish in 2009,[33] but is now at record equalling coral cover,[34] three times higher than at its low point in 2011.

It is interesting to note that every region is at record-equalling high coral cover,[35] once uncertainty estimates (the blue bands) are taken into account. None are at record-breaking high levels,[36] not even the Northern or Central regions, as has often been claimed in the media.[37] However, due to the large fluctuations, it is unusual that coral cover is high in all three regions simultaneously. Thus, although none of the three regions has seen a new record, the aggregate cover for the entire reef is at a new high, although only just (Figure 4).[38]

In order to demonstrate the large temporal variability of the coral cover, it is worth considering the Capricorn Bunkers sector in the Southern section, one of the eleven sub-sectors into which the three regions of the GBR are broken (Figure 6). In 2022, Capricorn Bunkers had record-equalling high coral cover of 0.59 ± 0.06, around four times the lowest value, seen in 2011, of 0.16 ± 0.03.

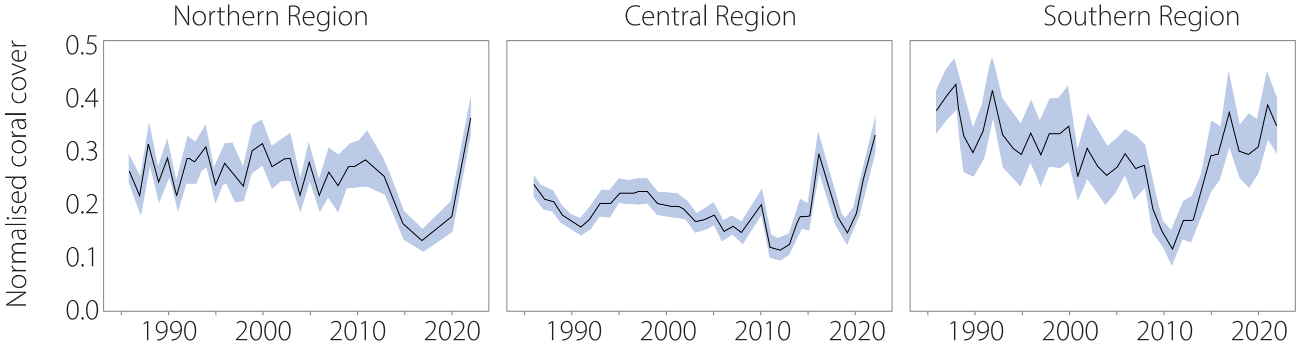
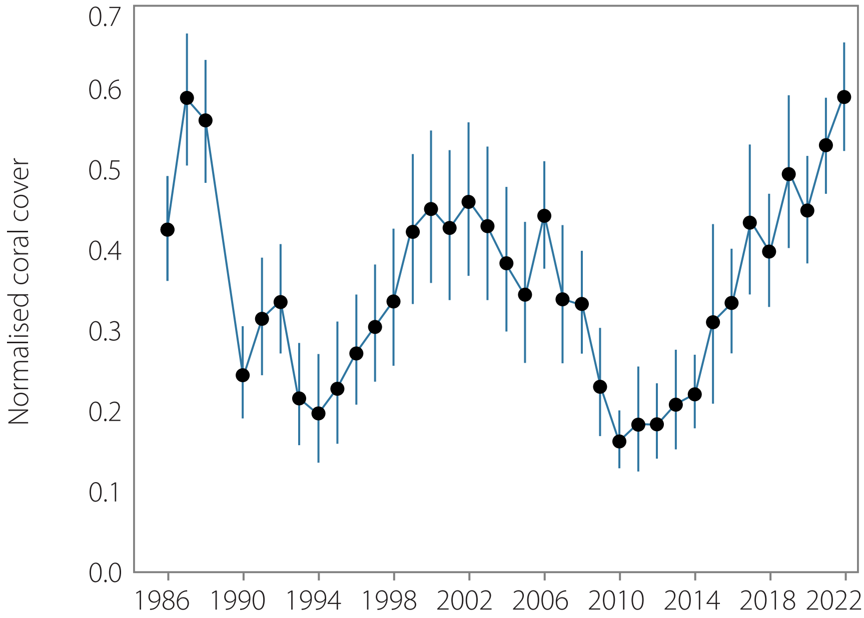


Figure 5: Coral cover for the Great Barrier Reef major regions, 1985–2022

As measured by the AIMS Long Term Monitoring Program. Redrawn from AIMS original. Blue shading represents the uncertainty band.

Figure 6: Coral cover for the Capricorn Bunkers

As measured by the AIMS Long Term Monitoring Program. Graphs redrawn from AIMS. Blue bars represent uncertainty margins.

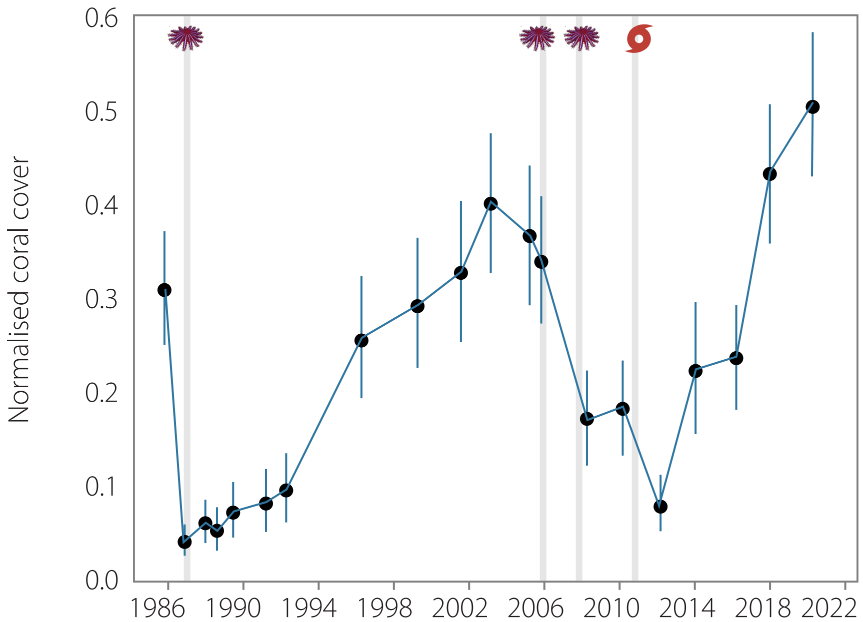


The sector has been through two cycles of crash and recovery since 1985. It will crash again in the future. Viewing the data in 1993 or 2010 might have given the mistaken impression that this region was in trouble, but one of the most important results of the LTMP is that we now have a much better idea of natural variability. It shows that variability of coral cover is not a recurring catastrophe – it is part of life on many coral reefs.

Temporal variability becomes greater for smaller areas of coral sampled. A reef with particularly large variability is Helix Reef,[39] which is about one kilometer across. Coral cover dropped to just 0.04 ± 0.02 in 1986, due to starfish outbreaks, recovered by 2003, increasing by almost a factor of ten to over 0.4, despite two bleaching events in 1998 and 2002 (Figure 7). However coral cover again collapsed, to 0.07 in 2012, due to the combined effects of starfish and cyclones. It has again recovered, to record-equalling high levels[40] of 0.50 ± 0.08, despite four bleaching events on the GBR since 2016.

Figure 7: Coral cover for Helix Reef

As measured by the AIMS Long Term Monitoring Program. Graphs redrawn from AIMS. Blue bars represent uncertainty margins. Fluctuations of coral cover are around a factor of 10 between the low and high points.



Disturbances

Crown of thorns starfish

Hurricanes

The analysis above should make it evident that coral cover varies dramatically with time. It is currently at record-breaking highs for the GBR as a whole, but can be expected to fall at some stage in the future. Such falls, whilst very concerning decades ago, when very little data on the reef was available, can now be put in context. They are just a part of life on many coral reefs. They are not 'disasters' unless there is no recovery. And for the GBR there has always been strong recovery.

GCRMN data for the world

World aggregate statistics

The time series of coral amount aggregated for the entire world (Figure 8) shows that the normalised coral cover varies around 0.3. Data before the late 1990s is of little value due to extremely large uncertainties due to small sample sizes, and lack of randomised sampling.

GCRMN data aggregated over the whole world does not support the proposition that there has been a major drop in coral cover since reliable records began in the late 1990s. At worst, the data might suggest a reduction in coral cover of 7% from 2000–19 (0.31 ± 0.02 to 0.29 ± 0.02), but the statistical significance of this change is very questionable, because the error margin is greater than the difference. In addition, there was an apparent increase in coral cover between 2000 and 2010 of around 10%, which may be indicative of natural variability, or may be due to artefacts in the data because of non-randomisation of sampling sites. If the inherent variability of the data is around 10%, it would be inadvisable to read too much into the 7% fall between 2000 and 2019.

The data certainly does not show a precipitate net reduction in coral cover over the last two decades. In addition, with only 20 years of useful data, it is difficult to determine the natural variability of the world aggregate figure.

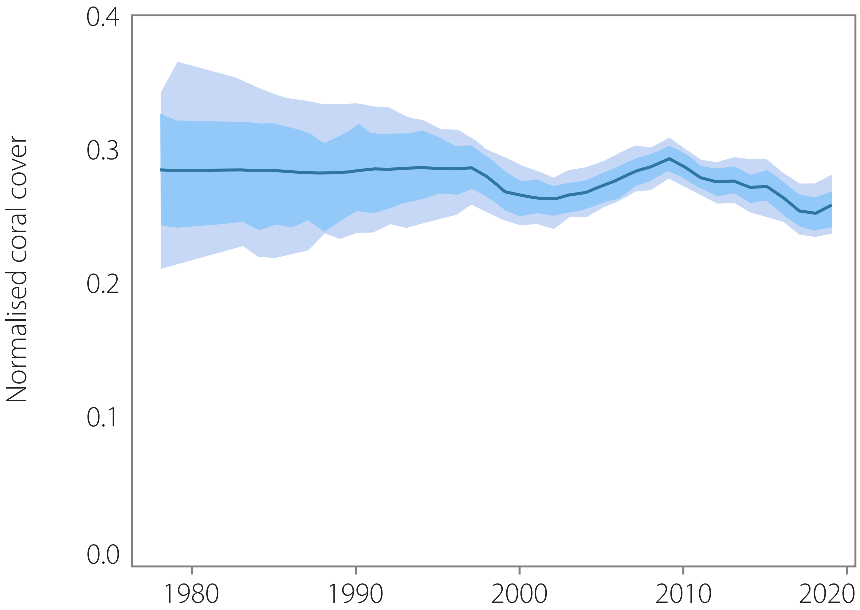


Figure 8: Global cover of hard coral

Estimated global average cover of hard coral (solid line) and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Graph redrawn from GCRMN data report. Note, data before 1998 has very high uncertainty due to low number of measurements and problems with randomisation of sampling sites.

Summary of regional data

The GCRMN data provides a summary of all the data of the 10 regions (Figure 9). The four most important regions, in terms of the number of reefs (East Asia, 30%; Pacific, 27%, Australia, 16%; and the Caribbean, 10%), will be considered in more detail below.

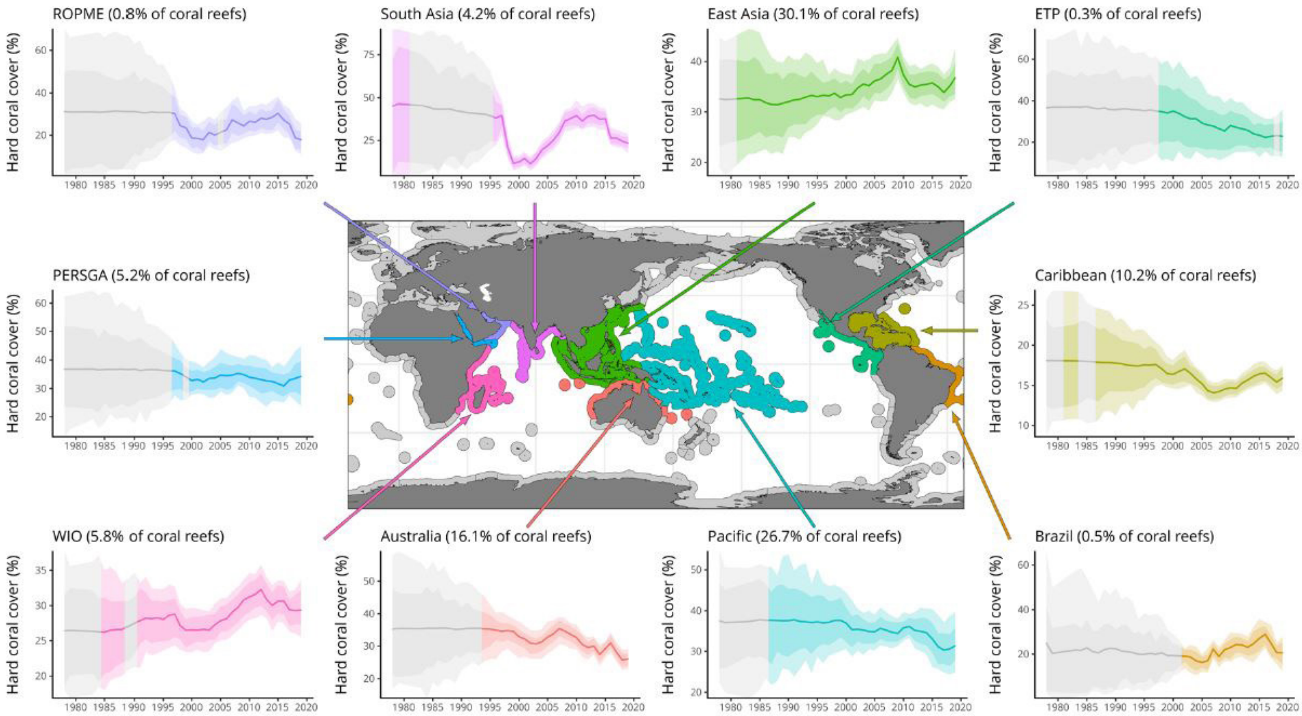


Figure 9: Global coral cover by region

Long-term trends in the average cover of live hard coral in each of the ten GCRMN regions. The solid line represents the estimated mean with 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods for which no observed data were available. Trends are coloured to match the GCRMN regions represented on the central map. The proportion of the world's coral reef area supported by each region is indicated by % of coral reefs. ETP is the Eastern Tropical Pacific. PERSGA is the Red Sea and Gulf of Aden. ROPME is the ROPME Sea Area. WIO is the Western Indian Ocean. Note this figure is copied directly from the GCRMN report so it reports coral cover as a percentage, unlike this document.

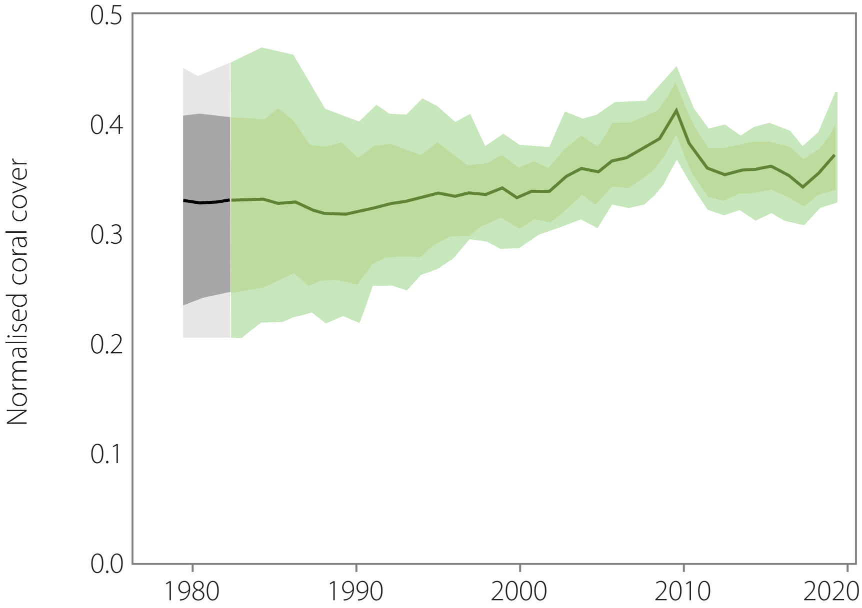
East Asia

The East Asia region includes waters off Japan, China, Thailand and Korea, as well as Indonesia, the Philippines and Malaysia. It contains around 30% of the world's coral reefs, including the 'Coral Triangle', an area located within the Indo-Pacific Warm Pool, the hottest large water mass on Earth.[41] The Triangle contains the most diverse and fastest growing population of corals known.

Coral cover in the region varies around an average of 0.35 (Figure 10). Data before the late 1990s is of little value due to extremely large uncertainties, the result of small sample sizes and non-randomisation of sampling sites. In 2019, coral cover was 0.35 ± 0.05 and, due to the large uncertainty margins, that figure is not statistically different from any other time during the record: there is overlap of the uncertainty margins of the 2019 figure with all other dates, including the nominal peak in around 2010,

Figure 10: Hard coral cover in East Asia Region.

Estimated average cover (solid line) and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. Graph taken directly from GCRMN data report. Note, data before about 1998 has very high uncertainty due to low number of measurements and problems with randomisation of sampling sites.



and with the pre-2000 data, which shows apparently lower coral cover. Even if the uncertainty margins were smaller, this dataset would suggest no long-term change in the coral cover for this region.

The data for the East Asia Region is well worth analysing in more detail in order to see the potential problems of changing sampling methods and lack of randomisation of sampling. The uncertainty of the data in Figure 10 is likely far higher than shown because of two problems:

- There is apparently almost no data from Indonesia, Malaysia and the Philippines between 1990 and 2010, according to a separate GCRMN report published in 2022.[42] These subregions[43] account for roughly 75% of the coral in the East Asia region, and over 20% of coral worldwide.
- Of the 2570 sites where coral cover was measured, only 158 had records longer than 15 years, 142 of them in Japan, which has only 3% of the coral of this region.[44] Thus the limited high-quality data for this region is dominated by measurements for an extremely small and unrepresentative subset of the coral of the region. Caution must therefore be exercised when making inferences about long-term trends in the data.

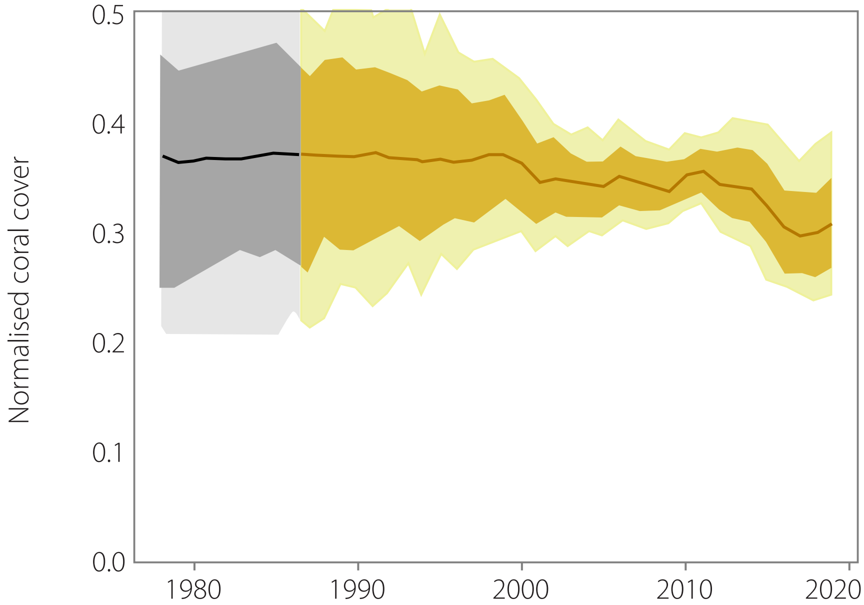
Similar issues exist in most other major regions considered by the GCRMN.

Pacific Region

The time series for the Pacific Region, which represents around 27% of the world's reefs (Figure 11), shows that the 2019 cover was around 0.31 ± 0.06. Data before the late 1990s is of little value due to extremely large uncertainties caused by small sample sizes. These large uncertainty margins mean that the 2019 figure is not statistically different from any time during the record; there is overlap of the uncertainty margins of the 2019 figure with all other dates, including the nominal peak around 2010. Even if the

Figure 11: Hard coral cover in Pacific Region.

Estimated average cover (solid line) and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. Graph taken directly from GCRMN data report. Note, data before about 1998 has very high uncertainty due to low number of measurements and problems with randomisation of sampling sites.



uncertainty margins were smaller, the data would represent a reduction in coral of only around 10%.

This region also highlights the problem in the GCRMN data of non-randomisation of sampling sites. Figure 11 shows data starting around 1987,[45] but closer analysis reveals that between 1987 and 1997, all the data came from only one of seven sub-regions (largely French Polynesia), which has only 10% of the coral of the Pacific Region. Thus, the data in Figure 11 before 1997 cannot be considered to be even approximately representative of the entire Pacific Region.

Australia Region

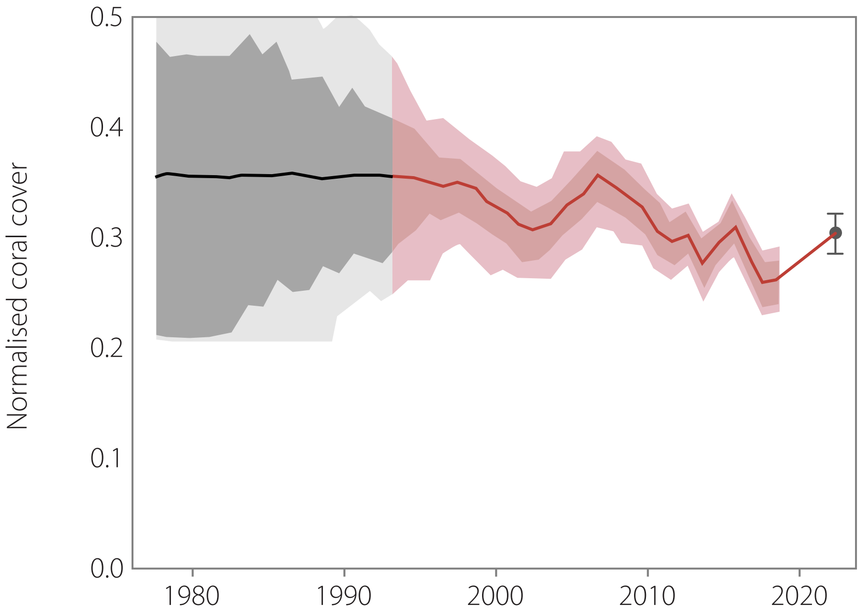
The Australia Region contains data from the GBR, Western Australia and the Cocos-Keeling/Christmas Islands. The data for the GBR, which represents 85% of the coral in this region, is a different measurement series, and uses different methodology (benthic surveys) to the long-term monitoring series shown in Figures 4–7. The GCRMN data also includes a large number of 'inshore' reefs, which are not part of the GBR, and in aggregate are only 1% of its size. This unfortunately raises questions of randomisation of sampling sites; it is biased toward a class of reefs with very small area.

The time series for the Australia Region (Figure 12), which represents around 16% of the world's coral, shows that the 2019 cover was around 0.26 ± 0.025. Figure 12 also shows the inferred value for 2022 of 0.31 ± 0.025, generated using the most recent data[46] to update the series to the present day.[47] Due to the large uncertainty margins, the 2022 figure is not statistically different from any other time during the record; the uncertainty margins of the 2022 figure overlap all other dates, including the nominal peak around 2007.

The data solely for the GBR (i.e. not including the Western Australia and the Cocos-Keeling/Christmas Islands data) is shown in Figure 13. It looks very similar to the regional aggregate, be-

Figure 12: Hard coral cover in Australia Region.

Estimated average cover (solid line) and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. Graph taken directly from GCRMN data report. Data point for 2022 was calculated using the most recent GBR data from AIMS website assuming no change in other regions.

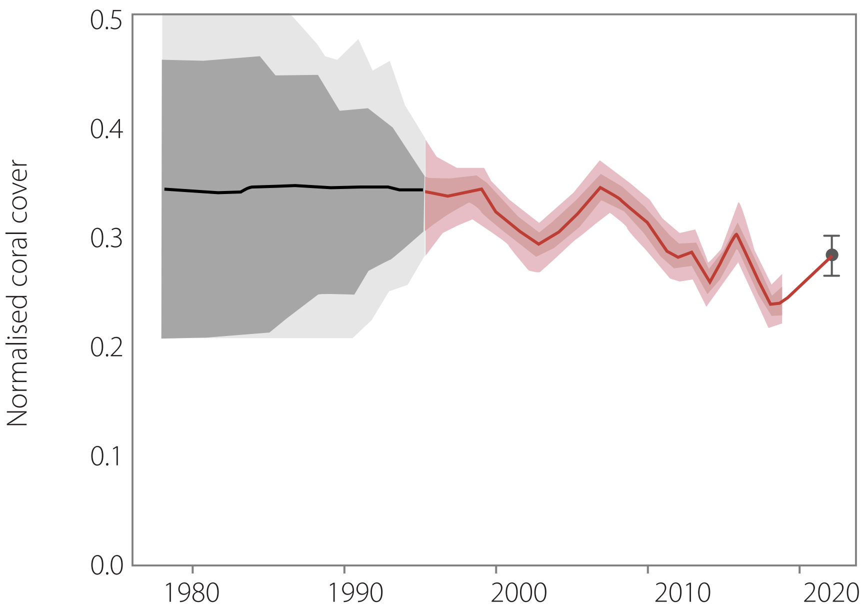


cause the GBR is roughly 85% of the coral in the region. Comparison of Figure 4 with Figure 13 (both for the GBR) is interesting, because it shows how different methodologies and site selection can lead to divergent estimates of the coral cover. Figure 4 is based on manta tow surveys over about 1000 km of transect each year, while Figure 13 is based on short photographic transects (and also includes a very large number of small fringing reefs). There are major differences between the results of the two surveys, even though they were conducted largely by the same institution.[48] This demonstrates clearly how differing methodologies can affect the results, even for the best monitored region.

It is therefore inadvisable to read too much into small changes in coral cover, especially in the GCRMN data which suffers from constantly changing methodology and very small and non-randomised site selections.

Figure 13: Hard coral cover in GBR Region.

Estimated average cover (solid line) and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. Graph taken directly from GCRMN data report. Comparison of this figure to Figure 4 shows the effect of different sampling methods and lack of randomisation. Data point for 2022 was calculated using the most recent GBR data from AIMS website.



Caribbean Region

Data from the Caribbean (Figure 14), which has around 10% of the world's coral reefs, varies around 0.15 ± 0.02. Differences are of similar size to the uncertainty margins, so it is difficult to discern any changes over time. The cover of 0.15 is very low compared with most other regions of the world, where the figure tends to vary between 0.2 and 0.4. This may be due to the Caribbean reefs having already sustained significant damage before these measurements started. There is certainly more human pressure on these reefs than on the relatively pristine ones in the Pacific Ocean or the Great Barrier Reef. However, it is also possible that the difference is a manifestation of the Caribbean being isolated from other major reef regions of the world for over 3 million years,[49,50] thus having a very different species composition.

There is no evidence of a major reduction in coral cover in the last two decades.

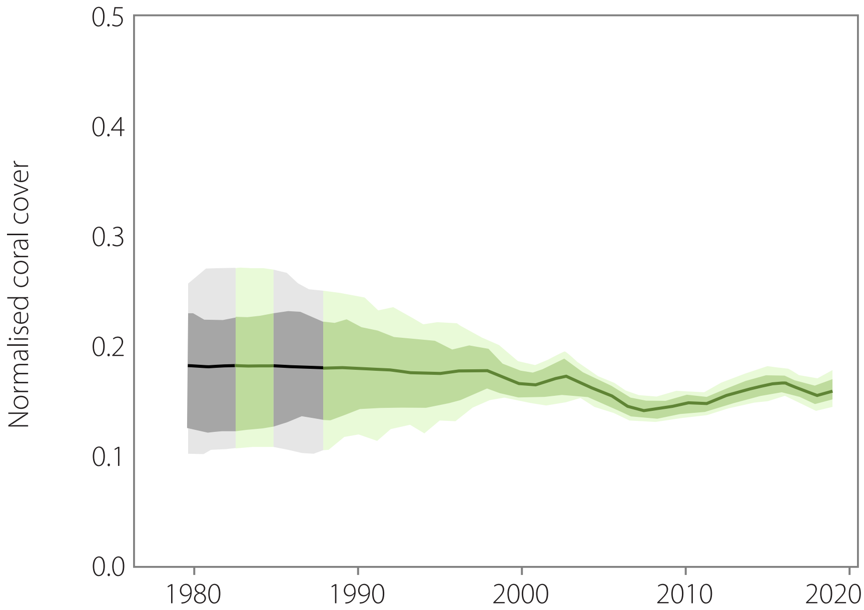


Figure 14: Hard coral cover in Carribean Region.

Estimated average cover (solid line) and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. Graph taken directly from GCRMN data report. Note, data before 1998 has very high uncertainty due to low number of measurements and problems with randomisation of sampling sites.

Conclusion

The data does not support the proposition that there has been a major loss of coral around the world over recent decades. It indicates that the GBR, for which there is the most consistent and longest record, has never been in better shape, despite suffering four supposedly catastrophic bleaching events in the last six years.

It is easy to find reports in the media, based on peer reviewed articles produced by science institutions, of a reduction in GBR coral cover of 50% between 1995 and 2020.[51] The data shows that coral reefs are very dynamic systems, often losing vast amounts of coral due to natural events, but recovering over a decade or so. It is apparent that science institutions are very vocal when there is a coral loss, but much quieter as recovery takes place. This inconsistent behaviour fuels a suspicion that they have a major integrity problem.

The data from other reefs around the world, compiled by the GCRMN, has significant limitations due to large, and underestimated, uncertainty margins. This is especially true of data before 2000. There are significant changes in methodology and a lack of proper randomisation of site selection. Perhaps the best example is that almost all the data for the Pacific region before 1997 comes just from a few small areas in French Polynesia, which has only 10% of the coral of the Pacific; this is obviously not a random sample of the Pacific. As a result, it is now very hard to estimate uncertainty margins. Nevertheless, the data certainly does not show that the amount of coral in the world has changed over the last two decades, once the error margins and natural variability are taken into account. As GCRMN data improves, it is likely that uncertainty margins will fall and more subtle changes in coral cover will be resolvable.

A worrying feature of the commentary on the GCRMN data, by the GCRMN itself, and by others, is that it is common to concentrate on periods where coral apparently declines, without mentioning other periods when coral cover increased. It is also common to ignore the uncertainty margins and natural variability of the data. For example, many media reports,[52] based on the world coral data (Figure 8), claimed a 14% coral loss between 2008 and 2019, but failed to mention that there was an apparent increase of a similar amount between 2000 and 2008. In addition, the very large uncertainty margin is generally not mentioned, partly because it is not treated properly in the GCRMN original report. In reality, the changes in coral cover are often too small to be resolved. This failure by the GCRMN leaves further questions of institutional integrity to be answered.

Good news about reefs is often downplayed. For example, the discovery that the GBR had the highest coral cover on record in 2022 was immediately downplayed by reef science and management institutions, and the media too. It was claimed that only the fast-growing corals[53] had recovered. However, since these were also the corals most susceptible to bleaching (and also to hurricanes and crown-of-thorns starfish), it was also claimed that this left the reef more vulnerable.[54]

The argument is unsustainable, however, because these fast-growing (and vulnerable) corals were the ones that were alleged to have been killed by the four bleaching events in the last six years. While they can indeed regrow extremely rapidly (within a year) from a small section that is left alive (the so-called 'phoenix effect'[55]), if they are killed, recruitment of larvae and regrowth takes 5–10 years.[56] They cannot regenerate within a few months. The rapid recovery of the reef cover therefore shows that they were bleached, but not killed.

In other words, the past few years' data has proven that very little coral was killed by the bleaching events – even the fast-growing coral that is most susceptible. Coral reefs can double or even quadruple their coral in a decade. The loss of a few percent from bleaching is a minor disturbance. When the reef cover crashes, it is almost always the fast-growing coral that declines, so it is hardly surprising, and certainly not concerning, when the fast-growing coral comes back.

A further concern about institutional integrity arises from the propensity to make misleading statements in the media about the extent and consequence of bleaching events. For example, it was widely reported that the 2016 bleaching event of the GBR affected 93% of reefs, with the implication that there was a 93% coral loss.[57] However, if a reef had only a very small amount of bleaching, it was classified as one of the 93% of reefs that bleached; the fact that most corals recover from bleaching was rarely mentioned. An analogy would be a medical authority stating that a new type of influenza had been reported in 93% of major cities of a country, even if only one case had been found in some cities, and implied that everyone in all those cities had died. The reality might be only a small percent of people had contracted the disease, and an even smaller number had died. Similarly for coral in the 2016 bleaching event, a relatively small amount of coral bleached, and most of it recovered.

The best estimate for total coral loss on the GBR during the 2016 bleaching event is that, at most, about 8% died. Almost all of this was in very shallow water, less than 5 meters deep. Frade et al. (2018)[58] showed that coral loss in water between 5 and 40 m depth was about 3%.[59] Figure 4 demonstrates without doubt that the coral loss was small compared to the regeneration capacity of the reefs. Although there is no doubt that a significant amount of coral was killed by bleaching in 2016, it was far less than can be destroyed by a major cyclone, and far less than what was effectively reported by the media. This confirms previous work by De'ath et al. (2012)[60] who found that cyclones and starfish plagues are responsible for 90% of coral mortality, and bleaching just 10%.

4. Corals and 'hot-water' bleaching

Introduction

Most reports in the media, often based upon news releases from science organisations, paint a bleak picture[61] for coral reefs if even a very small increase in temperature occurs due to anthropogenic climate change. For example, a recent study[62] that was widely reported in the world media[63] claimed that more than 99% of corals would be lost with a temperature increase of just 1.5°C over pre-industrial times. These sources predicted this warming will occur by the early 2030s – only a decade away. Considering that the data in Section 2 of this report shows little or no coral loss in recent decades, the rate of change of cover reefs is going to have to occur rapidly for this prediction to come true.

A 99% loss from a warming of just 1.5°C effectively proposes hyper-sensitivity of corals to a very small temperature change. What other organism is deemed so sensitive? Remarkably, even corals presently living in cool water will supposedly be 'overwhelmed' by such a small temperature increase, even though the same species may live in waters, like the Coral Triangle, that are far hotter.

This 'fragile reef hypothesis'[64] also proposes that mass coral bleaching events only started to occur recently. For example, an eminent coral ecologist at James Cook University Coral Reef Centre in Australia, stated on Australian Broadcasting Corporation radio:[65]

> …a critical issue here is that these bleaching events are novel. When I was a PhD student 30 years ago, regional scale bleaching events were completely unheard of. They are a human invention due to global warming.

The records show that there were 26 records of coral bleaching events in the world before 1982;[66] bleaching was observed on the first scientific expedition to the GBR, from England, in 1929.[67] Possibly the earliest representation of bleaching is a remarkable lithograph (Figure 15) by von Ransonnet, published in 1862.[68] There can be no doubt that bleaching is *not* a 'novel' phenomenon.

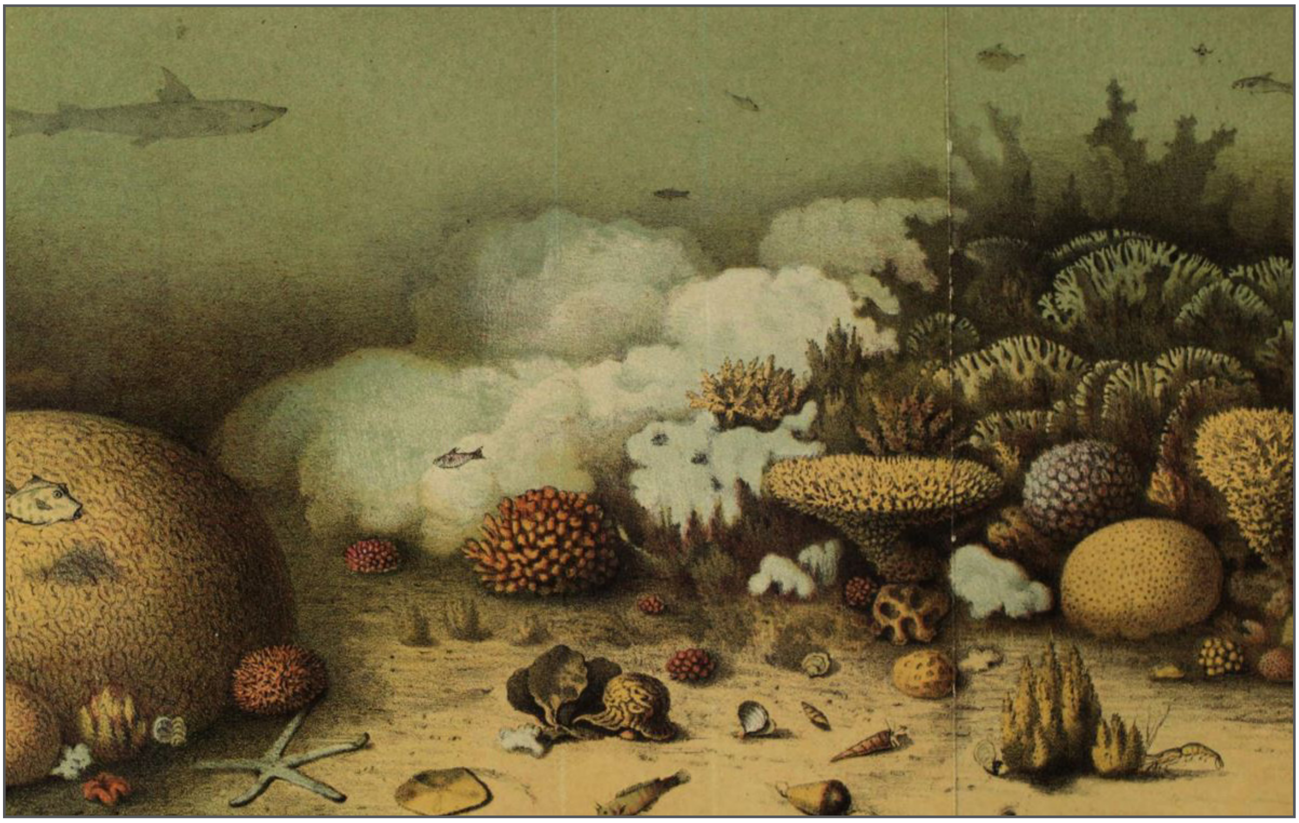


Figure 15: Lithograph of bleaching of coral in the Red Sea, 1862

By von Ransonnet. See Cedhagen (Endnote 68). The white coral is clearly bleached.

However, is *mass* coral bleaching a new phenomenon? Did major bleaching events, where large amounts of coral die over a large area, occur before the 1990s? It must be remembered that it was not until the 1960s that significant study of coral reefs began. Almost nothing was known about reefs before then. For example, on the GBR, the number of marine scientists in the 1930s was effectively zero; by 1960 there was just a handful. Today there would be easily more than a thousand scientists. It was not until the 1980s that large-scale study of reefs began. Remarkable discoveries, such as mass coral spawning, where every coral on the GBR spawns over one or two nights, producing a massive slick of eggs on the surface, were not documented by scientists before then. If such a remarkable phenomenon, which is highly visible on the water surface, was only discovered so recently, is it a surprise that mass coral bleaching, which takes place under the surface, and so is far more difficult to observe, was not documented until the 1990s?

If a major bleaching event had occurred in, say, 1925, who would have noticed? Who would have been measuring it? Who would have cared? Technology such as SCUBA equipment did not even exist. It would certainly be a remarkable coincidence if mass coral bleaching had only started when scientists arrived to study it.

Given that many bleaching events occur during El Niño years,[*] it is highly probable that some of the 26 such events observed before 1982 were part of what would now be termed a mass bleaching.

In order to answer the question of whether corals are indeed uniquely sensitive to temperature, and have been damaged by the temperature increase of less than 1°C over the last half century, it is necessary to look at the biology of corals. As will be seen, far from being uniquely at risk from global warming, they are actually able take it in their stride. Coral bleaching should not be viewed solely as a death sentence; it is actually a remarkable adaptive response to changing temperature.[69]

Corals and their algal friends

Being animals, coral polyps cannot get energy from sunlight by photosynthesis – they have no chlorophyll. After a couple of hundred million years of evolution, however, the polyps have built a partnership with microscopic algae called zooxanthellae, that live *inside* the polyp.[70] The zooxanthellae, like plants, have chlorophyll, so they can get energy from sunlight. The polyp gets energy from the zooxanthellae, and the zooxanthellae gets a comfortable home inside the polyp. Some corals can also consume plankton as an alternative energy source. The symbiotic relationship with zooxanthellae is key to how corals can adapt to different temperatures, as will be explained below.

Infant corals usually have no zooxanthellae, but can acquire

* El Niño is a weather phenomenon, in which warm water welling up from the deep ocean affects vast areas.

them from the surrounding water, where a selection of different species floats around. The zooxanthellae grow inside the polyp. However, on occasion, this cosy relationship breaks down and the coral rapidly ejects the zooxanthellae. The zooxanthellae give coral polyps most of their colour[71], so ejecting the zooxanthellae leaves the coral 'bleached' white, because the skeleton is now visible through the now clear polyp tissue (Figure 16). The coral polyp is in peril of starving if it does not take on new zooxanthellae.

Figure 16: Coral bleaching

Coral bleaches when the symbiotic algae are expelled. They turn white. The algae give the coral most of its colour. Not all the corals in this picture have bleached.

Bleaching is a survival strategy

Corals eject their zooxanthellae under many different types of stress. The best known and most dramatic example is high temperature in combination with light. They can also bleach when exposed to cold water, air,[72] or if too much freshwater from rivers or rainfall reduces seawater salt concentration.[73] Thermal bleaching is not so much a death sentence as a survival strategy. Corals bleach because the zooxanthellae within them have become 'poisonous', or at least disadvantageous, to the polyp and must be expelled. Coral actively expel the zooxanthellae during bleaching. The process is akin to many other survival strategies seen in nature. For example, many Australian trees shed their leaves during extreme droughts in order to conserve water. They regrow them once the drought is over.

Most corals that bleach will survive[74], although they will be a little shaken from the experience. After the stress is over, they take back or regrow a community/population of zooxanthellae, but not necessarily of the same type as before they bleached.[75]

Corals are highly adept at 'shuffling' or changing the zooxanthellae, which come in many different strains.[76] A particular species of coral can choose from many different types of zooxanthellae, and may have a few different types inside them at any one time.

Some 'high octane' zooxanthellae will allow the coral to grow fast, but will make it more susceptible to bleaching from high temperatures.[77] 'Low octane' zooxanthellae will make it grow slowly, but leave it less susceptible to bleaching. Which strategy is better at a particular location, at a particular time, is like a roll of a dice and will depend on the weather.[78]

The life strategy of many corals, particularly the light and delicate 'plate' or 'staghorn' corals (Figure 1b), is to live fast and probably die young. They produce a lightweight calcium carbonate skeleton, which means that they will probably be obliterated by a tropical cyclone within 20 years. They are also highly prone to being eaten by crown-of-thorns starfish. As it happens, the return incidence for bleaching events and cyclones is often roughly the same and it is probably no coincidence that these physically delicate and easily damaged corals are the most susceptible to bleaching,[79] and have a life expectancy of just a couple of decades. Taking on high octane zooxanthellae and growing quickly, while risking death by bleaching, is all part of their life strategy.

At the opposite extreme are the massive corals that can live for centuries and become a solid block of calcium carbonate, metres across, and weighing tons. These grow more slowly, and will generally pass through a cyclone/hurricane relatively unharmed and are less affected by starfish plagues. They have a long-term strategy, and quick death by bleaching is not part of it.

Few other organisms have this type of adaptability to changing temperatures. Whereas many organisms take generations to alter their genetic make-up, corals can adapt to changing temperatures in a few weeks, simply by switching zooxanthellae during bleaching.[80]

Corals thus have a remarkable, almost unique, ability to deal with changing climates. Are they the 'canary in the coal mine', or one of the toughest organisms on earth, or somewhere in between? It is certainly not obvious that they are one of the most susceptible organisms to climate change. Corals have survived hundreds of millions of years, most of which have been far hotter than the present relatively cool period of the Earth's history.

Final comments

Data from across the world has consistently shown that bleached corals are usually not killed, and even on reefs where bleaching has caused mortality, they regrow strongly.[81] Good news does not just come from the GBR, which has record high coral despite suffering four supposedly devastating bleaching events in the last six years. For example, in Palmyra, in the central Pacific, a bleaching event in 2015 caused up to 90% of the corals to bleach. However, it has now been reported that less than 10% died,[82] and the reefs have returned to excellent condition. Similar good news comes from Kiribati,[83] the Chagos Islands[84], Western Australia's Rowley Shoals[85], Japan[86] – essentially from around the world. We should be grateful that there are still many scientists and parts of organisations, such as the AIMS long-term monitoring team, that do sound science and report the data, even though it goes against the zeitgeist.

What is striking about these reports of good news is that the scientists rarely question, at least publicly, if there has been a general over-reaction to, or exaggeration of, coral bleaching. Perhaps they think to themselves that the presumption that bleaching is getting worse is wrong, and that maybe it is just a natural phenomenon about which we knew almost nothing just 20 years ago. Are they constrained by the groupthink in the coral reef science community, in which to challenge the prevailing wisdom is dangerous?

We cannot expect that the coral reef science community will admit that they have exaggerated threats of bleaching, or have been wilfully negligent in reporting recent research that shows corals' remarkable adaptability and toughness. There is little possibility that these organisations, or the eminent scientists who have built their reputation on crying wolf about the world's reefs, will suddenly admit they got it wrong. Tens of thousands of jobs depend upon the proposition that the reefs of the world will be gone sometime in the future – but not too distant future.

Many fields of science, particularly those in which errors have few consequences, can be hidden, or will not be known for decades, have become completely taken over by groupthink. This is an almost inevitable consequence of systems, such as peer review, where a scientist's ability to attract funding and publish results is determined by the approval of their peers. It is impossible to imagine a system better designed to create groupthink.

Although it is extremely encouraging news, the latest statistics about coral reefs around the world, and especially recent ones from the GBR, do not prove that the world's reefs are all going to be fine. However, they prove without any shadow of a doubt that the coral reef science community, with a few exceptions,[87] is lacking in scientific integrity. They have cried wolf too often. The great pity is that there are still many in this community who are good scientists, doing good work, but who are now tainted by association. They have to be careful, because to break out from the groupthink would likely be a career-ending move.

The biggest problem with the coral science community's loss of integrity is that it is now almost impossible to believe anything they say – and there are some real problems with many reefs in the highly populated regions. Just because a group is untrustworthy does not mean they are wrong all the time. For example, maybe the Caribbean reefs are in dire straits because of overfishing, or some other fact. But how can we believe anything about coral reefs unless there is a thorough audit of what has been said in the past, a breaking down of the groupthink, and a reintroduction of academic rigour?

Groupthink in the coral-reef research community is just a microcosm of the problems seen in many areas of science. Much has been written about the scientific replication crisis – it is now well accepted[88] that roughly 50% of the recent scientific literature has serious flaws. This is not a secret, and yet the public know little about it. Science institutions would rather not talk about the implications of this unreliability. Is there any other profession so unreliable?

It is impossible that reform of the coral reef science community will come from within. Only a concerted and well-funded scientific

'Red Team', where scientists from outside the peer group perform thorough antagonist audits, can force changes.

A Red Team will have to be imposed at a political level, when it becomes obvious to the general population that there are serious problems within the research community. There are many scientific issues, such as the broader climate change debate, where one can suspect that the scientific advice is not as reliable as it could be, and that the scientists are now mostly motivated by ideology, and have become 'whores of politics'.[89] However, nowhere has the untrustworthiness of science institutions become more obvious than in the latest statistics about the reefs – especially the Great Barrier Reef. Our once-trusted scientists told us the reefs are doomed, that there had been mass mortality – multiple times. And they have been proven wrong.

5. Extended summary and conclusions

- The longest and most reliable record of coral cover in the world is from the Great Barrier Reef, which has about 15% of the world's coral reefs.[90] Data shows 2022 had the highest normalised coral cover (0.34 ± 0.04) since records began in 1985. The GBR data shows remarkable variability, with lowest coral cover of 0.12 ± 0.03 occurring in 2011.
- In 2022 there is at least twice as much coral on the Great Barrier Reef as in 2011.
- Data from the Great Barrier Reef demonstrates that coral reefs often experience major cycles of death and regrowth over decadal timescales. They are not static ecosystems like many temperate forests or tropical rainforests.
- Cyclones/hurricanes, starfish plagues, and bleaching can occasionally cause almost complete loss of coral, an event which is followed by recovery over a decade or two. Changes are as significant as those caused by bushfires in dryland forests – an almost total destruction of the forest is followed by decades of recovery. Variability is not a recurring catastrophe.
- Data for other parts of the world, aggregated by the Global Coral Reef Monitoring Network (GCRMN), have much lower accuracy than the data for the Great Barrier Reef, because of smaller sampling sizes, non-randomised sampling locations, and varying methodologies. Only after about 2000 are the uncertainty margins low enough for the data to be useful.
- GCRMN data aggregated over the whole world does not support the proposition that there has been a major drop in coral cover since reliable records began in about 2000. At worst, it might suggest a reduction in cover of 7% from 2000–19 (0.31 ± 0.02 to 0.29 ± 0.02) but the statistical significance of this change is very questionable because the error margin is of similar size to the difference. In addition, natural variability of the data is also around 10% – higher than the difference between 2000 and 2019.

- GCRMN data for the most important coral bioregion, the East Asia Seas, with 30% of the world's coral reefs, and containing the most diverse coral of the 'Coral Triangle', show no statistically significant net coral loss since records began. The East Asia region has the biggest human population living in close proximity to reefs, and is located in the Indo-Pacific Warm Pool – the hottest major water mass on earth.

How much coral has been killed by bleaching

- The impact of bleaching due to hot water events is often very minor, and when it is significant, rapid regeneration of coral occurs regularly.
- The best data, by far, on the impacts of bleaching from high water temperature comes from the Great Barrier Reef, and this indicates the impact of bleaching[91] has been very minor. In 2022, the Great Barrier Reef had record high coral cover, despite having suffered four supposedly catastrophic bleaching events in the previous six years.
- Coral takes at least 5–10 years to recover from a major loss event, so the record high cover on the Great Barrier Reef proves that the massive coral loss reported by science institutions was erroneous and raises serious questions about institutional integrity. The media's propensity to exaggerate bad news has compounded the impact of institutional misreporting.
- Good news about reefs is often downplayed by science organisations. For example, the good news about the Great Barrier Reef having the highest coral cover on record was immediately downplayed. It was claimed that only the fast-growing corals had recovered after cyclones, starfish plagues, and bleaching. The fact that it was the fast-growing corals, which still take 5–10 years to regrow, that were supposedly affected in the first place was ignored.
- If large amounts of fast-growing coral were killed, four times in only six years, then how can it be possible to have record breaking amounts of this coral today?

The adaptability of corals

- Corals grow best in warm tropical water. For every 1°C temperature increase, they grow about 15% faster.
- Coral bleaching is when corals expel the symbiotic algae (zooxanthellae) that live inside the coral polyp. Most corals that bleach do not die. They usually regrow the zooxanthellae.
- Far from being a death sentence, bleaching should be viewed as an adaptive survival strategy. Bleaching is the mechanism that helps the coral select the species of zooxanthellae living inside it. Different species of zooxanthellae make the coral more or less susceptible to bleaching, but also change its growth rate.
- Corals are among the most adaptable organisms to changing temperature. Whereas many species take generations to alter

their genetic make-up to adapt to changing temperatures, corals can do so in the space of a few weeks, simply by switching zooxanthellae.

- Bleaching is not a new phenomenon caused by humans, as is often claimed. The oldest scientific studies of corals noted bleaching. However, with the explosion in the number of marine scientists over the last few decades, and the phenomenal improvement in technology, these events can now be easily observed.
- We are only just beginning to understand coral reefs. Because they are hidden below the surface, almost nothing was known about them 50 years ago. Bleaching, starfish plagues, and massive coral spawning events were only discovered recently. Although it was prudent to worry about the regular mortality events when they were first discovered, decades of research have shown the outlook for coral reef is extremely encouraging if problems of overfishing and pollution can be minimised.
- Reefs throughout the world are continuing to demonstrate remarkable and encouraging resilience to mortality events from cyclones/hurricanes, starfish plagues, bleaching and other human stresses. Resilience to stress, natural or otherwise, is a strong indicator of a robust ecosystem. Even a minor stress can cause a fragile ecosystem to crash and never recover.
- Despite the general resilience demonstrated by reefs around the world, some areas, such as in the Caribbean, should remain cause for grave concern. However, the main stressor there is people pressure rather than temperature.

Coral reefs: a tool for the merchants of doom

- The periodic mass loss of coral is visually spectacular, emotionally upsetting, and makes gripping media stories. The slow, but full, recovery is rarely reported.
- An uncharitable observer might conclude that periodic mass coral mortality events, which are largely completely natural, are exploited by some organisations with an ideological agenda and a financial interest. This includes many scientific organisations.
- A full audit of coral reef science is warranted. This will improve its veracity, so that important management decisions are based on reliable science.

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1. In this report, only hard, shallow-water corals living in the photic zone – typically less than 40 m depth – are considered, so as to be consistent with typical popular and media use of the word 'coral'. Deep-water corals that do not rely greatly on photosynthesis of symbionts are not included. The definition used covers almost all the coral reefs that are regularly mentioned in the media as being threatened by climate change.

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9. https://gcrmn.net/2020-report/.

10. Some scientists also worry about possible changes in species diversity, but the main message to the media is about coral loss.

11. Aerial pictures of coral are of limited value as only extremely shallow coral, a few meters deep can be seen. In addition, there are very few aerial images of reefs more than a few decades old.

12. https://www.abc.net.au/news/2016-01-25/south-china-sea-coral-reef-destruction-recoverable/7110878.

13. https://www.aims.gov.au/research-topics/monitoring-and-discovery/monitoring-great-barrier-reef/reef-monitoring-sampling-methods. For more details see https://platogbr.com/308-2/.

14. https://gcrmn.net/2020-report/.

15. See for example https://www.biology.ox.ac.uk/article/discovery-of-new-ecosystem-that-is-creating-oasis-of-life-in-the-maldives.

16. It is not clear what '83% of coral reefs' means. Many reefs do not have clear boundaries. Does this also represents 83% of the world's coral. We can only hope that consistent methodology was used.

17. https://theconversation.com/obama-protect-barrier-reef-from-climate-change-34278.

18. See, e.g., *Canberra Times* 22/5/1970, p. 7.

19. For their benthic surveys, which AIMS contributes to GCRMN, uncertainties of data for individual reefs are considerably higher – around 25%.

20. A normal distribution.

21. The size of the uncertainty margin should be subjected to further analysis in the future.

22. Note: AIMS stopped publishing the GBR average in 2017.

23. The Great Barrier Reef is an exception to this.

24. Kimura, T., L. M. Chou, D. Huang, K. Tun, and E. Goh, editors. 2022. *Status and trends of East Asian coral reefs: 1983–2019*. Global Coral Reef Monitoring Network, East Asia Region. See comments on p. 136.

25. See https://platogbr.com/308-2/ for details of the analysis. Nowadays, AIMS does not calcu-

late an average coral cover for the entire GBR, although it did so until 2017. The author has therefore performed this task to create Figure 4. AIMS does not give a reason why it stopped calculating the GBR average result, even though this is the statistic of most interest to the public and management.

26. At first glance, this may appear as almost a threefold increase, but the uncertainty in the data means that the 2011 figure may be as high as 0.14, and the 2022 figure may be as low as 0.30.

27. Great Barrier Reef Marine Park Authority (2022). *Reef Snapshot: Summer 2021-22*. https://elibrary.gbrmpa.gov.au/jspui/handle/11017/3916.

28. Marshall, P. and Schuttenberg, H. (2006). *A Reef Manager's Guide to Coral Bleaching.* Townsville, Australia.: Great Barrier Reef Marine Park Authority. Also https://www.aims.gov.au/research-topics/environmental-issues/coral-bleaching/coral-bleaching-events .

29. Diaz-Pulido, G., L.J. McCook, S. Dove, R. et al., 'Doom and boom on a resilient reef: Climate change, algal overgrowth and coral recovery'. *PLoS ONE*, 2009. 4 (4): p. e5239..

30. AIMS stated in reference to the 1998 'most reefs recovered fully, with less than five per cent of inshore reefs suffering high coral mortality.' The inshore reef in total represent only about 1 % of the coral on the GBR.

31. Aerial surveys hat are often used to monitor bleaching have greatly difficulty distinguishing bleached coral from dead coral.

32. https://www.aims.gov.au/reef-monitoring/gbr-condition-summary-2016-2017.

33. There can be a significant lag between the time the coral dies, and when those reefs are surveyed.

34. Although data for 1988 is 0.42 ± 0.04, and 2022 is 0.35 ± 0.04, there is overlap in the uncertainty range and therefore there is no statistically significant difference between the coral cover on those two years.

35. The upper and lower uncertainty margins overlap with previous highest years.

36. 'Record breaking' means the lower uncertainty bound is higher than the high uncertainty bound in any previous year.

37. These claims may be due to statements made to that affect by AIMS. However, this is an all-too-common misunderstanding of the uncertainty bands. If there is overlap between uncertainty bands between two years, then the two years are not statistically different.

38. 2022 is 0.34 ± 0.04, but 1986 is 0.26 ± 0.03. https://www.aims.gov.au/reef-monitoring/gbr-condition-summary-2016-2017.

39. Lat, Long., -18.618305, 147.302306.

40. The value in 2022 is not statistically different from the values in 2003. There is overlap of the uncertainty bars. So 2022 is not record-breaking for Helix Reef.

41. It is 3–4 degrees hotter than the southern part of the Great Barrier Reef.

42. Kimura, T., L. M. Chou, D. Huang, K. Tun, and E. Goh (eds) (2022). *Status and Trends of East Asian Coral Reefs: 1983–2019*. Global Coral Reef Monitoring Network, East Asia Region.

43. Sub-regions 1, 2, 4, and 5 of the East Asia region.

44. GCRMN data from Japan, shows major fluctuations in coral cover since 1980, but no sign of a declining trend. The last 20 years have been very stable.

45. There appears to be no explanation why 'data' is shown in the pre 1987 period when there is no data recorded at all.

46. AIMS data.

47. https://apps.aims.gov.au/reef-monitoring/reefs. Contact author for detailed analysis.

48. Australian Institute of Marine Science.

49. Isthmus of Panama closed around 3 million years ago.

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Cramer K.L., Lam V.V. (eds) (2014), *Status and Trends of Caribbean Coral Reefs: 1970-2012*. Global Coral Reef Monitoring Network, IUCN, Gland, Switzerland.

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53. Note even 'fast-growing' corals still take 5–10 years to totally cover the seabed after complete mortality.

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