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Impacts of Climate Change on World Heritage Coral Reefs

A First Global Scientific Assessment

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This assessment aims to make available the most current knowledge regarding the impacts of climate change on World Heritage properties as requested by the World Heritage Committee Decision 40 COM 7 (Istanbul/UNESCO, 2016).

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An artist's rendering of America's next-generation geostationary weather satellite

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1. Coral Reef Systems on UNESCO's World Heritage List

Since 1972, the UNESCO World Heritage Convention has united the world around a shared responsibility to protect natural and cultural places of Outstanding Universal Value (OUV). The World Heritage List includes 29 natural, marine properties that contain coral reef systems[a]. Stretching around the planet, these globally significant reefs include icons such as the Phoenix Islands Protected Area (Kiribati), the Great Barrier Reef (Australia), Papahānaumokuākea (USA), Belize Barrier Reef Reserve System (Belize) and Tubbataha Reefs Natural Park (Philippines). They are recognized for their unique and global importance and for being part of the common heritage of humanity.

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Belize Barrier Reef Reserve System

Coral reefs are ecologically and economically important ecosystems found across the world's tropical and sub-tropical oceans. Despite covering less than 0.1% of the ocean floor, reefs host more than one quarter of all marine fish species (in addition to many other marine animals)[1,2]. They are the most inherently biodiverse ecosystems in the ocean – comparable to rainforests on land. These 'Rainforests of the Sea' provide social, economic and cultural services with an estimated value of over USD $1 Trillion globally[3,4]. For example, the complex three-dimensional structure of reefs not only provides habitat but also dissipates wave energy to protect coastlines from erosion and damage. Coastal protection and human use (including tourism, recreation and fishing) supply the greatest economic benefits from coral reefs to over half a billion people around the world.

Despite their importance and value, most coral reefs are under enormous pressure from a range of different human activities globally including agricultural run-off, urban development, and over-fishing[5]. Superimposed on these local threats, increased ocean temperature has caused the death of corals around the world in recent years. At this point, rising atmospheric carbon dioxide caused by human activity is the greatest threat to coral reefs globally, primarily due to ocean warming but also due to ocean acidification that ensues.

2. Mass Coral Bleaching and its Implications for World Heritage

Corals are animals that live in a partnership with microscopic dinoflagellate algae (called zooxanthellae) that live inside the corals' tissue. Like other plants, these algae photosynthesize and in doing so, provide coral hosts with up to 90% of the energy they need to thrive[6]. This enables corals to construct limestone skeletons that form the three-dimensional structure of reefs, providing habitat for over a million species. However, this normally beneficial partnership can become toxic for the corals under certain stressful environmental conditions, including changes in temperature, light levels, salinity and water quality.

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Great Barrier Reef, Lizard Island

Coral bleaching is a stress response in which the coral animals expel their zooxanthellae, leaving the white coral skeleton visible through the transparent coral tissue[7]. Bleached corals are still alive – however, even mild bleaching can result in subsequent deleterious effects, such as reduced growth and reproduction. If stressful conditions persist for several weeks, corals may die from a lack of food or from disease. Coral mortality and subsequent erosion of their skeletons reduce the structural complexity and biodiversity of the reef system. These impacts lead to reduced habitat for marine organisms that depend upon the reef ecosystem, and fewer ecosystem goods and services, such as food, income and coastal protection, for dependent human communities.

The stressor that causes bleaching on broad spatial scales – "mass bleaching" – is heat stress[8], associated with global climate change and exacerbated by large climatic variability such as El Niño and La Niña events. Human activity has increased the atmospheric concentration of carbon dioxide and other heat-trapping gases dramatically during the past century, resulting in an increase in global surface temperature of approximately 1°C[b] since pre-industrial times[9]. As atmospheric carbon dioxide has raised temperatures in

a For the purpose of this assessment, coral reefs systems are included that are found within the boundaries of World Heritage properties but not necessarily identified as part of the assets of OUV. A full list is available in Annex I.

b Combined global land and ocean surface temperature relative to a reference period of 1850-1900.

the ocean, heat stress events causing coral bleaching have become more frequent and severe.

Elevated water temperature of even 1-2°C above the temperature a coral would normally experience can result in bleaching[8]. Temperature tolerance is location-specific, as corals have adapted to local conditions over long time periods (hundreds if not thousands of years). However, with the present era of rapid warming, most coral locations have already experienced temperatures sufficiently above their historical range to cause bleaching, and with unprecedented frequency and intensity[10,11]. Widespread mass coral bleaching was first documented in 1983 at the time of an extremely strong El Niño[12]. In 1998-99, during the next extremely strong El Niño and subsequent strong La Niña, widespread mass bleaching occurred in all three major ocean basins (Indian, Pacific, and Atlantic). This event is commonly recognized as the first global mass bleaching event[13]. The second global event, in 2010[10,14], was associated with a mild El Niño. These first two global events lasted less than 12 months. In contrast, the third global coral bleaching event began in June 2014 – almost a year before the 2015-16 El Niño – and is perhaps finally concluding as of May 2017[15,16]. Heat stress and bleaching spread across tropical oceans and intensified during the El Niño, then continued through the subsequent La Niña and beyond (Figure 1). This period has encompassed the three warmest years on record globally: 2014, 2015, and 2016[17]. To date, the global average temperature[c] in 2017 is comparable with the previous three years[18]. These extreme conditions caused back-to-back severe bleaching events; for example, in one of the world's most iconic coral reef systems, the Great Barrier Reef World Heritage area, in 2016[19] and 2017[20].

All three global bleaching events have caused severe bleaching and mortality of corals in various World Heritage listed reefs around the world. However, the frequency, intensity and duration of these heat stress events have worsened as global warming has increased, thereby increasing the impact on coral reefs and other marine systems around the world.

Other global factors can also exacerbate vulnerability to coral bleaching by lowering the corals' ability to recover. Approximately 30% of human-produced carbon dioxide is absorbed by the ocean's surface[21] and leads to ocean acidification. Ocean acidification reduces corals' ability to build their limestone skeletons and increases bioerosion and dissolution of reefs. At high CO_2 levels, ocean acidification is projected to cause reefs to erode. There is also growing evidence that intensifying storms are increasing the damage to coral reefs. Recent estimates indicate that climate-related loss of reef ecosystem services will total around US $500 billion per year or more by 2100[3,22]. The greatest impacts are likely to be experienced by people who rely upon reef services for day-to-day subsistence.

GLOBAL BLEACHING EVENTS HAVE CAUSED SEVERE CORAL BLEACHING AND MORTALITY OF WORLD HERITAGE LISTED REEFS AROUND THE WORLD.

Great Barrier Reef

c Combined global land and ocean surface temperature.

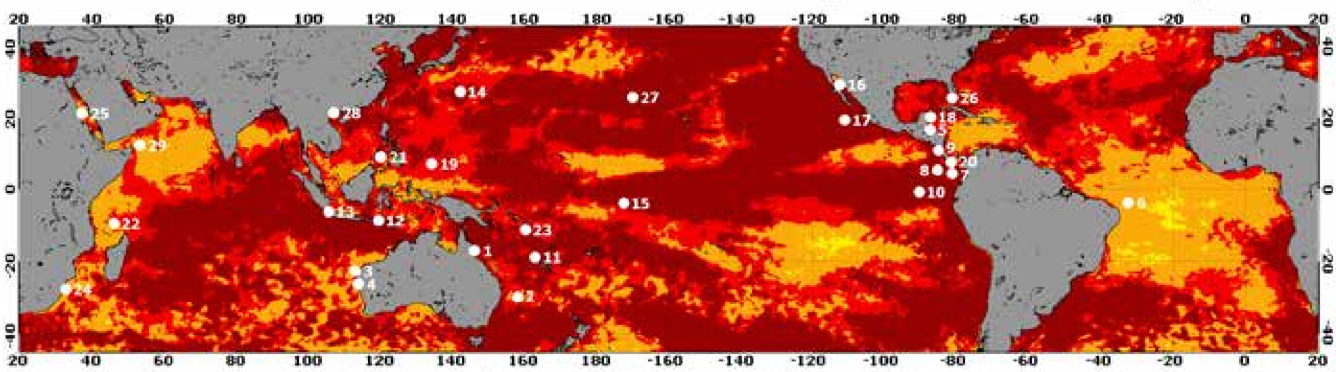
Local stressors can lower the resilience of coral reefs; i.e., the capacity to resist and/or recover from disturbance events, and maintain ecosystem function[23]. Over-fishing and pollution causing poor water quality can each harm corals' ability to recover from heat stress and can slow the recruitment of new corals after widespread mortality.

Efforts to build resilience by reducing local human pressure are central to World Heritage conservation, and are matters of concern to the World Heritage Committee, that provides requests and recommendations through the State of Conservation process of the 1972 World Heritage Convention. However, while essential, local management is no longer sufficient to protect the OUV of these properties. Some of the best-managed coral reef systems in the world have been seriously affected during recent bleaching events. This includes several World Heritage listed coral reef systems that experience minimal human pressures, such as Papahānamokuākea (USA) and Aldabra Atoll (Seychelles), and some that have invested heavily in building resilience, such as the Great Barrier Reef (Australia).

FIGURE 1 The highest level of heat stress recorded during the third global coral bleaching event, using NOAA Coral Reef Watch satellite products. More than 70% of global coral reef locations have been exposed to bleaching-level stress, and most of these twice or more, since June 2014.

Reef-containing, natural World Heritage properties (white dots) are numbered corresponding to the list of properties below and in Annex 1.

NOAA Coral Reef Watch 5 km Maximum Satellite Coral Bleaching Alert Area
June 2014 - April 2017



No Stress **Watch** **Warning** **Alert Level 1** **Alert Level 2**

n°	Country	Site
1	Australia	Great Barrier Reef
2	Australia	Lord Howe Island Group
3	Australia	Ningaloo Coast
4	Australia	Shark Bay, Western Australia
5	Belize	Belize Barrier Reef Reserve System
6	Brazil	Brazilian Atlantic Islands
7	Colombia	Malpelo Fauna and Flora Sanctuary
8	Costa Rica	Cocos Island National Park
9	Costa Rica	Area de Conservación Guanacaste
10	Ecuador	Galápagos Islands
11	France	Lagoons of New Caledonia
12	Indonesia	Komodo National Park
13	Indonesia	Ujung Kulon National Park
14	Japan	Ogasawara Islands
15	Kiribati	Phoenix Islands Protected Area

n°	Country	Site
16	Mexico	Gulf of California
17	Mexico	Archipiélago de Revillagigedo
18	Mexico	Sian Ka'an
19	Palau	Rock Islands Southern Lagoon
20	Panama	Coiba National Park
21	Philippines	Tubbataha Reefs Natural Park
22	Seychelles	Aldabra Atoll
23	Solomon Islands	East Rennell
24	South Africa	iSimangaliso Wetland Park
25	Sudan	Sanganeb Marine National Park and Dungonab Bay – Mukkawar Island Marine National Park
26	USA	Everglades National Park
27	USA	Papahānaumokuākea
28	Viet Nam	Ha Long Bay
29	Yemen	Socotra Archipelago

3. Observed Heat Stress and Bleaching Frequency in Reef-Containing World Heritage Properties

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Komodo National Park

NEARLY HALF OF WORLD HERITAGE PROPERTIES CONTAINING CORAL REEFS EXPERIENCED BLEACHING STRESS MORE THAN TWICE PER DECADE DURING 1985-2013; 25 OF 29 SITES EXPERIENCED BLEACHING STRESS IN THE LAST THREE YEARS.

Analysis of ocean surface temperatures recorded by satellites has been used in near real-time for over two decades to provide insight into conditions that cause coral bleaching on coral reefs[24]. Relevant satellite temperature records since 1985 are used here to provide over 30 years of data to assess past heat stress on World Heritage reefs.

Bleaching stress on the 29 reef-containing natural properties on the UNESCO World Heritage List was determined for historical (1985-2013) and recent (mid 2014-mid 2017) heat stress based on recently published studies[10] and newly developed data[25] from the United States National Ocean and Atmospheric Administration's (NOAA) Coral Reef Watch. The mid 2014-mid 2017 recent period corresponds to the third global coral bleaching event discussed in Section 2. Bleaching risk was assessed using a metric of accumulated heat stress, the Degree Heating Week (DHW). Satellite-based thresholds for bleaching-level heat stress (DHW of 4°C-weeks) and severe bleaching heat stress (8°C-weeks) are well established[24]; for over a decade, these thresholds have also been used to model the impact of bleaching under future climate scenarios. The established practice at Coral Reef Watch to summarize regional areas (i.e., Regional Virtual Stations[26], several of which correspond closely with World Heritage properties) is to calculate the heat stress experienced by the warmest 10% of reefs (i.e., the 90th percentile) in each area. For each year, the highest recorded heat stress in each property's summary value was compared with the DHW thresholds to indicate bleaching-level and severe stress events. Note that, in all cases, events above the severe stress threshold (DHW $\geq$ 8°C-weeks) are also counted as being above the bleaching stress threshold (DHW $\geq$ 4°C-weeks).

Coral communities typically take at least 15 to 25 years to recover from mass mortality events such as destructive cyclones and mass bleaching events[7]. If the frequency of mass mortality events increases to a point where the return time of mortality events is less than the time it takes to recover, the abundance of corals on reefs will decline. Consequently, the frequency of stress events that reached or exceeded the 4°C and 8°C-week DHW thresholds was calculated for each World Heritage reef-containing property (Table 1) to detect if the bleaching frequency exceeded the best-case rates of recovery.

This analysis showed that **World Heritage properties containing coral reefs have been increasingly exposed to heat stress during recent years. Nearly half (13) of the 29 World Heritage Listed reef properties were exposed to levels of heat stress that cause coral bleaching, on average, more than twice per decade during the 1985-2013 period** (Table 1a, red or dark red). A further six properties experienced heat stress more than once per decade (orange) and two properties were exposed more than once every 20 years (yellow). Eight sites had an exposure frequency less than once every 20 years (green). Of those, **only three properties experienced no heat stress events during the historical period – Ujung Kulon National Park (Indonesia), iSimangaliso Wetland Park (South Africa) and Socotra Archipelago (Yemen).** For eight World Heritage reefs (28%) heat stress that causes severe bleaching was experienced more than once per decade (Table 1b, red or dark red).

Recent heat stress (mid 2014-mid 2017, during the third global coral bleaching event) was categorized by the number and intensity of events, in a similar way as for the 1985-2013 period. The classification (color) scheme reflects both the higher impact of single severe events as well as the cumulative impact of recurrent stress, even at lower levels. Impact was considered most severe (dark red) where properties experienced three bleaching-level stress events (annual exposure to DHW ≥ 4°C-weeks, Table 1c), or two or more severe stress events (DHW ≥ 8°C-weeks, Table 1d) within the three-year period. The second-highest category of heat stress (red) included locations exposed to two bleaching-level stress events (Table 1c). A single severe stress event during the past three years was assigned to the third-highest category (orange), while locations exposed to only one bleaching-level stress event were colored yellow. Only properties that had no reefs exposed to any bleaching-level stress were assigned to the lowest category (green).

Seventy two percent of World Heritage reef properties (21 of 29) have been exposed to severe and/or repeated heat stress during the past three years. Within the three years of the current global bleaching event (mid 2014-mid 2017), 18 World Heritage reefs (62%) were in the highest impact category (dark red) at either one or both stress levels (Table 1c,d). A further three properties were exposed to recurrent bleaching stress (red) or a single severe stress event (orange). This illustrates the dramatic impact on coral reefs during this period, which has seen three consecutive years of record global temperature (2014, 2015 and 2016), and reflects an increase in bleaching frequency from that seen in the prior decades. Only four properties (14%) escaped bleaching-level heat stress during this three-year bleaching event: Brazilian Atlantic Islands (Brazil), iSimangaliso Wetland Park (South Africa), Sanganeb Marine National Park and Dungonab Bay – Mukkawar Island Marine National Park (Sudan) and Socotra Archipelago (Yemen).

Long-term observations of bleaching are available for some World Heritage reefs. These observations are from selected reefs within each property and reflect the extent of bleaching reported. Five World Heritage reefs with regular observations through at least much of the past almost four decades[27] were compiled (Table 2). For each location and each bleaching event, bleaching is classified as moderate (<30% of reefs bleached) or severe (≥ 30%). From these, the frequency of observed bleaching (for combined moderate or severe bleaching, and for severe bleaching alone) was determined.

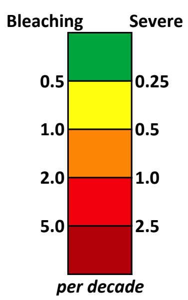
The bleaching observations also show that bleaching has occurred more frequently in recent years than in the decades prior, consistent with the results discussed above for the historical and recent thermal stress events derived from satellite data. **Coral mortality during the third global bleaching event has been among the worst ever observed, including at World Heritage reefs; e.g., Great Barrier Reef (Australia), Papahānaumokuākea (USA) and Aldabra Atoll (Seychelles).**

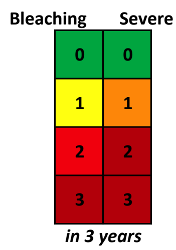
TABLE 1 Frequency (per decade) of bleaching-level (DHW ≥ 4°C-weeks) and severe bleaching (DHW ≥ 8°C-weeks) heat stress events for the period 1985-2013 (Historical); and number of events during the three years from mid 2014-mid 2017 (Recent). Note that events above the severe stress threshold are also counted as being above the bleaching stress threshold.

Color categories (shown below) are explained in the text.

	Historical Stress		Recent Stress	
Reef-containing World Heritage site	(a) #Bleaching stress per decade (1985-2013)	(b) #Severe stress per decade (1985-2013)	(c) #Bleaching stress in 3 years (mid2014-mid2017)	(d) #Severe stress in 3 years (mid2014-mid2017)
Great Barrier Reef	1,7	0,0	3	2
Lord Howe Island Group	2,1	1,0	1	0
Ningaloo Coast	3,1	2,1	2	0
Shark Bay, Western Australia	5,9	2,8	3	3
Belize Barrier Reef Reserve System	1,7	0,0	3	1
Brazilian Atlantic Islands	0,3	0,3	0	0
Malpelo Fauna and Flora Sanctuary	2,1	1,0	2	2
Cocos Island National Park	0,3	0,3	3	1
Area de Conservación Guanacaste	0,3	0,0	1	0
Galápagos Islands	4,5	3,4	3	3
Lagoons of New Caledonia	2,8	0,0	3	2
Komodo National Park	2,4	0,3	3	3
Ujung Kulon National Park	0,0	0,0	2	2
Ogasawara Islands	3,4	1,0	1	1
Phoenix Islands Protected Area	4,1	2,8	3	3
Gulf of California	2,8	0,3	3	2
Archipiélago de Revillagigedo	2,8	1,0	3	3
Sian Ka'an	3,1	0,0	3	3
Rock Islands Southern Lagoon	0,7	0,3	1	0
Coiba National Park	1,0	0,7	2	2
Tubbataha Reefs Natural Park	0,3	0,0	2	1
Aldabra Atoll	0,3	0,0	1	0
East Rennell	1,4	0,0	3	1
iSimangaliso Wetland Park	0,0	0,0	0	0
Sanganeb Marine National Park and Dungonab Bay – Mukkawar Island Marine National Park	1,4	0,0	0	0
Everglades National Park	2,4	0,7	3	3
Papahānaumokuākea	0,7	0,0	2	2
Ha Long Bay	1,4	0,0	3	2
Socotra Archipelago	0,0	0,0	0	0

Bleaching stress threshold defined as DHW of 4 °C-weeks; severe bleaching stress threshold defined as DHW of 8 °C-weeks.





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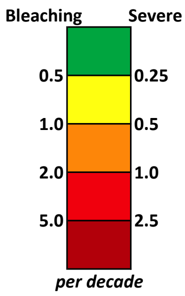
Great Barrier Reef

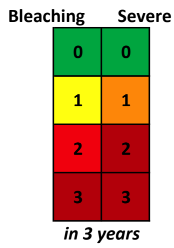
While the overall pattern of increased impact is reflected in both the heat stress exposure (Table 1) and observed bleaching impact (Table 2), there are some differences between the datasets, especially during lower levels of bleaching stress (4-8°C-weeks, or mild bleaching). There will always be some disagreement between remotely-sensed heat stress and measures of in situ bleaching responses. This may result from the surveyed locations not being representative of the entire property, particularly given the size of, for example, Papahānaumokuākea (USA) and the Great Barrier Reef (Australia), among the most spatially vast of all World Heritage properties. It may also reflect changing sensitivity of corals to heat stress. Furthermore, the current analysis does not consider timing of events within a period (e.g., the response of surviving corals in back-to-back heat stress events may be different between the years) or other contributing factors that can alter coral and reef resilience[23].

TABLE 2. Frequency of observed bleaching during 1980-2013 and mid 2014-mid 2017 at five reef-containing World Heritage properties. Note that severe events are also counted as being bleaching events.

Color categories (shown below) are explained in the text.

	Observed bleaching (1980-2013)		Observed bleaching (mid2014-mid2017)	
Reef-containing World Heritage site	**(a) #Bleaching events per decade**	**(b) #Severe events per decade**	**(c) #Bleaching events in 3 years**	**(d) #Severe bleaching in 3 years**
Great Barrier Reef	2.1	0.7	2	2
Lagoons of New Caledonia	0.7	0.7	1	1
Phoenix Islands Protected Area	1.0	0.7	2	2
Aldabra Atoll	0.7	0.3	1	1
Papahānaumokuākea	0.3	0.3	1	1





4. Projected Future Heat Stress on Reef-Containing World Heritage Properties under Two Climate Change Scenarios

The link between coral bleaching events and ocean heat stress exposure can also be applied to model projections of temperature to determine estimates of potential stress for the future. This allows us consideration of what the future may hold for World Heritage properties containing coral reefs. Projected stress exposure under different CO_2 emissions trajectories (Representative Concentration Pathways, RCP[28]), as used by the Intergovernmental Panel on Climate Change (IPCC), indicate a range of projected impacts depending upon atmospheric greenhouse gas concentrations in the years to come. Future estimates of accumulated heat stress at World Heritage properties with reefs were assessed using recently published analyses[29].

Current damage is already extensive and has accelerated with around 1°C[d] of global-average warming[19] since pre-industrial times[e]. Recent analyses have shown that most of the world's coral reefs will be seriously degraded at higher levels of warming[22,31]. It is a well-established conclusion of international peer reviewed literature and research[32,33] that only meeting the most ambitious target of the United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement[34], i.e., limiting the global average temperature increase to 1.5°C above pre-industrial levels, provides a chance of retaining coral-dominated communities for many reef locations around the globe. Acknowledging this and the presence of other stressors, one can look ahead to project the year in which severe bleaching stress will occur twice-per-decade (exceeding the frequency at which reefs can recover between bleaching events), and also the onset year in which severe bleaching stress will become an annual occurrence.

We consider future heat stress based on two projection scenarios that are readily available. The first is RCP8.5, in which emissions (and temperature) continue to rise through the 21st century, similar to what was previously described as the "business as usual" scenario in earlier IPCC assessments[28,35]. The second is RCP4.5, in which emissions peak around 2040 and then decline[28], although large inertia in the climate system will likely continue to raise temperature after that time but at a decelerating rate. These scenarios lead to projected global-mean temperature increases by 2100 of 4.3°C and 2.4°C[f], respectively, both of which well exceed the level of warming (1.5°C) beyond which severe degradation of the great majority of coral reefs is anticipated[22]. Based on recent estimates, countries' emissions are likely to raise the global-mean temperature by around 3.6°C by 2100, whereas the aggregated effects of the pledges made by countries under the Paris Agreement so far would likely result in about 3°C warming globally[36,37].

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Sian Ka'an

UNDER BUSINESS-AS-USUAL, 25 OF THE 29 WORLD HERITAGE REEFS WILL SEVERELY BLEACH TWICE-PER-DECADE BY 2040. REDUCING EMISSIONS COULD CUT THIS TO 14 PROPERTIES – OR FEWER.

Following the technique of the satellite analysis, future stress exposure is presented as the year in which stress first occurs at twice-per-decade and annual frequencies for at least 10% of reef locations within each property. This is a more conservative measure than the 10-15 years required for reefs to start to recover but has been used by the modeling community to reflect the time at which it can be certain corals no longer have sufficient time to recover between events. The color scheme for future stress exposure (Table 3) reflects that a later onset of frequent heat stress, while still damaging, is a far better outcome for coral reefs; the darkest red indicates the earliest onset of future stress. Green shading is used only where the stressful condition is not realized by 2100 in the modeling. The color categories are delineated by the same years in all analyses presented (2055, 2040 and 2025), allowing comparison between the two scenarios. Severe bleaching events 2014-17 reflect damage expected once warming results in a frequency between twice-per-decade and annual severe bleaching stress.

The projections under RCP8.5 most closely represent the current emissions trajectory. **Under RCP8.5, twice-per-decade severe bleaching will be apparent at 25 of the 29 World Heritage reefs (86%) by 2040 (Table 3a, dark red and red), with four of those locations experiencing frequent severe heat stress before 2025 (dark red).**

d Combined global land and ocean surface temperature relative to a reference period of 1850-1900.

e Tropical ocean temperature change usually equates to about 2/3 of these values and varies regionally. For example, the 1880-2015 warming reported at 0.88°C equates to a tropical ocean warming of 0.57°C[30].

f Combined global land and ocean surface temperature relative to a reference period of 1850-1900.

TABLE 3 Onset of recurrent severe bleaching heat stress events under Representative Concentration Pathways (RCP) 8.5 and 4.5. Event frequencies are twice-per-decade and annually.
Color categories (shown below) are explained in the text.

Reef-containing World Heritage site	Future Severe Stress - RCP8.5		Future Severe Stress - RCP4.5	
	(a) Projected Year of 2x/decade	(b) Projected Year of Annual	(c) Projected Year of 2x/decade	(d) Projected Year of Annual
Great Barrier Reef	2035	2044	2041	2051
Lord Howe Island Group	2034	2043	2036	2055
Ningaloo Coast	2041	2049	2052	2074
Shark Bay, Western Australia	2038	2047	2045	2074
Belize Barrier Reef Reserve System	2028	2036	2036	2044
Brazilian Atlantic Islands	2028	2039	2035	2049
Malpelo Fauna and Flora Sanctuary	2038	2050	2056	2077
Cocos Island National Park	2019	2032	2028	2036
Area de Conservación Guanacaste	2030	2043	2040	2055
Galápagos Islands	2017	2036	2027	2042
Lagoons of New Caledonia	2031	2040	2039	2050
Komodo National Park	2017	2025	2021	2032
Ujung Kulon National Park	2032	2043	2042	2053
Ogasawara Islands	2030	2038	2041	2049
Phoenix Islands Protected Area	2020	2035	2028	2040
Gulf of California	2044	2052	-----	-----
Archipiélago de Revillagigedo	2031	2042	2043	2052
Sian Ka'an	2025	2033	2033	2041
Rock Islands Southern Lagoon	2028	2036	2032	2044
Coiba National Park	2030	2043	2040	2053
Tubbataha Reefs Natural Park	2030	2039	2037	2048
Aldabra Atoll	2028	2036	2034	2042
East Rennell	2025	2033	2030	2044
iSimangaliso Wetland Park	2031	2040	2036	2048
Sanganeb Marine National Park and Dungonab Bay – Mukkawar Island Marine National Park	2037	2046	2055	2069
Everglades National Park	2036	2044	2056	2071
Papahānaumokuākea	2029	2041	2044	2052
Ha Long Bay	2077	2086	-----	-----
Socotra Archipelago	2040	2048	2061	2077

Severe bleaching stress threshold defined as DHW of 8 °C-weeks.

2025 2040 2055 never

Sites projected to encounter severe stress at least twice-per-decade within the next five years under RCP8.5 are Cocos Island National Park (Costa Rica), Galápagos Islands (Ecuador), Komodo National Park (Indonesia) and Phoenix Islands Protected Area (Kiribati). Four World Heritage reefs (14%) are not projected to severely bleach twice-per-decade until after 2040 (orange and yellow); however, **all 29 properties are projected to be exposed before the end of the century under RCP8.5.** Furthermore, the onset of annual severe bleaching occurs before the end of the century for all 29 properties under RCP8.5 (Table 3b), and before 2040 for 12 sites (41%, red).

Under RCP4.5, emissions peak around 2040 and then decline. **Under RCP4.5, twice-per-decade severe bleaching occurs at less than half (14) of the properties by 2040 (Table 3c, dark red and red).** Of these, only Komodo National Park (Indonesia) is projected to experience frequent severe stress before 2025 (dark red). Of the 15 remaining properties, four (14%) have the onset after 2055 (yellow): Malpelo Fauna and Flora Sanctuary (Colombia), Sanganeb Marine National Park and Dungonab Bay – Mukkawar Island Marine National Park (Sudan), Everglades National Park (USA) and Socotra Archipelago (Yemen). Importantly, under RCP4.5 twice-per-decade severe bleaching does not occur before 2100 for two World Heritage reefs (green): Islands and Protected Areas of the Gulf of California (Mexico) and Ha Long Bay (Viet Nam). The projected onset of annual severe bleaching under RCP4.5 would not occur before 2040 at 27 of 29 (93%) properties. The exceptions are: Cocos Island National Park (Costa Rica) and Komodo National Park (Indonesia) (Table 3d, red), each with onset of annual severe stress after 2025. Ten properties (34%) would not experience annual bleaching before 2055 and, again, Islands and Protected Areas of the Gulf of California (Mexico) and Ha Long Bay (Viet Nam) are not projected to experience annual bleaching before 2100.

Our results can be summarized as follows. For World Heritage sites containing coral reefs, projected reductions in thermal stress from RCP8.5 to RCP4.5 will:

- reduce the number (percentage) of sites that are likely to experience twice-per-decade (or worse) bleaching in 2040 from 25 (68%) to 14 (48%);
- reduce the sites likely to experience annual bleaching in 2040 from 12 (41%) to 2 (7%); and

- when averaged across all 29 sites, twice-per-decade severe stress will likely be delayed from 2032 to at least 2044.

These results are sobering. While RCP4.5 is a much better scenario than RCP8.5, it will not prevent significant decline in coral reefs. Only two sites do not cross the heat stress threshold until after 2100 (and these are not premier sites for corals). However RCP4.5 demonstrates that reduced emissions scenarios extend the window of less severe conditions by an average of 12 years across sites. Another way to frame the benefit is that RCP4.5 reduces the proportion of sites crossing a threshold in any given year by a significant measure. Corals are known to have some degree of adaptive capacity, though how far this can go is unknown.

High-resolution downscaling of lower-emissions scenarios was not available for this analysis, but projections have been described at coarser resolution. In the RCP2.6 scenario, emissions peak during the current decade, 2010-2020, and then decline substantially, resulting in a projected peak global temperature increase of 1.6°C and returning to 1.5°C or below by 2100. **The latest IPCC report assessed the consequence of RCP2.6 for corals finding that the frequency of severe bleaching and death of corals is dramatically reduced, compared with higher-emissions scenarios, including in regions where the reef-containing World Heritage properties are found[31].**

Warming of 1.5°C is recognized by many scientists to be a maximum for coral reefs to survive in the long term[22,32,33], although even this will result in significant reef loss. Multiple studies support the conclusion that corals will not thrive again until atmospheric CO_2 has been reduced to 320-350 ppm[38,39].

At present global average atmospheric CO_2 concentrations exceed 400 ppm, and under Paris Agreement-compatible emission pathways would not return below 350 ppm until the mid 22nd century, if at all[40]. Scientific attention has begun to consider the changed composition and dynamics of reefs, away from being coral-dominated, even with such drastic CO_2 reductions[30].

Reduced atmospheric CO_2 pathways give corals time to adapt and provide two key opportunities, through:

- improving opportunities for adaptation by corals, by reducing the rate of future warming, and extending the window before a critical threshold is reached; and
- expanding opportunities for the research and development of new solutions, reducing interacting stressors, developing new models for management, new techniques for rehabilitation, and innovations in industry and manufacturing to reduce CO_2 emissions and implement sequestration to remove CO_2 from the atmosphere and upper ocean.

The improvement from RCP8.5 to RCP4.5, while small, is real. A lower emissions scenario such as RCP2.6 would be considerably better, but we are still faced with a situation of great uncertainty about whether this will be enough. **Based on the above, this assessment finds that drastic reductions in CO2 emissions are essential – and the only real solution – to giving coral reefs on the World Heritage List a chance to survive climate change.**

5. Summary and Solutions

Climate change has been impacting coral reefs for more than three decades through the bleaching and mortality of corals due to heat stress. Bleaching events are becoming more frequent, more widespread and more severe, and are having major impacts on coral reefs globally. Warming is projected to exceed the ability of reefs to survive within 1-3 decades for the majority of World Heritage sites containing coral reefs, and the impact is aggravated by the additional pressures such as ocean acidification and local stressors.

In the past three years, only four reef-containing World Heritage properties escaped exposure to bleaching-level heat stress, while more than three-quarters of the properties have been affected by severe and/or repeated heat stress. Under RCP8.5 (similar to a "business-as-usual" scenario), this study predicts that 25 of the 29 World Heritage reefs will experience twice-per-decade severe bleaching by 2040, a frequency that will rapidly kill most corals present and prevent successful reproduction necessary for recovery of corals. **All properties will experience annual severe bleaching, and thus will cease to host functioning coral reef ecosystems, by the end of the century unless CO2 emissions are reduced.**

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Great Barrier Reef, Wilson Reef

LOCAL MANAGEMENT IS NO LONGER SUFFICIENT TO ENSURE THE FUTURE OF CORAL REEFS. PROTECTING WORLD HERITAGE REEFS REQUIRES COMPLEMENTARY NATIONAL AND GLOBAL EFFORTS TO LIMIT WARMING TO 1.5°C

Until now, the focus for World Heritage sites in maintaining the Outstanding Universal Value of their key features has been on maintaining integrity through on-site management and pressures, and national or regional enabling legislation. Efforts to restore resilience and reduce local human stressors remain necessary but are no longer sufficient. For the first time, a ubiquitous global threat - heat stress sufficient to cause frequent severe bleaching and mortality - now threatens the OUV of World Heritage sites in a way that cannot be resolved through local management alone. The only viable solution is for all countries with World Heritage coral reefs to not only act to reduce local stressors but also to reduce their greenhouse gas emissions to net zero, along with supporting active CO_2 removal from the atmosphere and upper ocean.

Reducing greenhouse gas emissions (and effecting carbon sequestration) reduces the rate at which heat stress increases this century, and delays the year when a critical threshold is crossed. It also results in eventual stabilization of temperatures and heat stress after 2100. Changing from RCP8.5 to RCP4.5 provides an additional 12 years (on average) of capacity for adaptive responses to occur and reduces the proportion of sites experiencing severe stress levels in any given year. While clearly not enough to 'save' reefs and insufficient as a solution, this is an important opportunity, 'buying time' for natural adaptation, and the search for solutions. Even greater emissions reductions, such as under RCP2.6, and **delivering on the Paris Agreement target of "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C"[32] offers the only opportunity to prevent coral reef decline globally, and across all 29 reef-containing natural World Heritage sites.**

6. Additional Research

This analysis provides a first scientific assessment of past impacts on World Heritage coral reefs and the risks under different emissions scenarios in coming decades. Further work to strengthen and provide a more comprehensive analysis to inform the World Heritage Committee and the global community could include efforts to:

- augment historical data collation efforts and expand monitoring of reef condition for all World Heritage properties containing coral reefs;
- enhance analysis of past bleaching and heat stress events to test for impacts of back-to-back heat stress or local factors that alter reef resilience;
- undertake high-resolution (downscaled) future projection analysis under both RCP2.6 and the new RCP1.9 scenarios, to fully understand the implications of meeting the long-term goal of the Paris Agreement for World Heritage properties. Under RCP2.6 emissions peak during the current decade, 2010-2020, and then decline substantially, resulting in a projected peak global temperature increase of 1.6°C and returning to 1.5°C or below by 2100[g]. RCP1.9 is being discussed as an emissions pathway that results in a peak global warming of around 1.5°C, and returning to around 1.3°C by 2100;
- increase capacity for the detection of impacts on corals, prior to visible signs of bleaching, and how impacts may be alleviated by physical and other mechanisms that confer bleaching resistance and resilience;
- expand the consideration of impacts beyond corals, to include broader ecosystem impacts of warming and acidification, and their socio-economic importance;
- identify and protect coral reefs (World Heritage or other) that stand in the best position to survive climate change and which are best located to help regenerate other coral communities once ocean conditions have stabilized; and
- develop guidance to support the management of World Heritage reefs in the face of climate change, and for industries that depend upon reefs (to enhance social adaptive capacity).

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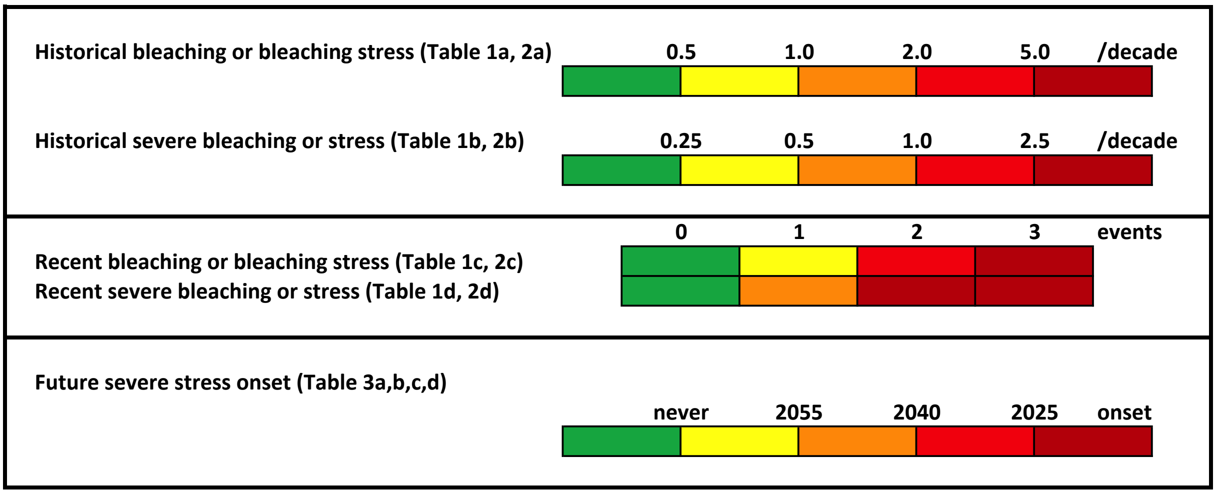
g Combined global land and ocean surface temperature relative to a reference period of 1850-1900.

ANNEX I
Natural Properties of Outstanding Universal Value Inscribed on UNESCO's World Heritage List (March 2017) that Contain Coral Reefs. Locations Are Displayed By Number in Figure 1[h]

N°	COUNTRY	SITE
1	Australia	Great Barrier Reef
2	Australia	Lord Howe Island Group
3	Australia	Ningaloo Coast
4	Australia	Shark Bay, Western Australia
5	Belize	Belize Barrier Reef Reserve System
6	Brazil	Brazilian Atlantic Islands
7	Colombia	Malpelo Fauna and Flora Sanctuary
8	Costa Rica	Cocos Island National Park
9	Costa Rica	Area de Conservación Guanacaste
10	Ecuador	Galápagos Islands
11	France	Lagoons of New Caledonia
12	Indonesia	Komodo National Park
13	Indonesia	Ujung Kulon National Park
14	Japan	Ogasawara Islands
15	Kiribati	Phoenix Islands Protected Area
16	Mexico	Gulf of California
17	Mexico	Archipiélago de Revillagigedo
18	Mexico	Sian Ka'an
19	Palau	Rock Islands Southern Lagoon
20	Panama	Coiba National Park
21	Philippines	Tubbataha Reefs Natural PArk
22	Seychelles	Aldabra Atoll
23	Solomon Islands	East Rennell
24	South Africa	iSimangaliso Wetland Park
25	Sudan	Sanganeb Marine National Park and Dungonab Bay – Mukkawar Island Marine National Park
26	USA	Everglades National Park
27	USA	Papahānaumokuākea
28	Viet Nam	Ha Long Bay
29	Yemen	Socotra Archipelago

ANNEX 2
Color Categories Used in Data Presentations of Tables 1, 2 & 3



h Full descriptions of World Heritage properties used in this publication are available at : http://whc.unesco.org/en/marine-programme/

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