UN environment programme

PROJECTIONS OF FUTURE CORAL BLEACHING CONDITIONS USING IPCC CMIP6 MODELS:

Climate policy implications, management applications, and Regional Seas summaries

Citation: UNEP 2020. ***Projections of future coral bleaching conditions using IPCC CMIP6 models: climate policy implications, management applications, and Regional Seas summaries.*** United Nations Environment Programme, Nairobi, Kenya

Authors: Ruben van Hooidonk[1, 2], Jeffrey Maynard[3], Gabriel Grimsditch[4], Gareth Williams[5], Jerker Tamelander[4], Jamison Gove[6], Heather Koldewey[7], Gabriella Ahmadia[8], Dieter Tracey[9], Kim Hum[10], Eric Conklin[10], and Michael Berumen[11]

1 Cooperative Institute for Marine and Atmospheric Studies, Rosenstiel School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149, USA

2 NOAA Atlantic Oceanographic and Meteorological Laboratory, Ocean Chemistry and Ecosystems Division, 4301 Rickenbacker Causeway, Miami, FL 33149, USA

3 SymbioSeas, Carolina Beach NC, 28428, USA

4 United Nations Environment Programme, Nairobi, Kenya

5 School of Ocean Sciences, Bangor University, Menai Bridge, Anglesey LL59 5AB, UK

6 National Oceanic and Atmospheric Administration, Honolulu, HI, USA

7 Zoological Society of London, UK

8 World Wildlife Fund, Washington, D.C., USA

9 Science Graphics, Stratford QLD 4870, Australia

10 The Nature Conservancy, Honolulu, HI, USA

11 Red Sea Research Center, KAUST, Saudi Arabia

Acknowledgements: Financial and in-kind support for this research was provided by: UNEP, NOAA Coral Reef Conservation Program, NOAA Atlantic Oceanographic and Meteorological Laboratory, RSMAS at the University of Miami, Bertarelli Foundation, SymbioSeas, NOAA National Marine Fisheries Service via the PIFSC, Bangor University, Principality of Monaco, and US Department of State.

Cover image: Howard Hall, Coral Reef Image Bank

Summary: This report updates this UN 2017 report:

> UNEP 2017. ***Coral Bleaching Futures - Downscaled projections of bleaching conditions for the world's coral reefs, implications of climate policy and management responses.*** United Nations Environment Programme, Nairobi, Kenya

This update includes projections of the timing of exposure to severe bleaching conditions for coral reef areas under the 2019-released IPCC CMIP6 climate models (versus the CMIP5 models used in the UNEP 2017 report), using the new Shared Socioeconomic Pathways. Projections results are shared, as is an evaluation of the implications of climate policy on coral reef futures. The projections are summarized by country, territory, UNEP Regional Sea and Marine Ecosystems of the World within the report appendices. This report is complemented by publicly accessible spatial data of the projections, available from the World Environment Situation Room.

Table of Contents

Executive Summary

The third global coral bleaching event, which started in 2014 and extended well into 2017, was the longest coral bleaching event on record. The length of the event means corals in some parts of the world had no time to recover in 2014, 2015 or 2016 during the cool/winter season, prior to experiencing bleaching the following year. This recent global bleaching event of 2014-2017 represents what climate model projections presented in this Report suggest may become the norm over the coming two decades. Importantly though, great spatial variation exists in the projected timing of the onset of annual severe bleaching (ASB) conditions among the world's coral reefs. ASB is calculated as the projected date beyond which a reef is expected to experience severe bleaching conditions annually (at least 8 Degree Heating Weeks). Variation in ASB timing will be a major driver of differences in the relative vulnerability of coral reef ecosystems to climate change. Reef areas projected to experience ASB much later than other reef areas could be temporary refugia that have lower climate vulnerability. These refugia may provide ecosystem goods and services for longer so should be considered as potential conservation and restoration priorities.

This project team previously developed projections of the exposure component of climate vulnerability in coral reef areas. These projections were based on the World Climate Research Programme's Working Group on Coupled Modelling (WGCM) Coupled Model Intercomparison Project Phase 5 (CMIP5) generation of climate models (used by the IPCC in the 5th Assessment Report – AR5). These projections, which were statistically downscaled to 4-km are reviewed in UNEP (2017) and van Hooidonk et al. (2016).

This report updates the UNEP 2017 report with projections of the timing of severe coral bleaching conditions using the new generation of climate models used by the IPCC – the CMIP6 generation of models. The motivation in providing this update is that some CMIP6 models have >4x the spatial resolution (some have native resolutions of ¼ x ¼°; ~ 27 x 27km at the equator) than CMIP5 models (native resolution of 1 x 1°; ~110 x 110km) and include other improvements. Further, the CMIP6 models are forced by the recently released Shared Socioeconomic Pathways (SSPs – see Riahi (2017) for an overview). The CMIP6 models represent the current state-of-the-art in climate modeling to deliver climate science that informs regional and global climate policy. These projections presented here are of future exposure to bleaching conditions (i.e., temperature stress); the socio-ecology of coral reefs within all grid cells will vary and this variance is not built into these projections.

Projections of the timing of annual severe bleaching conditions are compared in this report for SSP5-8.5 and SSP2-4.5 to examine the implications of climate policy for coral reefs.

SSP5-8.5 is the pathway that represents current rates of emissions and emissions growth; it is also considered a "worst-case scenario". This scenario assumes there is no climate policy or that policy is not effective. SSP5-8.5 represents a growing world economy heavily dependent on fossil fuels. Results from the SSP5-8.5 pathway are most of the focus of this report and can be seen as using the precautionary principle in planning.

SSP2-4.5 is a highly ambitious but plausible scenario. SSP2-4.5 is a "middle of the road" pathway in which emissions continue to increase through the end of the century, reaching between 65GtCO_2 and 85GtCO_2, with resulting warming of 3.8-4.2°C. This scenario was selected because it ***could*** represent future conditions *if greater levels of emissions reduction (~150% of* *pledges) are achieved than would result from all Nationally Determined Contributions in the Paris Agreement combined.*

The purpose of this report is threefold:

1. To present projections of coral bleaching conditions (i.e., exposure to the primary climate threat to coral reefs) and potential adaptation at a spatial scale that enables use of the data in management and conservation planning and in support of other decisions influencing coral reefs and reef use;

2. To evaluate the implications of the Paris Agreement as well as failure to achieve its goal, by comparing the projected timing of annual severe bleaching between Shared Socioeconomic Pathways SSP5-8.5 and SSP2-4.5; and

3. To provide public access to the projections data as well as the main findings to catalyze research that extends the purposes and applications described in 1 and 2, and informs new research.

The report has been prepared with the coral reef scientific and management community as the primary target audience.

Results highlights include:

- Under the fossil-fuel aggressive SSP5-8.5, ASB is projected to occur within this century for 100% of the world's coral reefs. The average projected year of ASB is 2034, nine years earlier than was projected as a global average for RCP8.5 using CMIP5 models. This suggests the previous CMIP5 generation of projections of future bleaching conditions underestimated the near future threat of annual severe bleaching.

- Projected exposure to annual severe bleaching conditions varies greatly among and within countries under SSP5-8.5. Coral reefs with relatively early and late exposure to annual bleaching conditions occur in all of the ocean basins; however, some countries have more temporary refugia than others. Six of the 20 countries with the greatest reef area have >25% temporary refugia (i.e., projected ASB after 2044), including: Indonesia (35%), western Australia (70%), The Bahamas (26%), Madagascar (30%), India (37%), and Malaysia (47%). Thirteen of the 20 countries with the greatest reef area have >25% of reef areas that are projected to experience annual bleaching conditions relatively early. Some of these countries include the Philippines, Solomon Islands, Fuji, Cuba, and Saudi Arabia.

  It is important to note that these projections should not be interpreted as predictions of exactly when bleaching will occur and do not imply that any reef areas, including relative refugia, are safe from severe bleaching.

- The average year for the projected timing of ASB under SSP2-4.5 is 2045, 11 years later than the average year projected under SSP5-8.5. Successful mitigation in line with the Paris Agreement would do little to provide reefs with more time to adapt or acclimate prior to severe coral bleaching conditions occurring annually.

- There are three major results from the projections that assume coral adaptation levels between 0.25° and 2°C: 1) Each quarter degree of assumed adaptation adds ~7 years to the global average timing of projected annual severe bleaching; 2) The great majority of coral reefs (≥80%) are expected to experience ASB this century even if 2°C of adaptation is assumed; 3) There is great spatial variation in the benefits to reefs, in terms of later ASB timing, at each assumed adaption level. The extent to which corals will adapt to increasing sea temperatures is unknown, but some level of adaptation is expected. If we assume 1°C of adaptation, the global average ASB timing is ~30 years later than if no adaptation is assumed.

The projections describe and quantify climate change exposure of coral reefs and thus contribute to our understanding of coral reef vulnerability. These projections can guide management, conservation and restoration planning, and be used in education and outreach programs.

Recommendations for next steps and research priorities include: downscaling the projections to 5-km scale to distinguish what are known to be local-scale differences in average summer temperatures and the bleaching threshold; better understanding the drivers and spatial patterns of coral and coral community adaptation to thermal stress; and, combining the projections with analyses of bleaching observations to identify reef areas that have fared better (‘bright spots’) or worse (‘dark spots’) than expected during recent bleaching events. Advances in any of those areas will increase confidence in the projections as well as the capacity of managers to use the projections in conservation planning, policy, and stakeholder engagement and outreach.

Introduction

Coral bleaching and climate modeling

Stony corals bleach when warm sea temperatures disrupt the mutualistic relationship between the algal symbionts, called zooxanthellae, that reside within the host coral tissues (Douglas 2003). Corals can either regain their zooxanthellae (Baker 2001) and survive or die if temperature stress persists. The third global coral bleaching event, which started in 2014 and extended well into 2017, was the longest coral bleaching event on record (Eakin et al. 2019). The length of the event means corals in some parts of the world had no time to recover in 2014, 2015 or 2016 during the cool/winter season, prior to experiencing bleaching the following year. Van Hooidonk et al. (2013, 2014, 2016 and 2017) found that a majority of coral reefs are projected to experience annual severe bleaching (ASB) by the mid-2040's under a business-as-usual emissions scenario (RCP8.5). This means that the recent global bleaching event of 2014-2017 represents what climate models suggest may become the norm over the coming few decades. Lower frequencies of bleaching events per decade (e.g., 2x or 4x per decade) are projected to occur earlier than ASB. ASB is projected here because annual severe bleaching is a time beyond which coral reefs seem certain to change (and possibly rapidly degrade). Importantly though, great spatial variation exists in the projected timing of the onset of ASB conditions among the world's coral reefs. This variation will be a major driver of differences in the relative vulnerability of coral reef ecosystems to climate change.

In the IPCC's widely adopted vulnerability assessment framework, vulnerability is a function of exposure to climate and non-climate threats and sensitivity to these threats, which yields potential impacts that are moderated by adaptive capacity (Turner et al. 2003). Sensitivity and adaptive capacity can be collectively seen as resilience (Marshall and Marshall 2007), i.e., the capacity of a system to absorb or withstand stressors such that the system maintains its structure and functions in the face of disturbance and change, and the capacity to adapt to future challenges (McLeod et al. 2019). Managing coral reefs for resilience entails reducing coral reef vulnerability to climate change by reducing exposure to non-climate threats (i.e., local-scale anthropogenic stress, Anthony et al. 2014).

A key challenge for reef management lies in deciding where to target actions to reduce anthropogenic stress, ensuring efficacy as well as cost effectiveness of actions taken. Ecosystem and Resilience Based Management (EBM and RBM) are becoming increasingly sophisticated (Mills et al. 2015, McLeod et al. 2019), and software that combines and analyzes spatial data is increasingly accessible and used in planning to strike a balance between what can be competing conservation and development objectives (Watts et al. 2009). For example, protecting biodiversity, providing for sustainable fisheries, and minimizing user conflicts are among the highest priorities during marine spatial planning (MSP) efforts in reef areas (Agardy et al. 2011). Incorporating spatial variation in coral reef vulnerability to climate change is frequently discussed during MSP but, as yet, is rarely operationalized (Anthony et al. 2014). This will require assessing spatial variation in the key vulnerability components – exposure and resilience - at a locally relevant scale (one km to 10s of km).

This project team previously developed projections of the exposure component of climate vulnerability in coral reef areas under the Intergovernmental Panel on Climate Change (IPCC) Coupled Model Interpolation Project Phase 5 (CMIP5) generation of climate models. These projections, which were statistically downscaled to 4-km were reviewed in UNEP (2017) and van Hooidonk et al. (2016).

This report updates the UNEP (2017) report with projections of the timing of severe coral bleaching conditions (exposure component of climate vulnerability) using the new generation of IPCC climate models – the generation of models included in CMIP6. The motivation in providing this update is that the CMIP6 models have much higher spatial resolution (most have native resolutions of 1/3x1/3° at the equator; some have a resolution of 1/4x1/4° ~ 27x27 km at the equator) than CMIP5 models (native resolution of >1x1°; ~110x110 km). A range of improvements or advances have been made to the models, including; increase in vertical resolution, improved representation of clouds and aerosols, and less parameterization. Further, the CMIP6 models have runs available for the recently released Shared Socioeconomic Pathways (SSPs – see Riahi (2017) for an overview). SSPs are scenarios of projected socioeconomic global changes up to 2100. They are used to derive greenhouse gas emissions scenarios with different climate polices. The SSPs are based on the Representative Concentration Pathways (emissions scenarios – see van Vuuren et al. (2011) for an overview). These projections have ¼° resolution and project future exposure to bleaching conditions (i.e., temperature stress); the socio-ecology of coral reefs within all grid cells will vary and this variance is not built into these projections. The CMIP6 models represent the current state-of-the-art in climate modeling to deliver climate science that informs regional and global climate policy.

Coral bleaching implications of climate policy

The UN Framework Convention on Climate Change (UNFCCC) is aimed at stabilizing atmospheric concentrations of greenhouse gases to avoid "dangerous anthropogenic interference with the climate system" (Article 2). The 21st Conference of Parties to the Convention (COP21), held in Paris in 2015, adopted a legally binding agreement (the 'Paris Agreement') with the goal of keeping global warming well below 2°C, while pursuing efforts to stay below 1.5°C. The Agreement entered into force after 55 Parties accounting for at least 55 % of the total global greenhouse gas emissions ratified it. The agreement required that countries prepare Nationally Determined Contributions (NDCs) in pursuit of its goal. New NDCs are expected in 2020 and then every five years thereafter with global stock-take to review progress planned for 2023.

If the Paris Agreement is not implemented (this is the path of fossil-fueled-development represented in SSP5-8.5, which is forced with RCP8.5), 58-61 Giga tons of carbon dioxide equivalents per year (Gtons CO_2-eq/yr) are projected to be emitted in 2030 (http://climateactiontracker.org/global.html). Assuming pledges do become reality would result in emission of 52-55 Gtons CO_2-eq/yr in 2030, which is below RCP8.5 and above the emissions concentrations associated with RCP4.5. Recent Intended Nationally Determined Contributions (INDCs) (2019 update) would have to be 150% greater on average to limit warming to 1.5°C by 2100 (UNEP 2019). In effect, RCP4.5, the forcing behind SSP2-4.5, represents a better future for coral reefs than would be projected using the emissions trajectory associated with the Paris Agreement. SSP2-4.5 represents a path where global and national institutions work toward but make slow progress in achieving sustainable development goals. Detailed comparison of each of the SSPs is offered in Gidden et al. (2018), which includes figures showing emissions trajectories (note Figure 2). In this report, projections of the timing of annual severe bleaching conditions are compared for SSP5-8.5 and SSP2-4.5 to examine the implications of climate policy for coral reefs.

Report purpose, scope and intended end-users

The purpose of this report is threefold:

1. To present projections of coral bleaching conditions (i.e., exposure to the primary climate threat to coral reefs) and potential adaptation at a spatial scale that enables use of the data in management and conservation planning and in support of other decisions influencing coral reefs and reef use;

2. To evaluate the implications of the Paris Agreement as well as failure to achieve its goal, by comparing the projected timing of annual severe bleaching between Shared Socioeconomic Pathways SSP5-8.5 and SSP2-4.5; and

3. To provide public access to the projections data as well as the main findings to catalyze research that extends the purposes and applications described in 1 and 2 as well as new research.

End-users of these projections include coastal/marine planners and managers, conservationists and the coral reef scientific community, as well as other stakeholders, including businesses dependent on reef resources. The report has been prepared with the coral reef scientific and management community as the primary target audience.

Information on *Accessing and using the projections* is provided at the end of the report. *Appendix 1* contains lists of IPCC CMIP6 models used to develop the projections. *Appendix 2* contains country and territory summaries of the projection results for SSP5-8.5, grouped based on the 10 Regional Seas (http://unep.org/oceans40/) that contain tropical coral reefs. *Appendix 3* contains a table of the projected timing of annual severe bleaching for SSP5-8.5 and SSP2-4.5 for the 111 Marine Ecoregions of the World (MEOWs) that include coral reef areas.

Important disclaimers

It is important to note that these projections should not be interpreted as predictions of exactly when bleaching will occur and do not imply that an area is safe from bleaching. Recent bleaching does not mean an area is no longer a relative refuge or priority for management interventions. Further, these projections do not account for what is likely to be great spatial variation in the capacity to adapt to the increasing sea temperatures that may cause annual severe bleaching. Here, adaptation levels are examined (see relevant section above) but are applied uniformly for all reef areas in each scenario; i.e., the 0.5°C adaptation level scenario assumes the bleaching threshold will increase 0.5°C at all coral reefs. In reality, some coral reefs may adapt at a level that equates to an increase to the bleaching threshold of 0.5°C and others just kilometers away may adapt at a level that equates to an increase to the bleaching threshold of 1.5°C. Perhaps most importantly, the projections represent just one of many information layers managers and conservationists will need to consider during spatial planning efforts.

Methods

Shared Socioeconomic Pathways: Sea surface temperature (SST) data from climate models was obtained from the CMIP6 for the SSP5-8.5 and SSP2-4.5 scenarios (Riahi 2017).

SSP5-8.5 is the pathway that represents current rates of emissions and emissions growth; it is also considered a "worst-case scenario". This scenario assumes there is no climate policy or that policy is not implemented. SSP5-8.5 represents a growing world economy heavily dependent on fossil fuels. Results from the SSP5-8.5 pathway are most of the focus of this report.

SSP2-4.5 is a highly ambitious but plausible scenario. SSP2-4.5 is a "middle of the road" pathway in which emissions continue to increase through the end of the century, reaching between 65GtCO_2 and 85GtCO_2, with resulting warming of 3.8-4.2°C by the end of the century. This scenario was selected because it ***could*** represent future conditions *if greater levels of emissions reduction (~150% of pledges) are achieved than would result from all Nationally Determined Contributions in the Paris Agreement combined.*

Climate model data: Values for the variable 'tos' (sea surface temperature) at the model native grid resolution was downloaded from https://esgf-node.llnl.gov/ on January 17th 2020, for all available models in SSP5-8.5 and SSP2-4.5 (see Appendix 1 for models lists for each scenario). Data were concatenated where needed to create complete time series (see Appendix 1). If multiple runs were present, they were averaged using *ncea* (gridpoint averages using equal weighting). Data was put on a regular 0.25° grid using CDO *remapbil*. Missing data was filled in the zonal direction using NCL's poisson function. All model runs were adjusted to the mean of a NOAA Coral Reef Watch coraltemp_v3.1 2005-2019 climatology (developed by this project team) by subtracting the mean of the first 5 years of the model run from the entire period and then adding the mean of the CoralTemp climatology.

Thermal stress and bleaching: Degree Heating Weeks (DHWs) were calculated for each year between 2015 and 2100 as summed anomalies above the warmest monthly temperature (the maximum monthly mean or MMM) from the CoralTemp climatology, during the 3-month period centered on the warmest month. A review of climatological thresholds from which bleaching stress can be calculated can be found in van Hooidonk et al. (2015), which includes justification of the use of MMM. Projections were developed for annual (10x per decade) bleaching conditions. The focus here and in using the projections to inform management and conservation, is on the annual severe bleaching projections under SSP5-8.5. Current emissions and concentrations are tracking very close to RCP8.5 (forcing for SSP5-8.5); the average CO_2 concentration for 2020 is 415.78 ppm in RCP8.5, and the current observed CO_2 concentration in June 2020 is 416.39 ppm at Mauna Loa (July 19, 2020). The onset of annual severe coral bleaching (ASB) is defined as the annual exceedance of >8 DHW accumulating during any 3-month period (as in van Hooidonk et al. 2014; 2015; 2016). Eight DHWs is higher than the mean optimum bleaching predictor of 6.1 DHWs for the globe (van Hooidonk and Huber 2009); i.e., at 8 DHWs there is a greater degree of confidence that thermal stress will be sufficiently great for bleaching to occur (van Hooidonk et al. 2014). This model makes no assumptions as to the depths at which bleaching will occur, but are based on bleaching observations datasets that nearly all come from <30 m. Readers should assume that annual severe bleaching means severe bleaching of corals up to and potentially exceeding 30 m in depth.

Model ensembles, uncertainty, and reef locations: All projections of ASB from the models were averaged to create a multi-model ensemble. This is a common approach and was done to reduce unknown, sometimes time-dependent errors in the models (Knutti et al. 2010). Further, it is not possible to robustly examine model performance (regionally or globally) in hindcasting DHWs to predict past bleaching events as the GCMs do not forecast weather or correctly time low frequency events such as El Niño; a driver of past global bleaching events. This is further hampered by the paucity of bleaching and non-bleaching observation data. For that reason, we have not selected some models or attached different weights to models before creating an ensemble (see also van Hooidonk et al. 2013, 2014; 2016). All climate model projections are uncertain and spatial variation in this uncertainty is unknown so is not mapped or shown here. Model agreement (or disagreement) is also not shown as model agreement is not necessarily a good proxy for model accuracy (i.e., since accuracy is unknown and cannot be assessed because these are projections of future events). All model outputs were reduced to a subset of only reef locations obtained using the UNEP World Conservation Monitoring Centre Global distribution of warm-water coral reefs. There are 8305 quarter degree pixels across the world that contain coral reefs. All interpolation was performed using Climate Data Operators version 1.9.8, a software package available from: https://code.zmaw.de/projects/cdo/. All model output adjustment, projections, data visualization and analysis were conducted using the NCAR Command Language Version 6.6.2 (NCL; http://www.ncl.ucar.edu/).

Climate policy effects: Differences in the projected timing of the onset of ASB between SSP5-8.5 and SSP2-4.5 examine the effects of climate policy, i.e., if emissions reductions that exceed those made under the Paris Agreement are partly achieved or exceeded. The ASB dates projected for SSP5-8.5 were subtracted from SSP2-4.5. This yielded the amount of additional time coral reefs will have (in most cases) or not (in rare cases) to adapt or acclimate to increasing temperatures if emissions cuts that are in keeping with SSP2-4.5 are made (e.g., under the Paris Agreement). The reef locations dataset was classified into countries and territories using www.marineregions.org (see Appendix 1), UNEP Regional Seas (see Appendix 2), and Marine Ecosystems of the World (see Appendix 3).

Adaptation: Evidence is increasing that responses of corals to thermal stress are changing with time. Coral communities are changing in response to altered thermal regimes; shifts are being recorded from more sensitive to more tolerant species due to selective mortality (Hughes et al. 2018, Guest et al. 2012). Scientists have also documented within-generation shifts in coral symbionts, as well as between-generation changes in thermal tolerance of the same species (Maynard et al. 2008). The extent to which each of these mechanisms explain observed increases in thermal tolerance will vary at all spatial scales. This project part includes re-running the projections assuming varying degrees of coral adaptation. No assumptions are made as to which of the various mechanisms by which coral thermal tolerance increases is at play in any place.

The timing of projected annual severe bleaching (ASB) is a function of: 1) the difference between typical warm season temperatures (i.e., how low or high is the starting point) and the MMM 'bleaching threshold'; and, 2) the rate sea temperature is expected to increase under climate change (these data come from IPCC CMIP6 climate models). ASB dates are later where the difference between typical and warm season maximum temperatures is greater and the rate of sea temperature increase is lower (Figure 1). We examine the potential effects of coral adaptation (for ASB timing) by increasing the bleaching threshold in quarter-degree increments from 0.25° up to 2° above the MMM (i.e., 8 additional sets of projections were developed for SSP5-8.5).

For example, an increase of 1.5° represents corals being able to withstand summer temperatures 1.5° greater than current typical summertime maxima prior to heat stress accumulating. Here, we model the effect of increased thermal tolerance on ASB timing. Changes in ASB timing are quantified by subtracting ASB dates for SSP5-8.5 from the ASB dates for each adaptation level (from 0.25° up to 2°).

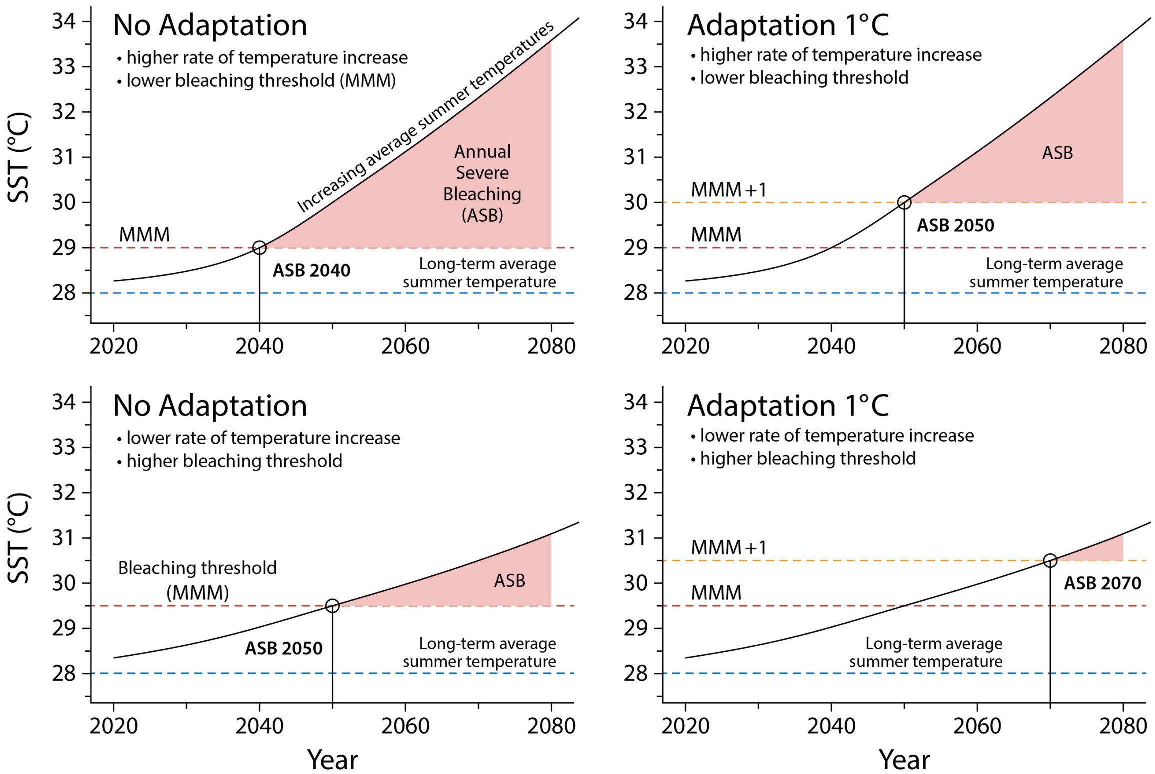


Figure 1. Conceptual diagram explaining how increased sea temperatures under climate change eventually lead to annual severe bleaching (ASB). ASB timing is driven mostly by: the magnitude of the difference between typical summertime temperatures and the bleaching threshold, and the rate sea temperatures are projected to increase under climate change. Where this difference is smaller and sea temperatures are increasing rapidly (top left – ASB 2040) ASB is earlier than where the difference is greater and sea temperatures are increasing less rapidly (bottom left – ASB 2050). The potential effects of adaptation are explored by increasing the temperature stress corals can experience before ASB is assumed to occur; this is modeled by increasing the bleaching threshold in quarter degree increments (here, 1° is shown). The plots show that some reefs benefit more at each adaptation level than others. For the reef shown in the bottom two plots, the greater difference between typical summer temperatures and the bleaching threshold and the lower rates of temperature increase result in an ASB date 20 years later than when no adaptation is assumed. The reef in the top two plots has an ASB date only 10 years later than when no adaptation is assumed. These graphics conceptually explain the math and driving forces behind the spatial variation seen in the projections. Reefs only 10's of km apart can have very different average summer temperatures, bleaching thresholds, and projected rates of temperature increase (from the climate models).

Results and Discussion

Projecting annual severe bleaching

Under the fossil-fuel aggressive SSP5-8.5 and using the CMIP6 models, ASB is projected to occur within this century for 100% of the world's coral reefs. The average projected year of ASB is 2034, nine years earlier than was projected as a global average for RCP8.5 using CMIP5 models. This is a significant result because the CMIP6 models represent the current state-of-art in climate modeling and include a range of improvements to model mechanics and resolution. Within the climate modeling community there is sensible discussion about the increase in equilibrium climate sensitivity (ECS). ECS is the expected long-term warming after a doubling of atmospheric CO_2 concentrations. Roughly a third of the models in CMIP6 have an ECS higher than the upper bound in ECS in CMIP5. The increase in ECS is probably due to improved representation of clouds and aerosols. The most recent climate models – CMIP6 generation – suggest the previous CMIP5 generation of projections of future bleaching conditions underestimated the near future threat of annual severe bleaching. The global range in ASB projections is 75 years (from 2015 to 2090). The large global range in ASB timing is driven by the 36% of reef areas (¼ x ¼° model pixels where coral reefs occur) projected to experience ASB before 2030 (higher relative climate vulnerability; from perspective of exposure – these are 'climate losers') and the 21% projected to experience ASB later than 2044 (i.e., 10 years later than the global average 2034). Locations projected to experience ASB later than 2044 are temporary 'refugia' (van Hooidonk et al. (2013); these have lower relative climate vulnerability and are 'climate winners').

Projected coral bleaching conditions – exposure to annual severe bleaching conditions - vary greatly among and within countries under SSP5-8.5. Coral reefs with relatively early and late exposure to annual bleaching conditions occur in all of the ocean basins; however, some countries have more temporary refugia than others. Six of the 20 countries with the greatest reef area (Table A2.2) have >25% temporary refugia (i.e., projected ASB after 2044), including: Indonesia (35%), western Australia (70%), The Bahamas (26%), Madagascar (30%), India (37%), and Malaysia (47%; Figures 2 and 3).

Thirteen of the 20 countries with the greatest reef area have >25% of reef areas that are projected to experience annual bleaching conditions relatively early (i.e., projected ASB before 2030), including Philippines (36%), eastern Australia (54%), Papua New Guinea (61%), Solomon Islands (55%), Fiji (99%), New Caledonia (95%), Cuba (39%), Federated States of Micronesia (95%), Saudi Arabia (87%), western and eastern Mexico (82%), Marshall Islands (79%), and Egypt (70%; Figures 1 and 2). Widespread severe bleaching has already been reported in these countries.

Among the top 20 countries in terms of reef area, four countries have a projected range in ASB timing >50 years, including: Indonesia (65 years), eastern and western Australia (64 years), Madagascar (52 years), India (56 years).

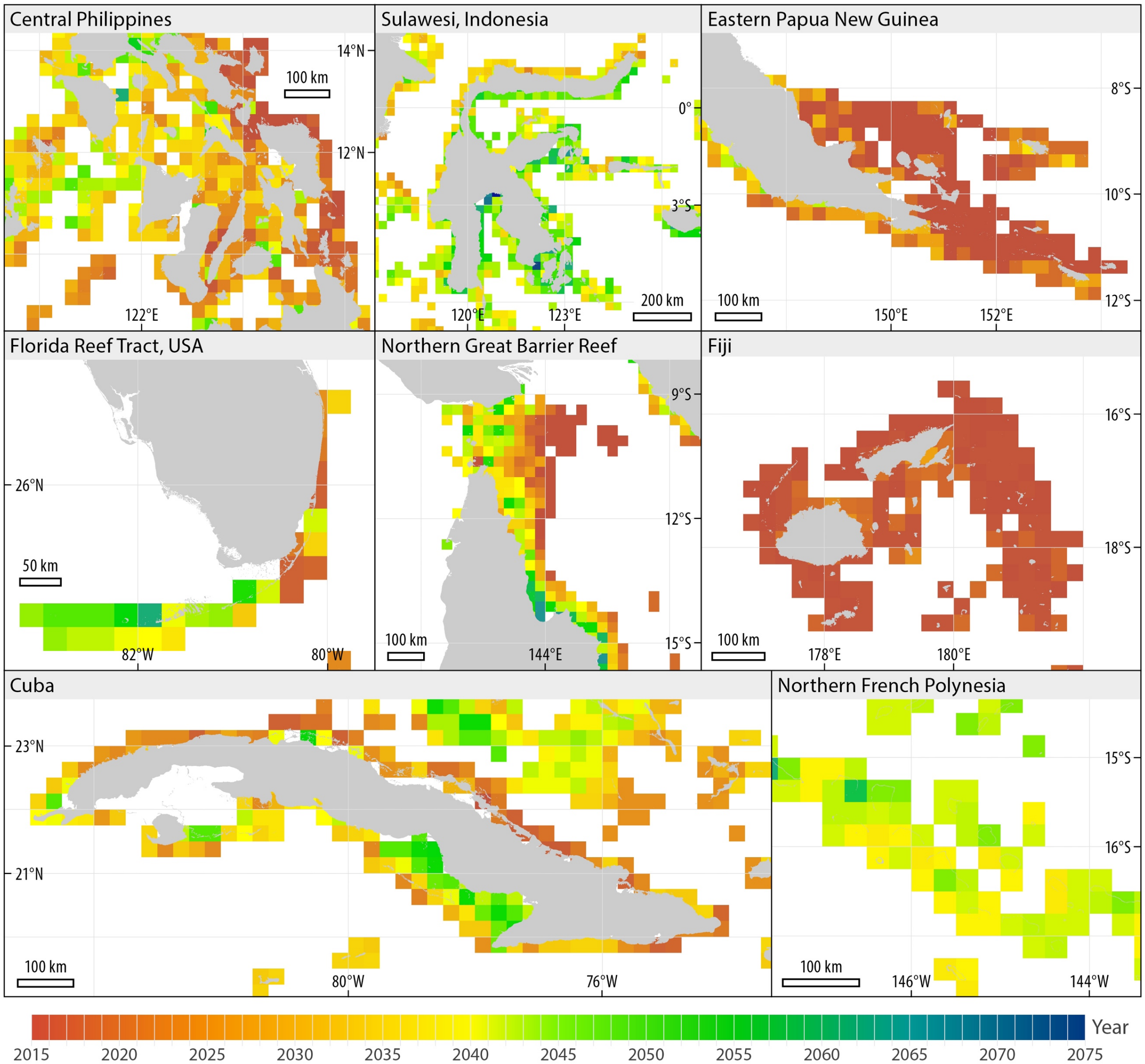


Figure 2. Projections of the timing of the onset of annual severe bleaching (ASB) conditions under SSP5-8.5. These exemplify the local-scale (10's of km) variation seen in projected ASB timing in many locations.

These projections can inform management decision-making where variation in projected ASB timing is ≥10 years (van Hooidonk et al. 2015). This is because differences among reefs, with respect to exposure to bleaching conditions, are not different enough to warrant making spatial management decisions where variation is <10 years. Variation among the climate models in the ensemble is usually greater than variation among coral reefs in projected ASB dates where variation in ASB is <10 years (van Hooidonk et al. 2016). 'Exposure' to the key climate threat of bleaching is sufficiently different where variation is ≥10 years to potentially be a driver of differences in relative vulnerability to climate change. Reefs projected to experience ASB 10 or more years later than other reefs in the same jurisdiction are *relative* refugia and are conservation priorities. A review of the theory behind reefs with lower/later exposure to annual severe bleaching being conservation priorities is presented within the *Applications* section. Projected ASB timing varies more than 10 years on local scales (at distances of <100 km) in many reef areas.

Model pixels are not management units. Management of coral reefs primarily takes place within national jurisdictions. The range in projected ASB timing is $\geq$18 years in all 30 countries with the greatest reef area (Table A2.2). In many areas there will be variation among relative refugia in exposure to anthropogenic stress. Management will have the greatest impact by targeting actions to reduce stress to relative refugia where anthropogenic stress is relatively high and most amenable to management influence (recommended in Mumby and Anthony (2015)). This strategy maximizes the likelihood that at least some reefs will remain healthy in the future (Game et al. 2008) and continue to provide ecosystem goods and services.

The high spatial variation in projected ASB timing is due to variation in the difference between typical warm season temperatures and the maximum monthly mean (MMM), as well as differences in the rates of sea temperature warming (from the climate models, see Figure 1). The MMM is the warmest month in the CoralTemp v3.1 climatology (1985-2012) and is the threshold used to determine when temperatures become stressful to corals and cause bleaching (Gleeson and Strong 1995, van Hooidonk et al. 2015). Typical warm season temperatures in some locations are closer to MMM than at locations only 10s of km away and these locations are projected to experience ASB sooner (and vice versa; see also section below on adaptation).

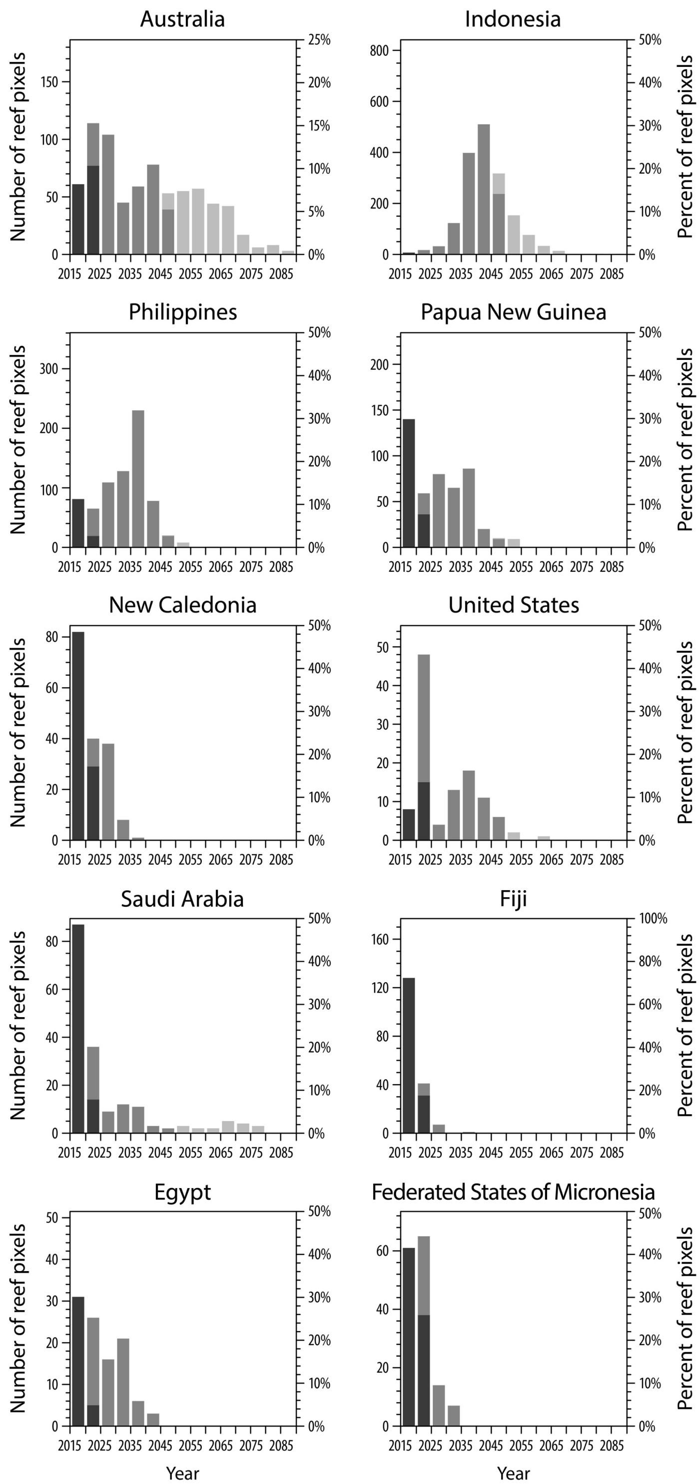


Figure 3. Histograms showing the distribution in projected timing of annual severe bleaching conditions under SSP5-8.5 for the 10 countries and territories with the greatest reef area (see Table A2.2 for average years, standard deviation and range). Shading of bars: dark grey indicates relative 'climate losers', projected ASB before 2025, medium grey indicates global average of 2034 ± 10 years (2025-2043), and light grey indicates the relative refugia 'climate winners' (projected ASB after 2044).

Variation within and among Regional Seas: Introduction to the Appendix

The Regional Seas Programme was launched in 1974 and aims to address degradation of the world's oceans and coastal areas through sustainable management and use of the marine and coastal environment. The programme engages neighboring countries in comprehensive and specific actions to protect their shared marine environment, stimulating the creation of Regional Seas programmes among countries sharing a common body of water. The Regional Seas programmes function through an Action Plan, in most cases underpinned with a strong legal framework in the form of a regional Convention and associated Protocols on specific problems (text adapted from http://www.unep.org/regionalseas/about/).

There is great regional variation in projected future exposure to coral bleaching conditions. The Appendix summarizes findings by region based on the 10 Regional Seas programmes within tropical coral reef ecosystems. We also include countries and territories within or adjacent to Regional Seas that are not party to Regional Seas conventions or do not participate in Action Plans, in keeping with the principles of taking an ecosystem approach to management and conservation.

Appendix 1 includes projected timing of ASB under SSP5-8.5 for all countries and territories, regional averages, and identification of countries and territories with the earliest and latest projected ASB timing. Regionally important climate refugia are also identified, i.e., the areas within (or near) each Regional Sea area projected to experience ASB latest (relative climate refugia) that also meet the global criterion set for refugia of projected ASB conditions after 2044.

The regions with the earliest average projected ASB timing are the *Wider Caribbean (2030)* and the *Pacific Islands* (2027). The regions with the latest projected ASB timing are the *ROPME Sea Area*[1] (2053) and *North-East Pacific* (2045). Countries/territories with the earliest and latest projected ASB timing within each region area are shown in Table 1.

The distribution of projected timing of ASB under SSP5-8.5 is presented for all countries and territories within tables and histograms in Appendix 2. Countries and territories are grouped based on Regional Seas programmes, but also including non-parties and reef areas near but not in the area covered by Regional Seas Conventions and Action Plans. For each region, the summaries in Appendix 2 present: the countries and territories with the greatest and least reef area; the average among countries and territories for projected timing of annual severe bleaching (ASB) conditions under SSP5-8.5; the countries/territories with the earliest and latest averages for projected timing of ASB under SSP5-8.5; and the countries/territories with the greatest numbers of relative climate losers and relative climate winners.

---

[1] Includes coastal areas of Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates.

Table 1. Countries or territories with the earliest and latest **average** projected timing of ASB conditions within each region (based on the Regional Seas, also including countries and territories that do not participate in conventions or action plans and that fall outside the area covered by the Regional Seas; see Table A2.1 for classification), as well as the **greatest reef area** projected to experience ASB before 2030 and after 2044 (temporary refugia).

Region (Average ASB date)	Earliest projected timing of ASB		Latest projected timing of ASB	
	Average ASB date	Greatest reef area projected to experience ASB before 2030 (km^2)	Average ASB date	Greatest reef area projected to experience ASB after 2044 (km^2)
Wider Caribbean (2030)	Nicaragua (2015)	Cuba (1051, 39%)	The Bahamas (2039)	The Bahamas (573, 26%)
Red Sea and Gulf of Aden (2026)	Israel (2018)	Saudi Arabia (2986, 87%)	Somalia (2045)	Yemen (301, 46%)
ROPME Sea Area (2053)	Oman (2044)	Iran (8, 7%)	Kuwait (2062)	United Arab Emirates (102, 79%)
Western Indian Ocean (2040)	Réunion Island (France) (2026)	Madagascar (300, 12%)	Somalia (2050)	Madagascar (726, 30%)
South Asian Seas (2044)	Bangladesh (2041)	India (84, 4%)	Sri Lanka (2051)	India (760, 37%)
East Asian Seas (2041)	Japan (2024)	Philippines (4405, 36%)	Brunei (2055)	Indonesia (7028, 35%)
Pacific Islands (2027)	Niue (2015)	Papua New Guinea (4468, 61%)	French Polynesia (2040)	Australia (7003, 22%)
South-East Pacific (2038)	Panama (2033)	Panama (159, 25%)	Colombia (2043)	Ecuador (40, 32%)
North-East Pacific (2045)	Clipperton Island (2019)	Mexico (309, 33%)	Mexico (2047)	Mexico (504, 54%)

Coral bleaching implications of climate policy

The average year for the projected timing of ASB under SSP2-4.5 is 2045, 11 years later than the average projected under SSP5-8.5 (Figure 5). However, ASB under SSP2-4.5 is projected to be >10 years later than under SSP5-8.5 for very few reef areas (~15%). Spatial patterns in the projections are the same or very similar for these scenarios; i.e., meeting mitigation targets does not change which areas are relative climate refugia and thus conservation priorities. Further, spatial patterns in the projections are similar under these CMIP6 projections as was described within our complementary UN technical report for the CMIP5 projections (and described within van Hooidonk et al. 2016). Readers should focus on these CMIP6 projections since the CMIP6 generation of climate models represents the current state-of-the-art in climate science to inform regional and global climate policy. These CMIP6 results suggest or indicate:

- successful mitigation in line with the Paris Agreement would buy some time for some reefs, but would not significantly change priority areas for reef management;
- the NDCs submitted and finalized after September, 2016 will do little to provide reefs with more time to adapt and acclimate prior to severe bleaching conditions occurring annually;
- coral reef adaptation to the changing climate, continued ecosystem service provision, and recovery of areas that have already been or will inevitably be lost, requires greatly increasing efforts to reduce direct stress on reefs, as well as more ambitious climate change mitigation than is committed to within the Paris Agreement.

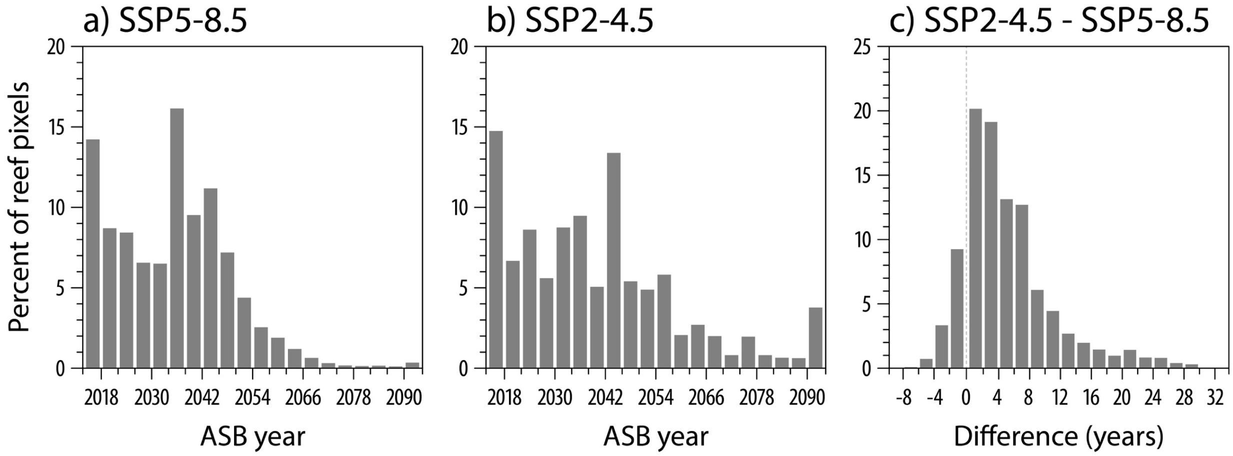


Figure 4. Histograms showing the distribution in projected timing of annual severe bleaching conditions under two emissions scenarios, SSP5-8.5 (a) and SSP2-4.5 (b). Under SSP5-8.5 (left plot) nearly all coral reefs experience ASB by 2060 (note low to no bars after 2066). In contrast, there are many more reefs experiencing ASB after 2060 under SSP2-4.5 (middle plot). The difference between these scenarios is shown in (c) for the 97% of reefs for which ASB is projected this century under both scenarios. Most reefs experience ASB under SSP2-4.5 within 16 years (note low bars after 16 years) of the ASB date projected under SSP5-8.5. Emissions reductions such that SSP2-4.5 becomes reality (extremely ambitious but plausible) does not provide much time (<15 years) for the great majority of coral reefs to adapt or acclimate to annual bleaching conditions.

Adaptation

There are two primary results from the projections that assume coral adaptation levels between 0.25° and 2°C.

- Each quarter degree of assumed adaptation adds ~7 years to the global average timing of projected annual severe bleaching.
- There is great spatial variation in the benefits to reefs, in terms of later ASB timing, at each assumed adaption level.

The global average projected ASB timing without adaptation was 2034. Assuming a quarter degree of adaptation increases global average ASB timing to 2041, and assuming a half degree of adaptation increases global average ASB timing to 2048. Assuming 2°C of adaptation results in over 20% of the world's reefs experiencing ASB after 2099 (exact timing unknown). The extent to which corals will adapt to increasing sea temperatures is unknown, but some level of adaptation is expected. If we assume 1°C of adaptation, the global average ASB timing is ~30 years later than if no adaptation is assumed. The great local spatial variation in ASB timing even at local scales is shown in Figure 5. For example, reefs in northern Cuba are projected to experience ASB >30 years later if one degree of adaptation is assumed than if no adaptation is assumed, while ASB dates are only ~20 years later for some reefs in southern Cuba. Other similar examples shown in Figure 5 include the northern Great Barrier Reef and the Florida Reef Tract in the U.S. For both, reefs within 10's of km vary >10 years in projected benefit (later ASB timing) from 1°C of assumed adaptation.

Differences in ASB timing with and without adaptation are driven by differences among reefs in the magnitude of the difference between average summer temperatures and the bleaching threshold as well as the rate sea temperatures are increasing (see Figure 1). Importantly though, each adaptation level examined here is assumed to apply to all reefs uniformly; i.e., at each adaptation level - 1°C, for example – all reefs are assumed to experience or benefit from **1°C of adaptation.** However, some reefs will have lower adaptation than others. There will be great spatial variation in the extent to which corals adapt – that variation cannot be included here since it is mostly unknown for all reef areas and will have many different drivers/causes. However, what is shown here is that adaptation will create a myriad of responses to the increasing sea temperatures projected under climate change (see Figures 5 and 6).

The great majority of coral reefs (≥80%) experience ASB this century even if 2°C of adaptation is assumed (Figure 7). This result serves as reminder that adaptation will not be a panacea. Further, these projections are for increasing thermal stress only and do not examine the interplay between increasing thermal stress and ocean acidification, which further challenges reef resilience (as in van Hooidonk et al. 2015). Even with adaptation, at any plausible level, there is an urgent and increasing need for conservation to address local stressors on reefs to give reefs the best chance of coping with climate change. Reefs that are temporary refugia with and without adaptation (i.e., in both cases presented here for SSP5-8.5) are the greatest conservation priorities. Targeting conservation efforts to these reefs provides the best chance efforts will help reefs continue to provide ecosystem goods and services.

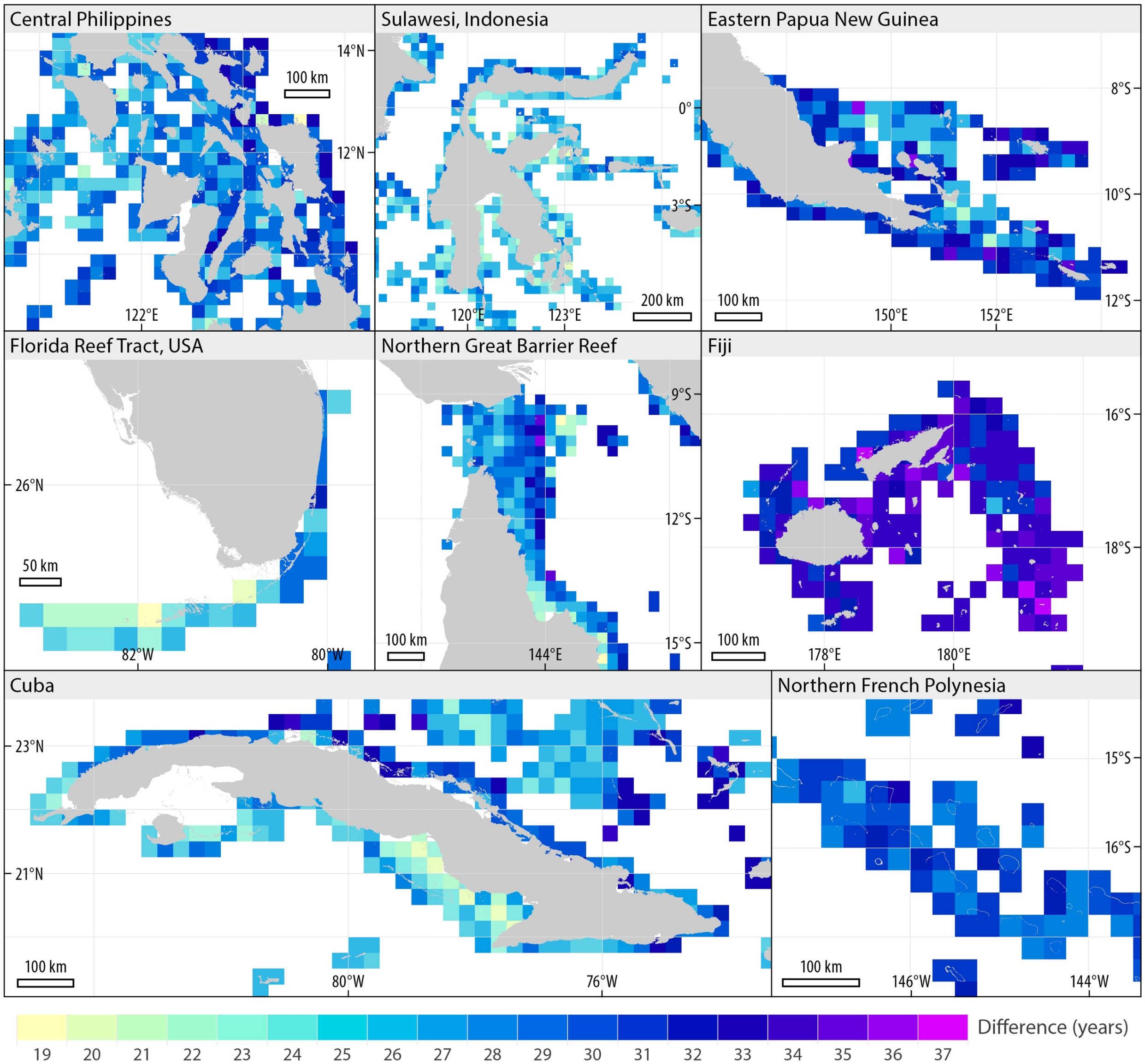


Figure 5. Projections of the timing of the onset of annual severe bleaching (ASB) conditions under SSP5-8.5 ***assuming 1°C of increased thermal tolerance (or adaptation)***. There is great spatial variation in the benefit for reefs from increases in thermal tolerance; benefit is mapped here as difference between the scenarios with and without adaptation (under SSP5-8.5).

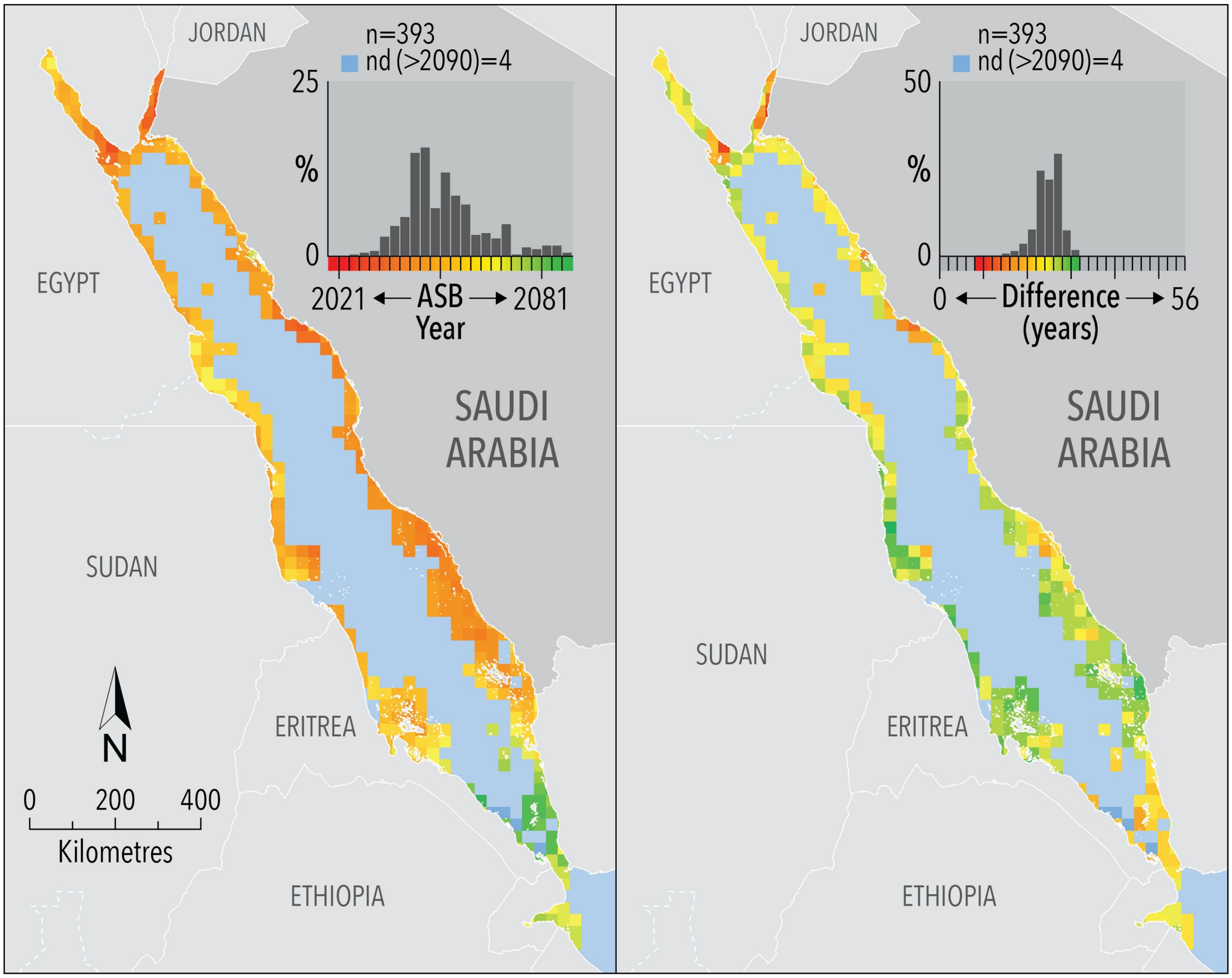


Figure 6. Projected timing of annual severe bleaching (ASB) assuming an increase in the bleaching threshold of 1.0°C (left). The projected benefit, in terms of number of additional years (compared to assuming no adaptation will occur, under SSP5-8.5) before ASB occurs if this potential adaptation level is achieved (right).

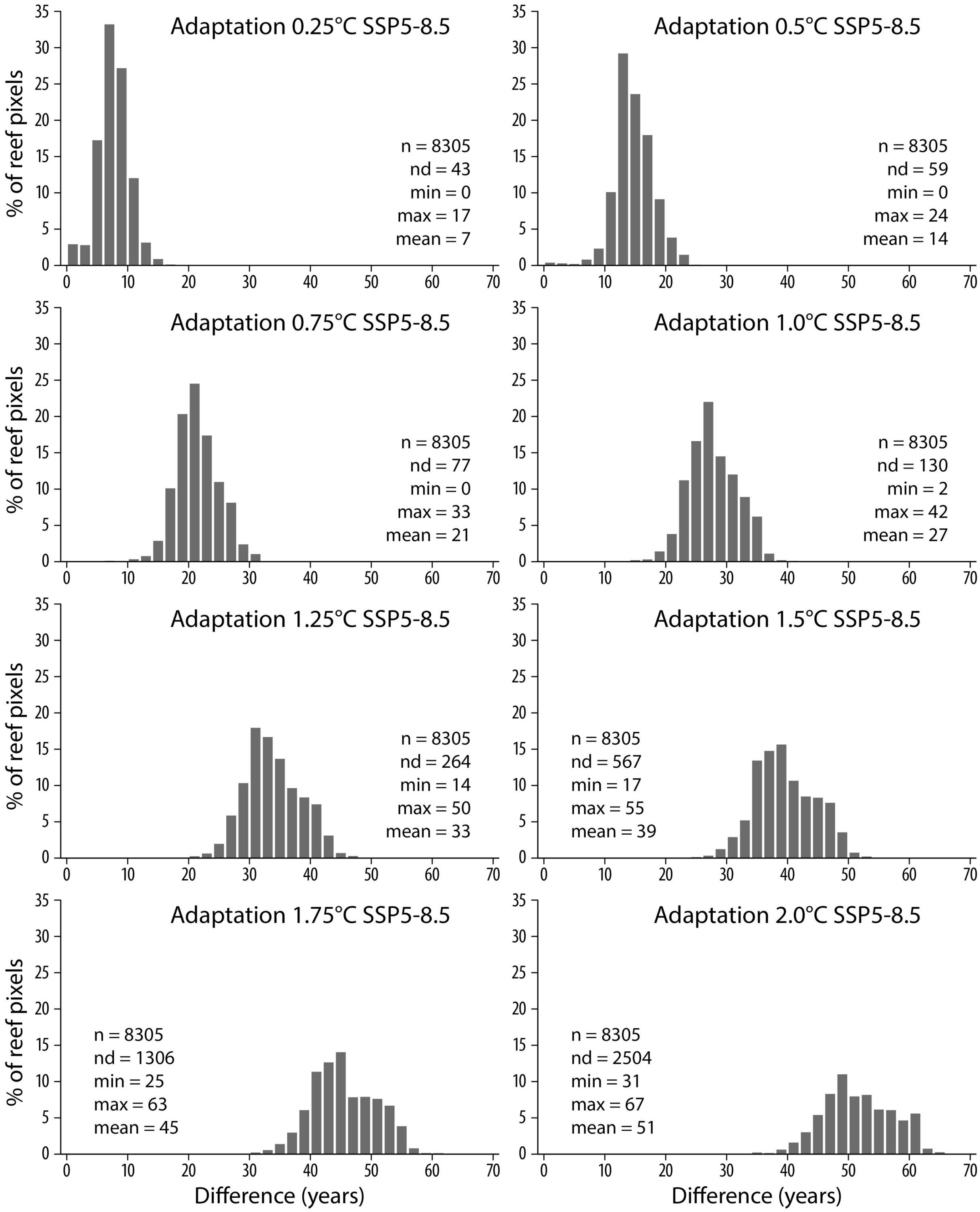


Figure 7. Histograms showing the distribution of differences in projected ASB timing for SSP5-8.5 when adaptation is assumed (0.25°C increments from 0 to 2°C above the MMM bleaching threshold) and not assumed (the base SSP5-8.5 projections for ASB). No data values refer to reef areas where ASB is projected to occur after 2090 (how long after is unknown).

Applications

These projections can guide management and conservation planning, be used in education and outreach programs, and inform policy. The utility of the projections stems from how they describe and quantify climate change exposure of coral reefs and thus contribute to our understanding of coral reef vulnerability. The level of urgency in applying the projections also varies to some extent between countries and territories. Level of urgency will depend on the current state of management and extent to which identified climate refugia are being sustainably managed.

Management and conservation planning

As the climate changes, environmental managers are increasingly akin to emergency room doctors undertaking triage (McLeod et al. 2019; Anthony and Maynard 2011). Many areas are under threat, the likelihood areas will benefit from management varies, and financial resources for management are limited and often insufficient (CBD 2013). Strategic choices must be made to maximize benefits (Bellwood et al. 2004). This can be done through a variety of processes, including marine protected area (MPA) planning, Marine Spatial Planning (MSP), Integrated Coastal Management (ICM) planning, as well as planning for coral nursery development, restoration and assisted migration.

The projections presented here can be included as data layers within such planning processes to support spatial prioritization of management. Specific management actions can then be devised focusing on priority areas, in order to limit or shape human activities to reduce direct stress and promote reef resilience (i.e., supporting and protecting the capacity of a reef to resist or recover from degradation and maintain provision of ecosystem goods and services (Mumby et al. 2007).

A very immediate application of the projections is an analysis of the extent to which existing MPAs (or other effective area-based conservation measures) and MPA networks protect relative climate refugia as well as areas projected to experience ASB relatively early. Such analysis can support MPA network development and reduce vulnerability to climate change.

There are two general guiding principles for use of the projections within management and spatial planning processes. These principles assume the goal is to maximize and maintain the number of healthy sites as the climate changes and hence maximize the long-term provision of ecosystem goods and services from coral reefs. That goal is common in coral reef management and conservation but there are often other goals (i.e., minimizing resource-user conflict) requiring trade-offs be made.

Guiding principle 1 – Reefs could be considered relative refugia in an area if projected to experience ASB 10 or more years later than other reefs or than the reef with the earliest projected ASB date. Relative refugia *are conservation priorities and should be among the highest priorities for the targeting of stress reduction or other management actions.* Relative climate refugia are priorities because benefits of management actions have more time to manifest at these locations and are likely to last longer (relative to locations that are relative climate losers). Managers and conservationists should keep in mind that a projection of a later ASB date for one area does not mean that severe bleaching will not occur many times (but not yet annually) per decade before the projected ASB date. Relative refugia are not safe from severe bleaching; rather annual severe bleaching is projected to occur later in these areas.

Guiding principle 2 *– Reef areas projected to experience ASB relatively early are mostly low priorities in the targeting of management actions.* These areas are lower conservation priorities because management efforts in these locations may either not have time to manifest or will not last as long (relative to locations that are relative winners). However, there may be other criteria or reasons to implement conservation measures in areas that are predicted to be experience ASB relatively early, and therefore these areas should not be discounted for conservation or management.

It is important to note that both principles are subject to the requirements of the planning process, planning objectives and other site/area features, and ultimately management decisions are likely to require consideration of many other factors and will require some trade-offs (see McLeod et al. 2019 for detailed review for managers on *The future of resilience-based management in coral reef ecosystems*). Guiding principle 1 is arguably more important than 2 and a precautionary approach implies emphasizing it more in planning processes. For example, there is some uncertainty associated with climate modeling and in some locations climate losers may not fare worse than relative refugia (especially where differences in projected timing of ASB are comparatively small). Further, climate losers may already be under management interventions; removal or reduction of these management regulations would have detrimental impacts.

Given the current emissions trajectory, planning processes may use the spatial data on the projected timing of the onset of ASB conditions, focusing on SSP5-8.5 (see *Accessing the projections* section). GIS programs such as ArcGIS can be used to identify relative climate losers and winners within any geographic area the user sets (i.e., country or other management jurisdiction). Countries and territories with a range for projected ASB timing that extends beyond 2044 can consider 'global relative climate winners' as primary conservation priorities. However, many countries and territories have few or none of these global relative refugia, and should instead focus on identification of reef areas that are refugia relative to other reef areas within the country, territory or management jurisdiction.

The average projected timing of ASB is shown for all countries and territories within Table A2.2, along with the standard deviation around this average. Reef areas projected to experience ASB later than the average $\pm$ 1 standard deviation are relative climate winners and typically represent <20% of the reef pixels in the country or territory. GIS users can easily identify these reef areas using logic functions that query the raster data grid for locations with values in the desired date range (i.e., after country avg+1SD).

Importantly, the guiding principles we present serve as a caution to strict implementation of a representation and replication approach. Representation and replication remains a valuable method to protecting biodiversity and spreading risk. However, representation and replication will result in greater long-term management gains if relative refugia are prioritized (i.e., disproportionately included in MPAs or areas subject to management regulations).

Vulnerability assessments and adaptation planning

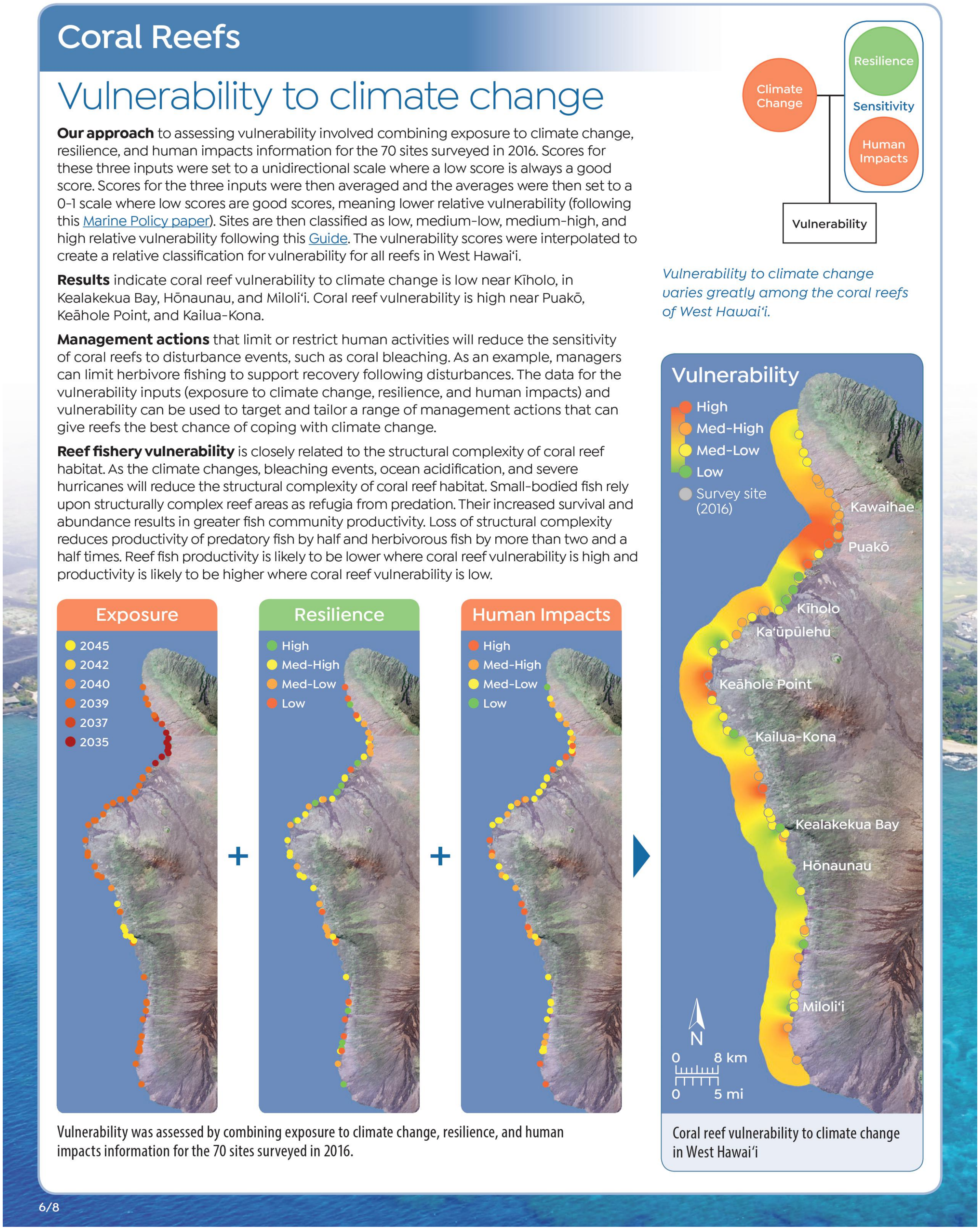
Long-term coral reef health depends on climate change vulnerability, which is driven by exposure to climate stress (modeled in this report for bleaching driven by climate change), and by reef resilience (GBRMPA 2007, Marshall and Marshall 2007). Vulnerability of coral reefs in turn affects communities and businesses dependent on their ecosystem services. Reducing vulnerability is thus one of the primary goals in coral reef planning and management, and needs to be informed by vulnerability assessments.

The projections presented in this report can, for example, support vulnerability assessments in coral reef areas and among coral reef dependent people (e.g. reef fishers) as well as economic sectors (e.g. reef and beach tourism). The projections enable identification of areas that are likely to be exposed to severe climate change impacts relatively soon, and thus stand to lose ecosystem services sooner than other areas. This can contribute to adaptation planning in the fisheries and tourism sector by helping to identify where introduction of different livelihood strategies may be needed, or helping to determine how and where to invest in tourism development. Spatial variation in the climate vulnerability of coral reefs can help in assessing and then reducing the climate vulnerability of coastal communities.

By combining the projections of bleaching conditions (exposure) with information on spatial variation in relative resilience potential (sensitivity and adaptive capacity) of coral reefs, coral reef vulnerability can be assessed. An example of this approach in West Hawaii is shown on the following page (Figure 7).

Key resilience indicators were identified by Obura and Grimsditch (2009), McClanahan et al. (2012), and Maynard et al. (2015); these studies describe methods for calculating and comparing relative resilience potential among reef areas, as well as anthropogenic stress on these areas. Maynard et al. (2015) presents a decision-support framework where relative resilience classes and anthropogenic stress data can be examined together to identify concrete management actions. For example, high resilience sites where fishing pressure is also high represent priorities for fishery regulations and enforcement. The projections of bleaching conditions add another information layer by enabling identification of sites with high relative resilience potential that are also relative climate winners.

Many resilience indicators are included as part of standard coral reef monitoring programs, although such programmes cover only a relatively small part (<10%) of the world's coral reefs. Resilience can also be assessed semi-quantitatively, usually over relatively limited areas or with uneven spatial distribution. However, reef resilience assessments are increasingly being undertaken (e.g., as a part of MPA planning efforts), meaning the opportunities to combine the projections presented here with resilience information are growing. To further support this, UNEP published *A Guide to Assessing Coral Reef Resilience Assessments for Decision-Support.*



Coral Reefs

Vulnerability to climate change

Our approach to assessing vulnerability involved combining exposure to climate change, resilience, and human impacts information for the 70 sites surveyed in 2016. Scores for these three inputs were set to a unidirectional scale where a low score is always a good score. Scores for the three inputs were then averaged and the averages were then set to a 0-1 scale where low scores are good scores, meaning lower relative vulnerability (following this Marine Policy paper). Sites are then classified as low, medium-low, medium-high, and high relative vulnerability following this Guide. The vulnerability scores were interpolated to create a relative classification for vulnerability for all reefs in West Hawaiʻi.

Results indicate coral reef vulnerability to climate change is low near Kīholo, in Kealakekua Bay, Hōnaunau, and Miloliʻi. Coral reef vulnerability is high near Puakō, Keāhole Point, and Kailua-Kona.

Management actions that limit or restrict human activities will reduce the sensitivity of coral reefs to disturbance events, such as coral bleaching. As an example, managers can limit herbivore fishing to support recovery following disturbances. The data for the vulnerability inputs (exposure to climate change, resilience, and human impacts) and vulnerability can be used to target and tailor a range of management actions that can give reefs the best chance of coping with climate change.

Reef fishery vulnerability is closely related to the structural complexity of coral reef habitat. As the climate changes, bleaching events, ocean acidification, and severe hurricanes will reduce the structural complexity of coral reef habitat. Small-bodied fish rely upon structurally complex reef areas as refugia from predation. Their increased survival and abundance results in greater fish community productivity. Loss of structural complexity reduces productivity of predatory fish by half and herbivorous fish by more than two and a half times. Reef fish productivity is likely to be lower where coral reef vulnerability is high and productivity is likely to be higher where coral reef vulnerability is low.

Vulnerability to climate change varies greatly among the coral reefs of West Hawaiʻi.

Vulnerability was assessed by combining exposure to climate change, resilience, and human impacts information for the 70 sites surveyed in 2016.

Coral reef vulnerability to climate change in West Hawaiʻi

6/8

Figure 8. Example of climate vulnerability assessment from West Hawaiʻi (see hyperlink for full report - NOAA et al. 2019) showing result of combing climate model projections of bleaching conditions with data on relative resilience and human impacts.

Stakeholder consultation, education and outreach

Maps of the projected timing of the onset of annual severe bleaching conditions can be powerful consultation, education and outreach tools. Visualizing the future threat of bleaching as maps for locations relevant to stakeholders helps them see the climate change threat to reefs and its implications. Many reef stakeholders are aware of the climate change threat posed by bleaching and know that coral bleaching events will increase in frequency and severity under climate change. However, often reef stakeholders do not fully understand what this means for the reefs they use or depend on. Through collective viewing of the projections as maps, stakeholders become engaged in understanding the spatial patterns and what increasingly frequent bleaching means for the future provision of ecosystem goods and services from local reefs. The projections are well suited for stakeholder consultation in relation to coastal management planning, MPA and marine spatial planning as well as climate change adaptation planning.

The projections are also useful for educational purposes, especially in training related to coral reef planning and management, as well as vulnerability assessment and adaptation planning. The projections can also be used with students of coral reef biology, marine environmental planning and management and climate change.

Lastly, the projections can be used for a variety of outreach and awareness raising purposes, as they can be used to describe climate threats to reefs, climate vulnerability, and the possible costs of inaction and opportunities for action in relation to climate change mitigation, adaptation and environmental management. The findings are applicable in all coral reef areas of the world, and can be used to target a range of audiences.

For all uses of the projects, whether for stakeholder consultation, education or outreach, it should be noted that many people are likely to find the projections concerning. Many people may not fully appreciate that all coral reefs are projected to experience bleaching conditions annually this century and large reef tracts even in the coming decade. While it is important to be realistic about the future of reefs during climate change, it is recommended that awareness raising activities emphasize the projections support management and conservation efforts that reduce vulnerability to climate change. The projections can also help to galvanize communities to take action locally to mitigate climate change, such as through personal efforts to reduce carbon footprints.

Policy

The projections have a number of policy applications, spanning development, natural resource use, environmental management and climate change policy.

Adoption of the 2030 development agenda and Sustainable Development Goals (SDGs) provides an opportunity to change the course for coral reefs and dependent people, and full implementation of the SDGs would address many of the root causes of coral reef degradation. By providing a holistic and comprehensive programme that cuts across the three dimensions of sustainable development, and by committing all countries to delivering on the Goals, the policy barriers to sustainable coral reef management have been lowered.

A UNEP analysis of 232 coral reef related policy instruments in 2019 found that the current body of international instruments related to coral reefs is vast and broad, with commitments corresponding to almost every anthropogenic driver of change in coral reef ecosystems. However, while the breadth of international coral reef-related instruments is vast, the 'depth' is less so – i.e., the nature of the commitments by states are quite general, and largely voluntary. This broad body of international reef-related instruments is focused on action by states, who have the primary responsibility for some 75 percent of the commitments. By virtue of the maritime zones established under the United Nations Convention on the Law of the Sea Treaty, ~85 percent of the world's warm-water coral reefs are under the jurisdiction of 25 countries. Tools that allow government agencies to improve the efficiency of marine spatial planning for coral reef conservation with climate change as a key layer will be useful in helping states achieve their international commitments for coral reef ecosystems. Such tools will increase the efficiency of the scant resources available for implementation of these policies. In this context, the climate projections presented within this report are an important tool to support the achievement of international commitments.

The projections can be directly used in national planning processes for SDG implementation, including in particular: planning for Sustainable Development Goal 14, target 2 "*sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience*"; and target 5 "*conserve at least 10 per cent of coastal and marine areas".*

Further, the projections may be applicable in planning related to other SDGs, implementation of which is essential to safeguard coral reefs and which require some consideration of the ecosystem services provided by coral reefs and climate vulnerability. This includes e.g. Goal 1 on poverty; 2 on food security; 6 on water and sanitation; 12 on sustainable consumption and production; and 13 on climate change. The projections can inform policies related to fisheries, coastal development, and land-use planning, all of which influence climate change vulnerability of reefs. For example, the projections can make a case for moderating land use change and agricultural impacts in the watershed of relative refugia, or placing restrictions on fishing gear that disproportionately targets species that maintain resilience at high priority sites.

An interesting additional international policy application related to climate projections and identifying climate refugia for coral reefs is to guide donor funding, funds and investment. Targeting these investments can help in identifying coral reef areas and projects with a maximum 'return on investment' potential for ensuring the survival of coral reefs through a changing climate (see also Research Priorities section below).

In relation to climate change policy, the projections can be used to inform decisions relating to mitigation and adaptation. It is clear that the success of the Paris Agreement depends on progressively more ambitious national mitigation actions, through delivering on the emissions-reductions commitments made as Nationally Determined Contributions (NDCs). These are expected to reflect the highest possible ambition. By illustrating implications of two mitigation scenarios for reef health and ecosystem service provision, the projections help make a case for more ambitious NDCs (in 2020 and beyond).

The Paris Agreement also establishes a qualitative adaptation goal, to enhance adaptive capacity, strengthen resilience, and reduce vulnerability in the context of the temperature goal. The projections can be applied towards assessment of vulnerability and adaptation needs in key coastal sectors, and directly used in the preparation of National Adaptation Plans as well as in sub-national or sectoral adaptation plans.

In addition to climate policy, the projections can also be important for supporting the Convention on Biological Diversity and the post-2020 global biodiversity framework. The Aichi Biodiversity Targets expire in 2020, and a new framework will be negotiated in 2021 presumably with targets and indicators included for coral reef ecosystems. Climate projections can be used to support member states in developing targets for protection of coral reefs and in identifying important coral reefs to protect in order to achieve the targets and to ensure the survival of associated biodiversity.

Research Priorities

1. Statistical downscaling of climate model projections: The projections presented here are at a resolution of 0.25x0.25° latitude x longitude (roughly 25x25 km at the equator) = this is the native resolution in the tropics of most CMIP6 climate models. These pixels or cells contain many different reefs in most coral reef areas. This resolution is coarse – too coarse to distinguish local-scale differences in average summer temperatures and bleaching threshold. These local-scale differences result in local-scale spatial variation in ASB timing (van Hooidonk et al. 2016). NOAA Coral Reef Watch has developed a new historical dataset for sea surface temperature (SST) called CoralTemp that has a 5-km resolution. The new CoralTemp dataset is now widely believed to be the most representative of SST in coral reef areas and can be used to develop statistically downscaled projections. Increasing the resolution of these CMIP6 projections is expected to further resolve differences among reefs that are within ~25 km of each other but within the same CMIP6 climate model cell (for this study with projections at model-resolution).

2. Local-scale variation in adaptation; drivers and patterns: The adaptation levels examined here were applied uniformly. For each adaptation level – 1°, for example – all reefs were assumed to experience or benefit from 1° of adaptation (modeled here as an increase to the bleaching threshold). Spatial variation in adaptation capacity is not well understood, and will have dozens of drivers and causes, many of which will shift and change through time in the coming decades, as will benthic community composition on reefs. In reality, there will be great spatial variation in the extent to which corals adapt and this will play out at all scales, including the local-scale. There is likely to always be great uncertainty in our knowledge of local-scale spatial variation in adaptation capacity. Even so, better understanding the drivers and spatial patterns of coral and coral community adaptation to thermal stress will help to target conservation to the reefs most likely to continue to provide ecosystem goods and services in the future.

3. Bright spots and dark spots: There will be places where coral reef ecosystems are substantially better (‘bright spots’) or worse (‘dark spots’) than expected (Cinner et al. 2016). These areas can provide insight to social, cultural and environmental conditions that help reefs defy expectations (Cinner et al. 2016). The projections presented here represent projected future exposure only. Spatial variation, at all scales, in bleaching impacts will depend as much or more on how coral reefs respond to the projected increases in sea temperature and thermal stress. In the Cinner et al. (2016) paper, bright and dark spots were identified from a global analysis. Researchers can also identify

bright and dark spots at more local scales, among reefs within the same management jurisdiction. Reefs identified as local bright spots that are also projected to be temporary refugia will be among those most likely to continue to provide goods and services.

Accessing the projections

To facilitate use of the projections, the results for SSP5-8.5 and SSP2-4.5 have been made publicly accessible via the UNEP World Environment Situation Room (WESR) website (https://wesr.unep.org/). Global map images are presented on the WESR and data layers are downloadable there that are compatible with use in ArcGIS.

Users can download and view the layer package in ArcGIS if interested in combining the projections data layers with other data, producing custom maps, or including these data layers within planning exercises. The technical capacity required to use the projections data layers varies depending on location and the intended use. Additional, outside expertise may be required for using the projections in marine spatial planning processes.

References

Agardy, T., di Sciara, G. N. & Christie, P. Mind the gap Addressing the shortcomings of marine protected areas through large scale marine spatial planning. *Marine Policy* **35,** 226–232 (2011).

Anthony, K. R. N. *et al.* Operationalizing resilience for adaptive coral reef management under global environmental change. *Glob. Change Biol.* n/a–n/a (2014). doi:10.1111/gcb.12700

Anthony, K. R. N., & Maynard, J. A. Coral reefs in the emergency room: continued carbon emissions will increase the need for intensive care. *Carbon Management*, **2**, 215-218 (2011).

Baker, A. C. Ecosystems: reef corals bleach to survive change. *Nature* **411,** 765–766 (2001).

Bellwood, D. R., Hughes, T. P., Folke, C., & Nyström, M. Confronting the coral reef crisis. *Nature*, **429***,* 827-833 (2004).

Cinner, J. E., Huchery, C., MacNeil, M. A., Graham, N. A., McClanahan, T. R., Maina, J., ... & Allison, E. H. (2016). Bright spots among the world's coral reefs. *Nature*, *535*(7612), 416-419.

Douglas, A. E. Coral bleaching--how and why? *Marine Pollution Bulletin* **46,** 385–392 (2003).

Eakin, C. Mark, Hugh PA Sweatman, and Russel E. Brainard. "The 2014–2017 global-scale coral bleaching event: insights and impacts." *Coral Reefs* 38.4 (2019): 539-545.

Game, E. T., McDonald-Madden, E., Puotinen, M. L. & Possingham, H. P. Should we protect the strong or the weak? Risk, resilience, and the selection of marine protected areas. *Conservation Biology* **22,** 1619–1629 (2008).

GBRMPA. Climate change and the great barrier reef; a vulnerability assessment. Great Barrier Reef Marine Park Authority, Townsville, QLD, Australia (2007).

Gidden, M., Riahi, K., Smith, S., Fujimori, S., Luderer, G., Kriegler, E., ... & Calvin, K. (2019). Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century. *Geoscientific model development discussions*, *12*(4), 1443-1475.

Gleeson, M. W., and A. E. Strong. "Applying MCSST to coral reef bleaching."*Advances in Space Research* 16.10 (1995): 151-154.

Guest, J. R., Baird, A. H., Maynard, J. A., Muttaqin, E., Edwards, A. J., Campbell, S. J., ... & Chou, L. M. (2012). Contrasting patterns of coral bleaching susceptibility in 2010 suggest an adaptive response to thermal stress. *PloS one*, *7*(3), e33353.

Hughes, T. P., Anderson, K. D., Connolly, S. R., Heron, S. F., Kerry, J. T., Lough, J. M., ... & Claar, D. C. (2018). Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science*, *359*(6371), 80-83.

Knutti, R., Furrer, R., Tebaldi, C., Cermak, J. & Meehl, G. A. Challenges in Combining Projections from Multiple Climate Models. *Journal of Climate* **23,** 2739–2758 (2010).

Marshall, N. A. & Marshall, P. A. Conceptualizing and operationalizing social resilience within commercial fisheries in northern Australia. *Ecology and Society* **12,** 1–14 (2007).

Maynard, J. A., Anthony, K. R. N., Marshall, P. A., & Masiri, I. (2008). Major bleaching events can lead to increased thermal tolerance in corals. *Marine Biology*, *155*(2), 173-182.

Maynard, J. *et al.* Projections of climate conditions that increase coral disease susceptibility and pathogen abundance and virulence. *Nature Climate Change* **5,** 688–694 (2015).

McClanahan, T. R., Donner, S. D., Maynard, J. A., MacNeil, M. A., Graham, N. A., Maina, J., ... & Eakin, C. M. (2012). Prioritizing key resilience indicators to support coral reef management in a changing climate. *PloS one*, *7*(8), e42884.

Mcleod, E., Anthony, K. R., Mumby, P. J., Maynard, J., Beeden, R., Graham, N. A., ... & Mangubhai, S. (2019). The future of resilience-based management in coral reef ecosystems. *Journal of environmental management*, *233*, 291-301.

Mills, M. *et al.* Real-world progress in overcoming the challenges of adaptive spatial planning in marine protected areas. *Biological Conservation* **181,** 54–63 (2015).
Mumby, P. J. & Anthony, K. R. N. Resilience metrics to inform ecosystem management under global change with application to coral reefs. *Methods Ecol Evol* **6,** 1088–1096 (2015).
Mumby, P., Hastings, A. & Edwards, H. Thresholds and the resilience of Caribbean coral reefs. *Nature* **450,** 98–101 (2007).
Obura, D., Grimsditch, G. (2009). Resilience assessment of coral reefs: assessment protocol for coral reefs, focusing on coral bleaching and thermal stress. Gland, Switzerland: IUCN.
Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O'neill, B. C., Fujimori, S., ... & Lutz, W. (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Global Environmental Change*, *42*, 153-168.
Turner, B. L. *et al.* A framework for vulnerability analysis in sustainability science. *Proc. Natl Acad. Sci.* **100,** 8074–8079 (2003).
UN Environment (2019) Analysis of Policies related to the Protection of Coral Reefs-Analysis of global and regional policy instruments and governance mechanisms related to the protection and sustainable management of coral reefs. Karasik, R., Pickle, A., Roady, S.A., Vegh, T. and Virdin, J. (Authors). United Nations Environment Programme, Nairobi, Kenya.
UNEP 2017. Coral Bleaching Futures - Downscaled projections of bleaching conditions for the world's coral reefs, implications of climate policy and management responses. United Nations Environment Programme, Nairobi, Kenya
UNEP (2019). Emissions Gap Report 2019. Executive summary. United Nations Environment Programme, Nairobi
UN Environment (2019) Analysis of Policies related to the Protection of Coral Reefs-Analysis of global and regional policy instruments and governance mechanisms related to the protection and sustainable management of coral reefs. Karasik, R., Pickle, A., Roady, S.A., Vegh, T. and Virdin, J. (Authors). United Nations Environment Programme, Nairobi, Kenya.
van Hooidonk, R. & Huber, M. Quantifying the quality of coral bleaching predictions. **28,** 579–587 (2009).
van Hooidonk, R. J., Maynard, J. A., Manzello, D. & Planes, S. Opposite latitudinal gradients in projected ocean acidification and bleaching impacts on coral reefs. *Glob. Change Biol.* **20,** 103–112 (2014).
van Hooidonk, R., Maynard, J. A. & Planes, S. Temporary refugia for coral reefs in a warming world. *Nature Climate Change* **3,** 1–4 (2013).
van Hooidonk, R., Maynard, J. A., Liu, Y. & Lee, S.-K. Downscaled projections of Caribbean coral bleaching that can inform conservation planning. *Glob. Change Biol.* **21,** 3389–3401 (2015).
Van Hooidonk, R., Maynard, J., Tamelander, J., Gove, J., Ahmadia, G., Raymundo, L., ... & Planes, S. (2016). Local-scale projections of coral reef futures and implications of the Paris Agreement. *Scientific reports*, *6*(1), 1-8.
Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., ... & Masui, T. (2011). The representative concentration pathways: an overview. *Climatic change*, *109*(1-2), 5.
Watts, M. E. *et al.* Marxan with Zones: Software for optimal conservation based land- and sea-use zoning. *Environmental Modelling & Software* **24,** 1513–1521 (2009).
Wilby, R. L., & Wigley, T. M. L. Downscaling general circulation model output: a review of methods and limitations. *Progress in physical geography*, *21*(4), 530-548 (1997).

Appendices

Appendix 1. Climate models

Climate models used to develop projections for the timing of annual severe bleaching (ASB) for coral reef areas for SSP2-4.5, SSP5-3.4OS, and SSP5-8.5.

Table A1.1. Models used to develop projections for SSP2-4.5.

Model name	Resolution	Runs
ACCESS-CM2	ACCESS-OM2 (GFDL-MOM5, tripolar primarily 1deg; 360 x 300 longitude/latitude; 50 levels; top grid cell 0-10 m	1
ACCESS-ESM1-5	ACCESS-OM2 (GFDL-MOM5, tripolar primarily 1deg; 360 x 300 longitude/latitude; 50 levels; top grid cell 0-10 m	3
BCC-CSM2-MR	MOM4 (1/3 deg 10S-10N, 1/3-1 deg 10-30 N/S, and 1 deg in high latitudes; 360 x 232 longitude/latitude; 40 levels; top grid cell 0-10 m	1
CESM2-WACCM	POP2 (320x384 longitude/latitude; 60 levels; top grid cell 0-10 m	1
CESM2	POP2 (320x384 longitude/latitude; 60 levels; top grid cell 0-10 m	3
CNRM-CM6-1-HR	Nemo 3.6 (eORCA025, tripolar primarily 1/4deg; 1442 x 1050 longitude/latitude; 75 levels; top grid cell 0-1 m	1
CNRM-CM6-1	Nemo 3.6 (eORCA1, tripolar primarily 1deg; 362 x 294 longitude/latitude; 75 levels; top grid cell 0-1 m	6
CNRM-ESM2-1	Nemo 3.6 (eORCA1, tripolar primarily 1deg; 362 x 294 longitude/latitude; 75 levels; top grid cell 0-1 m	5
CanESM5-CanOE	NEMO3.4.1 (ORCA1 tripolar grid, 1 deg with refinement to 1/3 deg within 20 degrees of the equator; 361 x 290 longitude/latitude; 45 vertical levels; top grid cell 0-6.19 m	3
CanESM5	NEMO3.4.1 (ORCA1 tripolar grid, 1 deg with refinement to 1/3 deg within 20 degrees of the equator; 361 x 290 longitude/latitude; 45 vertical levels; top grid cell 0-6.19 m	25
EC-Earth3-Veg	NEMO3.6 (ORCA1 tripolar primarily 1 degree with meridional refinement down to 1/3 degree in the tropics; 362 x 292 longitude/latitude; 75 levels; top grid cell 0-1 m)	4
EC-Earth3	NEMO3.6 (ORCA1 tripolar primarily 1 degree with meridional refinement down to 1/3 degree in the tropics; 362 x 292 longitude/latitude; 75 levels; top grid cell 0-1 m)	2

Model name	**Resolution**	**Runs**
FIO-ESM-2-0	POP2-W (POP2 coupled with MASNUM surface wave model, Displaced Pole; 320 x 384 longitude/latitude; 60 levels; top grid cell 0-10 m)	3
GFDL-CM4	GFDL-OM4p25 (GFDL-MOM6, tripolar - nominal 0.25 deg; 1440 x 1080 longitude/latitude; 75 levels; top grid cell 0-2 m	1
HadGEM3-GC31-LL	NEMO-HadGEM3-GO6.0 (eORCA1 tripolar primarily 1 deg with meridional refinement down to 1/3 degree in the tropics; 360 x 330 longitude/latitude; 75 levels; top grid cell 0-1 m	1
IPSL-CM6A-LR	NEMO-OPA (eORCA1.3, tripolar primarily 1deg; 362 x 332 longitude/latitude; 75 levels; top grid cell 0-2 m	14
MCM-UA-1-0	80x192	1
MIROC-ES2L	COCO4.9 (tripolar primarily 1deg; 360 x 256 longitude/latitude; 63 levels; top grid cell 0-2 m	1
MIROC6	COCO4.9 (tripolar primarily 1deg; 360 x 256 longitude/latitude; 63 levels; top grid cell 0-2 m)	3
MPI-ESM1-2-HR	MPIOM1.63 (tripolar TP04, approximately 0.4deg; 802 x 404 longitude/latitude; 40 levels; top grid cell 0-12 m	2
MPI-ESM1-2-LR	MPIOM1.63 (bipolar GR1.5, approximately 1.5deg; 256 x 220 longitude/latitude; 40 levels; top grid cell 0-12 m)	10
MRI-ESM2-0	MRI.COM4.4 (tripolar primarily 0.5 deg latitude/1 deg longitude with meridional refinement down to 0.3 deg within 10 degrees north and south of the equator; 360 x 364 longitude/latitude; 61 levels; top grid cell 0-2 m)	1
NESM3	NEMO v3.4 (NEMO v3.4, tripolar primarily 1deg; 362 x 292 longitude/latitude; 46 levels; top grid cell 0-6 m	2
UKESM1-0-LL	NEMO-HadGEM3-GO6.0 (eORCA1 tripolar primarily 1 deg with meridional refinement down to 1/3 degree in the tropics; 360 x 330 longitude/latitude; 75 levels; top grid cell 0-1 m	8

Table A1.2. Models used to develop projections for SSP5-8.5.

Model name	Resolution	Runs
BCC-CSM2-MR	ocean: MOM4 (1/3 deg 10S-10N, 1/3-1 deg 10-30 N/S, and 1 deg in high latitudes; 360 x 232 longitude/latitude; 40 levels; top grid cell 0-10 m)	1
CAMS-CSM1-0	MOM4 (tripolar; 360 x 200 longitude/latitude, primarily 1deg latitude/longitude, down to 1/3deg within 30deg of the equatorial tropics; 50 levels; top grid cell 0-10 m)	2
CanESM5	NEMO3.4.1 (ORCA1 tripolar grid, 1 deg with refinement to 1/3 deg within 20 degrees of the equator; 361 x 290 longitude/latitude; 45 vertical levels; top grid cell 0-6.19 m)	23
CanESM5-CanOE	NEMO3.4.1 (ORCA1 tripolar grid, 1 deg with refinement to 1/3 deg within 20 degrees of the equator; 361 x 290 longitude/latitude; 45 vertical levels; top grid cell 0-6.19 m)	3
CESM2	POP2 (320x384 longitude/latitude; 60 levels; top grid cell 0-10 m)	2
CESM2-WACCM	POP2 (320x384 longitude/latitude; 60 levels; top grid cell 0-10 m)	1
CNRM-CM6-1	Nemo 3.6 (eORCA1, tripolar primarily 1deg; 362 x 294 longitude/latitude; 75 levels; top grid cell 0-1 m)	6
CNRM-CM6-1-HR	Nemo 3.6 (eORCA025, tripolar primarily 1/4deg; 1442 x 1050 longitude/latitude; 75 levels; top grid cell 0-1 m)	1
CNRM-ESM2-1	Nemo 3.6 (eORCA1, tripolar primarily 1deg; 362 x 294 longitude/latitude; 75 levels; top grid cell 0-1 m)	5
EC-Earth3	NEMO3.6 (ORCA1 tripolar primarily 1 deg with meridional refinement down to 1/3 degree in the tropics; 362 x 292 longitude/latitude; 75 levels; top grid cell 0-1 m)	1,6,9,13,11,15
EC-Earth3-Veg	NEMO3.6 (ORCA1 tripolar primarily 1 degree with meridional refinement down to 1/3 degree in the tropics; 362 x 292 longitude/latitude; 75 levels; top grid cell 0-1 m)	3
FGOALS-f3-L	LICOM3.0 (LICOM3.0, tripolar primarily 1deg; 360 x 218 longitude/latitude; 30 levels; top grid cell 0-10 m)	1
FIO-ESM-2-0	POP2-W (POP2 coupled with MASNUM surface wave model, Displaced Pole; 320 x 384 longitude/latitude; 60 levels; top grid cell 0-10 m)	2
GFDL-CM4	GFDL-OM4p25 (GFDL-MOM6, tripolar - nominal 0.25 deg; 1440 x 1080 longitude/latitude; 75 levels; top grid cell 0-2 m)	1

Model name	Resolution	Runs
GFDL-ESM4	GFDL-OM4p5 (GFDL-MOM6, tripolar - nominal 0.5 deg; 720 x 576 longitude/latitude; 75 levels; top grid cell 0-2 m)	1
HadGEM3-GC31-LL	NEMO-HadGEM3-GO6.0 (eORCA1 tripolar primarily 1 deg with meridional refinement down to 1/3 degree in the tropics; 360 x 330 longitude/latitude; 75 levels; top grid cell 0-1 m)	1
IPSL-CM6A-LR	NEMO-OPA (eORCA1.3, tripolar primarily 1deg; 362 x 332 longitude/latitude	1,2,3,4,6,14
MCM-UA-1-0	80x192	1
MIROC-ES2L	COCO4.9 (tripolar primarily 1deg; 360 x 256 longitude/latitude; 63 levels; top grid cell 0-2 m)	1
MIROC6	COCO4.9 (tripolar primarily 1deg; 360 x 256 longitude/latitude; 63 levels; top grid cell 0-2 m)	3
MPI-ESM1-2-HR	MPIOM1.63 (tripolar TP04, approximately 0.4deg; 802 x 404 longitude/latitude; 40 levels; top grid cell 0-12 m)	1
MPI-ESM1-2-LR	MPIOM1.63 (bipolar GR1.5, approximately 1.5deg; 256 x 220 longitude/latitude; 40 levels; top grid cell 0-12 m)	1,10
MRI-ESM2-0	MRI.COM4.4 (tripolar primarily 0.5 deg latitude/1 deg longitude with meridional refinement down to 0.3 deg within 10 degrees north and south of the equator; 360 x 364 longitude/latitude; 61 levels; top grid cell 0-2 m)	1
NESM3	NEMO v3.4 (NEMO v3.4, tripolar primarily 1deg; 362 x 292 longitude/latitude; 46 levels; top grid cell 0-6 m)	2
NorESM2-LM	MICOM (1 degree resolution; 360 x 384; 70 levels; top grid cell minimum 0-2.5 m [native model uses hybrid density and generic upper-layer coordinate interpolated to z-level for contributed data])	1
UKESM1-0-LL	NEMO-HadGEM3-GO6.0 (eORCA1 tripolar primarily 1 deg with meridional refinement down to 1/3 degree in the tropics; 360 x 330 longitude/latitude; 75 levels; top grid cell 0-1 m)	1,2,3,4,8

Appendix 2. Regional Summaries

Introduction to Regional Seas and Coral Reefs

Today, more than 143 countries participate in 14 Regional Seas programmes established under the auspices of UNEP. The d10 Regional Seas that contain coral reefs (listed starting with the Wider Caribbean and moving east), include: Wider Caribbean, Western Africa, Red Sea and Gulf of Aden, ROPME Sea Area, Eastern Africa, South Asian Seas, East Asian Seas, Pacific, South-East Pacific, and North-East Pacific.

These Regional Seas governance mechanisms are the basis for presentation of findings in this report. However, coral reef ecosystems often span political boundaries and jurisdictions. Because of this, and in keeping with an ecosystem approach, countries and territories with tropical coral reefs in or near the geographic area of a Regional Sea but not parties to Regional Seas Conventions and/or not participating in Action Plans have also been included.

Table A1.1 Lists the regions, relevant Regional Seas Conventions and/or Action Plans, and countries and territories with coral reefs.

Table A1.2 presents summary data for each country and territory with coral reefs, for the projected timing of the onset of annual severe bleaching (ASB) conditions under SSP5-8.5, including: the number of reef pixels, the average projected timing of ASB, the range in projected timing of ASB (earliest to latest timing of ASB among reef pixels), and standard deviation among climate models in ASB timing. This table also shows the number and percent of reef pixels in seven 5-year bins, which is the basis for the histograms in the individual Regional Seas Summaries.

Introduction to Regional Seas Summaries

Each of the Regional Seas summaries lists:

1. The countries and/or territories with the greatest and least reef area (reef area comparisons are from UNEP 2017).
2. The average among countries and territories for projected timing of ASB conditions under SSP5-8.5.
3. The countries/territories with the earliest and latest averages for projected timing of ASB under SSP5-8.5.
4. The countries/territories with the greatest numbers of relative climate losers and relative climate winners.
5. The locations projected to experience ASB conditions latest: these are regionally important

   relative climate refugia that also meet the global criterion for refugia of projected ASB after 2052.

The summaries also provide histograms that present the distribution in the data of the projected timing of the onset of annual severe bleaching (ASB) under SSP5-8.5. Within these histograms, the data bars are in grey scale with three tones. Projected timing of the onset of ASB before 2030 represent relative climate losers (more than 4 years prior to the global average of 2034); these are in dark grey. ASB within 15 years of the global average (2030- 2044) are in the medium grey tone. Projected ASB timing more than 10 years after the global average of 2034 (i.e. after 2044) represent relative climate winners; these are in light grey.

Table A2.1. Regions based on the UNEP Regional Seas programmes, related Conventions and Action Plans.

Countries and territories are listed in alphabetical order, only including those that have coral reefs. *Asterisks indicate country, territory or reef tract in or near the geographic area of the Regional Sea but not party to the relevant Convention or not participating in the Action Plan.

Regions, based on Regional Seas programmes	Full Title of the relevant Regional Seas Convention, Action Plan and/or programme	Regional grouping for this study – ALL listed have coral reefs.
Wider Caribbean including the Western Atlantic	Cartagena Convention for the Protection and Development of the Marine Environment of the Wider Caribbean (CAR) / Caribbean Environment Programme (CEP)	Anguila, Antigua and Barbuda, Aruba, the Bahamas, Barbados, Belize, Bonaire and Sint Eustasius and Saba, British Virgin Islands, Cayman Islands, Colombia, Costa Rica, Cuba, Curacao, Dominica, Dominican Republic, French Guiana, Grenada, Guadeloupe, *Haiti, *Honduras, Jamaica, Martinique, Mexico, Montserrat, Netherlands Antilles, Nicaragua, Panama, Puerto Rico, St. Kitts and Nevis, Saint Lucia, Saint Martin, Sint Maarten, St. Vincent and the Grenadines, Trinidad and Tobago, Turks and Caicos Islands, United States of America (Florida and Texas), United States Virgin Islands, Venezuela as well as *Bermuda and *Brazil
***Western Africa including the eastern Atlantic *** *There are not any coral reefs in this Regional Sea under the Millenium Reefs update of 2019*	Abidjan Convention for Cooperation in the Protection and Development of the Marine and Coastal Environment of the West and Central African Region (Abidjan Convention)	Cameroon, Equitorial Guinea, *Cape Verde, *Saint Helena and Ascension Island, *Sao Tome and Principe

Red Sea and Gulf of Aden	Regional Convention for the Conservation of the Red Sea and Gulf of Aden Environment (Jeddah Convention) / Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden (PERSGA)	Djibouti, Egypt, *Eritrea, *Israel, Jordan, Saudi Arabia, Somalia, Sudan, *Yemen
ROPME Sea Area	Kuwait Regional Convention for Cooperation on the Protection of the Marine Environment from Pollution (Kuwait Convention) / Regional Organization for the Protection of the Marine Environment (ROPME)	Bahrain, I.R. Iran, Kuwait, Oman, Qatar Saudi Arabia, United Arab Emirates
Eastern Africa (Western Indian Ocean)	Nairobi Convention for the Protection, Management and Development of the Marine and Coastal Environment of the Eastern African Region (Nairobi Convention)	Comoros, Kenya, Madagascar, Mauritius, Mayotte, Mozambique, Reunion Island (France), Seychelles, Somalia, South Africa, and Tanzania
South Asian Seas including the central Indian Ocean	South Asian Seas Action Plan (SASAP) / South Asia Cooperative Environment Programme (SACEP)	Bangladesh, *Chagos, India, Maldives, Sri Lanka
East Asian Seas including the coral triangle and Japan	East Asian Seas Action Plan / Coordinating Body on the Seas of East Asia (COBSEA)	*Australia, *Brunei, Cambodia, People's Republic of China, *Christmas Island, Indonesia, *Japan, Malaysia, *Myanmar, *Paracel Islands, Philippines, Singapore, *Spratly Islands, Thailand, *Timor-Leste, Vietnam
Pacific Islands	Noumea Convention for the Protection of the Natural Resources and Environment of the South Pacific Region (Noumea Convention) / Secretariat for the Pacific Regional Environment Programme (SPREP)	American Samoa, Australia, Cook Islands, Federated States of Micronesia, Fiji, French Polynesia, Kiribati, Marshall Islands, Nauru, New Caledonia, New Zealand, Niue, Northern Mariana Islands and Guam, Palau, Papua New Guinea, *Pitcairn Islands, Samoa, Solomon Islands, Tokelau, Tong , Tuvalu, *United States (Hawaii), *US Minor Outlying Islands, Vanuatu, Wallis and Futuna

South-East Pacific	Convenio para la Protección del Medio Marino y la Zona Costera del Pacífico Sudeste (Lima Convention) and South East Pacific Action Plan / Comisión Permanente del Pacífico Sur (CPPS)	Chile, Colombia, Ecuador, Panama (not a member of CPPS but party to the Lima Convention)
North-East Pacific	Convention for Cooperation in the Protection and Sustainable Development of the Marine and Coastal Environment of the Northeast Pacific (not yet in force) and North East Pacific Action Plan (NEP)	*Clipperton Island, *Cocos Island, Colombia, Costa Rica, El Salvador, Honduras, Mexico, Nicaragua and Panama

Table A2.2. Country and territory summaries for projected annual severe bleaching (ASB) under RCP8.5.

Countries and territories are grouped by region based on the Regional Seas, only including those that have coral reefs, and listed in alphabetical order. *Asterisks indicate country, territory or reef tract in or near the geographic area of the Regional Sea but not party to the relevant Convention or not participating in the Action Plan.

The table provides, for each country and territory, the number of reef pixels, the range in timing of ASB (earliest to latest timing of ASB among reef pixels) as well as the average projected timing of ASB, and standard deviation among climate models in ASB timing. The following columns give the number and percent of reef pixels in seven 5-year bins (this data is the basis for the histograms in the individual Regional Seas Summaries).

Note: the following countries have coral reefs within two Regional Seas: Australia, Colombia, Costa Rica, Mexico, Panama, Saudi Arabia, Somalia, and USA. Pixel counts and percentages for the date ranges for these countries have been calculated for each Regional Sea but summaries (Pixels (n), Range, AVG Year, and SD) are for the entire country (marked in light grey shade).

Country	Pixels (n)	Range	AVG Year	SD		<2030	2030-2034	2035-2039	2040-2044	2045-2049	2050-2054	≥2055
Wider Caribbean including the western Atlantic												
Anguilla	4	3	2019	1.5	n	4	0	0	0	0	0	0
					%	100	0	0	0	0	0	0
Antigua and Barbuda	4	3	2017	1.4	n	4	0	0	0	0	0	0
					%	100	0	0	0	0	0	0
Aruba	4	10	2018	5.0	n	4	0	0	0	0	0	0
					%	100	0	0	0	0	0	0

Country	Pixels (n)	Range	AVG Year	SD		<2030	2030-2034	2035-2039	2040-2044	2045-2049	2050-2054	≥2055
Barbados	3	3	2016	1.7	n	3	0	0	0	0	0	0
					%	100	0	0	0	0	0	0
Belize	29	26	2030	7.6	n	14	6	5	4	0	0	0
					%	48	21	17	14	0	0	0
Bonaire, Sint Eustasius and Saba	9	3	2016	1.3	n	9	0	0	0	0	0	0
					%	100	0	0	0	0	0	0
British Virgin Islands	5	3	2017	1.2	n	5	0	0	0	0	0	0
					%	100	0	0	0	0	0	0
Cayman Islands	8	2	2035	0.6	n	0	2	6	0	0	0	0
					%	0	25	75	0	0	0	0
Colombia	41	27	2022	8.7	n	31	6	2	2	0	0	0
					%	76	15	5	5	0	0	0
Costa Rica	5	13	2033	5.7	n	1	1	3	0	0	0	0
					%	20	20	60	0	0	0	0
Cuba	153	38	2033	9.6	n	60	20	29	23	14	7	0
					%	39	13	19	15	9	5	0
Curaçao	4	3	2016	1.5	n	4	0	0	0	0	0	0
					%	100	0	0	0	0	0	0

Country	Pixels (n)	Range	AVG Year	SD		<2030	2030-2034	2035-2039	2040-2044	2045-2049	2050-2054	≥2055
Dominica	4	10	2021	5.1	n	4	0	0	0	0	0	0
					%	100	0	0	0	0	0	0
Dominican Republic	41	28	2027	7.2	n	28	8	1	4	0	0	0
					%	68	20	2	10	0	0	0
Grenada	6	16	2024	6.1	n	5	0	1	0	0	0	0
					%	83	0	17	0	0	0	0
Guadeloupe	11	3	2016	1.3	n	11	0	0	0	0	0	0
					%	100	0	0	0	0	0	0
Haiti	47	33	2026	9.2	n	30	7	5	4	1	0	0
					%	64	15	11	9	2	0	0
Honduras	35	25	2025	7.5	n	27	3	4	1	0	0	0
					%	77	9	11	3	0	0	0
Jamaica	33	19	2026	5.5	n	22	10	1	0	0	0	0
					%	67	30	3	0	0	0	0
Martinique	5	3	2016	1.6	n	5	0	0	0	0	0	0
					%	100	0	0	0	0	0	0
Mexico	102	39	2030	11.6	n	50	12	13	11	10	6	0
					%	49	12	13	11	10	6	0

Country	Pixels (n)	Range	AVG Year	SD		<2030	2030-2034	2035-2039	2040-2044	2045-2049	2050-2054	≥2055
Montserrat	2	3	2017	2.1	n	2	0	0	0	0	0	0
					%	100	0	0	0	0	0	0
Netherlands Antilles	2	3	2017	2.1	n	2	0	0	0	0	0	0
					%	100	0	0	0	0	0	0
Nicaragua	29	3	2015	0.6	n	29	0	0	0	0	0	0
					%	100	0	0	0	0	0	0
Panama	31	20	2023	6.8	n	24	6	1	0	0	0	0
					%	77	19	3	0	0	0	0
Puerto Rico	22	21	2022	4.9	n	21	0	1	0	0	0	0
					%	95	0	5	0	0	0	0
Saint Lucia	6	9	2017	3.6	n	6	0	0	0	0	0	0
					%	100	0	0	0	0	0	0
Saint Martin	2	0	2018	0.0	n	2	0	0	0	0	0	0
					%	100	0	0	0	0	0	0
St. Kitts and Nevis	3	3	2022	1.7	n	3	0	0	0	0	0	0
					%	100	0	0	0	0	0	0
St. Vincent and the Grenadines	4	3	2016	1.5	n	4	0	0	0	0	0	0
					%	100	0	0	0	0	0	0

Country	Pixels (n)	Range	AVG Year	SD		<2030	2030-2034	2035-2039	2040-2044	2045-2049	2050-2054	≥2055
The Bahamas	240	45	2039	10.5	n	46	26	68	38	15	26	21
					%	19	11	28	16	6	11	9
Trinidad and Tobago	5	10	2025	4.4	n	4	1	0	0	0	0	0
					%	80	20	0	0	0	0	0
Turks and Caicos Islands	16	15	2027	3.5	n	12	3	1	0	0	0	0
					%	75	19	6	0	0	0	0
United States of America (Florida and Texas)	32	42	2037	11.4	n	9	1	5	8	6	2	1
					%	28	3	16	25	19	6	3
United States Virgin Islands	7	1	2018	0.4	n	7	0	0	0	0	0	0
					%	100	0	0	0	0	0	0
Venezuela	34	45	2029	13.0	n	21	2	3	4	2	0	2
					%	62	6	9	12	6	0	6
East Africa												
Comoros	14	13	2038	3.2	n	0	0	13	0	1	0	0
					%	0	0	93	0	7	0	0

Country	Pixels (n)	Range	AVG Year	SD		<2030	2030-2034	2035-2039	2040-2044	2045-2049	2050-2054	≥2055
French Southern Territories	11	21	2034	8.3	n	4	1	2	4	0	0	0
					%	36	9	18	36	0	0	0
Kenya	24	24	2040	6.6	n	0	1	12	6	2	3	0
					%	0	4	50	25	8	13	0
Madagascar	153	52	2040	10.3	n	19	22	43	23	25	8	13
					%	12	14	28	15	16	5	8
Mauritius	20	21	2029	6.6	n	10	3	7	0	0	0	0
					%	50	15	35	0	0	0	0
Mayotte	10	15	2036	4.0	n	1	2	6	1	0	0	0
					%	10	20	60	10	0	0	0
Mozambique	63	44	2041	6.8	n	1	1	32	15	9	2	3
					%	2	2	51	24	14	3	5
Reunion Island (France)	4	18	2026	8.3	n	2	1	1	0	0	0	0
					%	50	25	25	0	0	0	0
Seychelles	57	18	2043	5.8	n	0	0	21	11	17	8	0
					%	0	0	37	19	30	14	0

Country	Pixels (n)	Range	AVG Year	SD		<2030	2030-2034	2035-2039	2040-2044	2045-2049	2050-2054	≥2055
Somalia	23	17	2050	5.4	n	0	0	0	5	7	5	6
					%	0	0	0	22	30	22	26
South Africa	2	3	2042	2.1	n	0	0	0	2	0	0	0
					%	0	0	0	100	0	0	0
Tanzania	59	38	2037	5.9	n	5	2	37	12	2	0	1
					%	8	3	63	20	3	0	2
East Asian Seas												
Australia	259	73	2052	14.8	n	18	10	22	28	31	36	114
					%	7	4	8	11	12	14	44
Brunei	4	4	2055	2.0	n	0	0	0	0	0	1	3
					%	0	0	0	0	0	25	75
Cambodia	16	20	2043	5.4	n	0	0	4	9	1	1	1
					%	0	0	25	56	6	6	6
Christmas Island	2	5	2042	3.5	n	0	0	1	1	0	0	0
					%	0	0	50	50	0	0	0
Indonesia	1642	65	2043	8.1	n	55	122	394	494	305	149	123
					%	3	7	24	30	19	9	7
Japan	76	29	2024	6.0	n	63	11	1	1	0	0	0
					%	83	14	1	1	0	0	0

Country	Pixels (n)	Range	AVG Year	SD		<2030	2030-2034	2035-2039	2040-2044	2045-2049	2050-2054	≥2055
Malaysia	95	39	2046	8.6	n	2	1	25	22	16	9	20
					%	2	1	26	23	17	9	21
Myanmar	2	11	2037	7.8	n	0	1	0	1	0	0	0
					%	0	50	0	50	0	0	0
People's Republic of China	38	71	2048	21.5	n	10	2	2	2	2	3	17
					%	26	5	5	5	5	8	45
Philippines	689	46	2031	8.6	n	251	123	213	74	20	7	1
					%	36	18	31	11	3	1	0
Singapore	1	0	2044		n	0	0	0	1	0	0	0
					%	0	0	0	100	0	0	0
Thailand	59	42	2044	10.2	n	6	3	9	12	13	10	6
					%	10	5	15	20	22	17	10
Timor-Leste	22	41	2052	11.8	n	0	1	3	4	1	3	10
					%	0	5	14	18	5	14	45
Vietnam	64	46	2051	8.6	n	0	0	1	17	20	11	15
					%	0	0	2	27	31	17	23

Country	Pixels (n)	Range	AVG Year	SD		<2030	2030-2034	2035-2039	2040-2044	2045-2049	2050-2054	≥2055
NE Pacific												
Clipperton Island	1	0	2019		n	1	0	0	0	0	0	0
					%	100	0	0	0	0	0	0
Costa Rica	18	25	2041	6.5	n	0	4	2	6	5	0	1
					%	0	22	11	33	28	0	6
Mexico	115	75	2047	24.9	n	38	5	4	6	6	10	46
					%	33	4	3	5	5	9	40
Nicaragua	1	0	2030		n	0	1	0	0	0	0	0
					%	0	100	0	0	0	0	0
Panama	16	24	2033	6.5	n	4	7	2	2	1	0	0
					%	25	44	13	13	6	0	0
Pacific												
American Samoa	9	8	2016	2.7	n	9	0	0	0	0	0	0
					%	100	0	0	0	0	0	0
Australia	472	64	2034	14.8	n	256	33	34	46	22	19	62
					%	54	7	7	10	5	4	13

Country	Pixels (n)	Range	AVG Year	SD		<2030	2030-2034	2035-2039	2040-2044	2045-2049	2050-2054	≥2055
Cook Islands	31	27	2024	8.9	n	22	0	8	1	0	0	0
					%	71	0	26	3	0	0	0
Federated States of Micronesia	147	19	2021	3.7	n	140	7	0	0	0	0	0
					%	95	5	0	0	0	0	0
Fiji	175	21	2017	3.2	n	174	0	1	0	0	0	0
					%	99	0	1	0	0	0	0
French Polynesia	215	48	2040	5.7	n	8	16	87	74	23	4	3
					%	4	7	40	34	11	2	1
Kiribati	17	14	2039	5.2	n	0	7	1	6	3	0	0
					%	0	41	6	35	18	0	0
Marshall Islands	99	23	2023	6.5	n	78	13	8	0	0	0	0
					%	79	13	8	0	0	0	0
Nauru	2	5	2038	3.5	n	0	0	1	1	0	0	0
					%	0	0	50	50	0	0	0
New Caledonia	169	24	2020	5.8	n	160	8	1	0	0	0	0
					%	95	5	1	0	0	0	0
Niue	3	0	2015	0.0	n	3	0	0	0	0	0	0
					%	100	0	0	0	0	0	0

Country	Pixels (n)	Range	AVG Year	SD		<2030	2030-2034	2035-2039	2040-2044	2045-2049	2050-2054	≥2055
Palau	21	23	2031	5.8	n	9	5	6	0	1	0	0
					%	43	24	29	0	5	0	0
Papua New Guinea	443	37	2026	9.3	n	271	61	80	14	10	7	0
					%	61	14	18	3	2	2	0
Samoa	16	9	2017	3.2	n	16	0	0	0	0	0	0
					%	100	0	0	0	0	0	0
Solomon Islands	202	43	2027	10.2	n	111	34	25	23	5	2	2
					%	55	17	12	11	2	1	1
Tokelau	5	12	2032	4.8	n	1	2	2	0	0	0	0
					%	20	40	40	0	0	0	0
Tonga	46	7	2016	1.8	n	46	0	0	0	0	0	0
					%	100	0	0	0	0	0	0
Tuvalu	37	37	2028	11.7	n	20	3	5	7	0	2	0
					%	54	8	14	19	0	5	0
United States of America	78	23	2026	6.7	n	50	12	13	3	0	0	0
					%	64	15	17	4	0	0	0
US Minor Outlying Islands	65	17	2039	4.3	n	0	10	19	27	9	0	0
					%	0	15	29	42	14	0	0

Country	Pixels (n)	Range	AVG Year	SD		<2030	2030-2034	2035-2039	2040-2044	2045-2049	2050-2054	≥2055
Vanuatu	82	31	2017	5.2	n	77	4	0	0	1	0	0
					%	94	5	0	0	1	0	0
Wallis and Futuna	31	8	2016	1.5	n	31	0	0	0	0	0	0
					%	100	0	0	0	0	0	0
Red Sea												
Djibouti	6	8	2044	3.0	n	0	0	0	4	2	0	0
					%	0	0	0	67	33	0	0
Egypt	95	27	2025	7.4	n	66	20	6	3	0	0	0
					%	69	21	6	3	0	0	0
Eritrea	46	55	2029	13.3	n	27	6	7	2	0	0	4
					%	59	13	15	4	0	0	9
Israel	1	0	2018		n	1	0	0	0	0	0	0
					%	100	0	0	0	0	0	0
Saudi Arabia	139	39	2020	7.5	n	121	8	8	0	0	2	0
					%	87	6	6	0	0	1	0

Country	Pixels (n)	Range	AVG Year	SD		<2030	2030-2034	2035-2039	2040-2044	2045-2049	2050-2054	≥2055
Somalia	5	4	2045	2.2	n	0	0	0	3	2	0	0
					%	0	0	0	60	40	0	0
Sudan	32	20	2021	6.7	n	26	4	2	0	0	0	0
					%	81	13	6	0	0	0	0
Yemen	46	52	2043	13.7	n	7	3	8	7	6	4	11
					%	15	7	17	15	13	9	24
ROPME												
Bahrain	12	33	2058	10.3	n	0	0	1	0	2	2	7
					%	0	0	8	0	17	17	58
I.R. Iran	29	62	2048	12.4	n	2	2	1	2	10	6	6
					%	7	7	3	7	34	21	21
Kuwait	5	28	2062	14.2	n	0	0	0	0	2	0	3
					%	0	0	0	0	40	0	60
Oman	14	24	2044	6.9	n	0	1	2	4	4	1	2
					%	0	7	14	29	29	7	14

Country	Pixels (n)	Range	AVG Year	SD		<2030	2030-2034	2035-2039	2040-2044	2045-2049	2050-2054	≥2055
Qatar	15	22	2054	6.9	n	0	0	0	3	1	4	7
					%	0	0	0	20	7	27	47
Saudi Arabia	14	40	2060	13.3	n	0	0	1	3	0	0	10
					%	0	0	7	21	0	0	71
United Arab Emirates	39	40	2053	10.5	n	0	0	0	8	12	8	11
					%	0	0	0	21	31	21	28
SE Pacific												
Colombia	4	11	2043	5.4	n	0	0	1	1	2	0	0
					%	0	0	25	25	50	0	0
Ecuador	22	33	2042	7.6	n	0	3	2	10	5	1	1
					%	0	14	9	45	23	5	5
Panama	16	24	2033	6.5	n	4	7	2	2	1	0	0
					%	25	44	13	13	6	0	0
South Asia												
Bangladesh	1	0	2041		n	0	0	0	1	0	0	0
					%	0	0	0	100	0	0	0

Country	Pixels (n)	Range	AVG Year	SD		<2030	2030-2034	2035-2039	2040-2044	2045-2049	2050-2054	≥2055
India	97	56	2046	10.1	n	4	2	14	41	11	7	18
					%	4	2	14	42	11	7	19
Maldives	92	18	2041	3.6	n	0	1	36	50	3	2	0
					%	0	1	39	54	3	2	0
Sri Lanka	26	31	2051	9.3	n	0	0	3	7	3	2	11
					%	0	0	12	27	12	8	42

Wider Caribbean

including the Western Atlantic

Reef Area

Within this Regional Sea area, the Bahamas has the greatest reef area (2100 pixels containing reefs), and then the USA (1479 pixels in Florida, Texas, US Virgin Islands) and then Cuba (1385 pixels). Montserrat, Sint Maarten and French Guiana all have less than 10 reef pixels. Reef area comparisons are for 4-km reef-containing pixels and are from UNEP 2017.

Average projected timing of annual severe bleaching (ASB) under SSP5-8.5

2030

Earliest and latest average projected timing of ASB under SSP5-8.5

Earliest – Turks and Caicos Islands (2015)
Latest – Bermuda (2039)

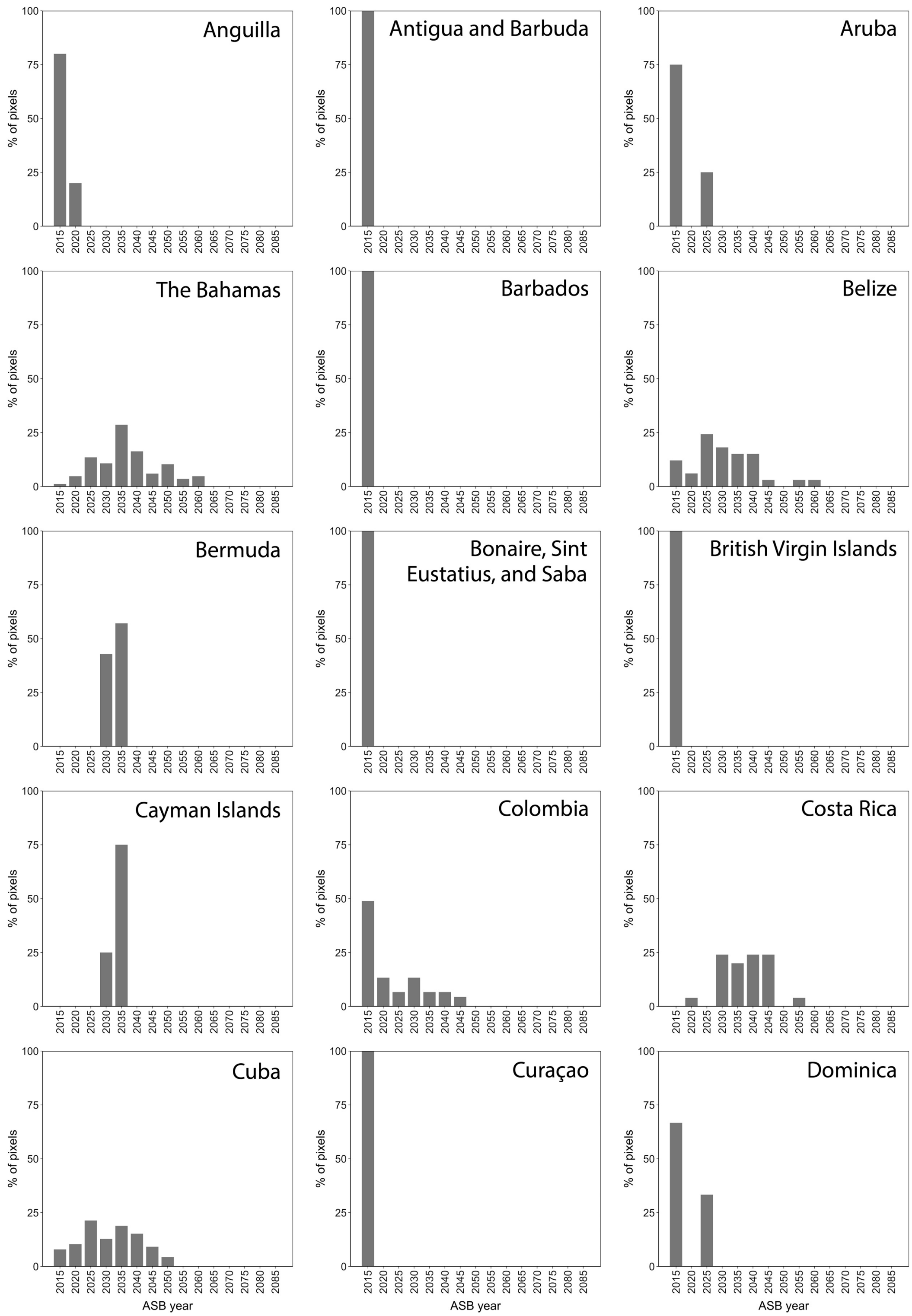
Most Relative climate losers and winners

Cuba has the greatest number of reef pixels projected to experience ASB before 2030 (relative climate losers) with 60, representing 39% of the reef pixels in the Bahamas.

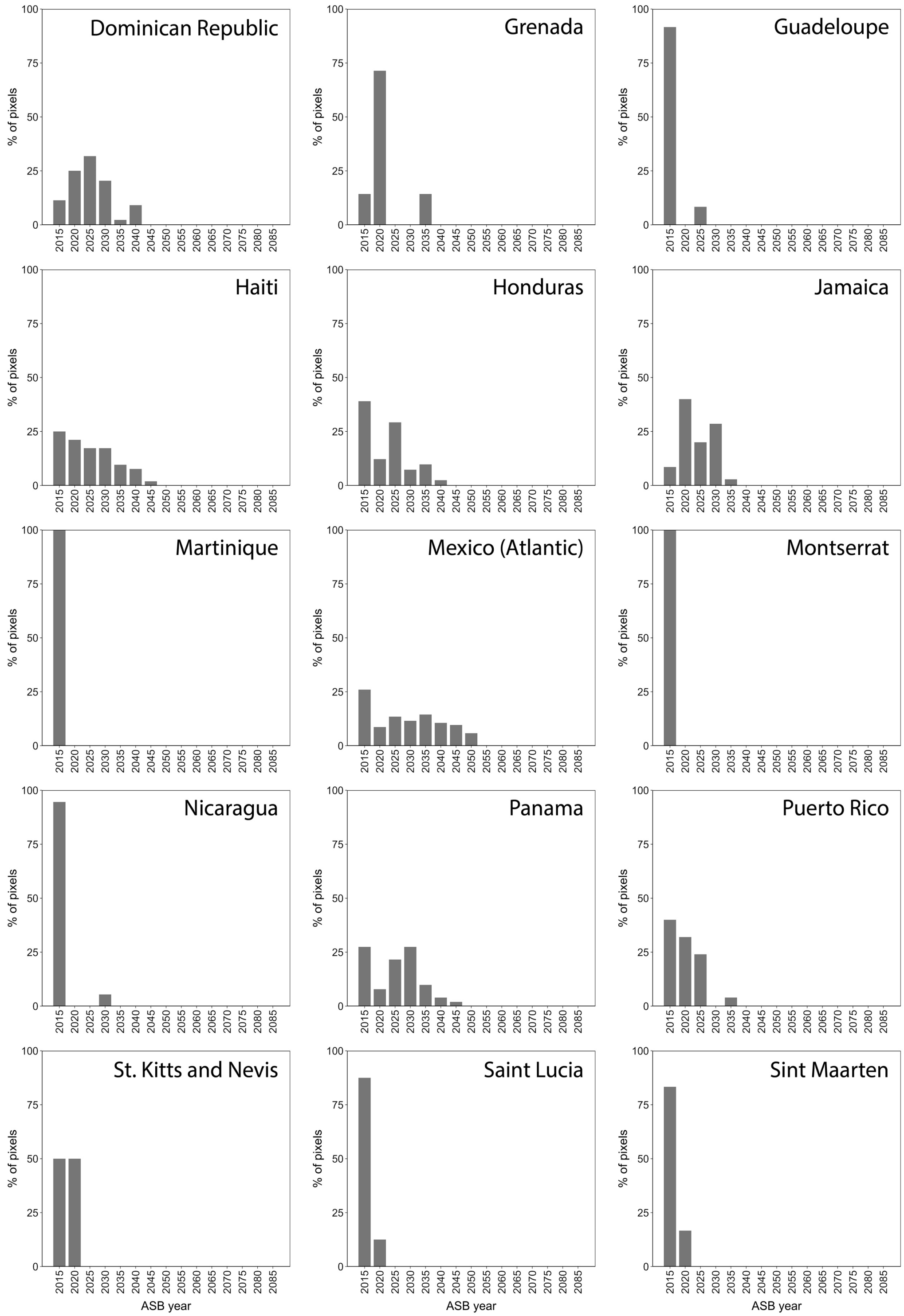
The Bahamas has the greatest number of reef pixels projected to experience ASB after 2044 (relative climate winners) with 21, representing 9% of the reef pixels in the Bahamas.

Top refugia

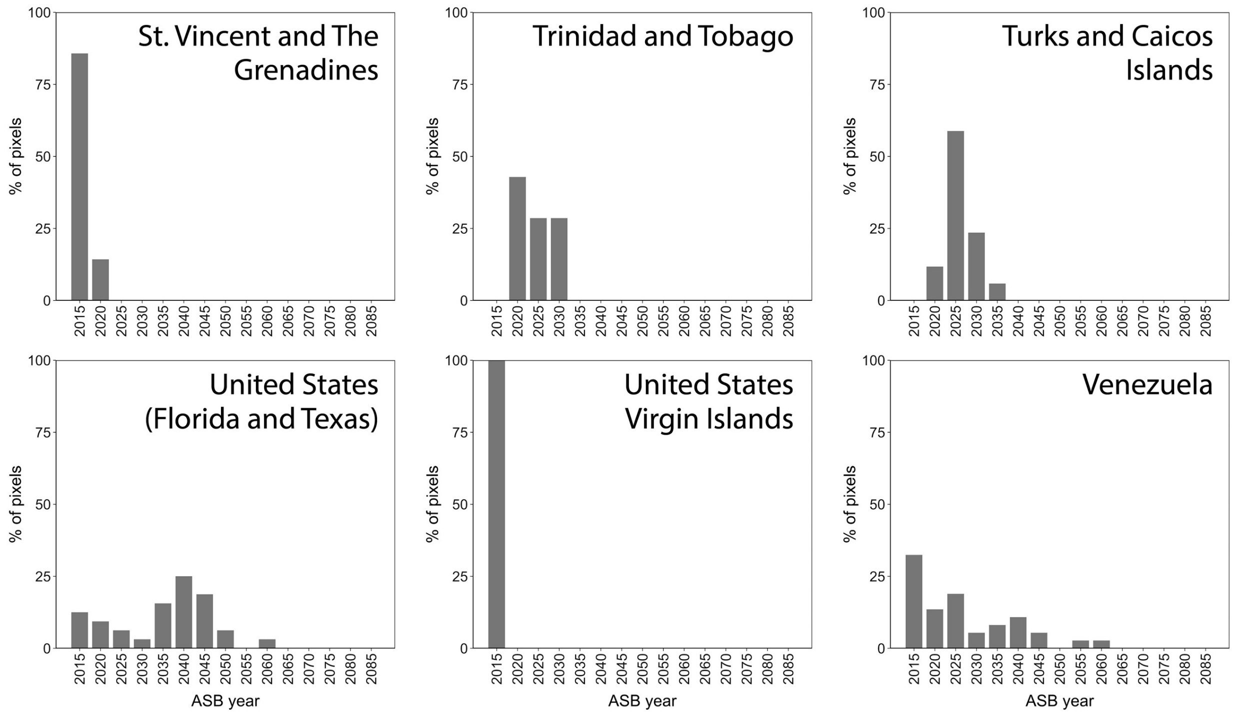
Nine of the ten locations within this region projected to experience ASB conditions latest (i.e., after 2044) in the Bahamas and in the US (Florida and Texas).



Wider Caribbean and Western Atlantic (1 of 3). Histograms of the distribution of projected timing among reef pixels of the onset of annual severe bleaching (ASB) conditions under SSP5-8.5 (including reef area not covered by Regional Sea convention or action plan, see Table A1.1 and A.1.2).

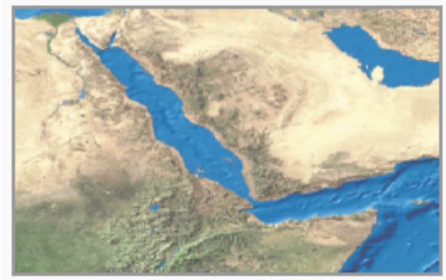


Wider Caribbean and Western Atlantic (2 of 3). Histograms of the distribution of projected timing among reef pixels of the onset of annual severe bleaching (ASB) conditions under SSP5-8.5 (including reef area not covered by Regional Sea convention or action plan, see Table A1.1 and A.1.2).



Wider Caribbean and Western Atlantic (3 of 3). Histograms of the distribution of projected timing among reef pixels of the onset of annual severe bleaching (ASB) conditions under SSP5-8.5 (including reef area not covered by Regional Sea convention or action plan, see Table A1.1 and A.1.2).

Red Sea and Gulf of Aden



Reef Area

Saudi Arabia and Egypt have the greatest reef area with 1311 and 843 reef pixels, respectively. Israel and Jordan both have only four reef pixels. Reef area comparisons are for 4-km reef-containing pixels and are from UNEP 2017.

Average projected timing of annual severe bleaching (ASB) under SSP5-8.5

2026

Earliest and latest average projected timing of ASB under SSP5-8.5

Earliest – Israel (2018)
Latest – Somalia (2045)

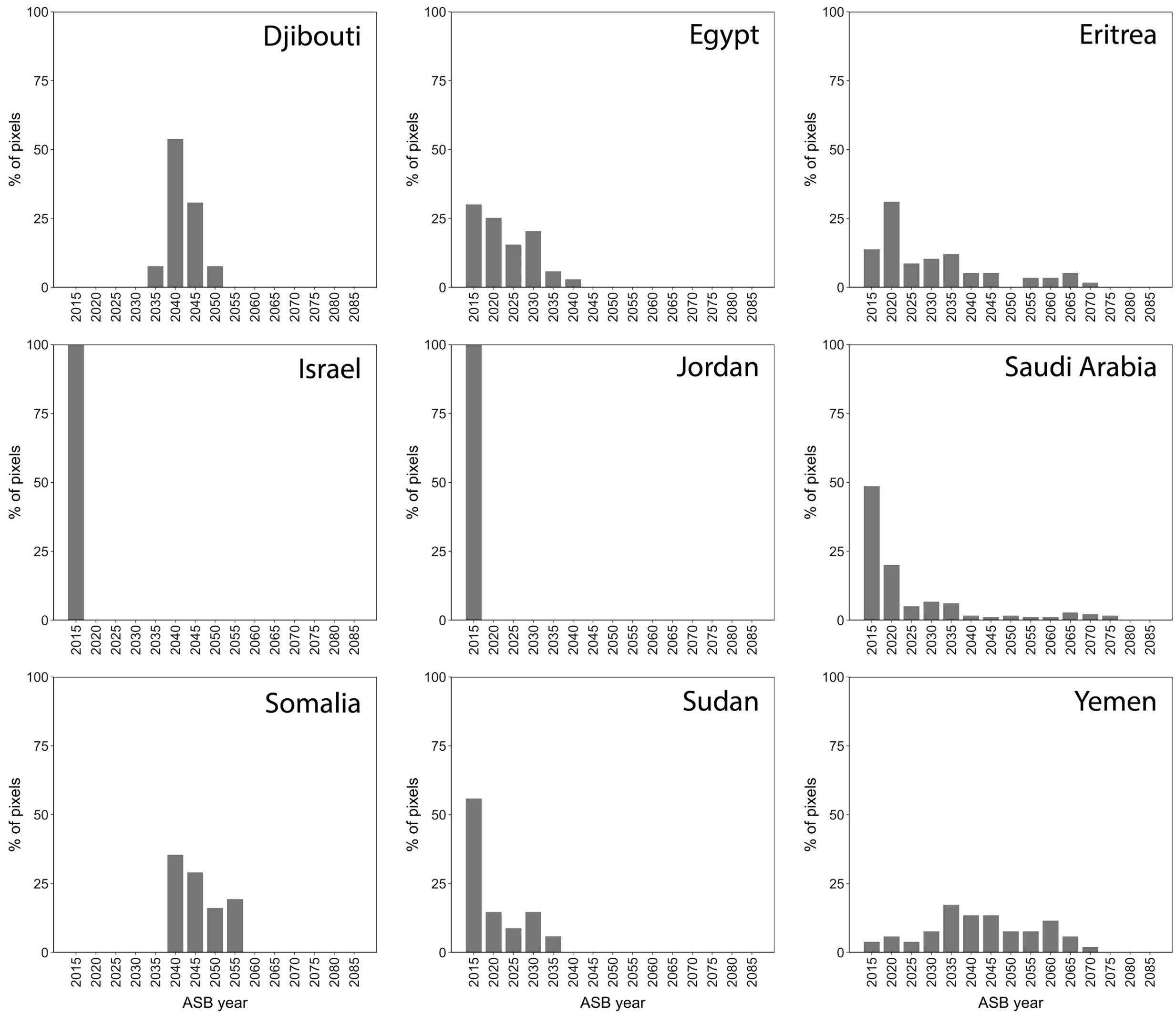
Most Relative climate losers and winners

Saudi Arabia has the greatest number of reef pixels projected to experience ASB before 2030 (relative climate losers) with 121, representing 87% of the reef pixels in Saudi Arabia.

Yemen has the greatest number of reef pixels projected to experience ASB after 2044 (relative climate winners) with 11, representing 24% of the reef pixels in Yemen.

Top refugia

The ten locations within this region projected to experience ASB conditions latest are in Eritrea and Yemen.



Red Sea and Gulf of Aden. Histograms of the distribution of projected timing among reef pixels of the onset of annual severe bleaching (ASB) conditions under SSP5-8.5 (including reef area not covered by Regional Sea convention or action plan, see Table A1.1 and A.1.2).

ROPME Sea Area

Reef Area

Oman and Iran have the greatest reef area with 192 and 107 reef pixels, respectively. Kuwait has the least reef area in this Regional Sea with five 4-km reef pixels. Reef area comparisons are for 4-km reef-containing pixels and are from UNEP 2017.

Average projected timing of annual severe bleaching (ASB) under SSP5-8.5

2052

Earliest and latest average projected timing of ASB under SSP5-8.5

Earliest – Oman (2044)
Latest – Kuwait (2062)

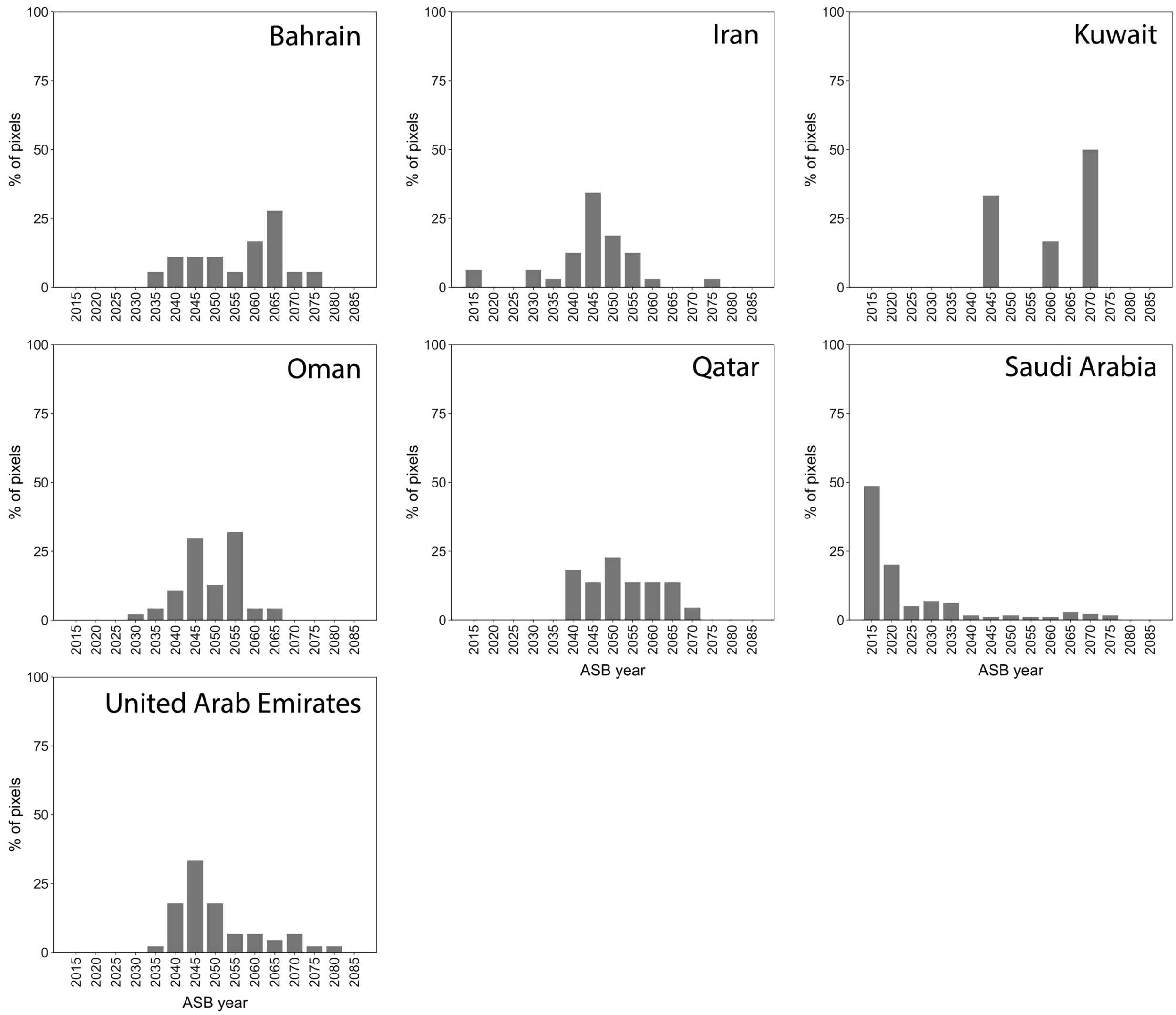
Most Relative climate losers and winners

I.R. Iran has the greatest number of reef pixels projected to experience ASB before 2030 (relative climate losers) with 2, representing 7% of the reef pixels in I.R. Iran.

U.A.E. has the greatest number of reef pixels projected to experience ASB after 2044 (relative climate winners) with 11, representing 28% of the reef pixels in U.A.E.

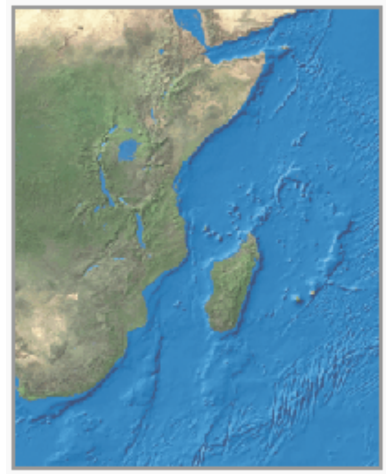
Top refugia

The ten locations within this region projected to experience ASB conditions latest are in the U.A.E. (4), Saudi Arabia (3), Kuwait (2), and I.R. Iran (1).



ROPME Sea Area. Histograms of the distribution of projected timing among reef pixels of the onset of annual severe bleaching (ASB) conditions under SSP5-8.5.

Eastern Africa / Western Indian Ocean



Reef Area

Madagascar has the greatest reef area with 1000 reef pixels. South Africa and Reunion Island have the least reef area with 18 and 13 reef pixels, respectively. Reef area comparisons are for 4-km reef-containing pixels and are from UNEP 2017.

Average projected timing of annual severe bleaching (ASB) under RCP8.5

2040

Earliest and latest average projected timing of ASB under SSP5-8.5

Earliest – Reunion Island, France (2026)
Latest – Somalia (2050)

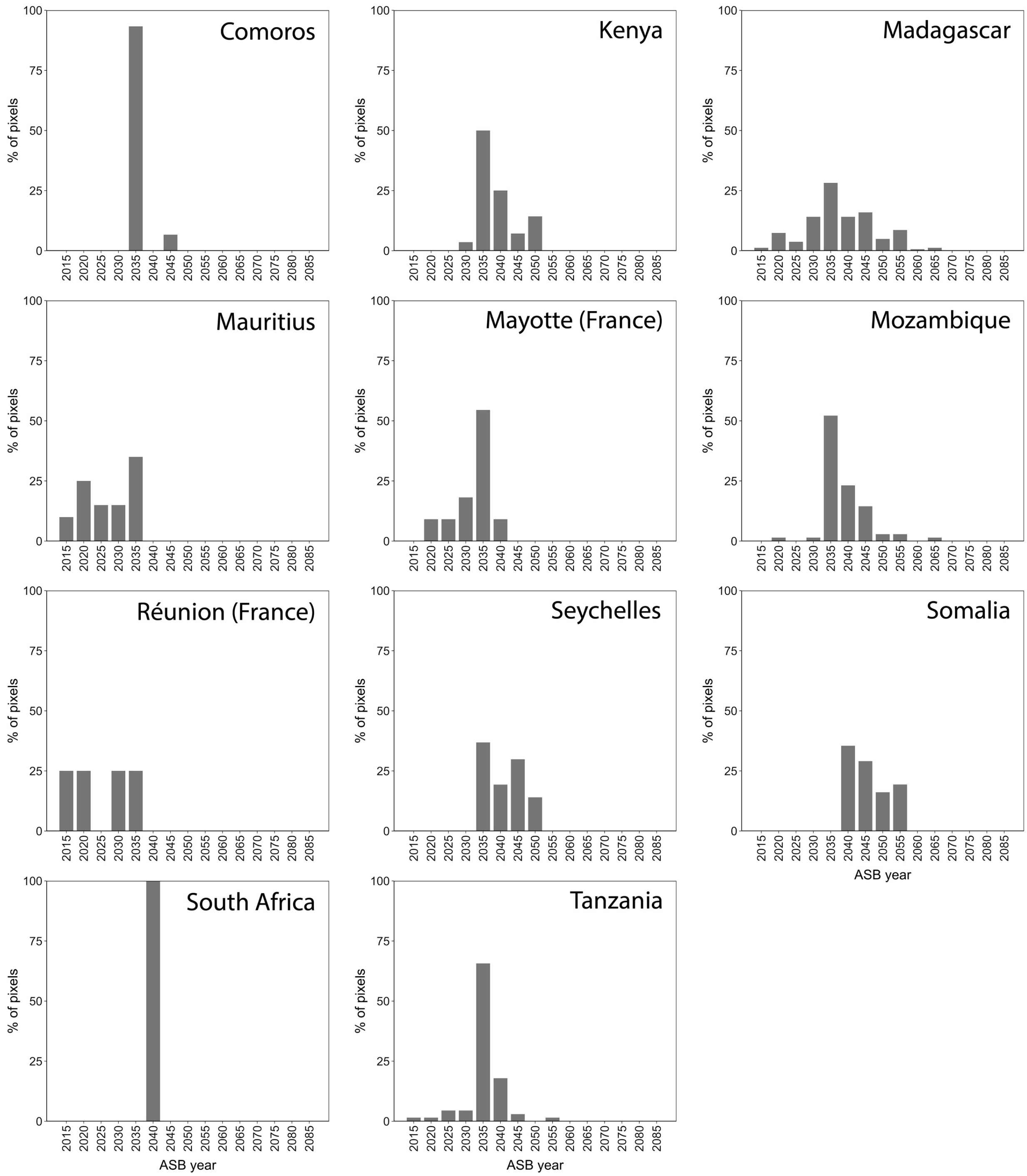
Most Relative climate losers and winners

Madagascar has the greatest number of reef pixels projected to experience ASB before 2030 (relative climate losers) with 19, representing 12% of the reef pixels in Madagascar.

Madagascar also has the greatest number of reef pixels projected to experience ASB after 2044 (relative climate winners) with 13, representing 8% of the reef pixels in Madagascar.

Top refugia

The ten locations within this region projected to experience ASB conditions latest are in Madagascar (7), Somalia (2), and Mozambique (1).



Eastern Africa (Western Indian Ocean). Histograms of the distribution of projected timing among reef pixels of the onset of annual severe bleaching (ASB) conditions under SSP5-8.5.

South Asian Seas

including the central Indian Ocean

Reef Area

Maldives has the greatest reef area with 1207 reef pixels. Bangladesh has the least reef area with 5 reef pixels. Reef area comparisons are for 4-km reef-containing pixels and are from UNEP 2017.

Average projected timing of annual severe bleaching (ASB) under SSP5-8.5

2044

Earliest and latest average projected timing of ASB under SSP5-8.5

Earliest – Bangladesh (2041) and Maldives (2041)
Latest – India (2046)

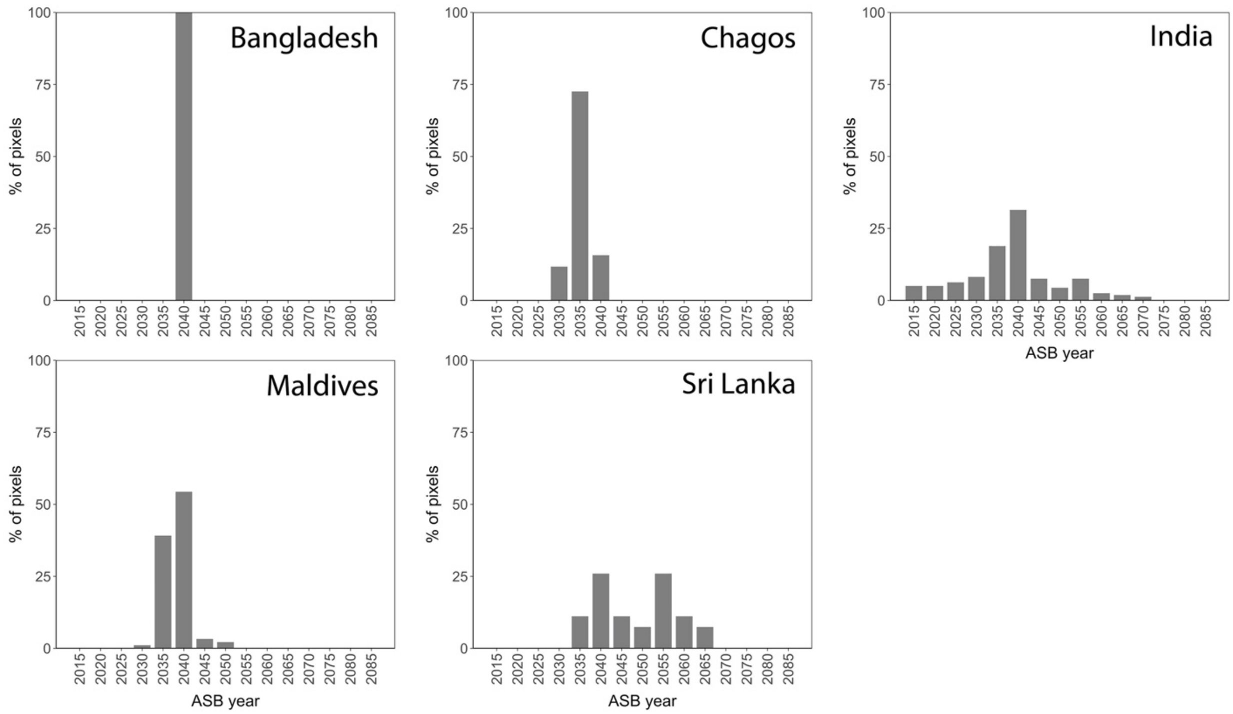
Most Relative climate losers and winners

India has the greatest number of reef pixels projected to experience ASB before 2030 (relative climate losers) with 4, representing 4% of the reef pixels in India.

India also has the greatest number of reef pixels projected to experience ASB after 2044 (relative climate winners) with 18, representing 18% of the reef pixels in India.

Top refugia

The ten locations within this region projected to experience ASB conditions latest are in India (6) and Sri Lanka (4).



South Asian Seas and central Indian Ocean. Histograms of the distribution of projected timing among reef pixels of the onset of annual severe bleaching (ASB) conditions under SSP5-8.5 (including reef area not covered by Regional Sea action plan, see Table A1.1 and A.1.2).

East Asian Seas

including the Coral Triangle and Japan

Reef Area

Indonesia has the greatest reef area of any country or territory in the world with 12340 reef pixels. Australia has 7334 reef pixels and Philippines has 6274 reef pixels. Singapore and Christmas Island have the least reef area with 13 and 11 reef pixels, respectively. Reef area comparisons are for 4-km reef-containing pixels and are from UNEP 2017.

Average projected timing of annual severe bleaching (ASB) under SSP5-8.5

2040

Earliest and latest average projected timing of ASB under SSP5-8.5

Earliest – Japan (2024)
Latest – Brunei (2044)

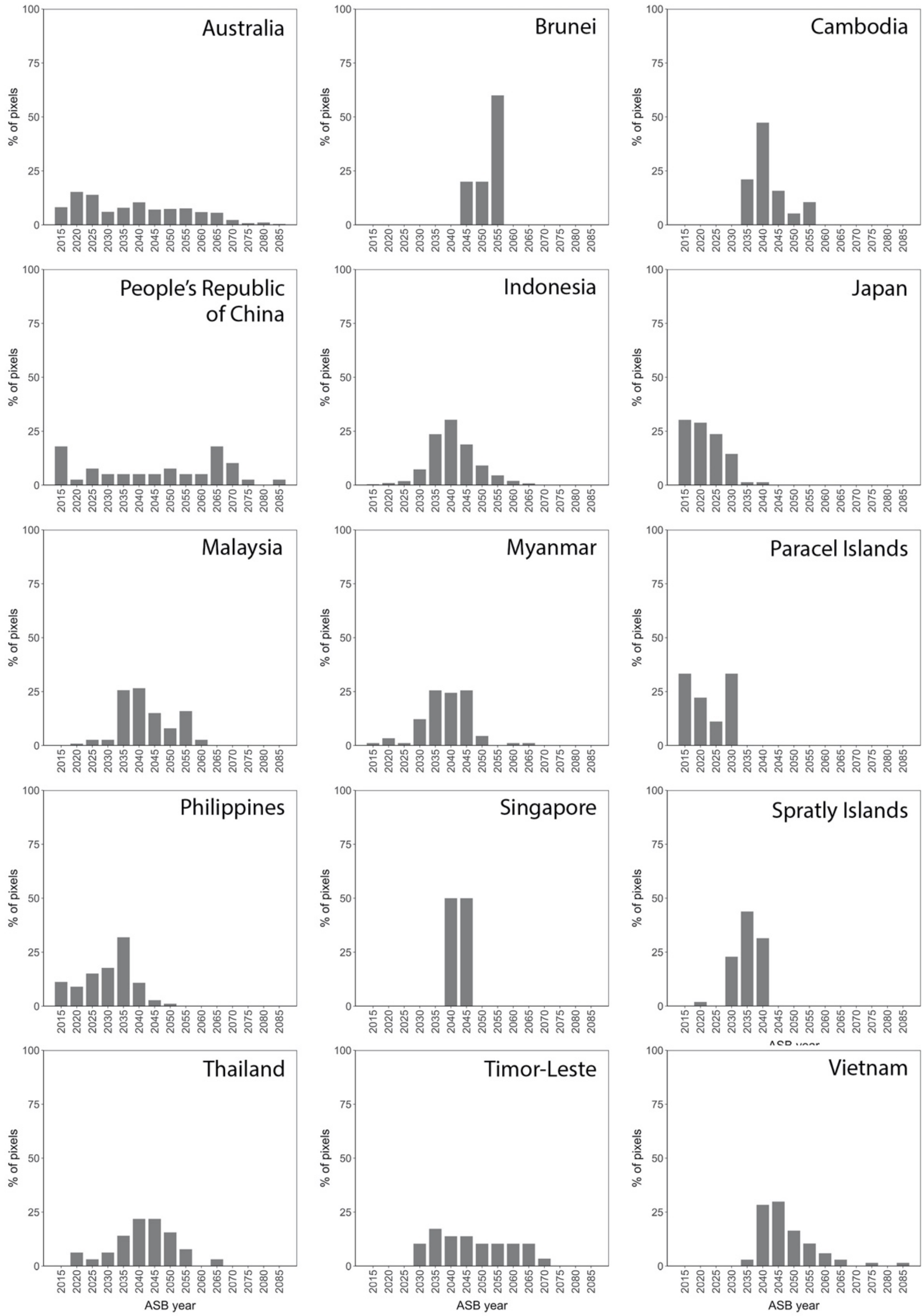
Most Relative climate losers and winners

Philippines has the greatest number of reef pixels projected to experience ASB before 2030 (relative climate losers) with 251, representing 36% of the reef pixels in the Philippines.

Indonesia has the greatest number of reef pixels projected to experience ASB after 2044 (relative climate winners) with 123, representing 7% of the reef pixels in Indonesia.

Top refugia

The ten locations within this region projected to experience ASB conditions latest are in Australia (8), China (1) and Vietnam (1).



East Asian Seas. Histograms of the distribution of projected timing among reef pixels of the onset of annual severe bleaching (ASB) conditions under SSP5-8.5 (including reef area not covered by Regional Sea action plan, see Table A1.1 and A.1.2).

Pacific Islands

Reef Area

Australia has the greatest reef area in the Pacific Islands Regional Sea with 7334 reef pixels. Papua New Guinea has 4197 reef pixels. Nauru and New Zealand (Niue and Kermadec Islands) have the least reef area with 6 and 4 reef pixels, respectively. Reef area comparisons are for 4-km reef-containing pixels and are from UNEP 2017.

Average projected timing of annual severe bleaching (ASB) under SSP5-8.5

2027

Earliest and latest average projected timing of ASB under SSP5-8.5

Earliest – Niue (2015)
Latest – French Polynesia (2040)

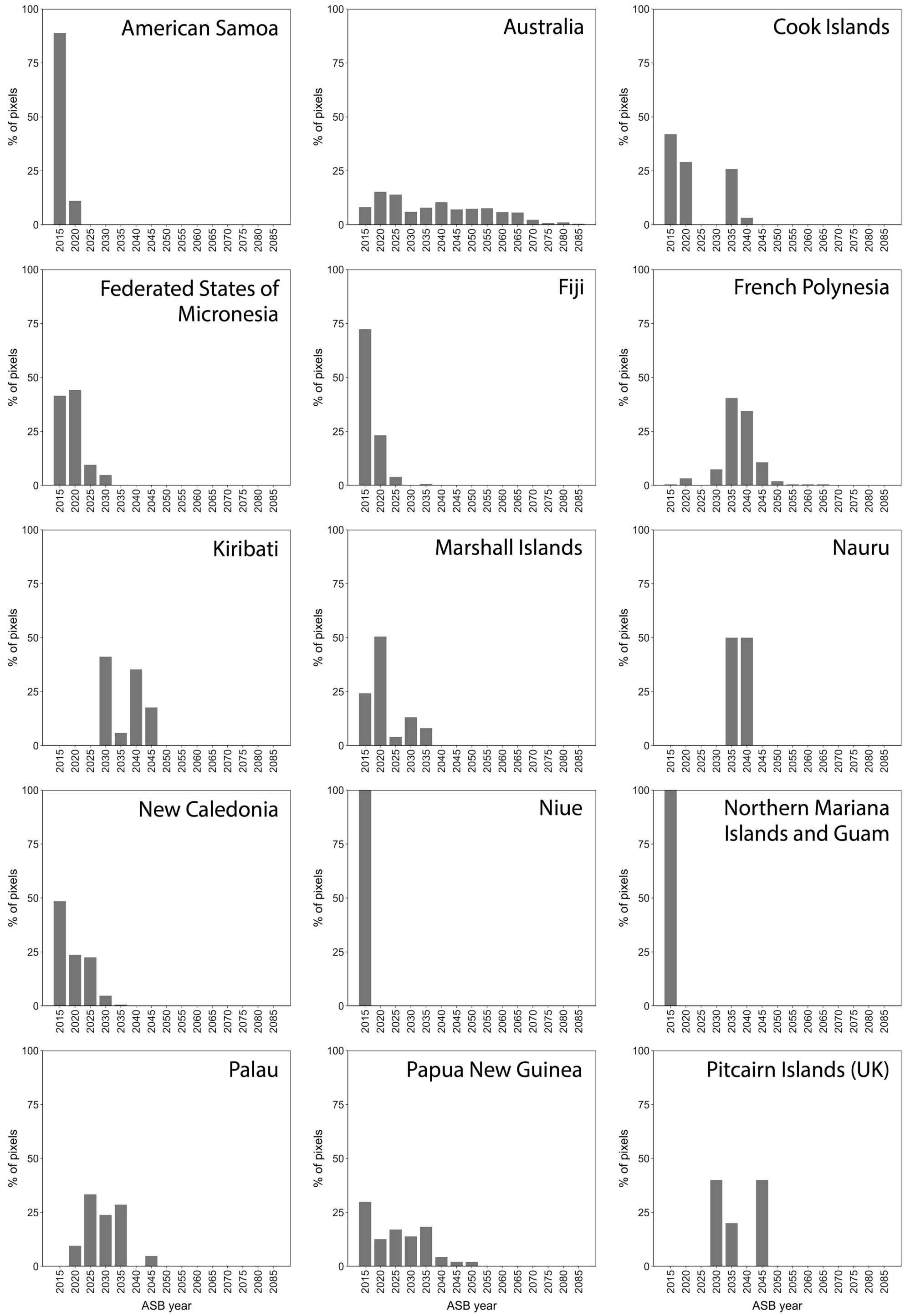
Most Relative climate losers and winners

Papua New Guinea has the greatest number of reef pixels projected to experience ASB before 2030 (relative climate losers) with 271, representing 61% of the reef pixels in Papua New Guinea.

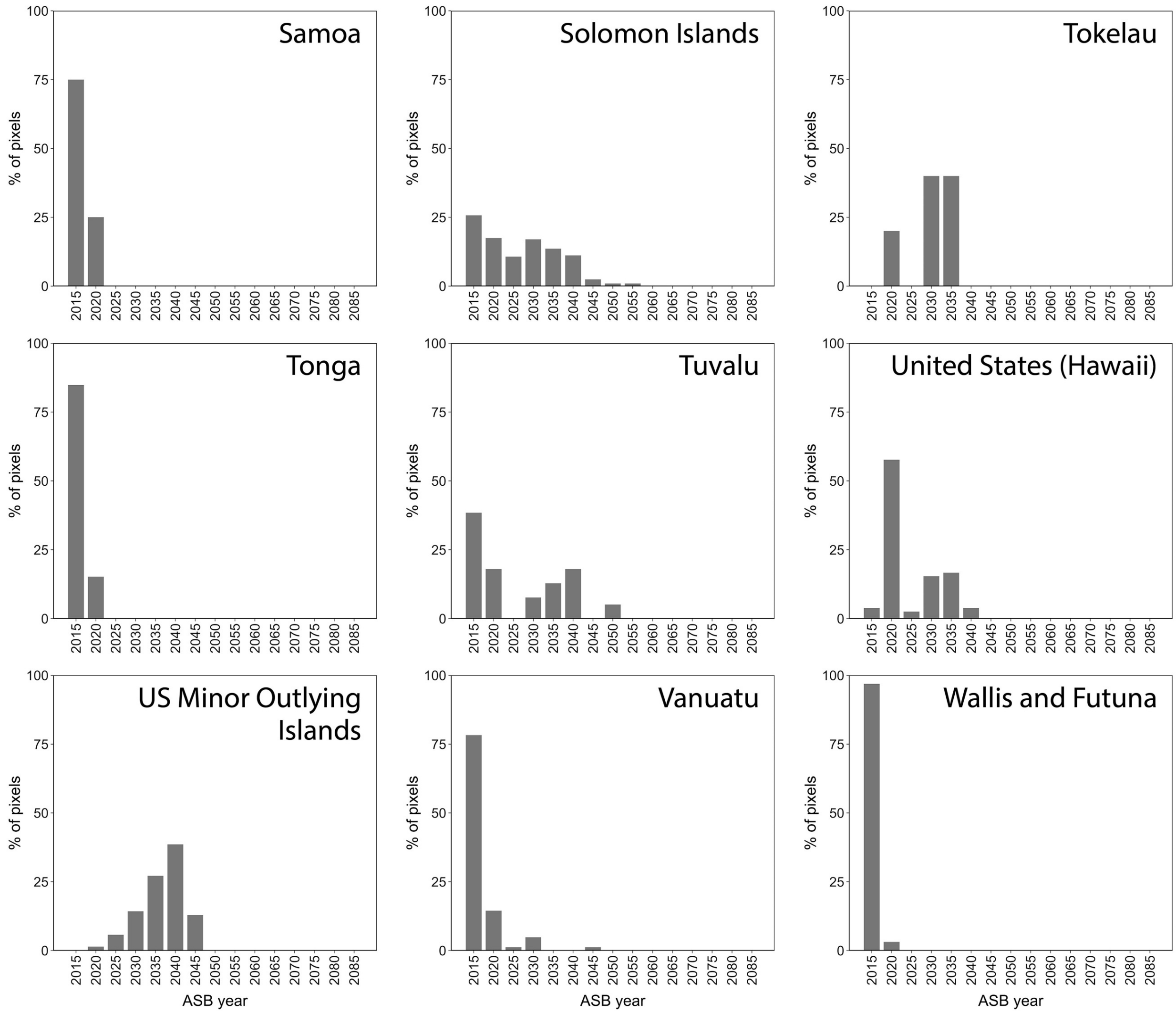
Australia has the greatest number of reef pixels projected to experience ASB after 2044 (relative climate winners) with 62, representing 13% of the reef pixels in Australia.

Top refugia

The ten locations within this region projected to experience ASB conditions latest are in Australia (8), China (1) and Vietnam (1).

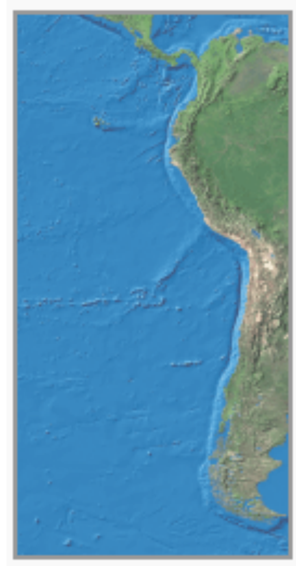


Pacific Islands (1 of 2). Histograms of the distribution of projected timing among reef pixels of the onset of annual severe bleaching (ASB) conditions under SSP5-8.5 (including reef area not covered by Regional Sea convention or action plan, see Table A1.1 and A.1.2).



Pacific Islands (2 of 2). Histograms of the distribution of projected timing among reef pixels of the onset of annual severe bleaching (ASB) conditions under SSP5-8.5 (including reef area not covered by Regional Sea convention or action plan, see Table A1.1 and A.1.2).

South-East Pacific



Reef Area

Panama has the greatest reef area in the South-East Pacific Regional Sea with 93 reef pixels. Chile has the least reef area with just 1 reef pixel. Reef area comparisons are for 4-km reef-containing pixels and are from UNEP 2017.

Average projected timing of annual severe bleaching (ASB) under SSP5-8.5

2038

Earliest and latest average projected timing of ASB under SSP5-8.5

Earliest – Panama (2033)
Latest – Colombia (2043)

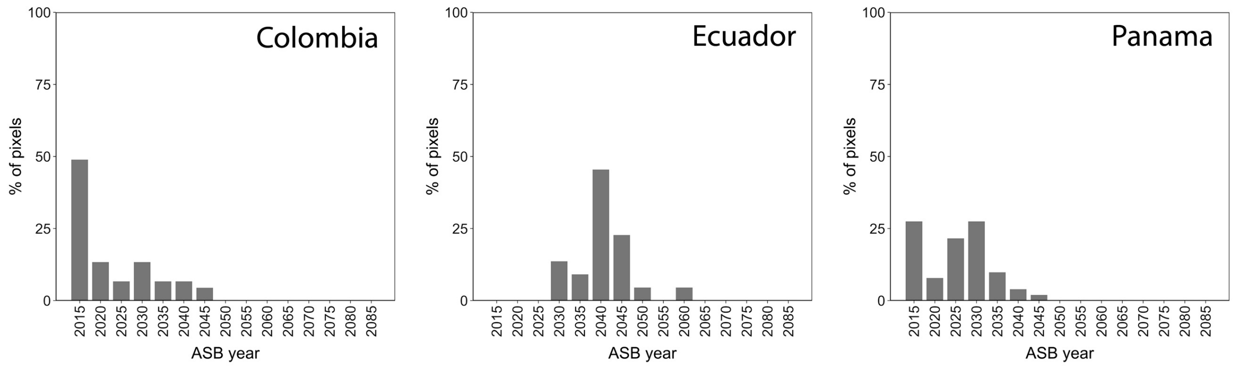
Most Relative climate losers and winners

Panama has the greatest number of reef pixels projected to experience ASB before 2030 (relative climate losers) with 4, representing 25% of the reef pixels in Panama.

Ecuador has the greatest number of reef pixels projected to experience ASB after 2044 (relative climate winners) with 1, representing 5% of the reef pixels in Ecuador.

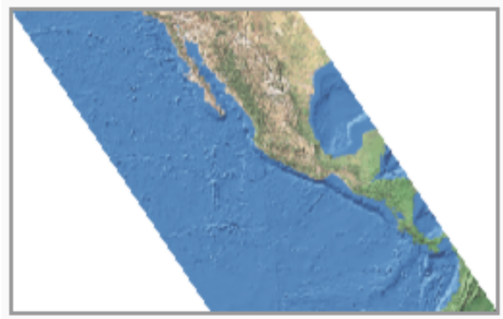
Top refugia

The ten locations within this region projected to experience ASB conditions latest are in Ecuador (8) and Colombia (2).



South-East Pacific. Histograms of the distribution of projected timing among reef pixels of the onset of annual severe bleaching (ASB) conditions under SSP5-8.5.

North-East Pacific



Nicaragua has the greatest reef area in the North-East Pacific Regional Sea with 278 reef pixels. El Salvador has the least reef area with just 2 reef pixel. Reef area comparisons are for 4-km reef-containing pixels and are from UNEP 2017.

Average projected timing of annual severe bleaching (ASB) under SSP5-8.5

2044

Earliest and latest average projected timing of ASB under SSP5-8.5

Earliest – Clipperton Island (2019)
Latest – Mexico (2047)

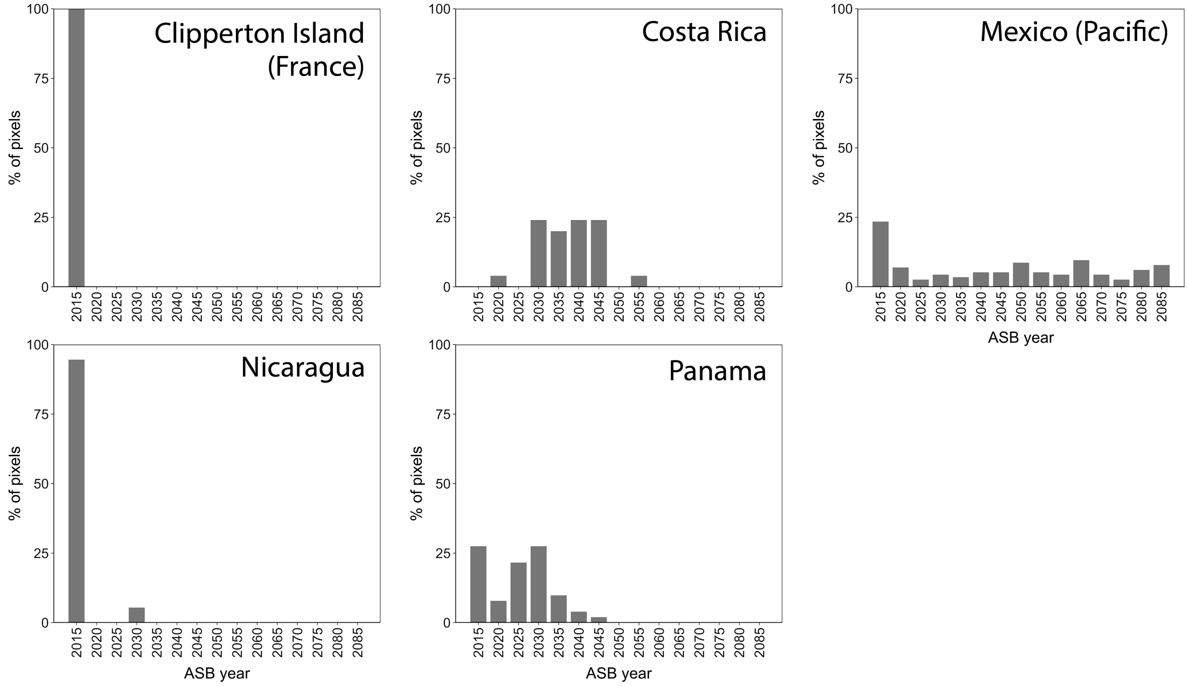
Most Relative climate losers and winners

Mexico has the greatest number of reef pixels projected to experience ASB before 2030 (relative climate losers) with 38, representing 33% of the reef pixels in Panama.

Mexico also has the greatest number of reef pixels projected to experience ASB after 2044 (relative climate winners) with 46, representing 40% of the reef pixels in Mexico.

Top refugia

The ten locations within this region projected to experience ASB conditions latest are in Mexico.



North-East Pacific. Histograms of the distribution of projected timing among reef pixels of the onset of annual severe bleaching (ASB) conditions under SSP5-8.5 (including reef area not covered by Regional Sea convention or action plan, see Table A1.1 and A.1.2).

Appendix 3 – Projections summarized for Marine Ecoregions of the World (MEOWs)

Table A1.3. Projected timing of annual severe bleaching for SSP5-8.5 and SSP2-4.5 for the 111 Marine Ecoregions of the World (MEOW)* that include coral reef areas. Countries included within each MEOW are listed to the right in each row.

** "Marine Ecoregions of the World (MEOW) is a biogeographic classification of the world's coasts and shelves. It is the first ever comprehensive marine classification system with clearly defined boundaries and definitions and was developed to closely link to existing regional systems. MEOW represents broad-scale patterns of species and communities in the ocean, and was designed as a tool for planning conservation across a range of scales and assessing conservation efforts and gaps worldwide. The current system focuses on coast and shelf areas and does not consider realms in pelagic or deep benthic environment. It is hoped that parallel but distinct systems for pelagic and deep benthic biotas will be devised in the near future. The project was led by WWF and The Nature Conservancy, with broad input from a working group representing key NGO, academic and intergovernmental conservation partners." – World Wildlife Fund.*

		SSP5-8.5							SSP2-4.5							
ECO #	ECOREGION	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	COUNTRIES (EEZ)
20043	Northern Gulf of Mexico	2	2035	2038	3	2037	1.5	2035	2	2033	2038	5	2036	2.5	2033	Mexico, United States
20051	Central Kuroshio Current	11	2015	2031	16	2020	5.2	2019	11	2015	2032	17	2020	5.5	2019	Japan
20052	East China Sea	22	2015	2086	71	2042	25.8	2031	14	2015	2068	53	2028	19.5	2015	China, Japan
20060	Cortezian	31	2048	2090	42	2072	13.5	2073	8	2056	2086	30	2071	11.0	2067	Mexico

		SSP5-8.5							SSP2-4.5							
ECO #	ECOREGION	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	COUNTRIES (EEZ)
20061	Magdalena Transition	4	2055	2078	23	2067	8.3	2064	2	2075	2088	13	2082	6.5	2075	Mexico
20062	Bermuda	7	2034	2038	4	2036	1.9	2035	7	2032	2039	7	2035	3.2	2035	Bermuda
20063	Bahamian	247	2018	2063	45	2038	10.5	2036	242	2021	2087	66	2045	16.0	2043	British Virgin Islands, Cuba, Dominican Republic, Haiti, Puerto Rico, The Bahamas, Turks & Caicos Is., United States, United States Virgin Islands

		SSP5-8.5							SSP2-4.5							
ECO #	ECOREGION	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	COUNTRIES (EEZ)
20064	Eastern Caribbean	70	2015	2025	10	2017	2.6	2017	70	2015	2028	13	2019	3.2	2018	Anguilla, Antigua & Barbuda, Barbados, Bonaire Sint-Eustasius and Saba, British Virgin Islands, Dominica, Grenada, Guadeloupe, Martinique, Montserrat, Netherlands Antilles, Puerto Rico, Saint Martin, Saint Vincent and the Grenadines, Sint Maarten, St. Kitts & Nevis, St. Lucia, Trinidad & Tobago, United States Virgin Islands, Venezuela

		SSP5-8.5							SSP2-4.5							
ECO #	ECOREGION	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	COUNTRIES (EEZ)
20065	Greater Antilles	209	2015	2053	38	2029	9.5	2026	209	2015	2071	56	2033	12.5	2031	Aruba, Cayman Is., Colombia, Cuba, Curacao, Dominican Republic, Haiti, Honduras, Jamaica, Mexico, Puerto Rico, The Bahamas, Turks & Caicos Is., United States, United States Virgin Islands, Venezuela
20066	Southern Caribbean	42	2015	2048	33	2024	9.4	2022	42	2015	2065	50	2026	12.2	2024	Aruba, Bonaire Sint-Eustasius and Saba, Colombia, Curacao, Dominican Republic, Grenada, Haiti, Jamaica, Puerto Rico, Trinidad & Tobago, Venezuela

		SSP5-8.5							SSP2-4.5							
ECO #	ECOREGION	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	COUNTRIES (EEZ)
20067	Southwestern Caribbean	93	2015	2041	26	2018	5.6	2015	93	2015	2045	30	2019	6.6	2015	Cayman Is., Colombia, Costa Rica, Honduras, Jamaica, Nicaragua, Panama
20068	Western Caribbean	65	2017	2061	44	2030	8.3	2028	64	2018	2081	63	2032	10.1	2031	Belize, Cayman Is., Cuba, Honduras, Mexico
20069	Southern Gulf of Mexico	62	2015	2054	39	2030	12.9	2030	62	2015	2076	61	2034	17.7	2033	Cuba, Mexico, United States
20070	Floridian	24	2019	2061	42	2041	10.0	2042	23	2021	2075	54	2046	13.6	2046	The Bahamas, United States
20071	Guianan	1	2028	2028	0	2028		2028	1	2031	2031	0	2031		2031	Brazil, Trinidad & Tobago, Venezuela
20072	Amazonia	5	2015	2017	2	2016	1.0	2017	5	2015	2018	3	2017	1.5	2018	Brazil
20074	Fernando de Naronha and Atoll das Rocas	2	2015	2015	0	2015	0.0	2015	2	2015	2015	0	2015	0.0	2015	Brazil

		SSP5-8.5							SSP2-4.5							
ECO #	ECOREGION	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	COUNTRIES (EEZ)
20075	Northeastern Brazil	18	2020	2040	20	2029	6.5	2024	18	2024	2045	21	2031	6.3	2032	Brazil
20076	Eastern Brazil	24	2019	2052	33	2032	7.2	2034	24	2024	2068	44	2037	8.7	2033	Brazil
20077	Trindade and Martin Vaz Islands	3	2048	2056	8	2051	3.6	2049	3	2065	2071	6	2068	2.4	2068	Brazil
20087	Northern and Central Red Sea	116	2015	2054	39	2024	7.8	2023	116	2015	2068	53	2022	9.0	2018	Egypt, Israel, Jordan, Saudi Arabia, Sudan
20088	Southern Red Sea	108	2015	2065	50	2026	14.0	2021	101	2015	2083	68	2025	14.3	2021	Eritrea, Saudi Arabia, Sudan, Yemen
20089	Gulf of Aden	18	2040	2070	30	2049	8.2	2047	15	2045	2081	36	2054	11.0	2051	Djibouti, Eritrea, Somalia, Yemen
20090	Arabian (Persian) Gulf	98	2033	2081	48	2054	11.0	2053	70	2045	2090	45	2063	11.5	2062	Bahrain, Iran, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates

		SSP5-8.5							SSP2-4.5							
ECO #	ECOREGION	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	COUNTRIES (EEZ)
20091	Gulf of Oman	7	2037	2057	20	2047	6.5	2046	7	2043	2079	36	2058	12.3	2056	Iran, Oman, United Arab Emirates
20092	Western Arabian Sea	26	2043	2068	25	2054	5.9	2055	25	2051	2090	39	2073	11.1	2071	Oman, Yemen
20093	Central Somali Coast	2	2056	2058	2	2057	1.0	2056	2	2081	2081	0	2081	0.0	2081	Somalia, Yemen
20094	Northern Monsoon Current Coast	16	2035	2058	23	2051	5.7	2052	16	2038	2084	46	2069	11.1	2068	Disputed Kenya/Somalia, Kenya, Somalia
20095	East African Coral Coast	79	2024	2056	32	2038	5.5	2036	79	2028	2079	51	2043	8.6	2043	Comoros, French Southern & Antarctic Lands, Kenya, Mozambique, Seychelles, Tanzania

		SSP5-8.5							SSP2-4.5							
ECO #	ECOREGION	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	COUNTRIES (EEZ)
20096	Seychelles	57	2035	2053	18	2043	5.7	2042	57	2038	2076	38	2052	11.0	2051	Comoros, French Southern & Antarctic Lands, Madagascar, Mauritius, Seychelles
20097	Cargados Carajos/Tromelin Island	9	2018	2039	21	2034	5.8	2036	9	2022	2043	21	2036	6.0	2038	French Southern & Antarctic Lands, Mauritius, Seychelles
20098	Mascarene Islands	13	2018	2030	12	2025	3.9	2024	13	2021	2034	13	2029	5.0	2033	French Southern & Antarctic Lands, Madagascar, Mauritius, Reunion
20099	Southeast Madagascar	5	2021	2039	18	2030	7.5	2032	5	2022	2043	21	2032	8.5	2034	Madagascar, Reunion

		SSP5-8.5							SSP2-4.5							
ECO #	ECOREGION	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	COUNTRIES (EEZ)
20100	Western and Northern Madagascar	134	2015	2058	43	2039	9.2	2038	134	2015	2088	73	2045	13.9	2044	Comoros, French Southern & Antarctic Lands, Madagascar, Mayotte, Mozambique, Seychelles
20101	Bight of Sofala/Swamp Coast	11	2038	2052	14	2043	4.5	2044	11	2043	2068	25	2053	7.5	2056	French Southern & Antarctic Lands, Mozambique
20102	Delagoa	12	2038	2068	30	2047	8.2	2043	11	2044	2076	32	2056	9.0	2056	French Southern & Antarctic Lands, Mozambique, South Africa
20103	Western India	27	2021	2061	40	2045	8.4	2043	27	2022	2090	68	2055	15.1	2052	India
20104	South India and Sri Lanka	33	2038	2073	35	2054	9.5	2056	25	2043	2088	45	2064	16.2	2057	India, Maldives, Sri Lanka

		SSP5-8.5							SSP2-4.5							
ECO #	ECOREGION	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	COUNTRIES (EEZ)
20105	Maldives	116	2034	2052	18	2042	3.4	2042	116	2033	2068	35	2048	5.5	2046	Mauritius(Chagos), India, Maldives
20106	Chagos	51	2030	2042	12	2036	2.8	2035	51	2028	2045	17	2037	4.6	2038	Mauritius(Chagos), Maldives
20107	Eastern India	3	2027	2036	9	2033	4.0	2035	3	2033	2043	10	2038	4.1	2038	India, Sri Lanka
20108	Northern Bay of Bengal	29	2031	2063	32	2041	6.1	2042	28	2029	2059	30	2044	7.9	2043	Bangladesh, India, Myanmar
20109	Andaman and Nicobar Islands	55	2015	2045	30	2032	8.1	2034	55	2015	2052	37	2033	9.8	2032	India, Indonesia, Myanmar, Thailand
20110	Andaman Sea Coral Coast	69	2015	2066	51	2038	9.1	2038	68	2018	2080	62	2042	13.3	2043	Malaysia, Myanmar, Thailand
20111	Western Sumatra	127	2018	2060	42	2040	6.2	2039	127	2020	2088	68	2042	9.5	2043	Indonesia, Thailand

		SSP5-8.5							SSP2-4.5							
ECO #	ECOREGION	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	COUNTRIES (EEZ)
20112	Gulf of Tonkin	22	2015	2085	70	2049	18.9	2054	16	2015	2084	69	2051	24.1	2058	China, Paracel Islands, Vietnam
20113	Southern China	12	2015	2071	56	2036	23.4	2021	8	2015	2047	32	2020	10.3	2015	China
20114	South China Sea Oceanic Islands	148	2018	2054	36	2035	7.1	2036	148	2018	2068	50	2038	10.2	2038	Brunei, China, Malaysia, Paracel Islands, Philippines, Spratly Islands, Vietnam
20115	Gulf of Thailand	46	2025	2066	41	2047	7.2	2047	44	2024	2081	57	2060	12.6	2058	Cambodia, Malaysia, Thailand, Vietnam
20116	Southern Vietnam	13	2048	2059	11	2051	3.6	2049	13	2056	2087	31	2062	9.3	2058	Vietnam
20117	Sunda Shelf/Java Sea	192	2031	2066	35	2046	5.7	2044	190	2029	2083	54	2053	10.5	2054	Indonesia, Malaysia, Thailand, Vietnam
20118	Malacca Strait	20	2037	2069	32	2048	6.7	2047	19	2042	2076	34	2056	9.2	2055	Indonesia, Malaysia, Singapore, Thailand

		SSP5-8.5							SSP2-4.5							
ECO #	ECOREGION	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	COUNTRIES (EEZ)
20119	Southern Java	51	2024	2059	35	2041	7.7	2040	51	2022	2077	55	2042	12.0	2038	Christmas I., Indonesia
20120	Cocos-Keeling/Christmas Island	4	2015	2044	29	2029	12.5	2019	4	2015	2051	36	2032	15.2	2019	Christmas I., Cocos Is., Indonesia
20121	South Kuroshio	78	2015	2044	29	2023	6.2	2024	78	2015	2048	33	2025	7.9	2024	China, Japan, Philippines
20122	Ogasawara Islands	1	2015	2015	0	2015		2015	1	2015	2015	0	2015		2015	Japan
20123	Mariana Islands	18	2015	2015	0	2015	0.0	2015	18	2015	2015	0	2015	0.0	2015	Japan, Micronesia, Northern Marinana Islands-Guam
20124	East Caroline Islands	133	2015	2034	19	2021	3.7	2020	133	2015	2031	16	2020	4.5	2017	Marshall Is., Micronesia
20125	West Caroline Islands	33	2015	2045	30	2027	7.1	2026	33	2015	2052	37	2028	8.4	2029	Indonesia, Micronesia, Palau

		SSP5-8.5							SSP2-4.5							
ECO #	ECOREGION	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	COUNTRIES (EEZ)
20126	Palawan/North Borneo	285	2015	2063	48	2035	8.9	2035	284	2015	2084	69	2039	13.8	2038	Brunei, Indonesia, Malaysia, Philippines, Spratly Islands
20127	Eastern Philippines	270	2015	2061	46	2030	9.0	2030	270	2015	2086	71	2031	11.6	2029	Indonesia, Palau, Philippines
20128	Sulawesi Sea/Makassar Strait	208	2018	2054	36	2037	6.8	2037	208	2020	2076	56	2041	9.7	2040	Indonesia, Malaysia, Philippines
20129	Halmahera	76	2025	2051	26	2037	5.4	2037	76	2028	2066	38	2041	7.5	2040	Indonesia, Palau
20130	Papua	140	2019	2066	47	2041	9.4	2040	136	2021	2089	68	2048	14.1	2045	Indonesia, Palau, Papua New Guinea
20131	Banda Sea	275	2030	2075	45	2046	7.5	2044	264	2032	2089	57	2054	12.0	2051	Area of overlap Australia/Indonesia, Indonesia, Timor-Leste

		SSP5-8.5							SSP2-4.5							
ECO #	ECOREGION	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	COUNTRIES (EEZ)
20132	Lesser Sunda	139	2015	2066	51	2042	9.3	2043	133	2015	2088	73	2047	13.6	2045	Area of overlap Australia/Indonesia, Australia, Indonesia, Timor-Leste
20133	Northeast Sulawesi	36	2035	2055	20	2045	4.5	2044	36	2036	2076	40	2053	8.1	2056	Indonesia
20134	Bismarck Sea	128	2015	2041	26	2027	6.4	2027	128	2015	2043	28	2028	6.9	2030	Papua New Guinea
20135	Solomon Archipelago	187	2015	2056	41	2029	9.4	2031	187	2015	2077	62	2030	11.1	2030	Micronesia, Papua New Guinea, Solomon Is.
20136	Solomon Sea	150	2015	2051	36	2019	6.1	2015	150	2015	2064	49	2020	7.7	2015	Australia, Papua New Guinea, Solomon Is.
20137	Southeast Papua New Guinea	25	2015	2043	28	2026	7.2	2028	25	2015	2049	34	2026	8.9	2026	Australia, Papua New Guinea

		SSP5-8.5							SSP2-4.5							
ECO #	ECOREGION	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	COUNTRIES (EEZ)
20138	Gulf of Papua	20	2015	2052	37	2026	12.2	2022	20	2015	2066	51	2029	16.2	2020	Australia, Papua New Guinea, Protected zone Australia/Papua New Guinea
20139	Arafura Sea	25	2030	2055	25	2045	5.9	2046	25	2032	2073	41	2055	11.1	2056	Australia, Indonesia, Papua New Guinea, Protected zone Australia/Papua New Guinea
20140	Arnhem Coast to Gulf of Carpenteria	62	2015	2088	73	2058	12.9	2059	37	2015	2087	72	2065	16.7	2066	Area of overlap Australia/Indonesia, Australia, Indonesia, Papua New Guinea
20141	Bonaparte Coast	57	2040	2068	28	2053	6.6	2052	52	2043	2088	45	2066	13.3	2063	Area of overlap Australia/Indonesia, Australia, Indonesia, Timor-Leste

		SSP5-8.5							SSP2-4.5							
ECO #	ECOREGION	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	COUNTRIES (EEZ)
20142	Torres Strait Northern Great Barrier Reef	134	2015	2066	51	2034	12.9	2035	131	2015	2084	69	2038	17.6	2036	Australia, Papua New Guinea, Protected zone Australia/Papua New Guinea
20143	Central and Southern Great Barrier Reef	220	2015	2079	64	2037	15.0	2029	195	2018	2084	66	2040	15.9	2035	Australia
20144	Exmouth to Broome	53	2028	2084	56	2052	16.7	2048	38	2029	2090	61	2053	19.9	2046	Area of overlap Australia/Indonesia, Australia, Indonesia
20145	Ningaloo	6	2045	2052	7	2050	2.5	2049	6	2060	2077	17	2065	5.7	2062	Australia
20146	Tonga Islands	41	2015	2022	7	2016	1.9	2016	41	2015	2030	15	2020	4.9	2021	American Samoa, Fiji, Niue, Tonga
20148	Vanuatu	97	2015	2046	31	2018	5.0	2015	97	2015	2059	44	2020	7.1	2015	Fiji, New Caledonia, Solomon Is., Vanuatu

		SSP5-8.5							SSP2-4.5							
ECO #	ECOREGION	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	COUNTRIES (EEZ)
20149	New Caledonia	153	2015	2039	24	2020	5.8	2017	153	2015	2045	30	2023	7.9	2026	Australia, New Caledonia, Solomon Is., Vanuatu
20150	Coral Sea	86	2015	2040	25	2021	4.8	2021	86	2015	2045	30	2023	5.8	2022	Australia, New Caledonia
20151	Lord Howe and Norfolk Islands	4	2029	2034	5	2032	1.9	2033	4	2031	2039	8	2037	3.5	2039	Australia
20153	Marshall Islands	98	2015	2038	23	2022	6.4	2020	98	2015	2037	22	2022	6.0	2021	Marshall Is., United States Minor Outlying Islands
20155	Line Islands	16	2034	2047	13	2039	4.4	2040	16	2031	2053	22	2041	5.3	2042	Cook Is., Kiribati, United States Minor Outlying Islands

		SSP5-8.5							SSP2-4.5							
ECO #	ECOREGION	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	COUNTRIES (EEZ)
20156	Phoenix/Tokelau/Northern Cook Islands	33	2018	2047	29	2035	6.0	2035	33	2021	2046	25	2036	7.1	2037	American Samoa, Cook Is., Kiribati, Samoa, Tokelau, United States Minor Outlying Islands, Wallis & Futuna
20157	Samoa Islands	55	2015	2021	6	2016	1.1	2015	55	2015	2021	6	2016	1.9	2015	American Samoa, Fiji, Niue, Samoa, Tonga, Tuvalu, Wallis & Futuna
20158	Tuamotus	174	2032	2061	29	2041	4.2	2042	173	2033	2077	44	2048	5.7	2046	Cook Is., French Polynesia, Kiribati, Pitcairn Is.
20159	Rapa-Pitcairn	10	2023	2045	22	2035	6.3	2033	10	2030	2050	20	2040	7.6	2039	French Polynesia, Pitcairn Is.
20160	Southern Cook/Austral Islands	26	2015	2032	17	2020	5.1	2017	26	2015	2039	24	2024	5.3	2023	American Samoa, Cook Is., French Polynesia
20161	Society Islands	30	2023	2065	42	2037	6.9	2035	29	2022	2046	24	2038	7.2	2043	French Polynesia

		SSP5-8.5							SSP2-4.5							
ECO #	ECOREGION	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	COUNTRIES (EEZ)
20164	Revillagigedos	8	2015	2033	18	2022	5.6	2021	8	2015	2032	17	2022	5.0	2021	Mexico
20165	Clipperton	1	2019	2019	0	2019		2019	1	2021	2021	0	2021		2021	Clipperton Island
20166	Mexican Tropical Pacific	11	2019	2053	34	2035	11.4	2035	11	2023	2075	52	2043	17.3	2037	Mexico
20167	Chiapas-Nicaragua	6	2024	2041	17	2031	5.7	2030	6	2028	2046	18	2035	5.7	2032	Costa Rica, Honduras, Mexico, Nicaragua
20168	Nicoya	12	2034	2047	13	2039	4.4	2036	12	2033	2055	22	2044	5.8	2042	Colombia, Costa Rica, Nicaragua, Panama
20169	Cocos Islands	1	2047	2047	0	2047		2047	1	2055	2055	0	2055		2055	Colombia, Costa Rica, Ecuador, Panama
20170	Panama Bight	10	2023	2047	24	2034	8.1	2030	10	2021	2055	34	2035	11.4	2031	Colombia, Costa Rica, Ecuador, Panama

		SSP5-8.5							SSP2-4.5							
ECO #	ECOREGION	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	COUNTRIES (EEZ)
20172	Northern Galapagos Islands	3	2047	2047	0	2047	0.0	2047	3	2045	2051	6	2047	2.8	2045	Costa Rica, Ecuador
20173	Eastern Galapagos Islands	15	2030	2063	33	2042	7.9	2040	14	2031	2067	36	2046	9.4	2045	Costa Rica, Ecuador
20174	Western Galapagos Islands	1	2040	2040	0	2040		2040	1	2042	2042	0	2042		2042	Ecuador
20202	Tweed-Moreton	6	2034	2070	36	2049	12.0	2049	5	2043	2073	30	2058	11.8	2064	Australia
20203	Manning-Hawkesbury	1	2035	2035	0	2035		2035	1	2043	2043	0	2043		2043	Australia
20209	Leeuwin	2	2023	2025	2	2024	1.0	2023	2	2027	2035	8	2031	4.0	2027	Australia
20210	Shark Bay	14	2015	2085	70	2038	22.2	2026	11	2015	2090	75	2037	19.7	2035	Australia
20211	Houtman	11	2020	2046	26	2033	8.5	2033	11	2024	2060	36	2043	11.7	2042	Australia

		SSP5-8.5							SSP2-4.5							
ECO #	ECOREGION	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	#	MIN	MAX	RANGE	MEAN	STD	MEDIAN	COUNTRIES (EEZ)
25059	Southern California Bight	21	2015	2051	36	2017	7.7	2015	21	2015	2060	45	2018	9.6	2015	Mexico, United States
25147	Fiji Islands	144	2015	2028	13	2017	2.5	2016	144	2015	2034	19	2018	4.8	2015	Fiji, Tonga, Wallis & Futuna
25152	Hawaii	67	2018	2038	20	2024	5.1	2022	67	2017	2044	27	2025	7.7	2024	United States, United States Minor Outlying Islands
25154	Gilbert/Ellis Islands	102	2015	2052	37	2031	10.8	2035	102	2015	2057	42	2033	11.3	2037	Fiji, Marshall Is., Nauru, Tuvalu, United States Minor Outlying Islands, Wallis & Futuna

Glossary

ASB – Annual Severe Bleaching. This report presents the projected year by which sea temperature stress on coral reefs is expected to be severe enough to cause bleaching annually. At this point, reefs are certain to change and recovery will be very limited.

CMIP5 – Coupled Model Intercomparison Project, phase 5; a framework project for global coupled ocean-atmosphere general circulation models.

CMIP6 – Coupled Model Intercomparison Project, phase 6; a framework project for global coupled ocean-atmosphere general circulation models.

DHW – Degree Heating Week; one DHW is equal to 1°C above the maximum monthly mean (i.e. the coral bleaching threshold) for one week.

GCM – General Circulation Model or Global Climate Model; numerical models representing physical processes in the atmosphere, ocean, cryosphere and land surface to simulate the response of the global climate system to increasing greenhouse gas concentrations.

GIS – Geographic Information System; a system designed to present and analyze geographical data, used; e.g., in marine spatial planning and marine protected area design.

INDC – Intended Nationally Determined Contributions; planned greenhouse gas emissions reductions that all parties to UNFCCC were asked to publish in the lead up to the 21st Conference of Parties in Paris in late 2015.

MMM – Maximum Monthly Mean; the warmest monthly mean sea surface temperature experienced by corals, based on satellite measurements.

MPA – Marine Protected Area: areas of seas and oceans protected to conserve biodiversity, natural or cultural resources; they typically limit (but not necessarily prohibit) human activity and are often managed for multiple use.

MSP – Marine Spatial Planning; a process for allocating human activities and use in marine areas to achieve ecological, economic, and social objectives.

NDC – Nationally Determined Contributions; The Paris Agreement requires that countries prepare NDCs in pursuit of its goal. New NDCs are expected in 2020 and then every five years thereafter with global stock-take to review progress planned for 2023.

PA - Paris Agreement; the legally binding agreement adopted by the 21st Conference of Parties to UNFCCC in Paris in 2015, with the goal of keeping global warming well below 2°C, while pursuing efforts to stay below 1.5°C. The Agreement enters info force when at least 55 Parties accounting for at least 55 % of the total global greenhouse gas emissions have ratified it.

RCP – Representative Concentration Pathway: four greenhouse gas concentration trajectories adopted by the Intergovernmental Panel on Climate Change (IPCC) for its Fifth Assessment Report in 2014. These supersede the Special Report on Emissions Scenarios (SRES) published in 2000. Among these RCP8.5 represents a business-as-usual scenario in that it assumes emissions will continue to grow largely unabated. RCP4.5 represents a successful mitigation pathway and assumes emissions peak around 2040 and then decline.

RSCAP – Regional Seas Conventions and Action Plans; the world's only legal framework for protecting the oceans and seas at the regional level. Individual Conventions and Action Plans reflect a similar approach but are tailored to suit their particular environmental challenges.

SDG – Sustainable Development Goals, adopted by the United Nations General Assembly in September, 2015. There are 17 SDGs and they build on the principle of ‘leaving no one behind’ and emphasize a holistic approach to achieving sustainable development for all.

SST - Sea Surface Temperature; the temperature of water at or very close to the ocean surface.

UNFCCC – United Nations Framework Convention on Climate Change: an international environmental treaty negotiated at the Earth Summit in Rio de Janeiro in 1992 with the objective “to stabilize greenhouse gas concentrations in the atmosphere at a level that will prevent dangerous human interference with the climate system.” The convention entered into force in 1994. As of September 2016, 197 countries have ratified the Convention.