ASSESSING THE EXTENT OF GLOBAL MASS CORAL BLEACHING WITH AN UPDATED DATABASE

by

Alejandra Virgen Urcelay

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The following individuals certify that they have read, and recommend to the Faculty of Graduate and Postdoctoral Studies for acceptance, the thesis entitled:

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Examining Committee:

Dr. Simon D. Donner, Department of Geography, UBC
Supervisor

Dr. Brian Klinkenberg, Department of Geography, UBC
Supervisory Committee Member

Dr. Scott F. Heron, Department of Physics, James Cook University
Additional Examiner

Abstract

The recurrence of mass coral bleaching events and associated coral mortality driven by climate change in the past few decades has raised numerous questions about the future of coral reef ecosystems. Although these phenomena have been widely studied, our understanding of the geographical extent of these events has been limited. In this study, I present an updated version of the global mass coral bleaching database. The updated database provides the most comprehensive collection of global bleaching reports from 1963 to 2017, which were used to spatially model the probability of bleaching occurrence for 1985 through 2017 across the world's warm-water coral reefs at a 0.05° x 0.05° resolution using indicator kriging. With this new spatially-explicit data, I provide a more accurate and up-to-date global and regional assessment of the extent of bleaching through the 1985-2017 period with a focus on the three global mass coral bleaching events that occurred in 1997-1998, 2009-2010, and 2014-2016. Results indicate that between 56% and 71% of the world's coral reefs have experienced bleaching at least once during the assessed time period, with the greatest extents observed in the Southeast Asia, Australia, and Caribbean regions. High bleaching probabilities were more common towards the last decade of the period, and the most recent global bleaching event was assessed as up to 2.6 times more extensive than each of the first two. Results also show a positive relationship between the annual maximum Degree Heating Week, a measure of thermal stress, and high bleaching probability values. The updated database will help make global-scale analyses more robust, enhance real-time predictions, calibrate models for future projections, test for evidence of adaptive responses from corals and gain insights into the spatial-temporal trends of coral bleaching over time.

Lay Summary

Although a lot of research has focused on studying coral bleaching, a phenomenon that is mainly driven by climate change, our understanding of what coral bleaching looked like in the past few decades around the world is still incomplete. My research focused on developing an updated version of the comprehensive global mass coral bleaching database that was first released in 2017. In addition to the observational data from reef surveys included in the database, I used a refined methodology to developed global maps that show the probability that bleaching occurred at a given region in the world in a given year. Results showed that the updated database is useful to better assess the extent of historical bleaching events and can support future research to enhance existing methods for predicting mass coral bleaching, calibrate new ones, and examine changes in coral bleaching over time.

Preface

This thesis is the original, unpublished work of Alejandra Virgen Urcelay. The research objective for this thesis was proposed by my supervisor, Dr. Simon D. Donner, with whom I worked with to design and develop the project. This thesis was developed with data collected from 2012 through 2018 by Dr. Simon D. Donner and Alex Tso and Sri Budha Utami who worked as research assistants for the Climate and Coastal Ecosystems research laboratory. The spatial interpolation method used in the first iteration of this study was developed by Dr. Gregory Rickbeil. I designed all modifications applied to the method and produced all the global maps of probability of bleaching occurrence. I completed the statistical analyses drawing on the published work of Dr. Simon D. Donner, Dr. Gregory J. M. Rickbeil, and Dr. Scott F. Heron (2017). I also completed the writing presented in this thesis and Dr. Simon D. Donner contributed to the edits.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AU	Australia
CA	Caribbean
CI	Central Indian
CRW	Coral Reef Watch
DHW	Degree Heating Week
EP	East Pacific
ME	Middle East
MEL	Melanesia
MIC	Micronesia
MMM	Maximum Monthly Mean
NOAA	National Oceanic and Atmospheric Administration
POL	Polynesia
SEA	Southeast Asia
SD	Standard Deviation
SST	Sea Surface Temperature
WI	West Indian

Acknowledgements

I was fortunate to have many people supporting me throughout my master's program.

First, I would like to express my endless gratitude to my supervisor, Professor Simon Donner, for giving me the opportunity to be part of his research group, encouraging me to pursue my research interests, and for his invaluable support, guidance, patience, inspiration, and expertise that were fundamental for making this work possible. Simon was always willing to support me with regard to this project but also in the building of intrinsic interpersonal and professional skills that have opened many doors for me and will help me excel in my professional life. For that, I will forever be thankful. I also want to thank my committee member, Dr. Brian Klinkenberg, for his guidance and helpful feedback that contributed to this project's success.

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I am thankful to my friends at UBC and those who are physically far away for giving me all the moral support a graduate student could ask for; thank you for the long talks, the dancing, and the tears, particularly to Axel Canseco, Darinka Montes, Myriam Mora, Joseph O'Rourke, Annie Mejaes, Erika Luna, and Claire Ewing. I am also extremely grateful for my partner, Arzan Irani, for helping me understand the stats and for all the laughter that got me through the rainy days.

Finally, I want to thank my family, especially my mother, Ileana Virgen and my grandmother, Hilda Urcelay, for their love, priceless life lessons and support, and my cousin Giselle Aranda for her support throughout my academic journey. You three are the strongest women that I will ever know. Thank you for always encouraging me to pursue my dreams and for teaching me to believe in myself.

Chapter 1: Introduction

Coral reefs are one of the most biologically diverse and socioeconomically important ecosystems on Earth, offering a wide range of ecosystem services, including coastal protection, tourism attraction, and provision of seafood, building materials, and medicinal compounds (Hoegh-Guldberg et al., 2007; Moberg & Folke, 1999). Because millions of people depend on coral reefs (Moberg & Folke, 1999), there is a growing concern regarding their survival in our changing world.

Coral reefs have persisted through geological time and are pivotal in the marine world; however, they are one of the most vulnerable ecosystems (Hoegh-Guldberg, 1999). A diverse range of human-related threats have endangered coral reefs in the past decades, including overfishing, tourism activities, and water quality degradation (Hoegh-Guldberg, 1999; Hughes et al., 2003), but the most pressing threat today is climate change (Donner et al., 2005; Hoegh-Guldberg et al., 2007; Hughes et al., 2003, 2018). Climate change impacts, along with other anthropogenic disturbances, threaten the survival of coral reefs in the future.

1.1 Coral Bleaching

Ocean temperatures of 1 ℃ greater than the usual summer maximum can cause a phenomenon known as mass coral bleaching (Glynn & D'Croz, 1990). Coral bleaching refers to the paling of reef building taxa, resulting from the breakdown of the symbiosis with zooxanthellae residing within the tissues of host animals (Glynn, 1993). Several stressors such as temperature, salinity, light, sedimentation, aerial exposure, and pollutants can cause small scale bleaching events (Glynn, 1993), but when it comes to mass coral bleaching events, heat stress is the most common driver

(Donner et al., 2017; Hughes et al., 2018). When the heat stress causing coral bleaching is not very severe, corals can recover from bleaching after a few weeks; however, an intense disturbance can cause the death of corals and other reef taxa along with massive bleaching (Glynn, 1993).

Global episodes of mass coral bleaching since the early 1980s have caused widespread coral mortality, inciting concerns amongst the scientific community (Hoegh-Guldberg et al., 2007; Hughes et al., 2018). The projected increase in sea surface temperature (SST) over the next few decades is expected to increase the frequency of the conditions that can cause mass coral bleaching and coral mortality (Donner et al., 2005; IPCC, 2018; Logan et al., 2014; van Hooidonk et al., 2015, 2016). In addition, other impacts of global climate change, such as more frequent or severe storms, will also have devastating impacts on coral reefs (Madin et al., 2012).

The declines in coral cover caused by extensive coral mortality have caused shifts in the distribution of other reef-dwelling organisms (Baker et al., 2008), threatening marine biodiversity. Beyond the threats to the natural balance of these ecosystems, some commercially important species are facing extinction and other species that could be important for bioprospection can disappear even before being identified (Cesar et al., 2003). Additionally, global coral cover declines can significantly impact the millions of people who depend on coral reefs with the increased coastal hazard risks associated with storms and floods due to the loss of coastal protection (Ferrario et al., 2014), potential rises in poverty, particularly in developing countries associated with declines in reef fish stocks, and threats to food security (Cesar et al., 2003).

The extinction risk of many corals has dramatically increased after the first global massive bleaching event (Carpenter et al., 2008). Estimates from 2008 revealed that the world had lost about 19% of the original reef area then (Wilkinson, 2008), and projections indicate that, without thermal adaptation, approximately 89% of coral reefs could experience dangerously frequent bleaching by 2050, even in a 1.5°C warming scenario (Frieler et al., 2013; IPCC, 2018). Although a lot of research has focused on monitoring and studying coral bleaching events, there are data limitations related to the characteristics of an event, including its duration, extent, and severity.

1.2 Research summary and objectives

With the expected increase in the frequency and intensity of coral bleaching events, it is essential to address existing data gaps related to historical mass coral bleaching events to advance our understanding of how coral bleaching has changed through the years and what this phenomenon will look like in the future. Though global databases of bleaching observations have been compiled, they are limited because of their partial maintenance and unequal sampling effort across reef locations (Donner et al., 2017; Hughes et al., 2018). The sampling effort is often more significant in reefs located in developed countries and areas of high research interest (Donner et al., 2017). These limitations were addressed by Donner et al. (2017) by developing the first gridded, global-scale historical coral bleaching database that offers annual global maps of the probability of bleaching occurrence. The database includes bleaching observational data for 1963 through 2010 and probability of bleaching occurrence data for 1985 through 2010, providing insights into the extent of bleaching over some of the worst events (e.g., 1997-1998, 2009-2010). Given that the third and worst global bleaching episode driven by El Niño related heat stress occurred during 2014-2016, the global database needed to be updated to provide up-to-date information.

A comprehensive global mass coral bleaching database can contribute to making global-scale analyses more robust, enhancing real-time predictions, calibrating models for future projections, testing for evidence of possible acclimation or adaptation (Donner, 2011; Donner et al., 2017; Logan et al., 2014), and gaining insights into the spatial-temporal trends of bleaching over time (Hughes et al., 2018).

The goal of this thesis was to strengthen the scientific knowledge on historical mass coral bleaching events through three main objectives:

- To provide an updated version of the existing high-resolution global mass coral bleaching database
- To analyze the regional extent of historical mass coral bleaching using reef regions defined by Kleypas et al. (2008), with a focus on the three global mass coral bleaching events
- To assess the relationship between SSTs and the modelled bleaching probabilities that result from this study

The development of the updated version (version 2) of the coral bleaching database aimed to improve the methodology used in version 1 by (1) adding more data, (2) implementing a more rigorous data quality control, and (3) refining the interpolation method involved. Version 2 comprises bleaching reports from 1963 through 2017, thus including data for the three global bleaching events (1997-1998, 2009-2010, and 2014-2016).

Because the updated database includes a significant increase in observational data and uses a more recent heat stress dataset, it can provide a clearer picture of the history of coral bleaching and improve the accuracy of future models.

Chapter 2: An updated global mass coral bleaching database

2.1 Introduction

The effect of coral bleaching in extensive reef areas across the Pacific was first described by Glynn (1984). Since then, coral bleaching has been observed in the Caribbean, Indian, and Pacific Oceans regularly (Donner et al., 2017; Hughes et al., 2018). Three global bleaching events (periods in which bleaching was observed in many ocean regions) have occurred within the last three decades, driven by periods of anomalous heat stress (Eakin et al., 2017; Skirving et al., 2019). In addition, bleaching has been observed in conjunction with abnormal heat stress in intervening years in one or more ocean regions (Donner et al., 2017). Although a lot of research has focused on monitoring and studying coral bleaching, there are data limitations related to the characteristics of an event, including its duration, extent, and severity.

Some bleaching events can go unnoticed in reefs due to their remote location (Glynn, 1993). Additionally, there is an uneven global distribution of bleaching reports due to geographical biases in the surveying effort (Donner et al., 2017). Despite the existence of global bleaching databases, they are limited due to their intermittent maintenance and the uneven effort across locations and years (Hughes et al., 2018). For instance, the reports compiled in the widely known historical coral bleaching database ReefBase (reefbase.org) are mostly clustered in more developed countries and areas of high research interest, like the Caribbean and the Galapagos (Donner, 2011).

In addition to data gaps in coral bleaching events, the available data may be difficult to compare or partly unreliable. Methods used for reef monitoring can vary across different organizations and researchers (Vallès et al., 2019). For example, methods can have different bleaching metrics, and they can use different protocols (e.g., photo-quadrats vs. transects, different depths, among others). Bleaching observations depend on what the assessors perceive to be bleached (Suggett & Smith, 2011) and, therefore can be misidentified. For instance, they can be mistaken by a disease or an impact from a different disturbance, such as a predator (Glynn, 1993) or can be misclassified as lethally severe when they are not (Suggett & Smith, 2011).

Because it is nearly impossible to monitor all reefs in the world continually, predicting bleaching occurrence is necessary to inform reef management. The simplest theoretical model used in real-time prediction assumes that mass coral bleaching can occur when the temperature in a reef area exceeds a certain threshold (Hoegh-Guldberg, 1999). The U.S. National Oceanic and Atmospheric Administration (NOAA) produced a real-time SST-based product suite to monitor global oceanic thermal conditions, highlighting areas of the likelihood of mass bleaching, as well as to assess the intensity and extent of thermal stress (Liu et al., 2014). The Degree Heating Week (DHW) metric has become the standard global predictor of bleaching (Gleeson & Strong, 1995). DHW describes the accumulation of heat stress in an area over the past 12 weeks, combining both the intensity and duration of heat stress into a single number (Liu et al., 2003). The "bleaching threshold" associated with this metric is 1°C above the mean SST of the warmest month in a climatology, referred to as the maximum monthly mean (MMM, Liu et al., 2014). Therefore, Coral Reef Watch (CRW) accumulates only temperature anomalies above the MMM that are equal to or higher than 1°C to calculate DHW. For DHW values at or above 4°C-weeks threshold, significant coral bleaching is expected; at an 8°C-weeks threshold, severe bleaching and significant mortality are expected (Liu et al., 2014).

Real-time prediction is critical to help scientists and agencies prepare for monitoring and to inform decision-makers. However, the simple theoretical model that uses an invariant threshold (e.g., 1°C above maximum summer conditions) to define bleaching conditions might not be accurate for all periods and all regions in the world because it assumes that all corals will respond identically to heat stress and that corals are incapable of adapting to temperature changes (Hughes et al., 2003). Therefore, in reality, there might be different thresholds at which bleaching conditions start for different taxa, and changes in those thresholds might occur because of adaptive responses (Hughes et al., 2003; Logan et al., 2014).

Enhancing both real-time prediction and models for future projections was one of the main motivations to create the global mass coral bleaching database (Donner et al., 2017). The database provides comprehensive data about historical coral bleaching events that can be used to enhance existing methods and calibrate new ones, and test for evidence of adaptive responses.

2.2 Methods

2.2.1 Background

The development of the updated global mass coral bleaching database is based on the data and methods used in version 1 of the database (Donner et al., 2017). For the creation of version 1 of the database, Donner et al. (2017) used the coral bleaching observational reports available in ReefBase and conducted a targeted search for additional bleaching reports that were not included in ReefBase by contacting members of the international coral reef monitoring community that usually work in under-reported locations and by conducting a systematic grey and academic literature search. After compiling the observational database, the authors produced annual 0.04° x

0.04° global maps showing the probability that bleaching occurred in the 1985-2010 period across all warm-water coral reefs by using the indicator kriging geostatistical approach (Donner et al., 2017).

Geostatistics or kriging provides techniques to estimate variables that vary spatially (Curran & Atkinson, 1998). Spatial prediction or spatial interpolation is one of the main objectives of geostatistics and refers to the inference about the unobserved values of the target variable (Hengl, 2009). Ordinary kriging is the most common type of kriging (i.e. geostatistics) and offers an optimal and unbiased technique for estimates of unknown values from sample data (Curran & Atkinson, 1998). These estimates are obtained by assigning weights to each of the sample points that are proximate to the estimate (Curran & Atkinson, 1998). Predictions from ordinary kriging are based on the model:

$$Z(s) = \mu + \varepsilon'(s)$$

where μ represents an unknown constant (global mean) and $\varepsilon'(s)$ is the spatially correlated stochastic component of variation (Hengl, 2009). The locations being estimated (in this case, each grid cell with coral reefs) are surrounded by actual sampling points (observational bleaching data) and are within the spatial auto-correlation range (Hengl, 2009). The weights assigned to each sample point is determined in an objective way that considers spatial dependence, with closer data receiving more weight because of the greater likelihood of values to be similar to the unknown values (Curran & Atkinson, 1998), thus reflecting the actual spatial auto-correlation structure (Hengl, 2009). Semivariograms are used to estimate the degree of variance between multiple pairs of sample points separated by a distance and provide information on the scale and pattern of spatial variance (Hohn, 1988). To describe the semivariogram and use it for kriging, it is necessary to fit a mathematical model to the semivariance estimates (Curran & Atkinson, 1998). The variance that is spatially independent is estimated by the nugget parameter (Tsui et al., 2013); the range refers to the distance where the model flattens out. Locations separated by distances closer than the range are spatially autocorrelated and locations farther apart than the range are not (*Understanding a Semivariogram: The Range, Sill, and Nugget—ArcGIS Pro | Documentation*, n.d.).

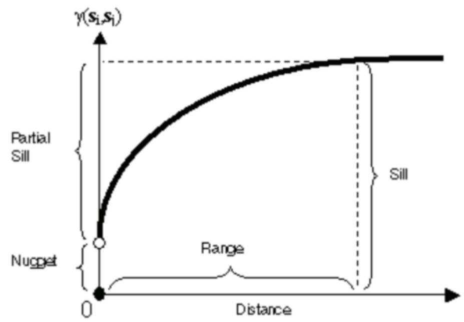

Figure 2-1. Anatomy of a typical semivariogram (ArcGIS Pro Documentation, n.d.)

Indicator kriging proceeds the same as ordinary kriging assuming the model (*Understanding Indicator Kriging—ArcGIS Pro | Documentation*, n.d.):

$$I(s) = \mu + \varepsilon'(s)$$

where $I(s)$ is a binary variable. The binary data can be produced through the use of a threshold for continuous data, or it can be observed data depicted as 0 or 1 (Glacken & Blackney, 1998; *Understanding Indicator Kriging—ArcGIS Pro | Documentation*, n.d.). Some examples of the applications of this technique are species distribution models (Barbet-Massin et al., 2012; Chefaoui & Lobo, 2008; Hengl et al., 2009), mineral resource estimation, and other natural resource mapping applications (Glacken & Blackney, 1998). Indicator kriging will provide a value for each point estimate between 0 and 1 (Glacken & Blackney, 1998). For the development of the database, the bleaching observational data were used as presence data ('1's). However, because indicator geostatistics cannot be conducted without absence data, it was necessary to generate the 'pseudo-absence’ data to depict areas where bleaching is not likely to occur (‘0’s) (Hengl et al., 2009). This pseudo-absence data was generated using heat stress data to obtain locations with none or minimal heat stress (Donner et al., 2017).

2.2.2 Observational database

The updated coral bleaching observational database followed the approach used in the development of version 1. The updated database includes all reports from version 1 plus additional reports obtained by downloading more recent records from ReefBase, conducting another targeted search for reports in the academic and grey literature (using Google Scholar and searches of all International Coral Reef Symposium archives), the International Coral-List (e-mail list), and by contacting scientists from the international coral reef monitoring community and representatives of monitoring organizations (e.g., ReefCheck, Coral Cay Conservation, Wildlife Conservation Service, XL Catlin Seaview Survey, Florida Reef Resilience Program). This search aimed to infill gaps in the pre-2010 data from the previous version of the database and to update the database through the year 2017. NOAA Coral Reef Watch also contributed its internal database of reports collected as part of research on 2014-2017 heat stress and mass coral bleaching.

The updated observational database follows the ReefBase format as in version 1, which includes categories for source, country, site names, latitude and longitude, year, month, percent bleached, percent mortality, depth, and survey method (Table 2-1). The percent bleached and mortality variables (where available) were converted into the ‘bleaching severity’ categorical variable following the same protocol used in ReefBase (Table 2-2).

Table 2-1 Updated coral bleaching observational database legend.

Category	Description
Ocean_Region	See Figure 2-2
Country	Follows ReefBase convention
Location	State, region or island
Site_Name	Dive site or local community
Latitude	In decimal degrees
Longitude	In decimal degrees
Date	Date of observation *
Month	Month of observation *
Year	Year of observation
Depth	Depth of observation *
Severity_Code	See Table 2-1
Percent_Bleached	Percent of coral cover bleached
Mortality Code	See Table 2-1
Percent_Mortality	Percent mortality, as a percentage of coral cover *
Survey_Type	Survey type (e.g., random dive, point intercept transects) *
Source	Initial source of the report (i.e., existing database or research group)
Citation	Source manuscript or report
Comments	Other comments on the report
Database_Code	1 = ReefBase reports in V1, 2 = V1 additions, 3 = V2 additions from ReefBase, 4 = V2 additions from literature search and outreach, 5 = V2 additions from Coral Reef Watch 2014-2017 database
	*if available

Table 2-2 Bleaching severity categories

Code	Severity
-1	Percent unknown
0	No bleaching
1	Mild (1-10% bleached)
2	Moderate (11-50% bleached)
3	Severe (>50% bleached)

The 'Ocean_Region' categorical variable was used in the interpolation to reduce computational requirements of space and time and at the same time preserving spatial autocorrelation within basins. I used the spatial boundaries previously defined by Donner et al. (2017) for dividing the world's reefs into regions (Figure 2-2) and populate this variable.

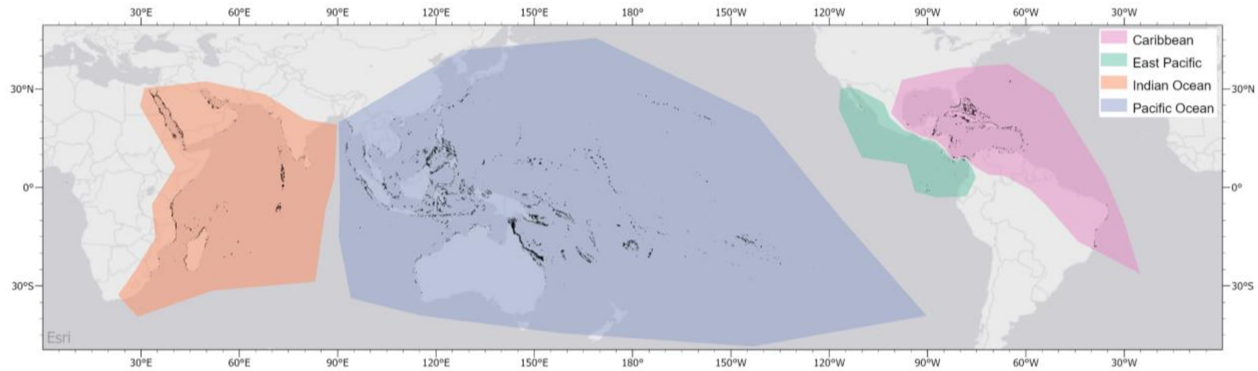

Figure 2-2. Defined boundaries for the Ocean Region category. Black pixels, 0.05° x 0.05° reef cells

2.2.3 Quality control

All reports were submitted to a quality control procedure. First, by reviewing that the information of each report was accurate, and then by correcting any location errors where needed. To identify the reports with location issues, I used ArcMap (version 10.6.1; Esri, 2018) and Google Earth Web (https://earth.google.com/web/) to verify that the coordinates provided were located in the country listed for each report; if these did not match, I corrected the coordinates manually where possible using other location information. In the cases where the coordinates of a report were located over land, I provided alternative coordinates corresponding to the closest coral reef location by obtaining the shortest distance between each report and a coral reef location using the distance matrix tool from QGIS software (Version 3.8; QGIS Development Team, 2019). To define the coral reef locations, I developed a 0.05° x 0.05° raster layer using the Millennium Coral Reef Mapping Project (UNEP-WCMC, 2018) dataset as a reference and added as reef cells the coordinates of the compiled bleaching reports that were not labelled as reefs in the map.

2.2.4 Interpolated bleaching probabilities

I conducted indicator kriging for the development of global maps of probability of bleaching occurrence for a given year (between 1985 and 2017) in a given ocean region (as defined in Figure 2-2) using R statistical computing environment (R Core Team, 2020) and RStudio software (RStudio Team, 2020). Only the bleaching reports with severity code >1 were used in the interpolation because they were considered to be more reliable (Donner et al., 2017). The presence of bleaching was defined by the locations of these reports. Bleaching pseudo-absences were defined by setting a threshold for the lack of heat stress, based on the assumption that heat-driven bleaching was unlikely with no or low heat stress. For annual heat stress data, I used the maximum Degree Heating Week (DHW) value recorded each year in the Annual Maximum Degree Heating Week (DHW) (1985-2020) 0.05° x 0.05° product developed by NOAA CRW (NOAA Coral Reef Watch, 2019).

In the previous version of the database, pseudo-absences were defined as grid cells were the maximum annual DHW that year was 0 °C-weeks. However, no tests were conducted to assess the effect of that assumption on the interpolated bleaching probability values. Since CoralTemp V1 has higher temporal resolution in SST values than the Heron et al. (2016) dataset used to define pseudoabsences in Donner et al. (2017), non-zero but low (<1) annual maximum DHW values are more common in CoralTemp (W. Skirving, personal communication, November 06, 2020); using annual maximum DHW=0 could lead to overprediction of bleaching probabilities. I, therefore, conducted systematic tests to assign a more appropriate threshold for defining pseudo-absences. Each region and year were tested using four different thresholds (0 °C-weeks, <0.25 °C-weeks, <0.5 °C-weeks, and <1 °C-weeks) over two different years: a year with numerous reports and a year with a low or moderate abundance of reports. Summary statistics from the outputs of each iteration were analyzed, but because some iterations were not possible to complete (model fitting failed), the threshold chosen was the one that worked for all iterations (DHW <0.5 °C-weeks). Results from these tests are presented in Appendix A.

I used raster (Hijmans, 2020) and sp (Pebesma & Bivand, 2005) packages for spatial data manipulation. Semivariograms for each combination of region and year were automatically fitted using autofitVariogram function from automap (Hiemstra et al., 2008) package that iterated over eight different mathematical models (Exponential, Spherical, Gaussian, Matern, Stein's Matern, Circular, Linear, Bessel, and Pentaspherical), selecting the one with the smallest residual sum of squares (Hiemstra, 2015). Automap was chosen over manual fitting to avoid biases in model fitting, increasing the method's reproducibility. The variogram model was then used in the krige function from gstat package (Pebesma, 2004) using the formula z~1 for ordinary kriging and passing the variogram model. To speed up real-time computation, I used the parallel package (R Core Team, 2020).

Automap was attempted for all regions and years with data (1985-2017); however, in some case where semivariograms failed to converge or produced no estimations, initial estimates for range, sill, and nugget values were provided to the autofitVariogram function because sometimes the model fitting required actual visual inspection (Hohn, 1988). After obtaining all possible interpolation outputs, all raster outputs were exported into ArcGIS Pro (version 2.6; Esri, 2020) to create global maps using the Mosaic Rasters function. Interpolations were not possible to complete in all regions and years because of insufficient data available, which could mean no bleaching was observed that year or lack of reporting, or because of clustering of reports in small areas of a region.

In years for which kriging was not possible to complete, grid cells with bleaching reports of severity >1 were assigned a probability of 100% and all other cells in the region were assigned a probability of 0%. Examples of each interpolation outputs are presented in Appendix D.

2.2.5 Data Analysis

To assess the observational data in the context of bleaching extent at the global and regional levels, I converted the point locations of bleaching reports into a 0.05° x 0.05° grid and calculated the number of cells by severity code within each reef region as defined by (Kleypas et al., 2008). The boundaries of these reef regions are presented in Figure 2-3.

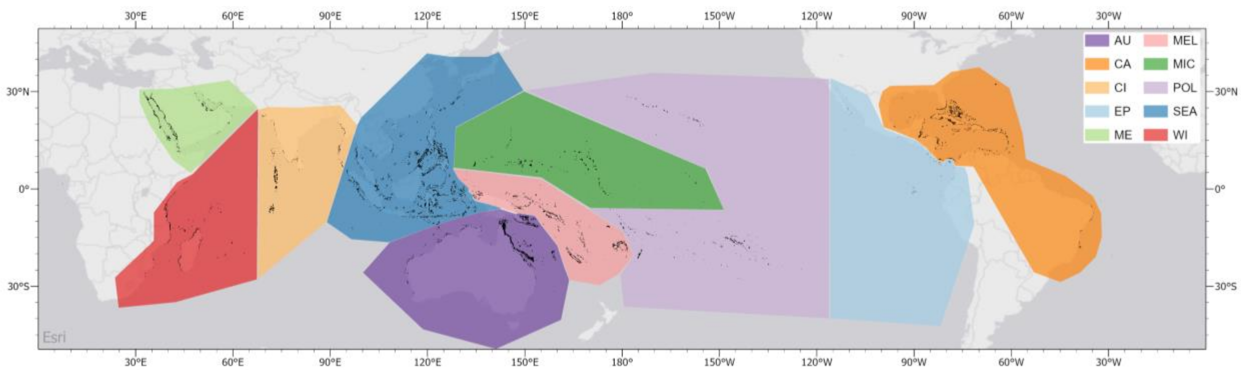

Figure 2-3. Defined boundaries for the world's reef regions. Adapted from Kleypas et al. (2008). AU, Australia; CA, Caribbean/Atlantic; CI, Central Indian; EP, East Pacific; ME, Middle East; MEL, Melanesia; MIC, Micronesia; POL, Polynesia; SEA, Southeast Asia; WI, West Indian. Black pixels, 0.05° x 0.05° reef cells

To test whether the interpolation results were significantly different between version 1 and version 2, I conducted Welch two-sample t-tests with the bleaching probability values of the grid cells that contained one or more bleaching reports within them for a given year and region in each version, respectively. To evaluate the interpolated bleaching probability results of version 2, I created two subsets with the resulting data: (1) the values of all reef cells where indicator kriging was conducted and (2) the values of cells where indicator kriging was conducted and contained bleaching reports within their area. I used Welch two-sample t-tests to compare these two groups.

To assess the extent to which the interpolation increased the area of observed bleaching in each region, I also calculated the number of cells that had a likely (>66%) and a very likely probability of bleaching (>90%) and compared these two groups against the extent resulting from the observational data, considering bleaching reports with severity code >1. This analysis was done globally and regionally, and it was repeated for the periods in which the three global bleaching episodes occurred. Subsequently, these results were assessed as a proportion of total reef cells globally and regionally.

To analyze the relationship between SSTs and the modelled bleaching probabilities, I calculated the mean Annual Maximum DHW for six groups of cells that were created based on their bleaching probability values. These groups were: >90%, >66–90%, >50–66%, >33–50%, >10–33%, ≤10. I used Welch two-sample t-tests to test whether the DHW values from these six groups were significantly different from one another and from that of all cells (all bleaching probability values). This analysis was done for the global and regional scales, and it was repeated for the periods in which the three global bleaching episodes occurred. To test whether the threshold for bleaching conditions increased over time, I compared the increases in heat stress for all reef cells with the increase in heat stress for cells that likely and very likely experienced bleaching (>66% and >90% bleaching probability) across the 1985-2017 period.

All the statistical analyses were done using the R statistical computing environment (R Core Team, 2020). The package ggplot2 (Wickham, 2016) was used to produce all plots. All maps were produced using ArcGIS Pro (version 2.6; Esri, 2020).

2.3 Results

2.3.1 Observational bleaching data

The updated database provides seven new years of observational data (2011-2017) and includes more reports for past years within the 1963-2010 period. Additionally, some duplicated reports were removed in certain years (e.g., 1998, 2005). The number of positive bleaching reports increased by 204.5%, from 7,437 to 22,650 compared to version 1. The years with the most reports were 2016 (22% of total bleaching reports), followed by 2014 (11.3% of total bleaching reports), 2015 (10.7% of total bleaching reports), 2005 (10.5 % of total bleaching reports), 2017 (8.8% of total bleaching reports), and 1998 (5.6%) (Figure 2-4). These years correspond to some of the most intense bleaching events, including the 1997-1998 and 2014-2017 events (Hoegh-Guldberg, 1999; Skirving et al., 2019) and the 2005 event in the Caribbean (Eakin et al., 2010). The database also includes 15,124 non-bleaching reports (absence of bleaching at a given point in the year); however, these were not used for the analyses in this study.

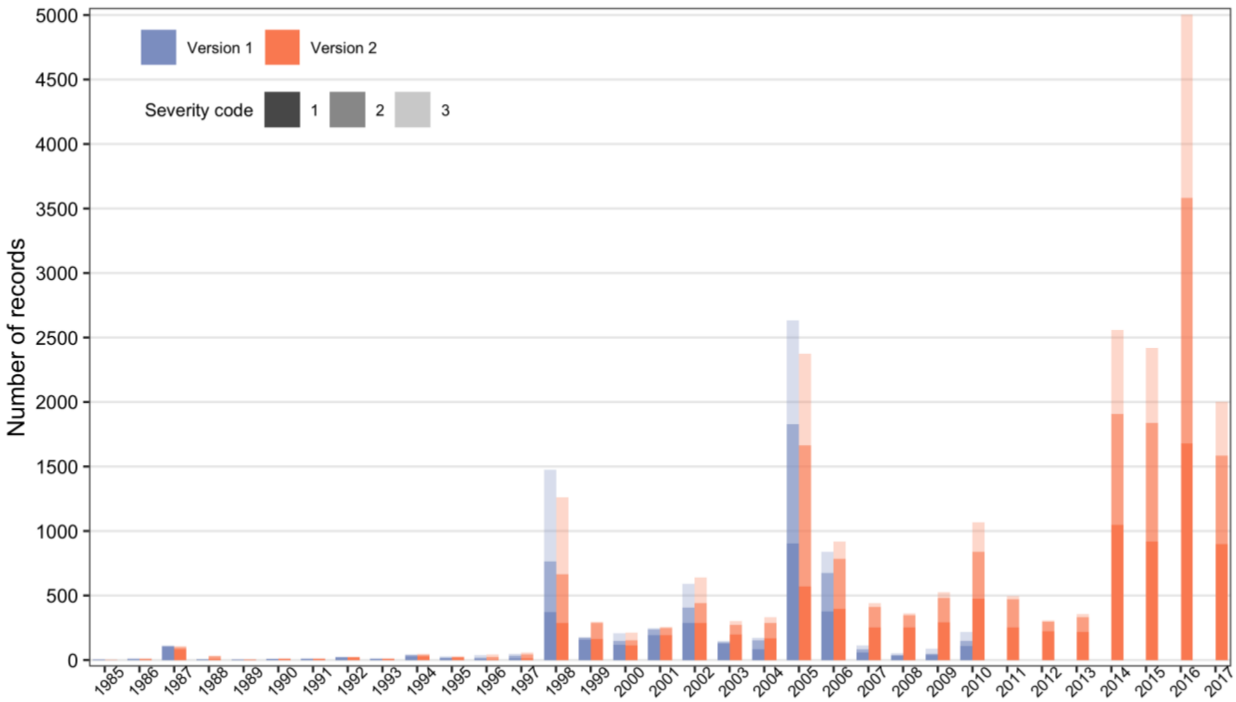

Figure 2-4. Number of bleaching reports by year for 1985-2017 in version 1 and version 2 of the database. Note that severity code 1 in this figure refers to severity code -1 or 1. Years: 1963, 1969, 1973, 1976-1977, and 1979-1984 do not appear in this figure but had bleaching reports

From the 22,650 positive bleaching reports in the database, 57% of reports coincide with the four "global" mass coral bleaching events, each of which occurred during periods with El Niño events. The first large-scale event recorded in 1982-1983 (Glynn, 1984) accounts for 0.3% of total reports, the 1997-1998 global event for 6% of total reports, the 2009-2010 global event for 7% of total reports; and the 2014-2016 global event for 44% of total reports (Table 2-3). Most reports from the 1982-1983 event have an unknown severity. Reports from the 1997-1998 event were predominantly "severe" (code 3); in 2009-2010, reports were predominantly "mild" (code 1) and in 2014-2016, reports were predominantly "moderate" (code 2).

Table 2-3. Summary of observational bleaching reports for all years and for significant bleaching periods

Reports		Unknown	Mild	Moderate	Severe	Total
Version 1	**1982-1983**	42	0	4	31	77 (1%)
	1997-1998	32	354	412	723	1,521 (20%)
	2009-2010	93	53	54	109	309 (4%)
	2014-2016	-	-	-	-	-
	All years	752	2,408	2,046	2,231	7,437
Version 2	**1982-1983**	37	0	12	29	78 (0.3%)
	1997-1998	32	266	412	609	1,319 (6%)
	2009-2010	197	574	551	272	1,594 (7%)
	2014-2016	331	3,291	3,702	2,658	9,982 (44%)
	All years	1,235	7,896	8,160	5,359	22,650

Because of the uneven sampling effort, the number of bleaching reports can be a misleading measure of the extent of bleaching in a given year or region (Donner et al., 2017). For example, a particular area could have been consistently surveyed throughout a year leading to clustering of reports in a small area and fewer reports in others. The gridded coral reef area in this study was comprised of 53,621 0.05◦ x 0.05◦ grid cells across the world's oceans. The gridded data from bleaching reports show bleaching occurred in at least one cell in 1963, 1969, 1973, 1976-1977, and each year from 1979 through 2017, and that it was observed at different severity levels ranging from mild to severe. In some years, the number of reports had a positive relationship with the size of the area of bleaching (i.e., bleaching extent). Such is the case of 2016, which had the most reports throughout the entire period (1963-2017) and had the most considerable bleaching extent (Figure 2-5). However, the gridded data results show that this relationship is not consistent for the entire database. For instance, although 2005, 2014, and 2015 include more reports than 1998, the observational data's bleaching extent was greater in 1998.

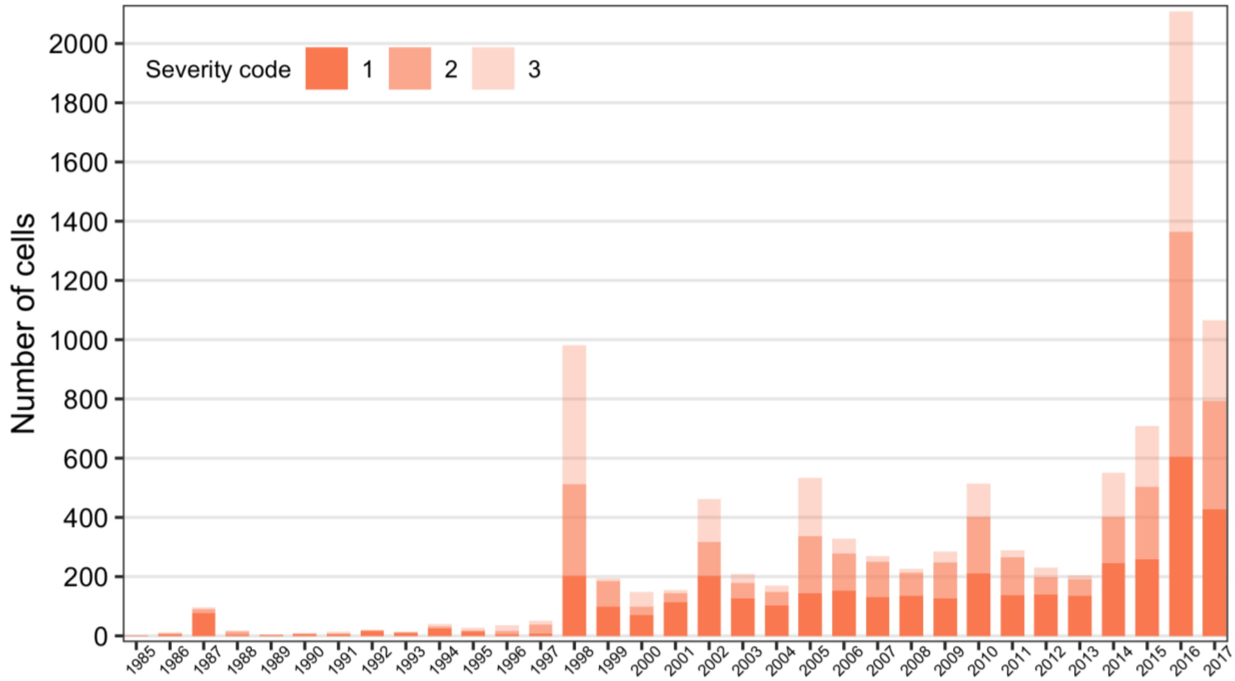

Figure 2-5. Number of 0.05 x 0.05 latitude-longitude grid cells with bleaching reports by year for 1985-2017 in version 2 of the database. Note that severity code 1 in this figure refers to severity code -1 or 1

The spatial extent of bleaching varied widely at the regional level, partly explained by differences in reef area amongst regions, with Southeast Asia, Australia, and the Caribbean having the largest number of reef cells and the East Pacific the smallest (Table 2-4).

Table 2-4. Number of total cells with reef areas within each region considered in this study

Region	Total Reef cells
Southeast Asia	17,997
Australia	8,611
Caribbean	6,758
Melanesia	6,299
Middle East	3,441
Polynesia	2,636
West Indian	2,632
Central Indian	2,546
Micronesia	2,379
East Pacific	300

The Caribbean was the region with the greatest extent of reports, followed closely by Australia, while the East Pacific region had the smallest extent amongst all other regions (Figure 2-6). When analyzing these results with respect to the total reef area in each region, the East Pacific had the highest proportion of cells with reports (37.33%), followed by the Caribbean (22.34%) and Australia (16.46%) regions (Figure 2-7). The lowest proportions were observed in Melanesia (2.92%) and Southeast Asia (4.67%). At the regional level, the relationship between the number of reports and the bleaching extent was more apparent but, similarly to the analysis by year, this was not consistent in every case. For example, Micronesia had more reports than the Central Indian region but had a lower areal bleaching extent, indicating a higher fraction of grid cells with multiple bleaching reports in the same year.

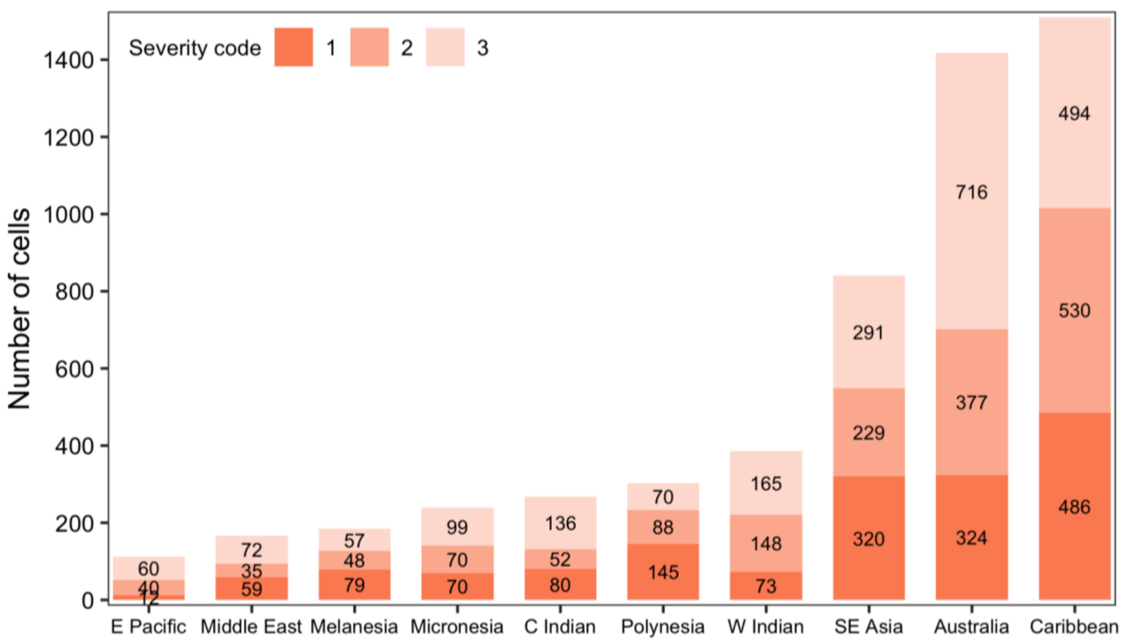

Figure 2-6. Number of 0.05° x 0.05° grid cells with bleaching reports by region for 1963-2017

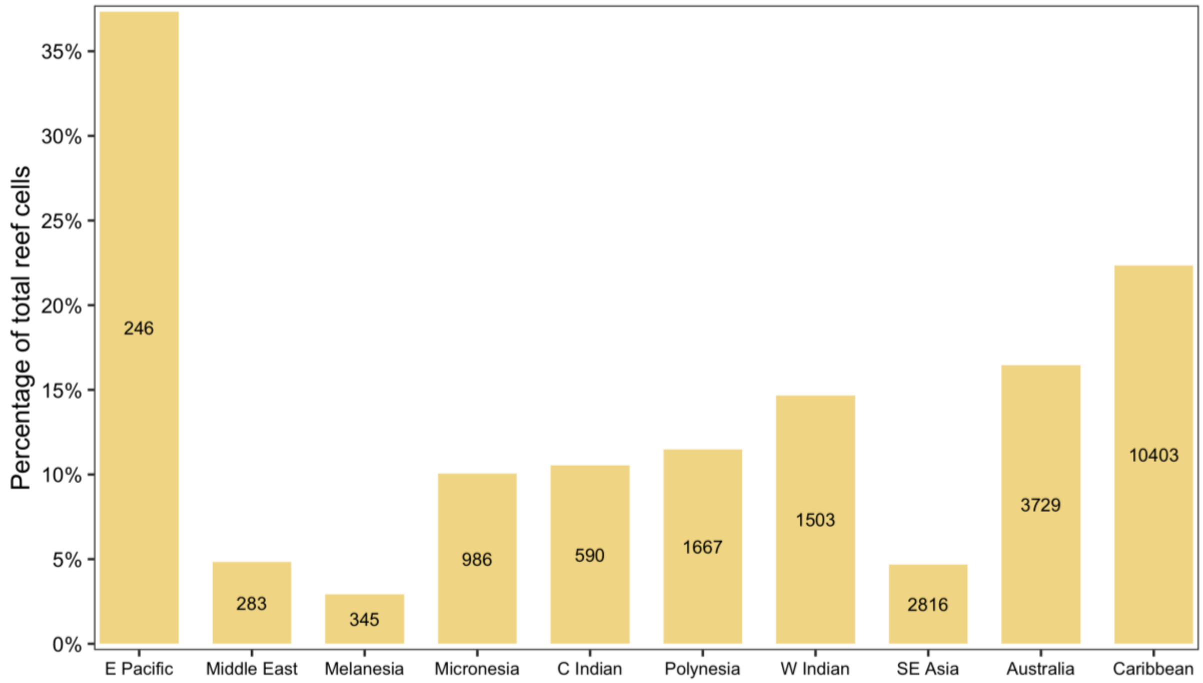

Figure 2-7. Percentage of 0.05° x 0.05° grid cells in each region with bleaching reports and total number of reports for 1963-2017

2.3.2 Interpolated bleaching probabilities

The observational bleaching reports were sufficient to produce interpolated maps of bleaching probabilities for 27 years within 1985 through 2017, adding nine years of data (1991, 1994, and 2011-2017) compared to version 1. Only three years (1998, 2015, and 2016) had sufficient reports to interpolate within all four kriging regions; in 16 years, interpolations were completed in two or three of the regions, and in eight years, interpolations were completed in only one of the regions (Table 2-5). In 1985, 1986, 1989-1990, and 1992-1993 there were either no reports or too few for completing the interpolation. Version 2 also provides interpolated bleaching data in more years than version 1 for each kriging region. For the Caribbean, bleaching probability maps were produced for 23 years, 19 years for the Pacific Ocean, 14 years for the Indian Ocean, and four years for the East Pacific. In contrast, in version 1, indicator kriging was conducted in 13 years for the Caribbean, nine years for one or more of the Pacific Ocean sub-regions, seven years for the

Indian Ocean, and two years for the East Pacific. Additionally, version 2 includes values across the entire Pacific Ocean region (as defined in boundaries presented in Figure 2-2), while version 1 includes a partial area of this region in some cases (see Table 4 in Donner et al. (2017)). Notably, although indicator kriging was conducted for the Indian Ocean in 1996 and 2004 in version 1, in this analysis, the semivariograms failed to converge, and thus, kriging was not completed in version 2.

Table 2-5. Years for which indicator kriging was conducted

Year	Caribbean	East Pacific	Indian Ocean	Pacific Ocean
1985				
1986				
1987	✓			
1988	✓			
1989				
1990				
1991				✓
1992				
1993				
1994				✓
1995	✓			
1996				✓
1997		✓		✓
1998	✓	✓	✓	✓*
1999	✓			
2000	✓		✓	✓
2001	✓		✓	✓
2002	✓		✓	✓*
2003	✓		✓	
2004	✓*			✓*
2005	✓		✓	
2006	✓*			
2007	✓		✓	✓
2008	✓*			✓*
2009	✓		✓	✓
2010	✓		✓	✓
2011	✓		✓	✓
2012	✓*		✓*	
2013	✓			✓
2014	✓			✓*
2015	✓	✓	✓	✓
2016	✓	✓*	✓*	✓
2017	✓*		✓*	✓

*Semivariogram completed by providing an initial estimate for range, sill, and nugget values

The means of the calculated bleaching probabilities for grid cells with reports in version 2 were higher than those in version 1 in 65.5% of the analyzed cases (see Appendix B). The results from the t-tests showed that the mean probability of cells with reports from both versions was statistically significant ($p<0.05$) in 72.4% of the analyzed cases. Significant differences were expected between the two versions because of the new data added in version 2.

The analysis of interpolated bleaching probabilities in version 2 showed that the mean bleaching probabilities for the reef cells with reports were greater and significantly different ($p<0.05$) than those of all reef cells in all years (Figure 2-8). The mean bleaching probability for cells with reports across version 2 was 53.9%, while all reef cells' mean was 0.09% ($p<0.001$). Notably, the mean bleaching probability values of all reef cells for some of the years in which the worst bleaching episodes occurred (including 1998, 2005, 2010, and 2016) ranged between 29% and 45%.

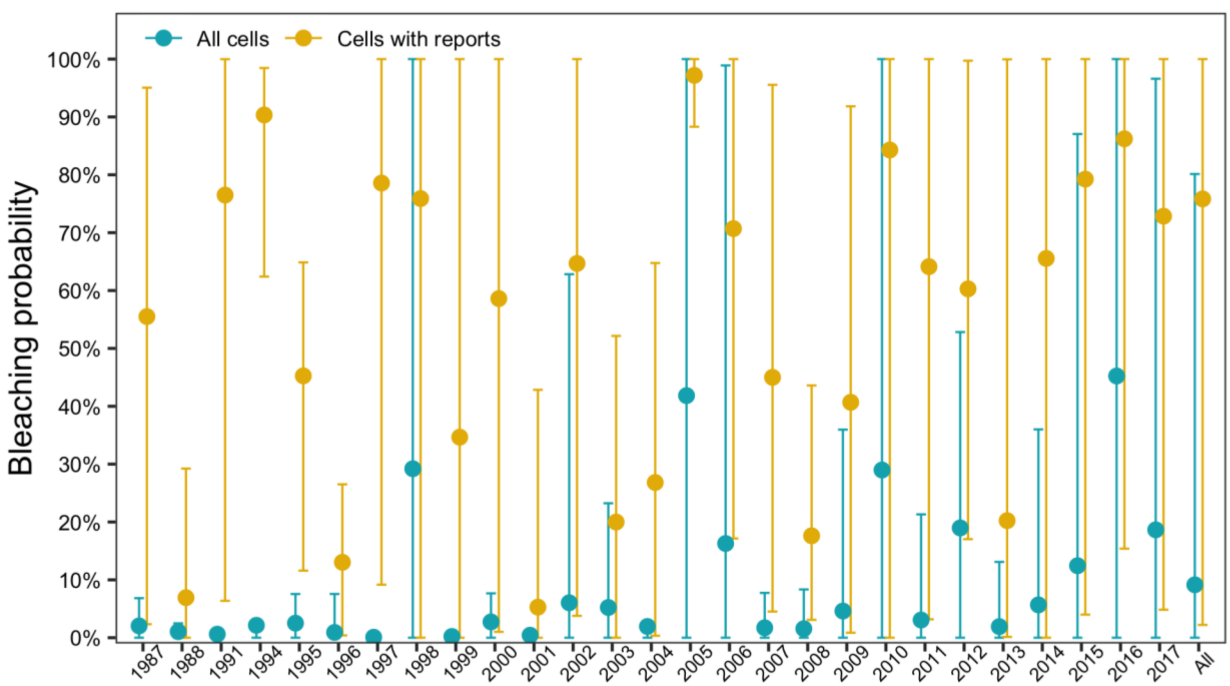

Figure 2-8. Mean, 5th and 95th percentile of bleaching probability of all cells and cells with reports

The mean values of the interpolated bleaching probabilities across all cells highlight a greater extent of bleaching during the three global mass coral bleaching episodes compared to other years (Figure 2-9). These mean values vary across regions, but overall, higher bleaching probability values were most common in the last decade (2010-2017).

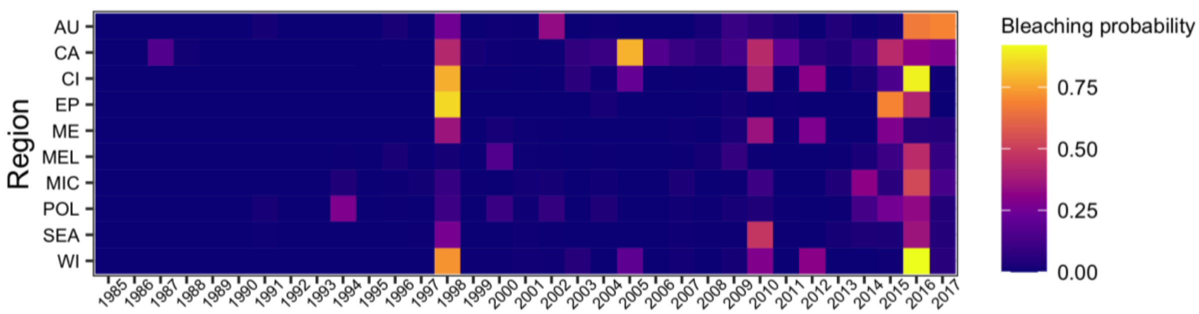

Figure 2-9. Mean bleaching probability by year and region

Most cells with reports of severity code >1 and the ones nearby had a high bleaching probability (>80%) in years when some of the worst bleaching episodes occurred, including the three global mass coral bleaching events and the severe event in 2005 in the Caribbean. Cells further away from reports had a lower probability in these years. As an example of interpolation results for each ocean region, the following figures show observational data (severity code >1) and interpolated bleaching probabilities for the Caribbean in 2005 (Figure 2-10), the East Pacific in 1998 (Figure 2-11), the Indian Ocean in 2010 (Figure 2-12), and the Pacific Ocean near the Great Barrier Reef (Figure 2-13). However, in some cases, although there were reports, the absence of heat stress (DHW <0.5°C-weeks) introduced pseudo-absences in the same cells or in cells nearby, leading to very low bleaching probability values. For example, in the Caribbean in 2013, moderate to severe bleaching was reported in parts of Florida despite DHW not exceeding 0.5°C-weeks (Figure 2-14).

This could suggest high local bleaching sensitivity, errors in satellite SSTs temperature, or that those bleaching reports are not related to thermal anomalies, and there was another environmental factor involved.

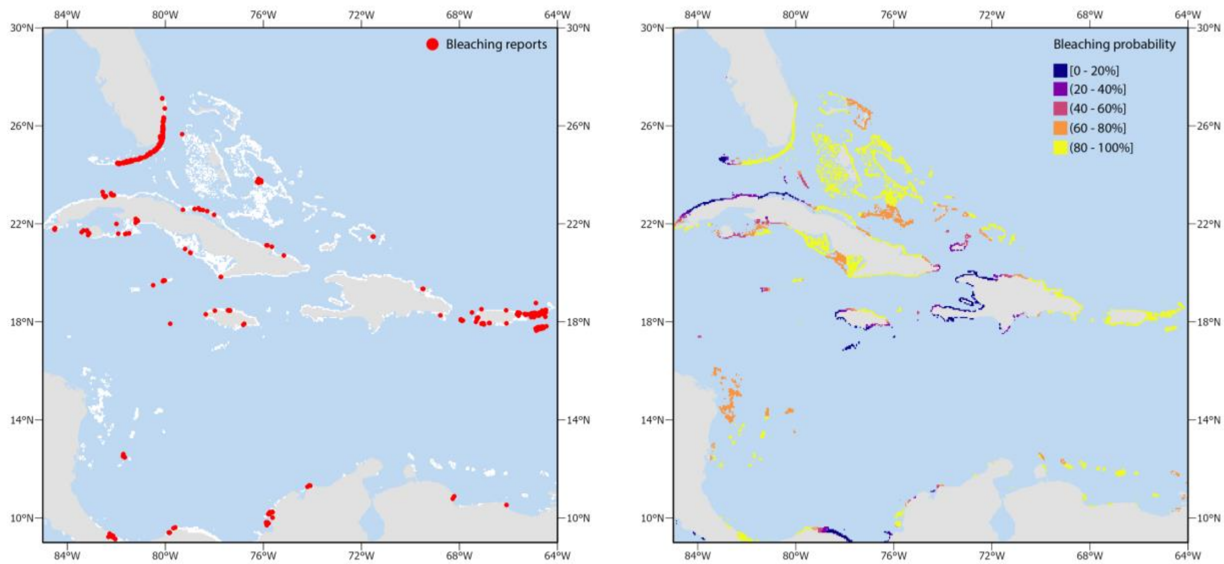

Figure 2-10. Example of bleaching observations and probabilities for the Caribbean region in 2005: bleaching reports with severity code >1 (left) and interpolated bleaching probabilities (right)

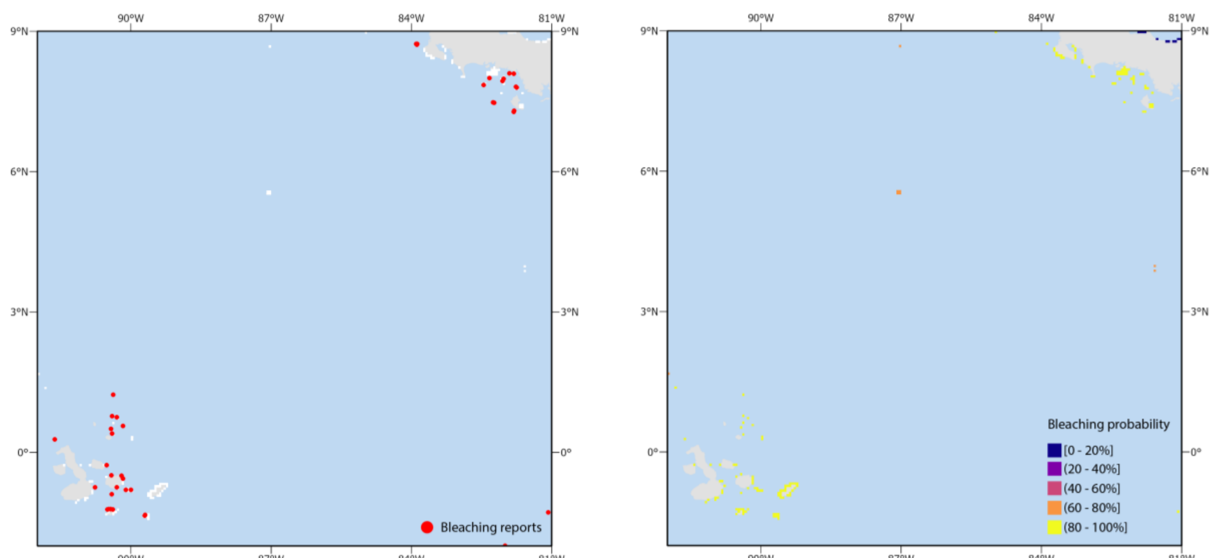

Figure 2-11. Example of bleaching observations and probabilities for the East Pacific region in 1998: bleaching reports with severity code >1 (left) and interpolated bleaching probabilities (right)

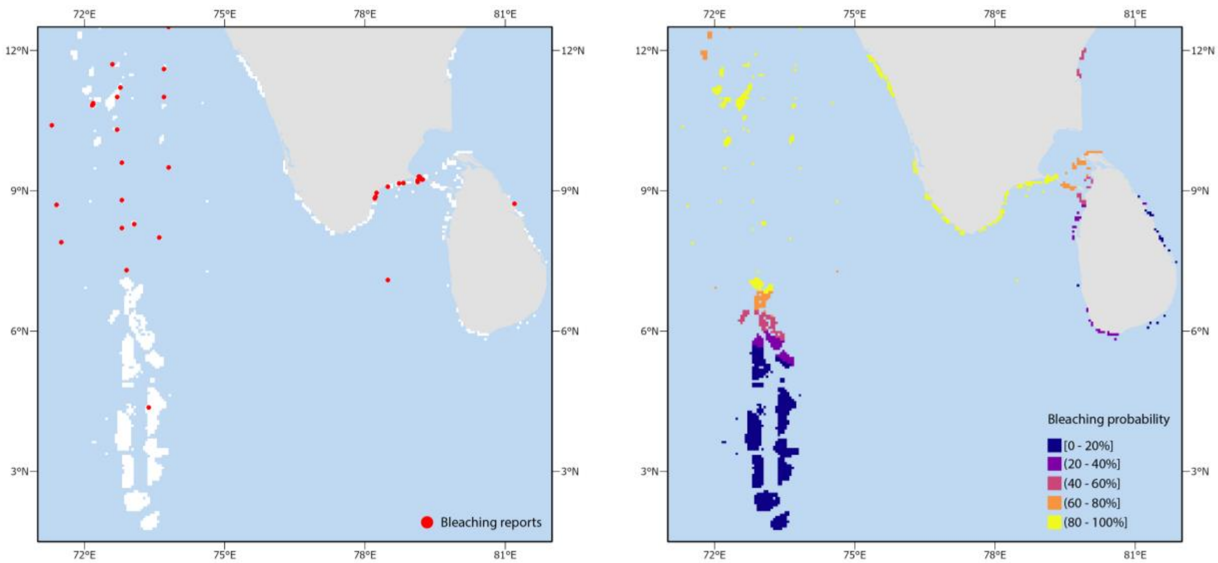

Figure 2-12. Example of bleaching observations and probabilities for the Indian Ocean region in 2010: bleaching reports with severity code >1 (left) and interpolated bleaching probabilities (right)

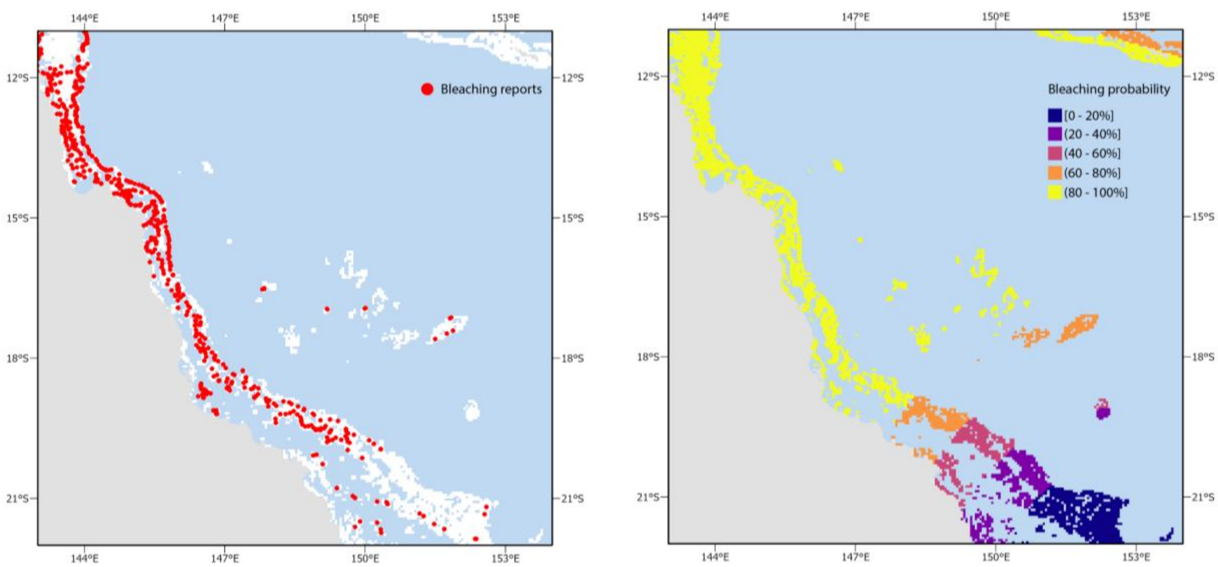

Figure 2-13. Example of bleaching observations and probabilities for the Pacific Ocean region in 2016: bleaching reports with severity code >1 (left) and interpolated bleaching probabilities (right)

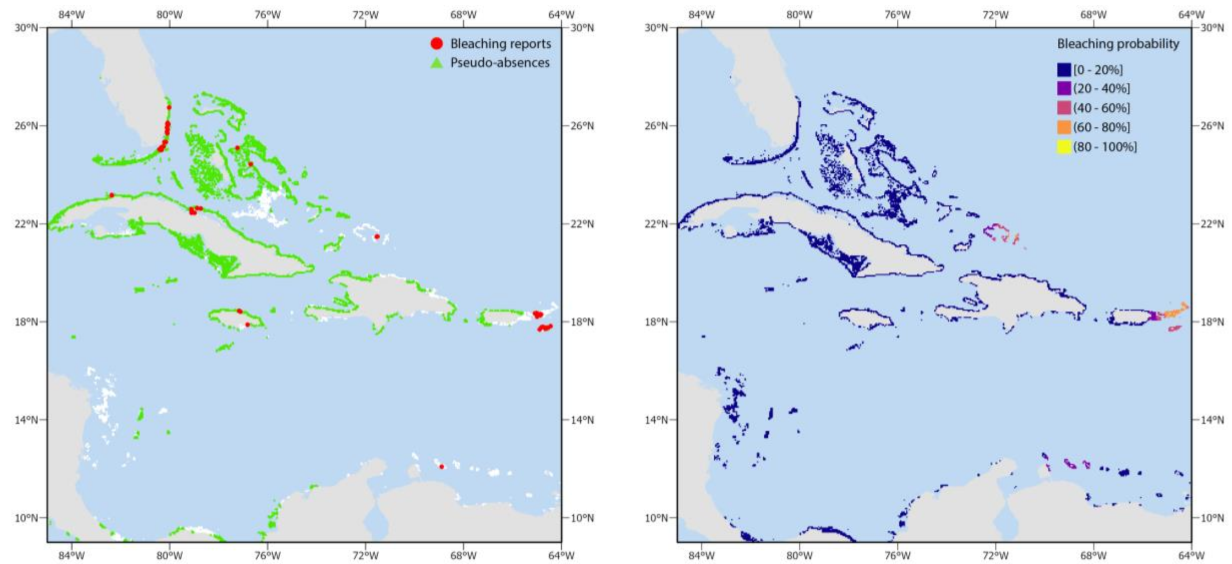

Figure 2-14. Example of cells with bleaching observations but annual maximum DHW < 0.5C (pseudo-absences) for the Caribbean in 2013

The interpolated bleaching probabilities results drastically increased the number of grid cells which likely (>66% change) or very likely (>90% chance) experienced bleaching at least once across the 1985-2017 period compared to that shown only from the observational data (Figure 2-15). At the regional level, Southeast Asia, Australia and the Caribbean had a more significant extent in terms of total cells; however, as a proportion of total reef cells in each region, the extent was greater in the East Pacific, West and Central Indian, and the Caribbean (74.2-95% of reefs very likely experienced bleaching and 91-100% likely experienced bleaching). Melanesia, Polynesia, Micronesia, and the Middle East had the lowest extent (18.5-36.5% of reefs very likely experienced bleaching and 45.1-58.8% likely experienced bleaching; Figure 2-16).

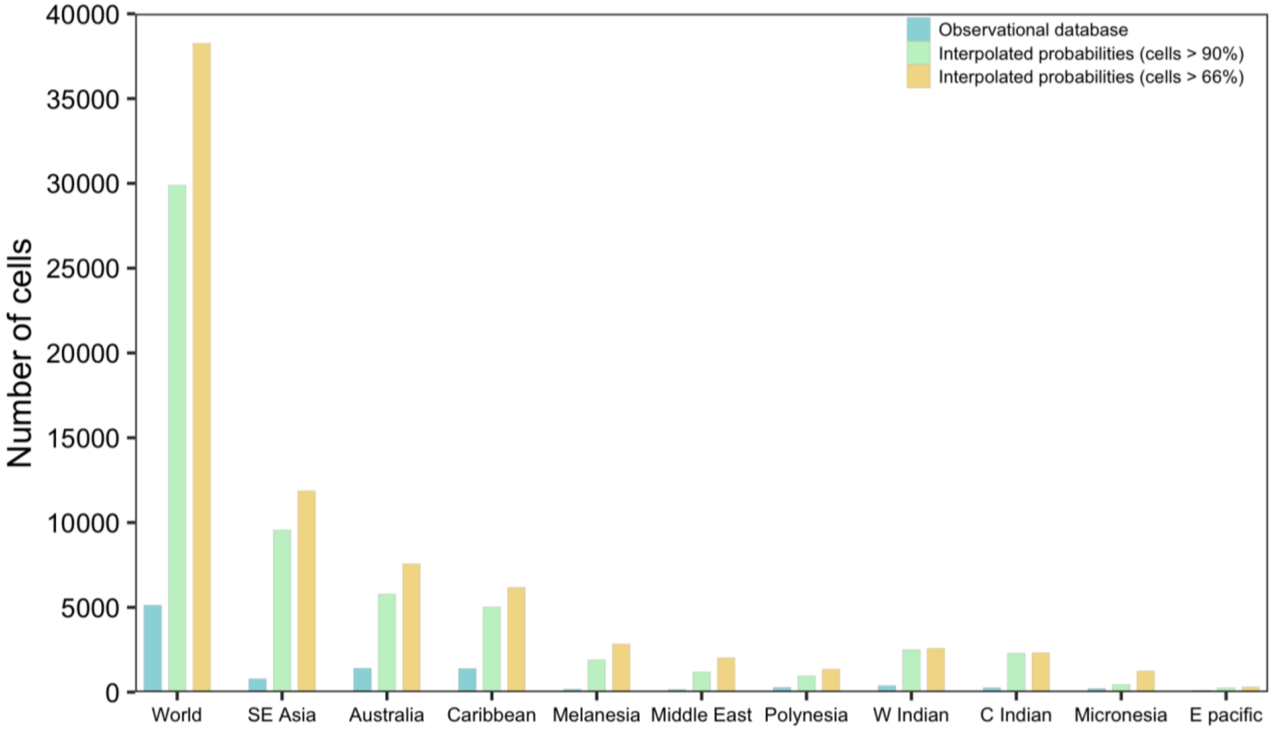

Figure 2-15. Number of cells with bleaching reports (observational database) and total cells that very likely and likely experienced bleaching (>90% and >66% bleaching probability, respectively) across the 1985-2017 period

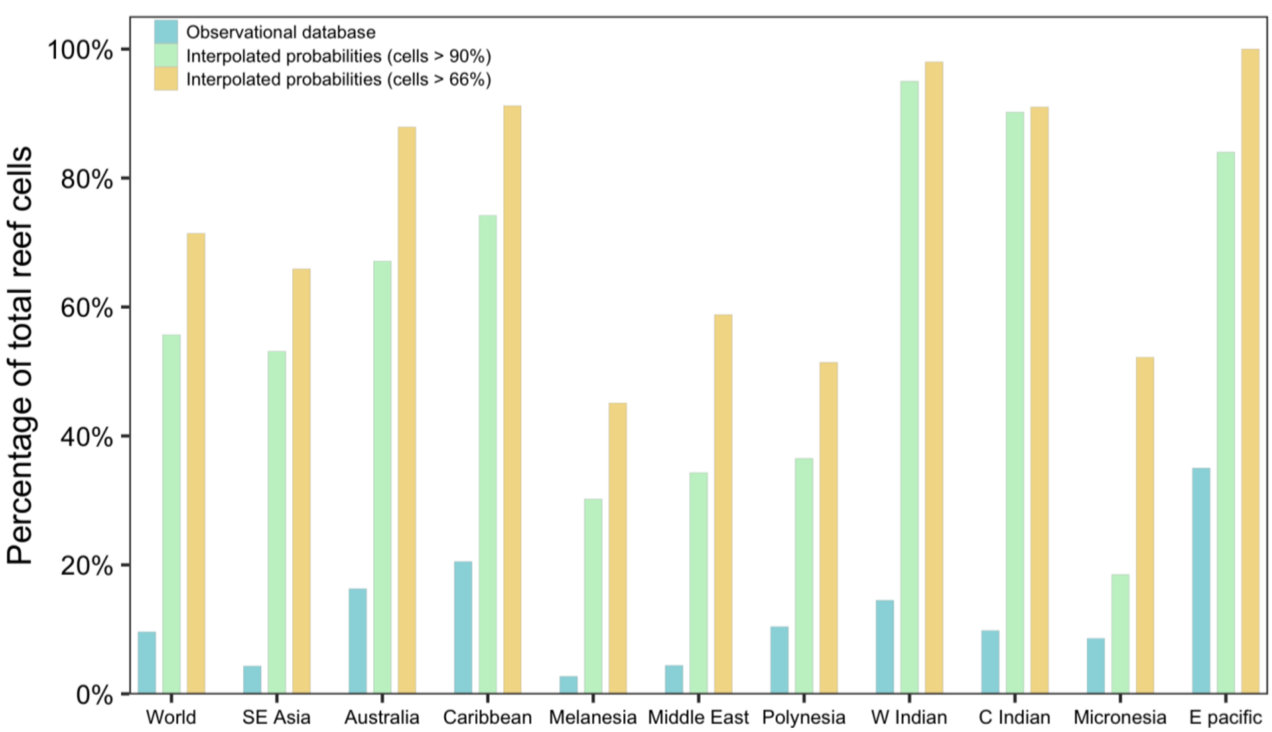

Figure 2-16. Percentage of total cells with bleaching reports (observational database) and percentage of total cells that very likely and likely experienced bleaching (>90% and >66% bleaching probability, respectively) across the 1985-2017 period

As previously described in Table 2-3, most reports occurred during the 2014-2016 global mass coral bleaching event, which was consistent with a greater bleaching extent than in each of the other two global events (

Figure 2-17). Most regions also saw more extensive bleaching during 2014-2016 compared to the other two global events; however, Southeast Asia had the greatest extent in the 2009-2010 event and the East Pacific and the Middle East in the 1997-1998 event. The proportion of total reef cells affected was more significant in the East Pacific, West and Central Indian regions (4.3-87.3% of reefs very likely experienced bleaching and 14.1-90.3% likely experienced bleaching) across the three events. Melanesia, Polynesia, Micronesia and the Caribbean saw the lowest proportions (0-29.4% of reefs very likely experienced bleaching and 0-44.4% likely experienced bleaching) during these periods (Figure 2-18).

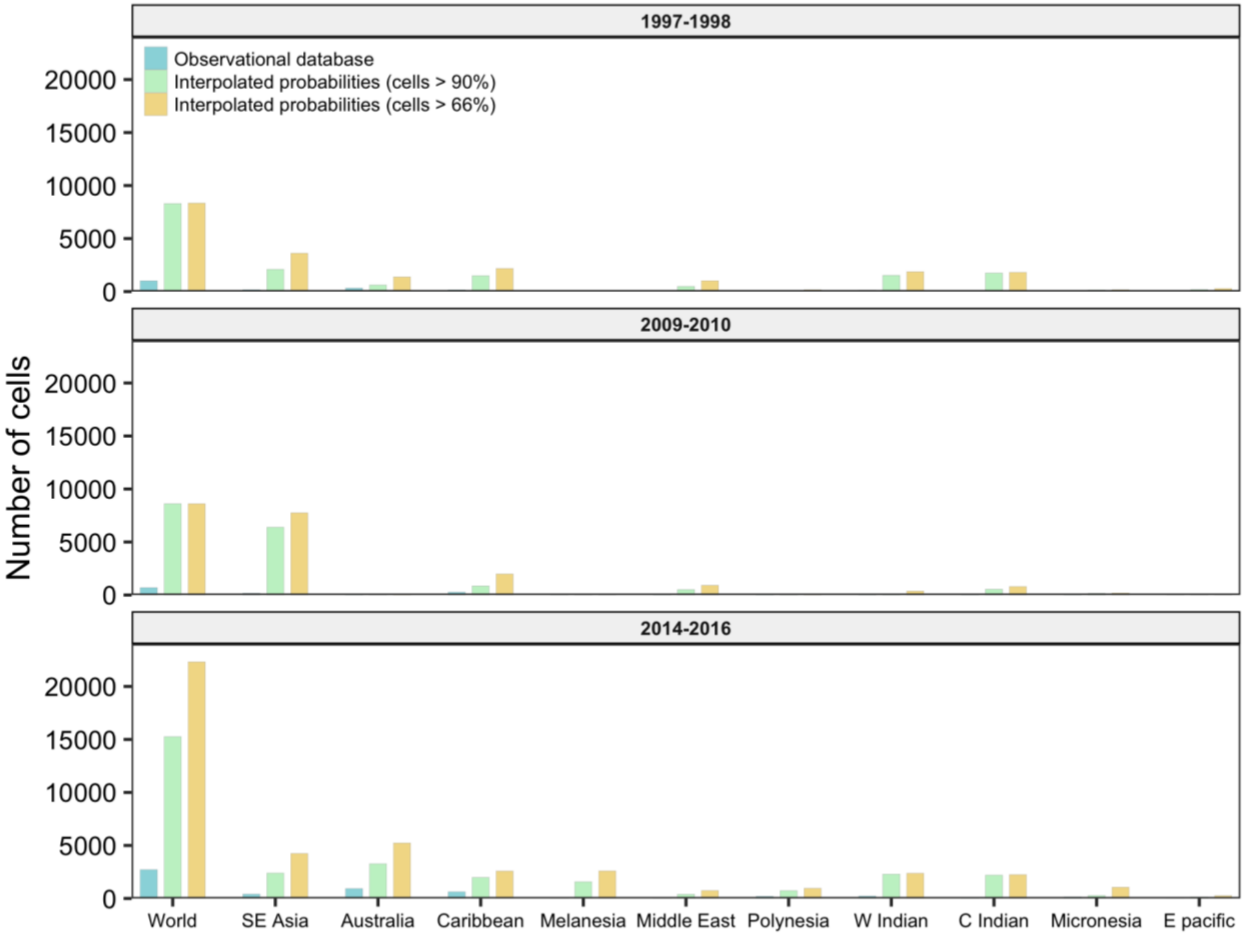

Figure 2-17. Number of cells with bleaching reports (observational database) and total cells very likely and likely experienced bleaching (>90% and >66% bleaching probability, respectively) across the three global mass coral bleaching events

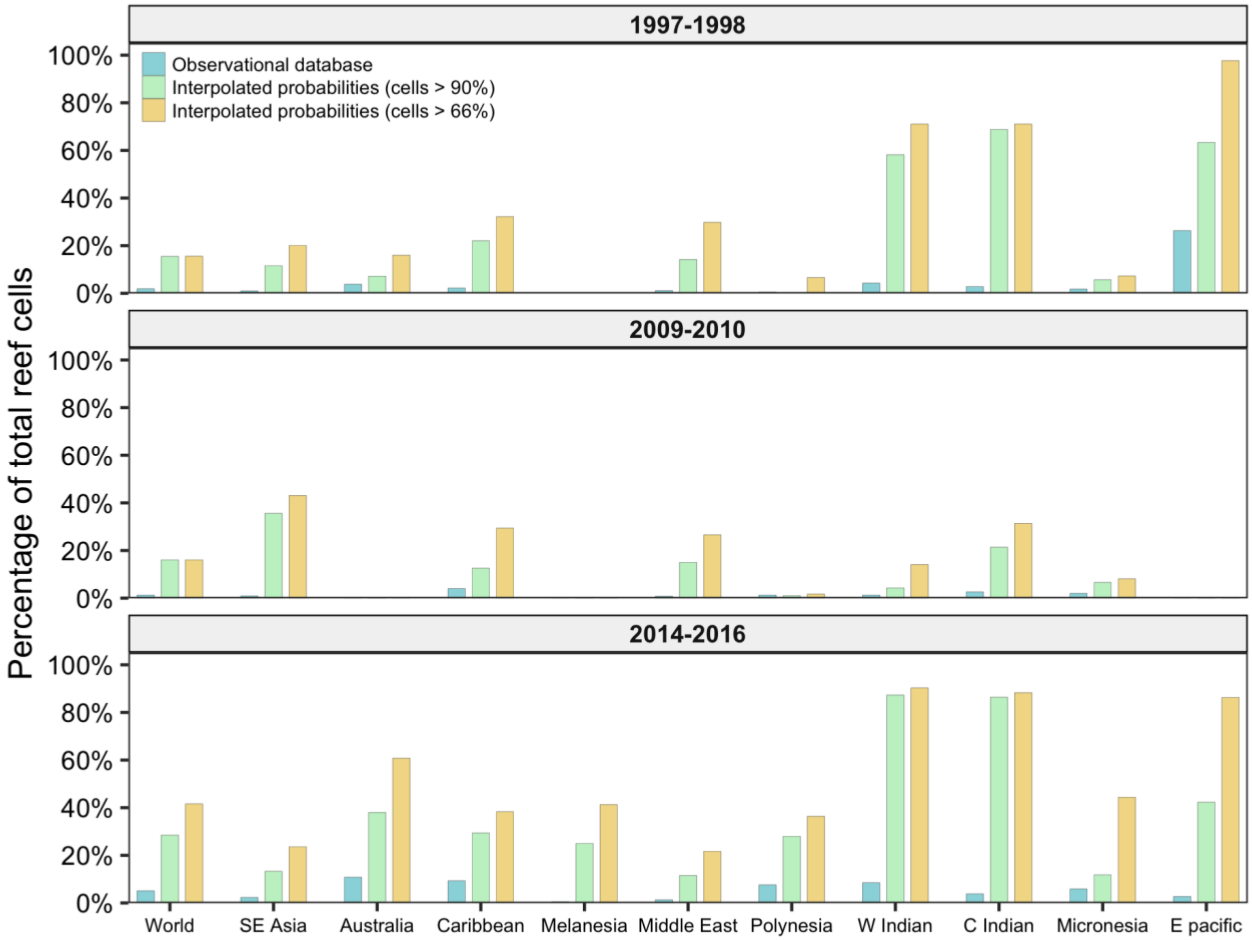

Figure 2-18. Percentage of total cells with bleaching reports (observational database) and percentage of total cells that very likely and likely experienced bleaching (>90% and >66% bleaching probability, respectively) across the 1985-2017 period

The results from the analysis of the relationship between the interpolated bleaching probability values and thermal stress (measured as the mean annual maximum DHW) show significant differences ($p<0.01$) between the six groups of cells with different bleaching probability values and that of all cells (Table 2-6). The bleaching probability values positively correlated with heat stress across all years ($p<0.001$), and in each global event ($p<0.01$). This relationship was observed in all groups with an exception in the 2009-2010 global event, where the >33-50% bleaching probability group had a slightly higher mean DHW value than that of the >50-66% group. The mean DHW values of cells with >33% bleaching probability across all years ranged between

CRW's thresholds for Bleaching Alert Level 1 (4 ◦C-weeks) and Bleaching Alert Level 2 (8 ◦C-weeks). This range was also observed in the 2009-2010 and 2014-2016 events; however, in the 1997-1998 event, only the cells >90% bleaching probability had a mean DHW value within that range.

Table 2-6. Thermal stress for reef cells with different bleaching probabilities

Mean Annual maximum DHW (°C-weeks)	All cells	>90%	>66–90%	>50–66%	>33–50%	>10–33%	≤10%
All years (1985-2017)	1.63*	6.34*	5.46*	4.44*	4.05*	3.05*	1.05*
1997-1998	1.39*	5.39*	3.91*	3.14*	2.94*	2.19*	0.54*
2009-2010	2.4*	6.22*	5.61*	4.57	5.12	3.47*	1.4*
2014-2016	2.96*	6.98*	6.77*	4.73*	4.23*	3.99*	1.58*

*Statistically significant ($p < 0.01$) from all bleaching probability groups and positive relationship between DHW and bleaching probability (higher probability group has higher mean DHW)

The results of this analysis varied regionally, with some probability groups being absent in some cases or not significantly different in others; however, in 77.5% of the cases, the mean DHW values of cells with very likely bleaching probability (>90%) were statistically different to all other groups (see Appendix C).

To test if the bleaching threshold has increased through time because of adaptative responses (Logan et al., 2014) or loss of susceptible taxa (Donner & Carilli, 2019), the mean DHW values of all reef cells were compared with those of cells that experienced bleaching to see if the cells that experienced bleaching had a faster increase. The mean DHW of all reef cells significantly increased ($p < 0.001$) by 0.06 ◦C-weeks per year and by 2.22 ◦C-weeks for the entire period (Figure 2-19A). Meanwhile, the DHW values of reef cells that very likely experienced bleaching increased by 0.17 ◦C-weeks ($p = 0.0942$) per year and by 6.86 ◦C-weeks for the entire period (Figure 2-19B). The mean DHW of reef cells that likely experienced bleaching (>66% bleaching probability) did not significantly increase. At the regional scale, the Caribbean saw the greatest annual increase compared to the rest of the regions (0.09 ◦C-weeks per year, 2.89 ◦C-weeks for the entire period, $p < 0.001$), followed by Micronesia (0.08 ◦C-weeks per year, 2.77 ◦C-weeks for the entire period, $p < 0.01$), Melanesia (0.07 ◦C-weeks per year, 2.3 ◦C-weeks for the entire period, $p < 0.001$), and Australia (0.07 ◦C-weeks, 2.26 ◦C-weeks for the entire period, $p < 0.01$). Southeast Asia saw an increase of 0.05 ◦C-weeks (1.64 ◦C-weeks for the entire period, $p < 0.001$), as well as the Middle East (0.05 ◦C-weeks per year, 1.56 for the entire period, $p < 0.05$), and Polynesia (0.05 ◦C-weeks per year, 1.42 ◦C-weeks for the entire period, $p < 0.01$). Mean DHW values did not significantly increase in the Central Indian, East Pacific, or West Indian regions. There were no significant increases in the cells that likely or very likely experienced bleaching at the regional level in the 1985-2017 period.

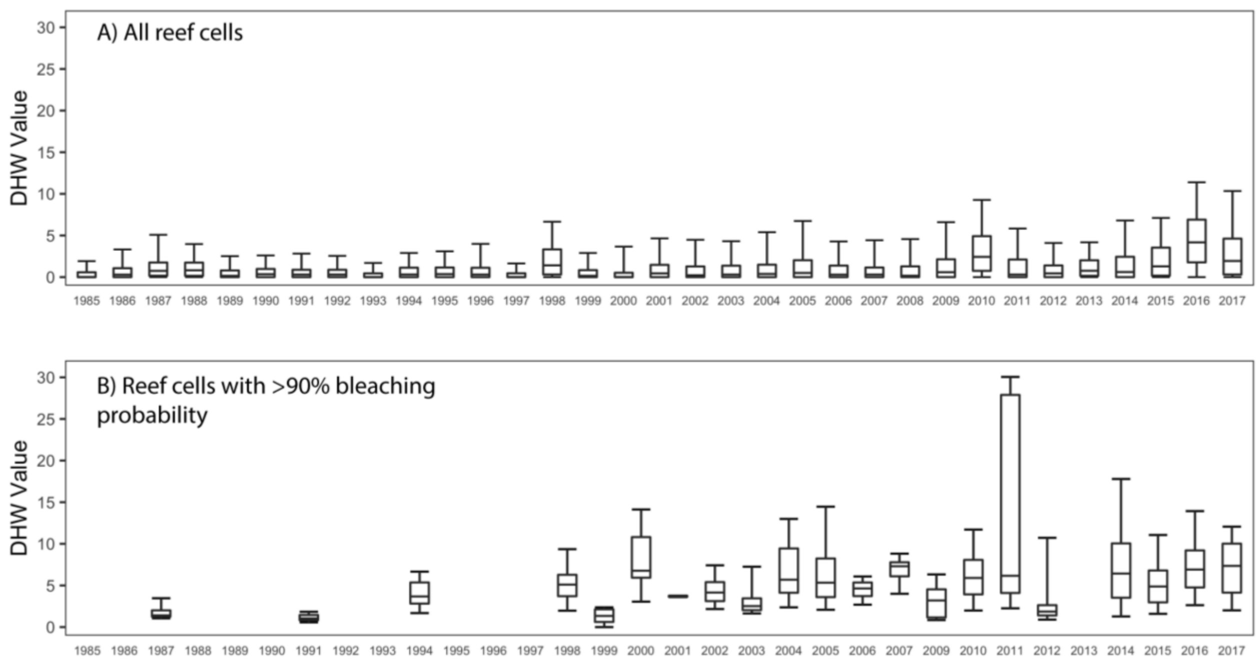

Figure 2-19. Median, quartile range, and 5^{th} and 95^{th} percentile of annual maximum DHW of A) all reef cells and B) reef cells with a bleaching probability above 90% 1985–2017

2.4 Discussion

The updated database provides a comprehensive description of coral bleaching extent over the past few decades. The observational data provides information as far back as 1963; however, because the 0.05° thermal stress data are available from 1985, the interpolation could not be completed for the years 1963-1984. The observational data represents the most comprehensive collection of bleaching reports from around the world. The interpolated bleaching probability data provide a more robust spatial representation of the likelihood of bleaching each year than is possible from observational data alone, which is limited by the geographical biases in reef monitoring. Like version 1, the interpolated data can be used to examine drivers of bleaching and changes in bleaching response over time, and to calibrate global models (Logan et al., 2014).

The updated version of the coral bleaching database includes 205% more reports than version 1. This drastic increase represents a recent surge in both surveying effort and in the extent of bleaching. The amount of new data allowed for providing estimations of probabilities of bleaching occurrence in more regions and years than in version 1, expanding the knowledge on historical coral bleaching events, in particular of the global mass coral bleaching episodes. Because heat stress varies across regions (Heron et al., 2016), it was essential to analyze bleaching extent at the regional level, providing more granularity to this global assessment.

The estimated bleaching probabilities across years in this updated version were higher than those in version 1. This difference can be partially explained because of the additional observational data but can also be related to the method adjustments. For instance, several reports were discarded in version 1 due to location errors (Donner et al., 2017); here, discarding was minimal after the manual corrections and nearest neighbour analysis stages.

The results revealed that an estimate of 56-71% (very likely and likely probability) of the world's reefs experienced bleaching at least once over the 1985-2017 period. This is consistent with the assessed heat stress for global reef locations over the 1985-2017 period by Skirving et al. (2019) (>50%). The assessment of the three global bleaching events showed that while the 1997-1998 and 2009-2010 events saw a similar bleaching extent (15.5-16.1% of reefs very likely experienced bleaching), the 2014-2016 event was between 1.8 and 2.6 times more extensive (28.5% very likely experienced bleaching and 41.6% likely experienced bleaching). These results differ from the findings in the global study by Hughes et al. (2018) that show a comparable extent for the 1997-1998 and 2015-2016 periods (74% and 75%, respectively). However, those estimates are based on whether bleaching was observed at any sites within 100 selected reef regions (e.g., island chains), whereas this analysis is based on data for 0.05° x 0.05° grid cells; the coarser resolution analysis by Hughes et al. (2018) leads to higher probabilities of observed bleaching. The analysis presented here does suggest similar findings to Hughes et al. (2018) in regard to the regular bleaching occurring in the Western Atlantic (Caribbean region here) compared to other regions in the world, although recurrence was not explicitly assessed in this study. The results for the 1997-1998 event showed an estimate of 15.5% of reefs that very likely bleached and 15.6% likely bleached (Figure 2-18), which is comparable with the estimate of 16% of reefs affected in Wilkinson (2008). The comparison between global episodes is consistent with Skirving et al. (2019) and Eakin et al. (2017) that assessed the 2014-2017 episode as the most extensive and probably the most destructive.

The increase in bleaching towards the last part of the period can be explained by the larger increase in severity and extent of heat stress events in the last years of the period (Laufkötter et al., 2020). Yet, the results presented here might be conservative, given that estimates put the extent of heat stress amongst global coral reefs at >50% (Eakin et al., 2017; Skirving et al., 2019). In this study, bleaching extent was calculated considering the likely (>66%) and very likely (>90%) probabilities only. However, the mean of annual-maximum DHW values of cells with bleaching probability >33% were high (> 4°C-weeks; Table 2-6) in most of the analyzed cases, so a lower probability might be more representative of the actual bleaching extent. This is hard to define because the accuracy of results may vary across regions and years.

The results show a relationship between thermal stress and high bleaching probability, with values close to those used as thresholds for Bleaching Alert 1 and Bleaching Alert 2 by CRW. However, the variable for analyzing thermal stress in this study was the annual maximum DHW; this might not be representative of the thermal stress conditions at the time of bleaching occurrence (Donner et al., 2017). The results do not provide clear evidence of the existence of adaptive responses, but there is evidence that the cells that likely experienced bleaching (>90%) saw a more rapid increase in the annual maximum DHW than that of all coral reefs.

Although one of the main motivations for this study was to address existing geographical biases from observational data, this was not completely resolved because the level of surveying effort is linked to the robustness of the interpolation method and results. More geographically spread survey efforts can lead to the interpolation results being more complete or accurate, while little geographic spread or no observations represent a major challenge for the method. For example, 1988 has few bleaching reports and a very low bleaching probability (see Appendix D) the reports in 1996 in the Indian Ocean kriging region could not be interpolated because they were concentrated in a small region.

The differences observed in bleaching probability values for cells with reports between years point to a potential opportunity for a verification technique for the observational data (Suggett & Smith, 2011). For example, for the Caribbean case in 2013 presented in the results (Figure 2-14), reports should be further investigated. This approach could further refine the accuracy of the database, providing more precise information on historical bleaching to inform retrospectice understanding and future research.

Chapter 3: Conclusion

This study provides an updated version of a comprehensive database describing historical mass coral bleaching events from 1963 through 2017. In addition to providing global estimates of bleaching throughout the past few decades, a regional analysis provides new insights regarding the extent of bleaching for all warm-water reef areas split into ten regions of the world. The new observational data from this updated version better informed the spatial modeling, providing more global maps of bleaching probability for recent and past years compared to the first version. This is valuable because it offers more up-to-date information that can be used to enhance our understanding of how coral bleaching has changed through time and can support future research on regional and global scale bleaching.

The assessment of the updated database shows that bleaching extent has increased through time, with a drastic increase in the 2014-2017 period. It also presents the relationship between maximum annual heat stress and coral bleaching and highlights potential uses for future research. The analysis presented here focused on the most widespread bleaching events in history: the three global events that occurred in 1997-1998, 2009-2010, and 2014-2016, providing valuable information about how each of these events affected different regions of the world and how they compare to one another.

While the interpolated data can be very valuable to support analyses on historical and future bleaching events, it is important to acknowledge the limitations of the data. One of the main limitations of this study is the fact that the observational data were not derived using a single standardized bleaching monitoring method; thus what is considered bleaching can vary across methods. Additionally, each monitoring method can have biases that are not accounted for in this study (Vallès et al., 2019). Furthermore, because the interpolation is directly influenced by the density and accuracy of the observational data, the accuracy of the interpolation results may vary across regions and years. Another important consideration is the period of historical events presented here that was defined by the availability of heat stress data (which only starts from 1985), which limits analyses on trends of changes through time considering older events. Finally, the bleaching extent described here does not refer to actual proportions of coral reefs but areas (grid cells) where reefs might occur at varying extents.

This study has the potential to support vast future research. Although here I focused on global bleaching events, there are other periods that are worth assessing separately, including the 2002 and 2011 events in Australia and the 2005 event in the Caribbean. Additionally, the assessment of bleaching severity and frequency presents an important opportunity to create a more complete picture of what bleaching looked like in the past few decades. Finally, the constant update and maintenance of the global bleaching database are crucial to have the most up-to-date data that can ultimately inform management.

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Appendix A: Comparison of different thresholds to define pseudo-absences

Summary statistics of bleaching probabilities for cells with reports for each different threshold

Region	Year	Pseudo-absence threshold	Mean	Median	SD
Caribbean	1987	DHW = 0	0.99881	1	0.00422
Caribbean	1987	DHW <0.25	0.67358	0.88996	0.39167
Caribbean	1987	DHW <0.5	0.55484	0.70117	0.37638
Caribbean	1987	DHW <1	0.28374	0.12477	0.31806
Caribbean	2005	DHW = 0	0.99629	1	0.03054
Caribbean	2005	DHW <0.25	0.98852	0.99988	0.06909
Caribbean	2005	DHW <0.5	0.97701	0.99928	0.10574
Caribbean	2005	DHW <1	0.97199	0.99961	0.12549
East Pacific	1998	DHW = 0	-	-	-
East Pacific	1998	DHW <0.25	0.97472	0.99440	0.05946
East Pacific	1998	DHW <0.5	0.90810	0.94683	0.10772
East Pacific	1998	DHW <1	-	-	-
East Pacific	2015	DHW = 0	-	-	-
East Pacific	2015	DHW <0.25	-	-	-
East Pacific	2015	DHW <0.5	0.99998	1	0.00005
East Pacific	2015	DHW <1	0.99980	1	0.00052
Indian Ocean	2010	DHW = 0	0.92810	0.99939	0.19414
Indian Ocean	2010	DHW <0.25	0.85671	0.97672	0.27017
Indian Ocean	2010	DHW <0.5	0.90217	0.99244	0.20827
Indian Ocean	2010	DHW <1	0.68860	0.80507	0.33811
Indian Ocean	2016	DHW = 0	-	-	-
Indian Ocean	2016	DHW <0.25	0.95391	0.98963	0.08286
Indian Ocean	2016	DHW <0.5	0.92103	0.98640	0.12274
Indian Ocean	2016	DHW <1	0.89919	0.96672	0.13808
Pacific Ocean	2000	DHW = 0	0.95333	1	0.10071
Pacific Ocean	2000	DHW <0.25	0.90126	0.96267	0.15615
Pacific Ocean	2000	DHW <0.5	0.71261	0.85159	0.31190
Pacific Ocean	2000	DHW <1	0.39615	0.45508	0.16791
Pacific Ocean	2016	DHW = 0	0.93355	0.99734	0.17812
Pacific Ocean	2016	DHW <0.25	0.90941	0.99079	0.21369
Pacific Ocean	2016	DHW <0.5	0.87984	0.98682	0.24816
Pacific Ocean	2016	DHW <1	0.82764	0.97224	0.27989

- No result because semivariograms failed to converge

Appendix B: Comparison between version 1 and version 2 of the database

Results of Welch two-sample t-tests for each year and region where indicator kriging was conducted

Year	Region	Mean V1	Mean V2	t-stat	p-value
1987	Caribbean	0.6498852	0.5549954	0.8072611	0.4289981
1988	Caribbean	0.489886	0.0692227	1.9495456	0.1070474
1995	Caribbean	0.009717	0.4525482	-6.3625027	0.0000813*
1997	East Pacific	0.8594734	0.9122989	-1.1009108	0.2758041
1998	Caribbean	0.0000052	0.692704	-23.331146	0*
1998	East Pacific	0.7112802	0.9088689	-8.1229562	0*
1998	Indian Ocean	0.4650539	0.8820459	-14.963371	0*
1998	Pacific Ocean	0.322683	0.7064251	-23.68172	0*
1999	Caribbean	0.6296439	0.3466263	3.6086274	0.0017222*
2000	Pacific Ocean	0.4821943	0.6531391	-3.5659993	0.0004817*
2001	Pacific Ocean	0.8168254	0.0640222	14.1498585	0*
2002	Caribbean	0.2417538	0.0660955	7.7176127	0.0002031*
2002	Indian Ocean	0.2245842	0.2788097	-0.7426841	0.4659617
2002	Pacific Ocean	0.0000904	0.7032597	-41.00425	0*
2003	Caribbean	0.0894908	0.1662759	-1.2163401	0.2463958
2004	Caribbean	0.6666485	0.2836232	5.8389517	0.0000003*
2004	Pacific Ocean	0.8648563	0.2199339	8.0320718	0*
2005	Caribbean	0.890003	0.9770231	-19.719136	0*
2005	Indian Ocean	0.5477842	0.7952154	-4.7181035	0.0000092*
2006	Caribbean	0.7562746	0.7070138	3.2796662	0.0010813*
2007	Caribbean	0.0691534	0.506591	-17.418555	0*
2007	Indian Ocean	0.2565017	0.3776686	-1.3629354	0.1845871
2007	Pacific Ocean	0.6204642	0.2292471	4.5915236	0.0000813*
2008	Caribbean	0.8059882	0.2069577	7.3562717	0.0002405*
2008	Pacific Ocean	0.0117727	0.0614809	-4.0915975	0.0003056*
2009	Caribbean	0.4210708	0.4606641	-1.0128609	0.3193843
2009	Pacific Ocean	0.0591297	0.1030499	-1.9341716	0.0589201
2010	Indian Ocean	0.6752651	0.9167018	-7.1590388	0*
2010	Pacific Ocean	0.1435075	0.8782891	-32.568945	0*

* Significantly different ($p < 0.05$)

Appendix C: Regional thermal stress for reef cells with different bleaching probabilities

Mean annual maximum DHW values for groups with different bleaching probabilities in each global event and in the entire assessed period (1985-2017) by region

Australia

Mean Annual maximum DHW (°C-weeks)	All cells	>90%	>66–90%	>50–66%	>33–50%	>10–33%	≤10
All years	2.09*	6.66*	5.19	5.17	4.75*	2.97*	1.49*
1997-1998	0.91*	3.82*	2.29	1.94	2.19	1.61*	0.5*
2009-2010	2.88*	-	4.8	4.94	7.17	4.8	2.14*
2014-2016	2.66*	7.57*	6.7*	4.74*	3.83*	1.7*	1.22*

Caribbean

Mean Annual maximum DHW (°C-weeks)	All cells	>90%	>66–90%	>50–66%	>33–50%	>10–33%	≤10
All years	1.98*	5.6*	5.23*	3.9*	3.73*	2.82*	0.94*
1997-1998	2.98*	4.91*	4.53*	4.05*	2.98*	2.68*	1.09*
2009-2010	3.3*	5.73*	7.21	4.97	5.38	2.67*	1.46*
2014-2016	2.38*	5.2*	3.58*	3.09*	3.85*	2.68*	0.99*

South East Asia

Mean Annual maximum DHW (°C-weeks)	All cells	>90%	>66–90%	>50–66%	>33–50%	>10–33%	≤10
All years	1.28*	6.46*	5.49*	4.12*	3.96*	3.69*	0.88*
1997-1998	1.23*	5.73*	4.12*	3.06	3.22	2.38*	0.52*
2009-2010	2.43*	6.2*	4.96*	4.13*	3.63	3.75	1.15*
2014-2016	2.47*	7.33*	7.02*	4.74*	4.31*	4.09*	1.49*

W Indian

Mean Annual maximum DHW (°C-weeks)	All cells	>90%	>66–90%	>50–66%	>33–50%	>10–33%	≤10
All years	1.42*	5.44*	4.21*	3.05*	2.47*	1.12*	0.66*
1997-1998	3.28*	4.27*	3.67*	2.48*	1.77*	1.49*	0.63*
2009-2010	2.1*	3.97	4.12	3	3.44	3.15	1.56*
2014-2016	3.19	6.35*	4.98*	4.14	3.3	1.18*	0.47*

Polynesia

Mean Annual maximum DHW (°C-weeks)	All cells	>90%	>66–90%	>50–66%	>33–50%	>10–33%	≤10
All years	1.08*	6.69*	5.24*	3.88*	3.08	3.24	0.58*
1997-1998	0.46*	-	3.39	3.18	2.12*	1.52*	1.52*
2009-2010	0.77*	3.18	3.71	3.67	1.28	1.26	0.69*
2014-2016	3.01*	6.68*	4.99	4.53	4.76	4.08*	1.66*

C Indian

Mean Annual maximum DHW (°C-weeks)	All cells	>90%	>66–90%	>50–66%	>33–50%	>10–33%	≤10
All years	1.49*	6.44*	4.05*	3.67*	2.42*	1.03*	0.6*
1997-1998	3.39	4.82*	3.31	2.6*	1.44	1.36	1.18
2009-2010	1.94*	6.8*	4.26*	2.21*	2.18*	3.05*	0.72*
2014-2016	4.58*	7.86*	5.26*	5.64*	3.63	3.19	1.77*

Micronesia

Mean Annual maximum DHW (°C-weeks)	All cells	>90%	>66–90%	>50–66%	>33–50%	>10–33%	≤10
All years	1.76*	8.60*	9.71*	5.73	4.11*	5.60	1.02*
1997-1998	0.74*	5.59*	4.09*	1.49*	12.66*	1.98*	0.42*
2009-2010	2.03*	7.31*	4.71	3.23*	4.18	8.38	1.52*
2014-2016	4.55*	10.41*	10.73*	5.80*	3.04	4.52	2.43*

Melanesia

Mean Annual maximum DHW (°C-weeks)	All cells	>90%	>66–90%	>50–66%	>33–50%	>10–33%	≤10
All years	1.73*	7.69*	6.08*	4.43	4.24	3.79*	1.40*
1997-1998	0.50*	-	6.29*	-	-	1.54*	0.47*
2009-2010	1.73*	-	-	2.59	2.71	2.75	1.56*
2014-2016	3.86*	7.97*	7.50*	5.27	6.59	4.96*	2.58*

Middle East

Mean Annual maximum DHW (°C-weeks)	All cells	>90%	>66–90%	>50–66%	>33–50%	>10–33%	≤10
All years	1.92*	7.04*	5.32	5.69	6.03	2.90*	1.25*
1997-1998	3.55*	8.09*	4.17	4.82	3.85*	2.95*	1.82*
2009-2010	2.55*	7.05*	5.14	5.92	6.81	4.26*	1.20*
2014-2016	3.65*	5.90	5.65	6.82	7.16	6.15	2.45*

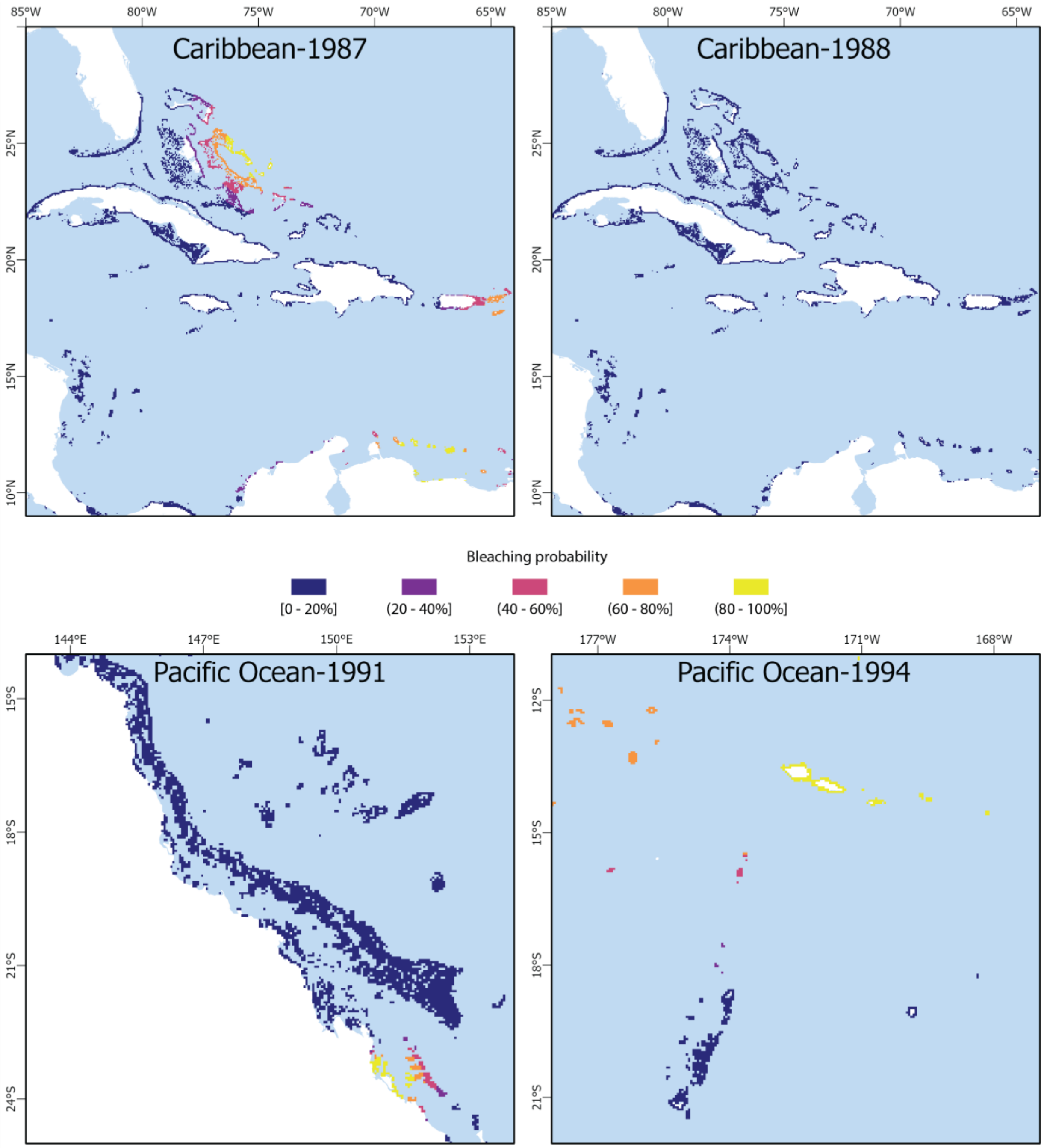
East Pacific

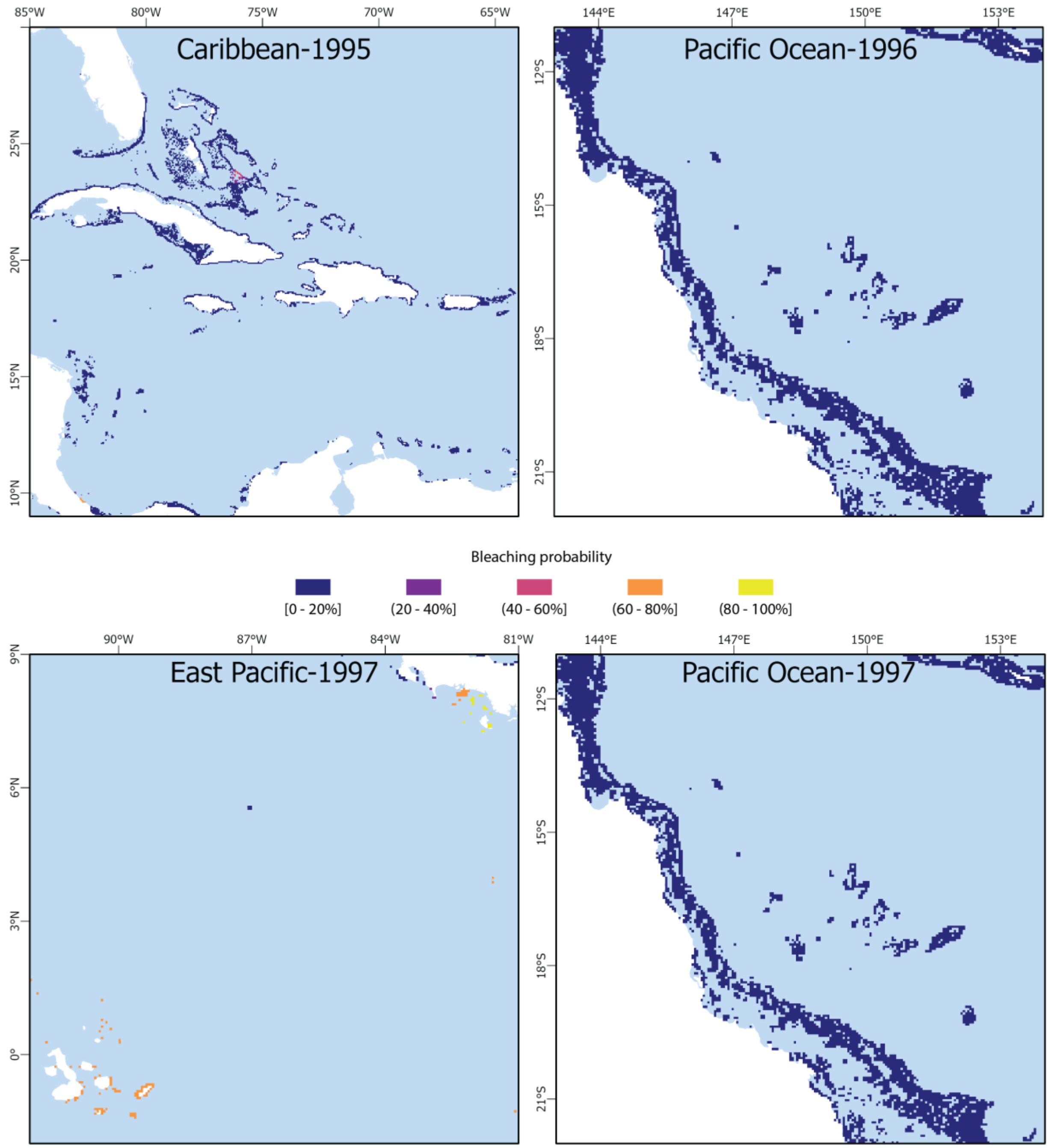
Mean Annual maximum DHW (°C-weeks)	All cells	>90%	>66–90%	>50–66%	>33–50%	>10–33%	≤10
All years	7.78	13.31*	8.11	5.47	5.39	2.09*	0.69*
1997-1998	13.70*	22.93*	7.34*	0.41	0.13	0.00	0.00
2009-2010	0.12	-	-	-	-	-	0.12
2014-2016	5.06	4.78	8.94	6.92	5.56	2.51*	0.66*

*Statistically significant ($p < 0.05$) from all bleaching probability groups and positive relationship between DHW and bleaching probability (higher probability group has higher mean DHW)

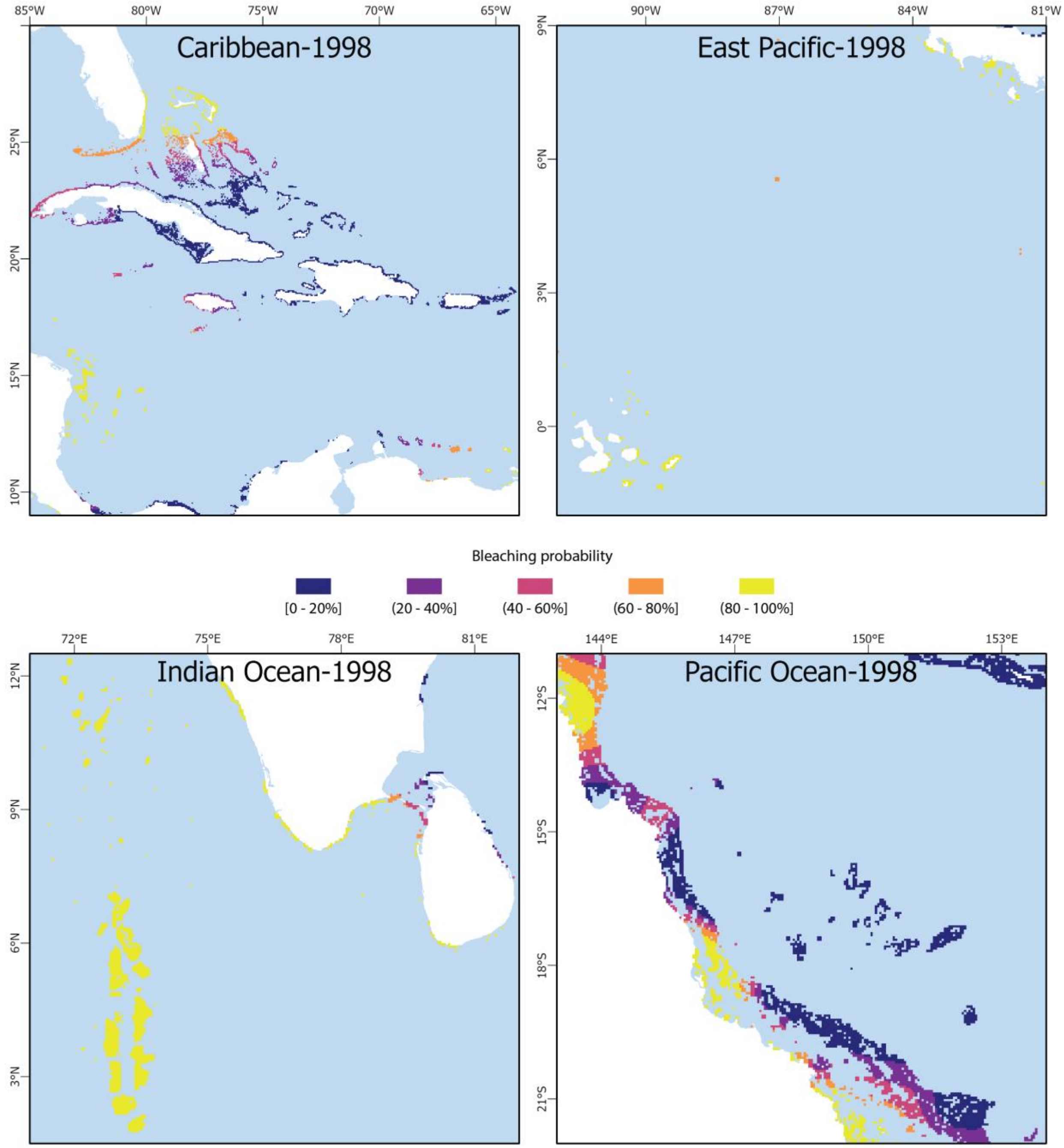
Appendix D: Maps of bleaching probability – example locations

Examples of each output from the spatial interpolation showing bleaching probability

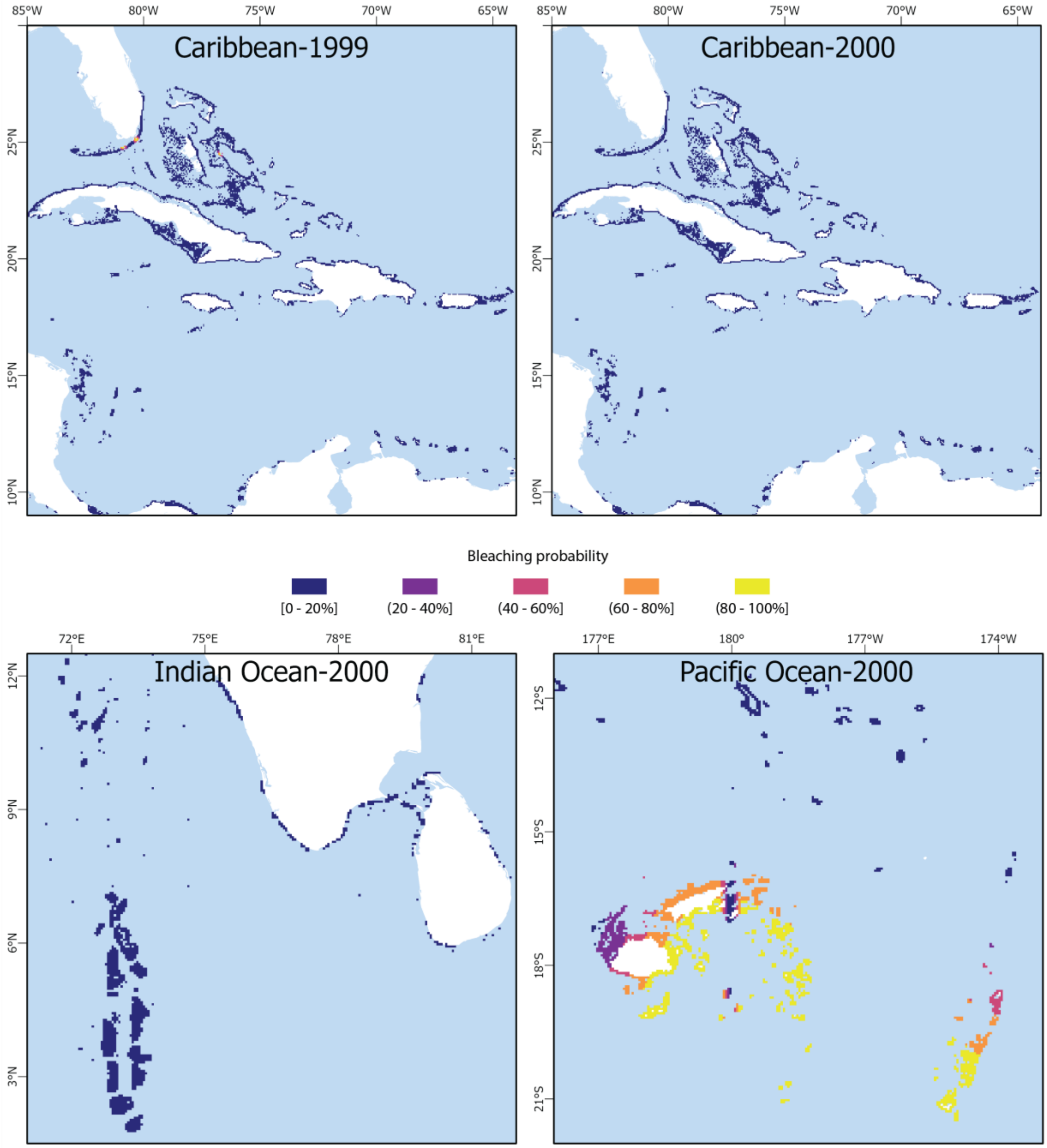


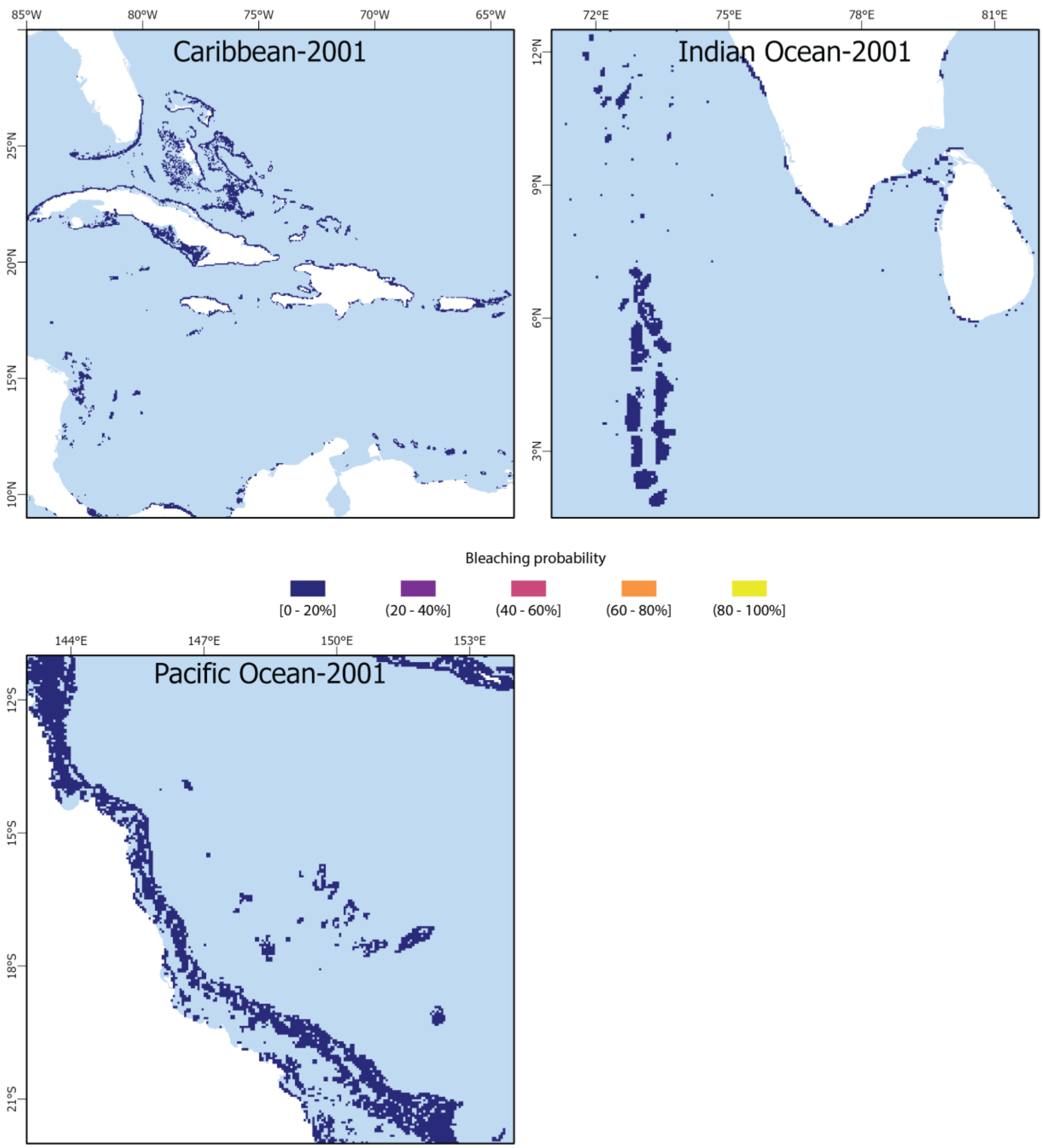


Caribbean-1995
Pacific Ocean-1996
East Pacific-1997
Pacific Ocean-1997
85°W
80°W
75°W
70°W
65°W
25°N
20°N
15°N
10°N
144°E
147°E
150°E
153°E
12°S
15°S
18°S
21°S
90°W
87°W
84°W
81°W
9°N
6°N
3°N
0°
Bleaching probability
[0 - 20%]
(20 - 40%]
(40 - 60%]
(60 - 80%]
(80 - 100%]

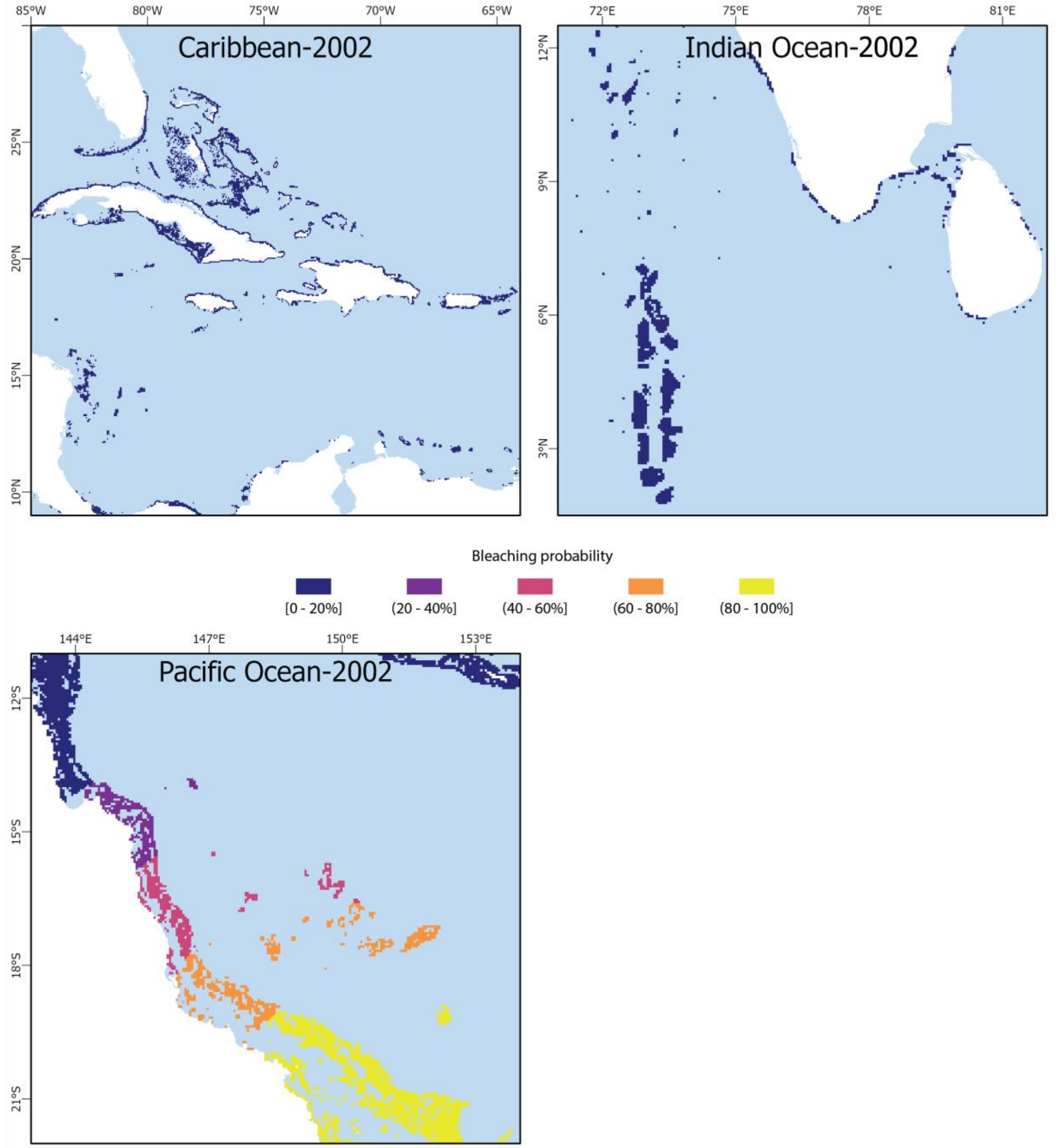


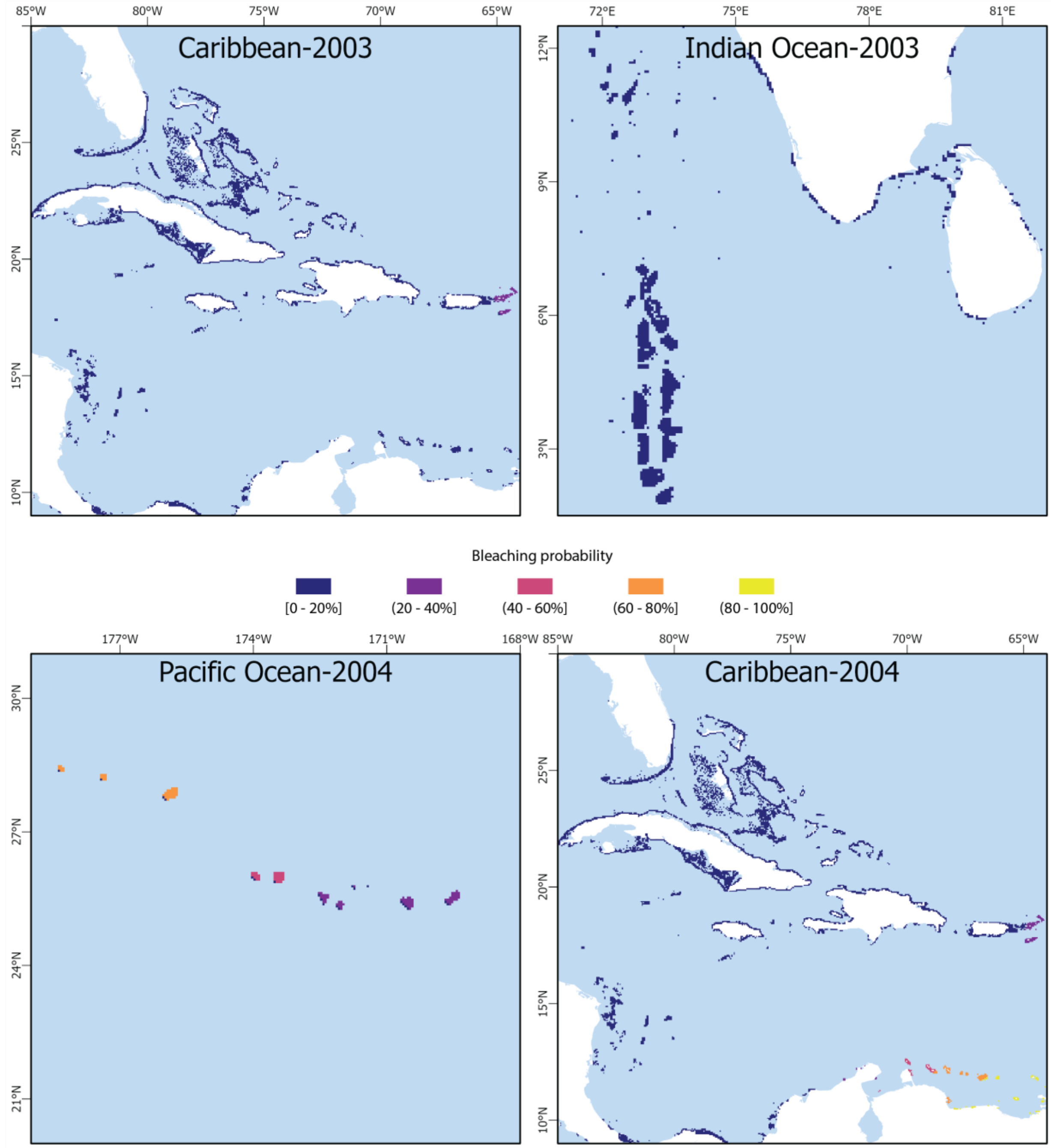
Caribbean-1998
East Pacific-1998
Indian Ocean-1998
Pacific Ocean-1998
85°W
80°W
75°W
70°W
65°W
90°W
87°W
84°W
81°W
72°E
75°E
78°E
81°E
144°E
147°E
150°E
153°E
25°N
20°N
15°N
10°N
9°N
6°N
3°N
0°
12°N
12°S
15°S
18°S
21°S
Bleaching probability
[0 - 20%]
(20 - 40%]
(40 - 60%]
(60 - 80%]
(80 - 100%]


Caribbean-1999
Caribbean-2000
85°W
80°W
75°W
70°W
65°W
25°N
20°N
15°N
10°N
Bleaching probability
[0 - 20%]
(20 - 40%]
(40 - 60%]
(60 - 80%]
(80 - 100%]
Indian Ocean-2000
72°E
75°E
78°E
81°E
12°N
9°N
6°N
3°N
Pacific Ocean-2000
177°E
180°
177°W
174°W
12°S
15°S
18°S
21°S

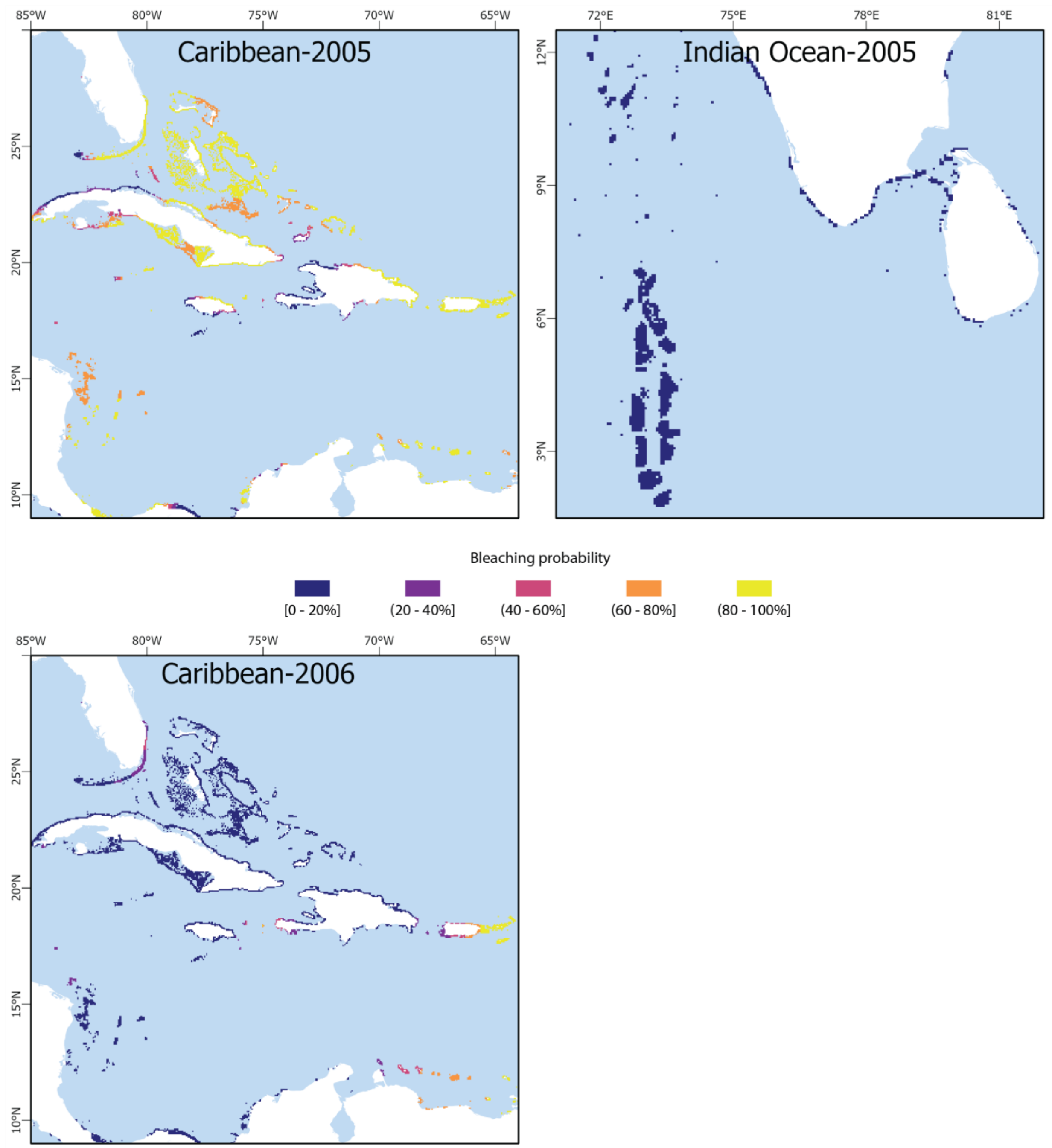


Caribbean-2001
85°W
80°W
75°W
70°W
65°W
25°N
20°N
15°N
10°N
Indian Ocean-2001
72°E
75°E
78°E
81°E
12°N
9°N
6°N
3°N
Bleaching probability
[0 - 20%]
(20 - 40%]
(40 - 60%]
(60 - 80%]
(80 - 100%]
Pacific Ocean-2001
144°E
147°E
150°E
153°E
12°S
15°S
18°S
21°S

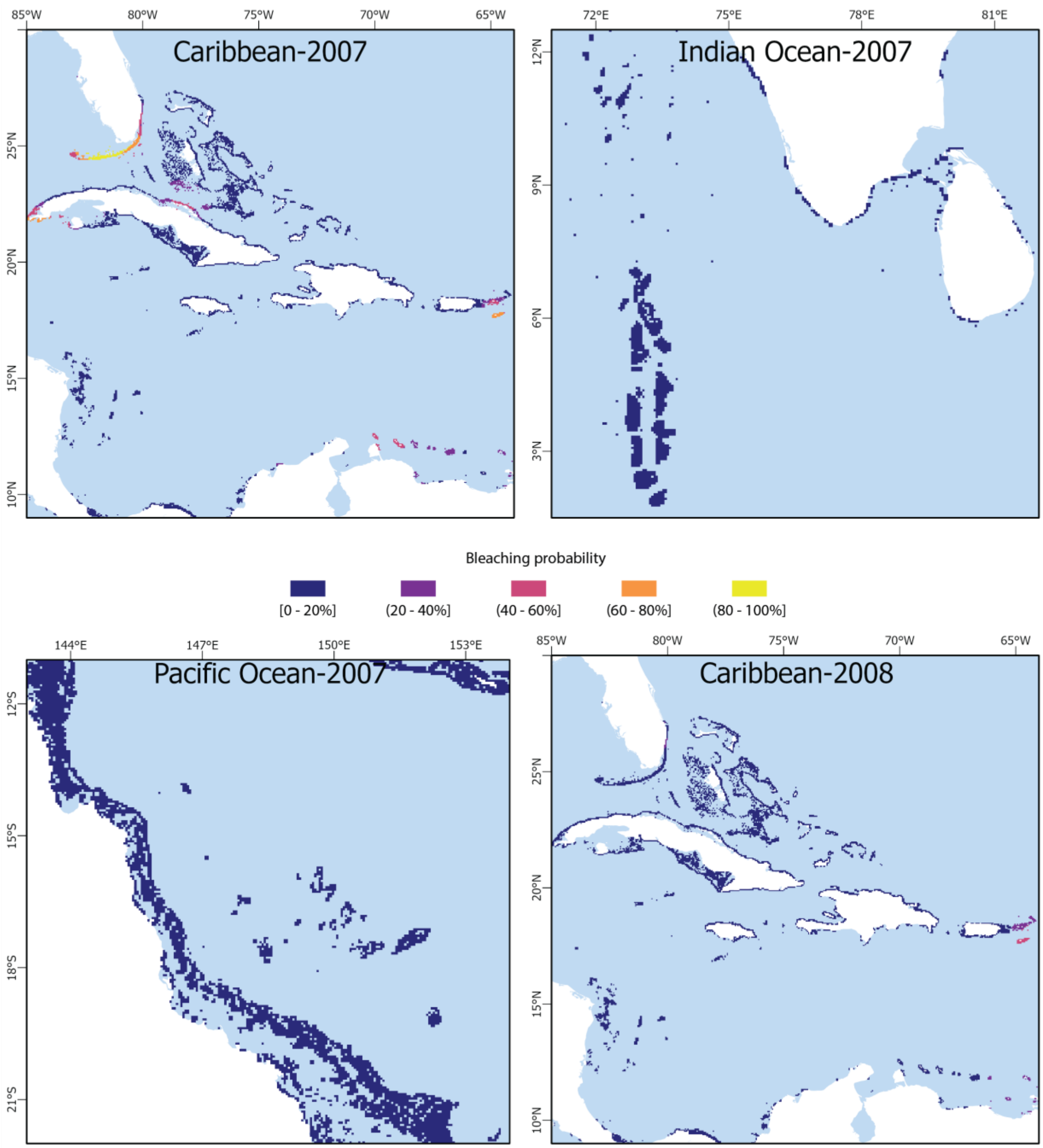

Caribbean-2002
85°W
80°W
75°W
70°W
65°W
25°N
20°N
15°N
10°N
Indian Ocean-2002
72°E
75°E
78°E
81°E
12°N
9°N
6°N
3°N
Bleaching probability
[0 - 20%]
(20 - 40%]
(40 - 60%]
(60 - 80%]
(80 - 100%]
Pacific Ocean-2002
144°E
147°E
150°E
153°E
12°S
15°S
18°S
21°S

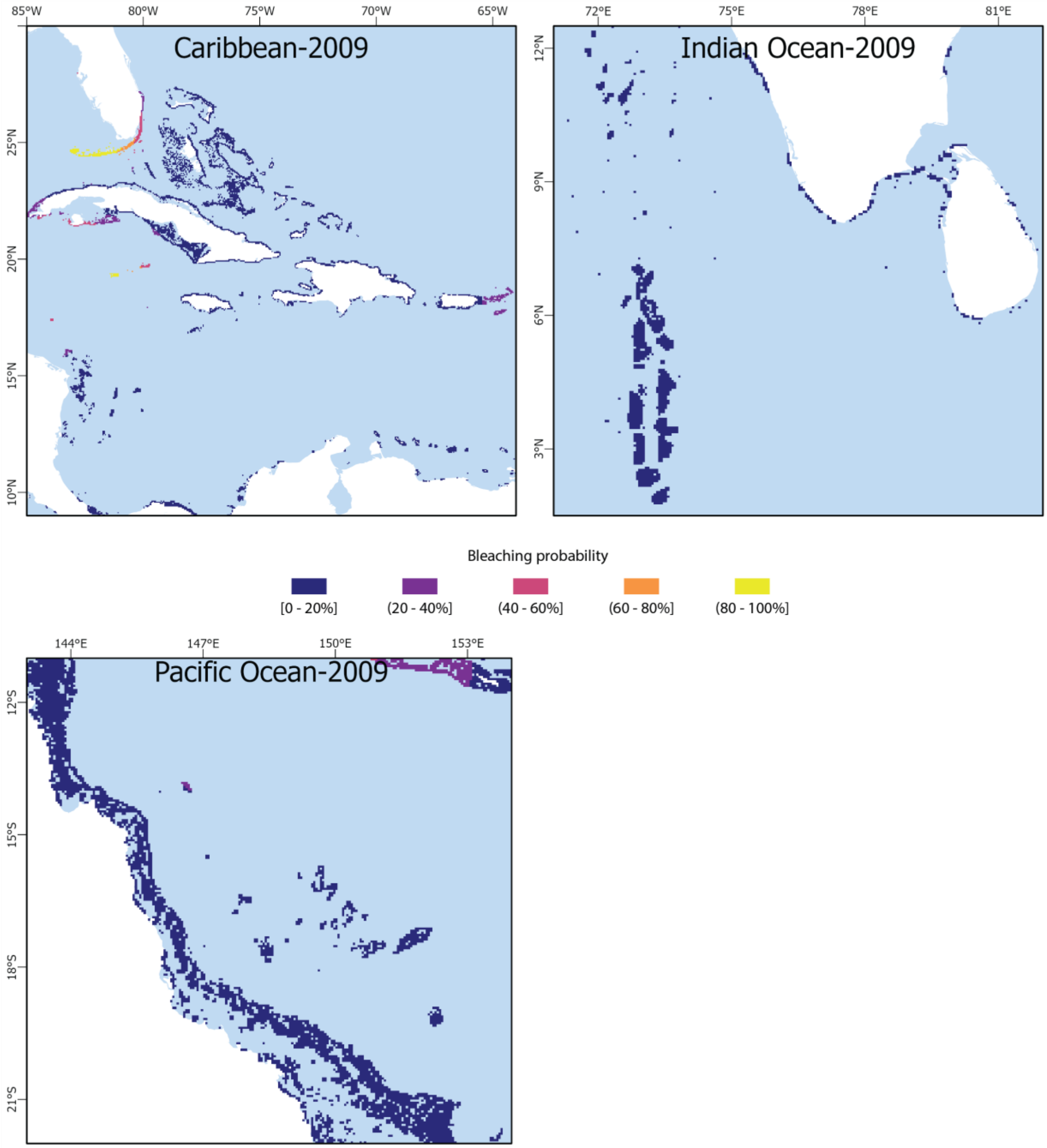


Caribbean-2003
Indian Ocean-2003
Pacific Ocean-2004
Caribbean-2004
85°W
80°W
75°W
70°W
65°W
72°E
75°E
78°E
81°E
177°W
174°W
171°W
168°W
25°N
20°N
15°N
10°N
12°N
9°N
6°N
3°N
30°N
27°N
24°N
21°N
Bleaching probability
[0 - 20%]
(20 - 40%]
(40 - 60%]
(60 - 80%]
(80 - 100%]

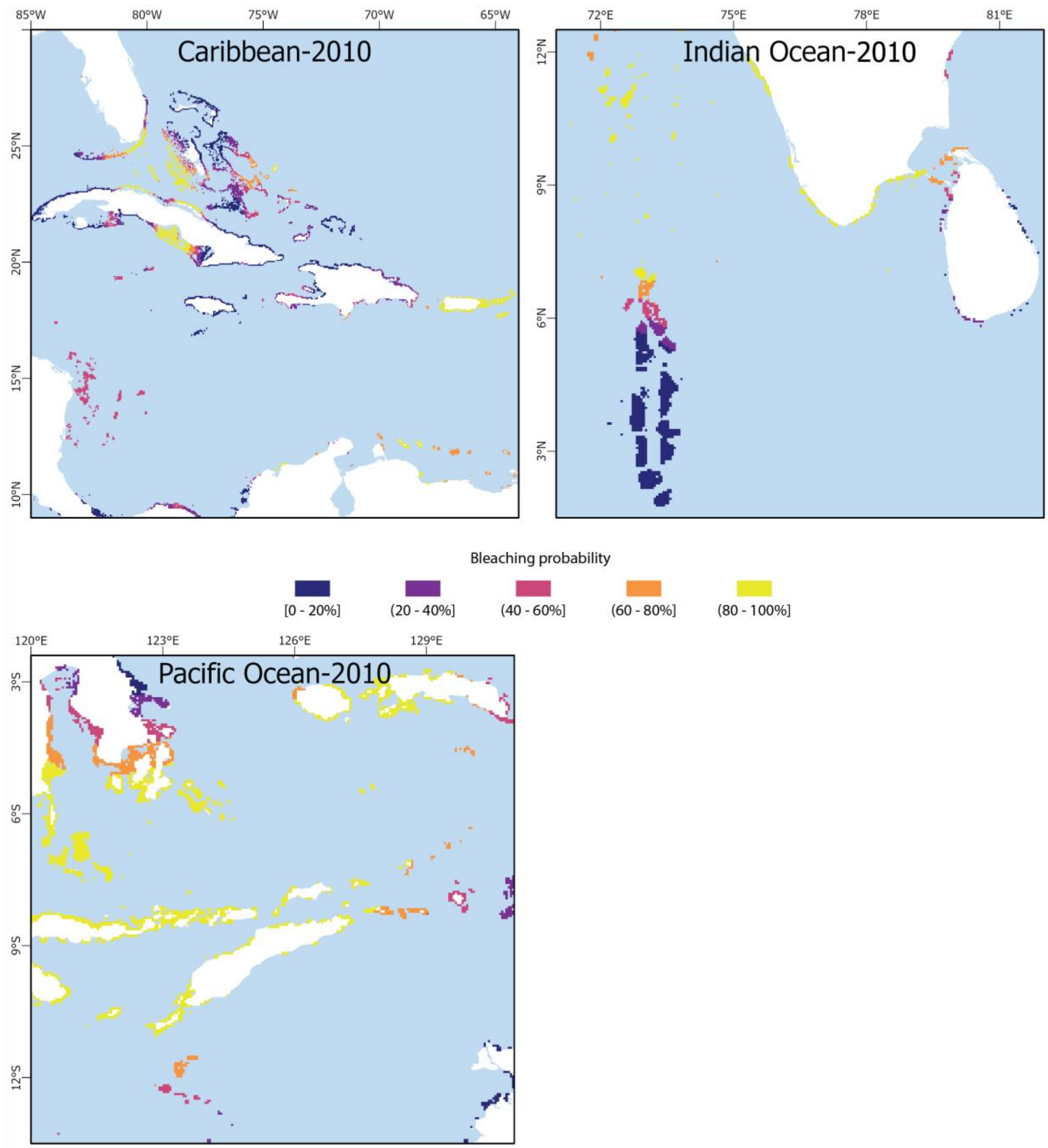


Caribbean-2005
85°W
80°W
75°W
70°W
65°W
25°N
20°N
15°N
10°N
Indian Ocean-2005
72°E
75°E
78°E
81°E
12°N
9°N
6°N
3°N
Bleaching probability
[0 - 20%]
(20 - 40%]
(40 - 60%]
(60 - 80%]
(80 - 100%]
Caribbean-2006

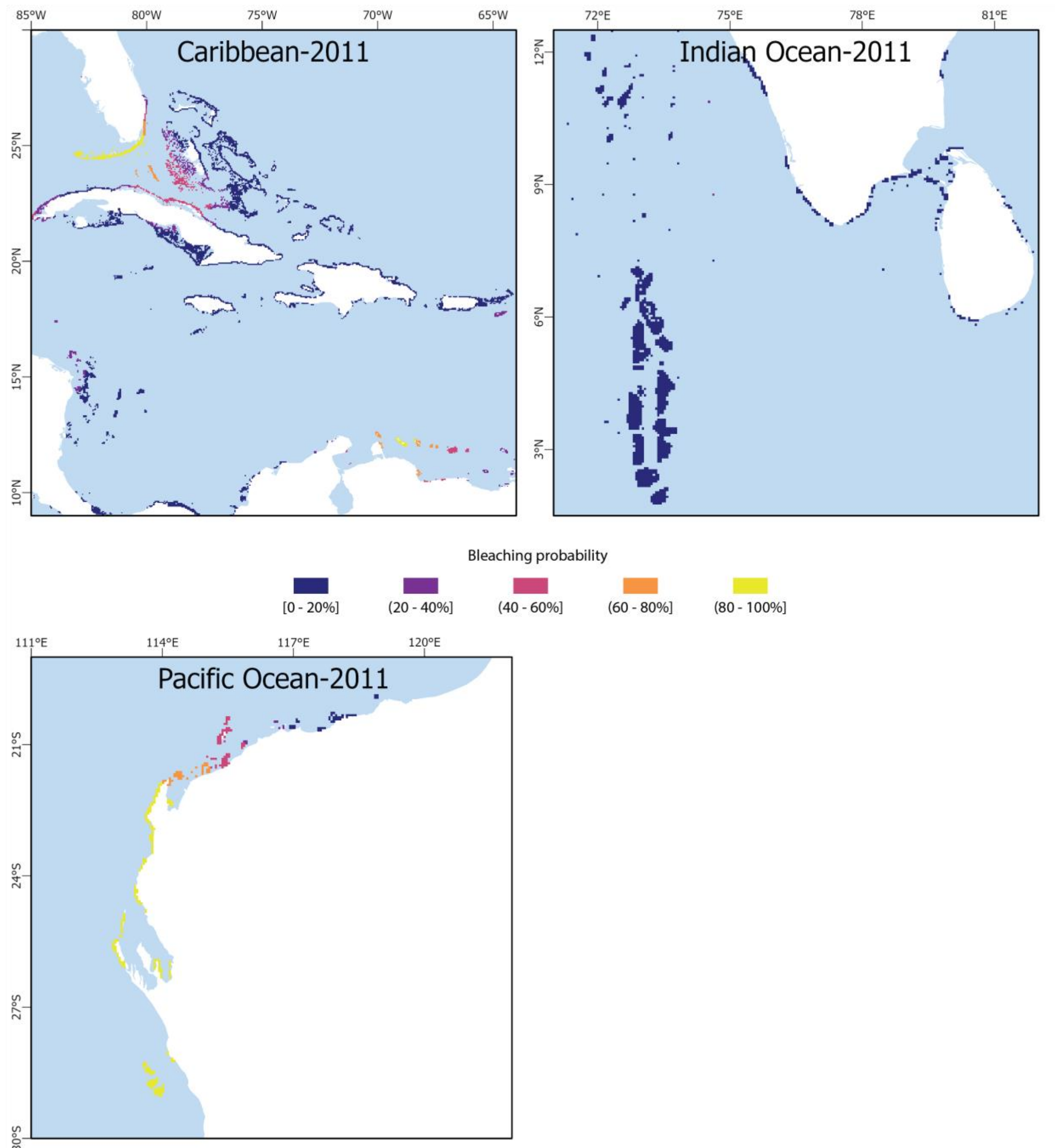

Caribbean-2007
85°W
80°W
75°W
70°W
65°W
25°N
20°N
15°N
10°N
Indian Ocean-2007
72°E
75°E
78°E
81°E
12°N
9°N
6°N
3°N
Bleaching probability
[0 - 20%]
(20 - 40%]
(40 - 60%]
(60 - 80%]
(80 - 100%]
Pacific Ocean-2007
144°E
147°E
150°E
153°E
12°S
15°S
18°S
21°S
Caribbean-2008
85°W
80°W
75°W
70°W
65°W
25°N
20°N
15°N
10°N

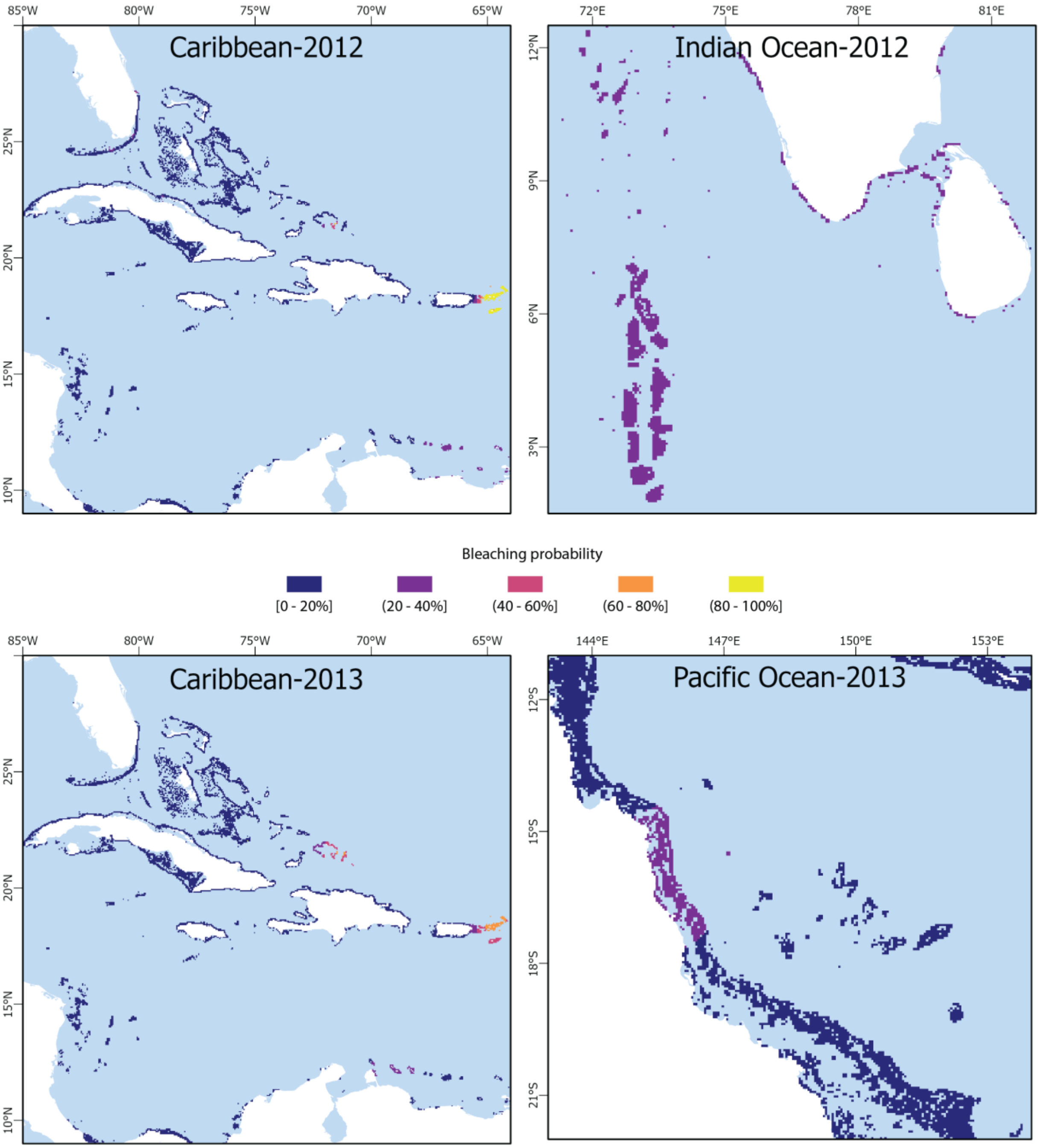


Caribbean-2009
85°W
80°W
75°W
70°W
65°W
25°N
20°N
15°N
10°N
Indian Ocean-2009
72°E
75°E
78°E
81°E
12°N
9°N
6°N
3°N
Bleaching probability
[0 - 20%]
(20 - 40%]
(40 - 60%]
(60 - 80%]
(80 - 100%]
Pacific Ocean-2009
144°E
147°E
150°E
153°E
12°S
15°S
18°S
21°S

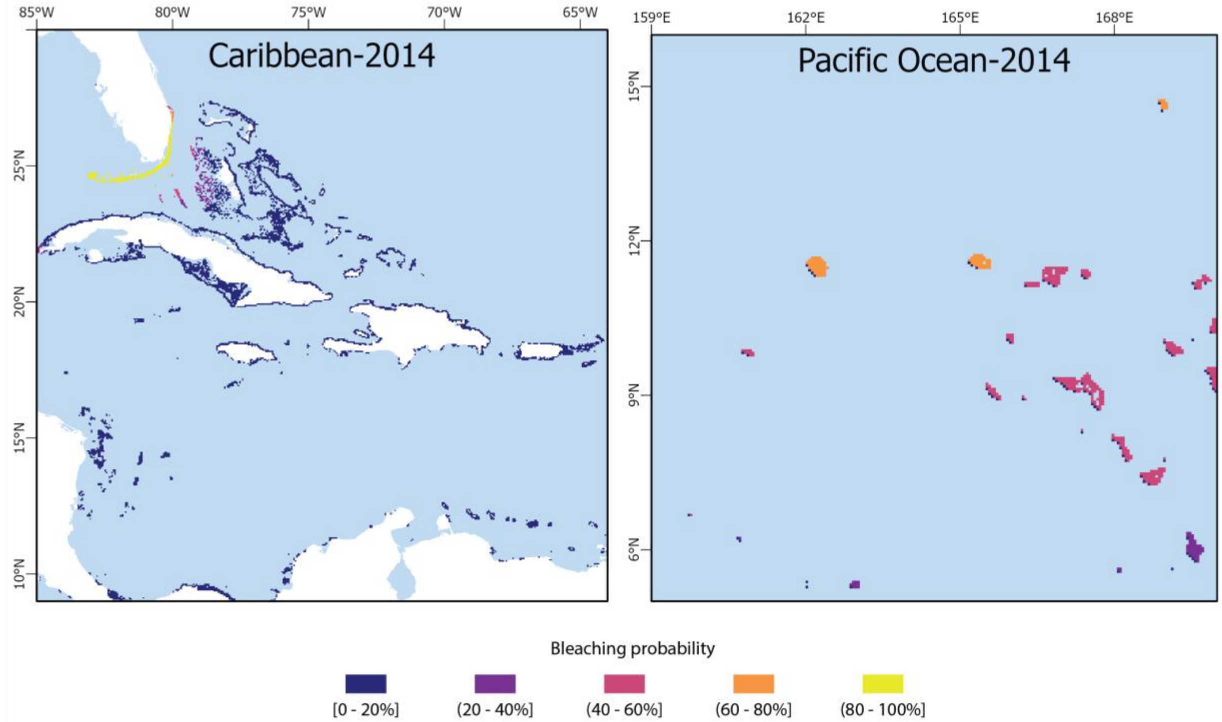


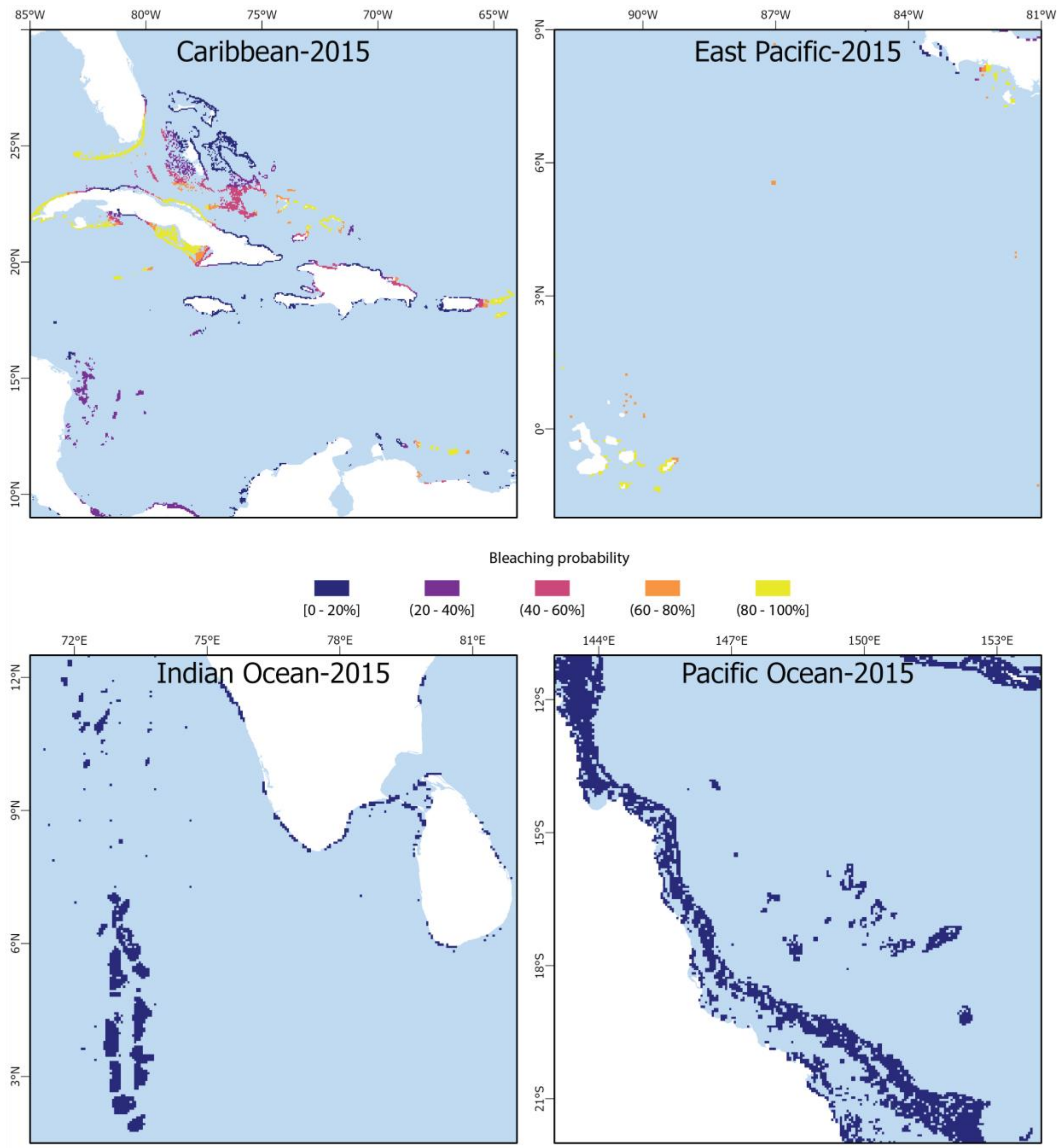
Caribbean-2010
85°W
80°W
75°W
70°W
65°W
25°N
20°N
15°N
10°N
Indian Ocean-2010
72°E
75°E
78°E
81°E
12°N
9°N
6°N
3°N
Bleaching probability
[0 - 20%]
(20 - 40%]
(40 - 60%]
(60 - 80%]
(80 - 100%]
Pacific Ocean-2010
120°E
123°E
126°E
129°E
3°S
6°S
9°S
12°S


Caribbean-2011
85°W
80°W
75°W
70°W
65°W
25°N
20°N
15°N
10°N
Indian Ocean-2011
72°E
75°E
78°E
81°E
12°N
9°N
6°N
3°N
Bleaching probability
[0 - 20%]
(20 - 40%]
(40 - 60%]
(60 - 80%]
(80 - 100%]
Pacific Ocean-2011
111°E
114°E
117°E
120°E
21°S
24°S
27°S
30°S

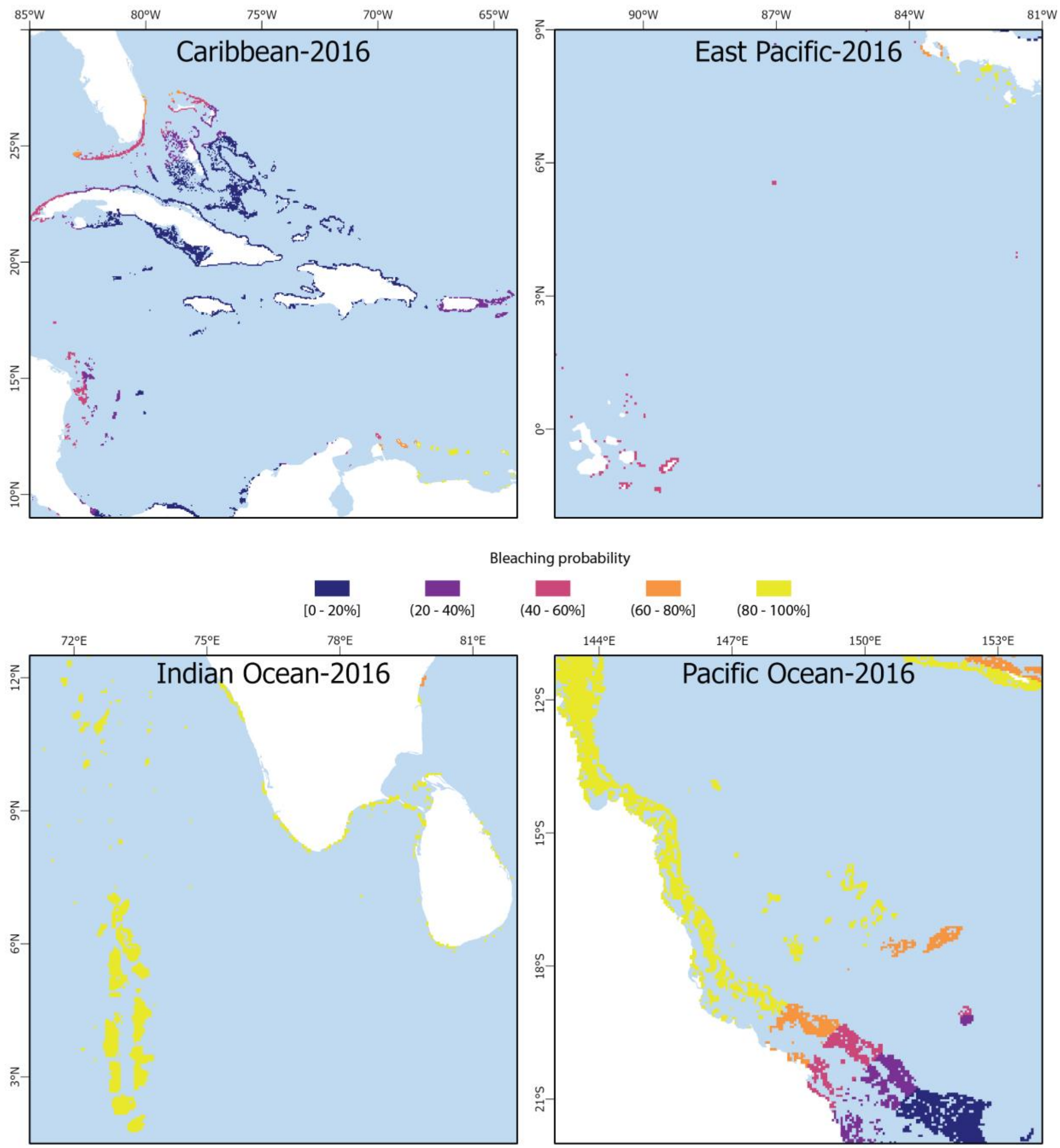


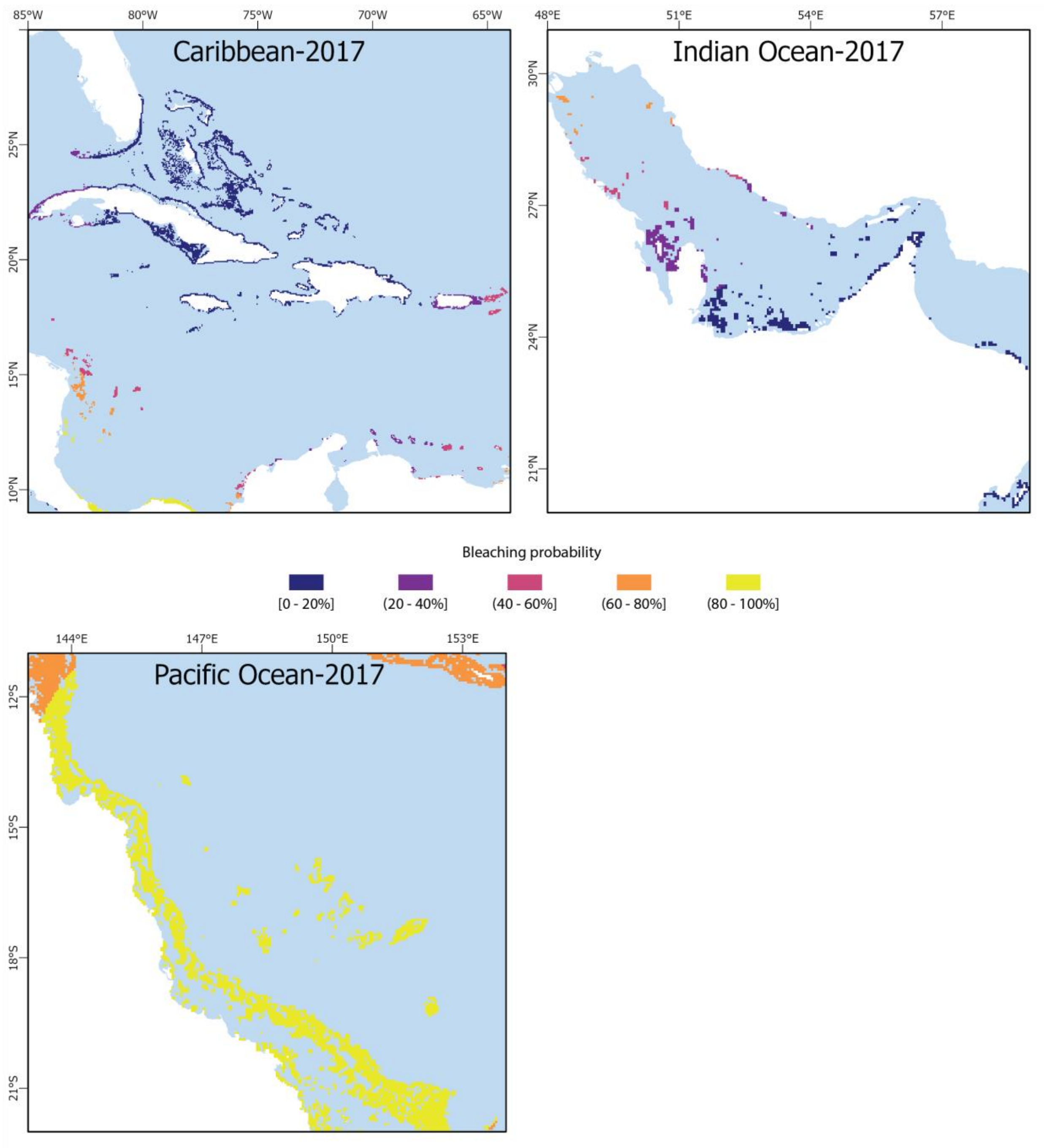
Caribbean-2012
Indian Ocean-2012
Bleaching probability
[0 - 20%]
(20 - 40%]
(40 - 60%]
(60 - 80%]
(80 - 100%]
Caribbean-2013
Pacific Ocean-2013
85°W
80°W
75°W
70°W
65°W
72°E
75°E
78°E
81°E
144°E
147°E
150°E
153°E
25°N
20°N
15°N
10°N
12°N
9°N
6°N
3°N
12°S
15°S
18°S
21°S


85°W
80°W
75°W
70°W
65°W
25°N
20°N
15°N
10°N
Caribbean-2014
159°E
162°E
165°E
168°E
15°N
12°N
9°N
6°N
Pacific Ocean-2014
Bleaching probability
[0 - 20%]
(20 - 40%]
(40 - 60%]
(60 - 80%]
(80 - 100%]



Caribbean-2015
85°W
80°W
75°W
70°W
65°W
25°N
20°N
15°N
10°N
East Pacific-2015
90°W
87°W
84°W
81°W
9°N
6°N
3°N
0°
Bleaching probability
[0 - 20%]
(20 - 40%]
(40 - 60%]
(60 - 80%]
(80 - 100%]
Indian Ocean-2015
72°E
75°E
78°E
81°E
12°N
9°N
6°N
3°N
Pacific Ocean-2015
144°E
147°E
150°E
153°E
12°S
15°S
18°S
21°S


Caribbean-2016
East Pacific-2016
Bleaching probability
[0 - 20%]
(20 - 40%]
(40 - 60%]
(60 - 80%]
(80 - 100%]
Indian Ocean-2016
Pacific Ocean-2016
85°W
80°W
75°W
70°W
65°W
90°W
87°W
84°W
81°W
25°N
20°N
15°N
10°N
9°N
6°N
3°N
0°
72°E
75°E
78°E
81°E
144°E
147°E
150°E
153°E
12°N
9°N
6°N
3°N
12°S
15°S
18°S
21°S


Caribbean-2017
85°W
80°W
75°W
70°W
65°W
25°N
20°N
15°N
10°N
Indian Ocean-2017
48°E
51°E
54°E
57°E
30°N
27°N
24°N
21°N
Bleaching probability
[0 - 20%]
(20 - 40%]
(40 - 60%]
(60 - 80%]
(80 - 100%]
Pacific Ocean-2017
144°E
147°E
150°E
153°E
12°S
15°S
18°S
21°S