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COMPARATIVE ANALYSIS
OF RISKS FACED BY **THE WORLD'S CORAL REEFS**

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INTRODUCTION

INTRODUCTION

Coral reefs face a variety of increasing and potentially severe threats, and reef managers and decision makers need to understand their impact to properly allocate scarce resources and to implement appropriate actions such as prevention, risk reduction, and repairs. The impact risks have varies greatly depending on the severity of the damage, the type of damage (physical or biological), the spatial scale of the impact, and how often risks may occur.

This report presents the results of the analysis of the severity of the impacts caused by risks faced by coral reefs to compare their relative importance globally and regionally; risks were categorized by scale of the impact and frequency of the events to better comprehend their relevance.

The results will help decision-makers and reef managers understand the relative importance of the risks reefs face. The analysis only included risks which occur as events, with a clear beginning and end to fit in our methodology. We assessed 16 risks, naturally occurring events such as cyclones, tsunamis, diseases, and bleaching, as well as events caused by humans such as ship groundings, oil spills, and scuba diving. The study did not include chronic stressors such as water pollution and overfishing because they cannot be assessed using this approximation.

We conducted the analysis with data published literature in scientific journals and technical reports. We estimated the severity impacts using two widely reported indicators: live coral cover and rugosity. We characterized the different risks, the type of impacts they have, and the spatial scale of the events. To estimate the impact, we compared the reef condition before and after an event of any risk type. We also assessed the severity of cyclones and bleaching by magnitude or intensity of the event (Fabina et al., 2015; De'Ath et al., 2012; Hughes et al., 2018), as the impacts vary greatly and are correlated to the intensity. We also explored the severity of the damage across marine realms (sensu Spalding, 2007) to assess if the impact varies by region. We classified and assessed the risks according to the spatial extent of impact, ranging from local events (e.g., ship grounding) to large-scale events (e.g., cyclone) and by order of frequency (Nyström and Folke (2001).

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UNDERSTANDING THE RISKS FACED BY REEFS

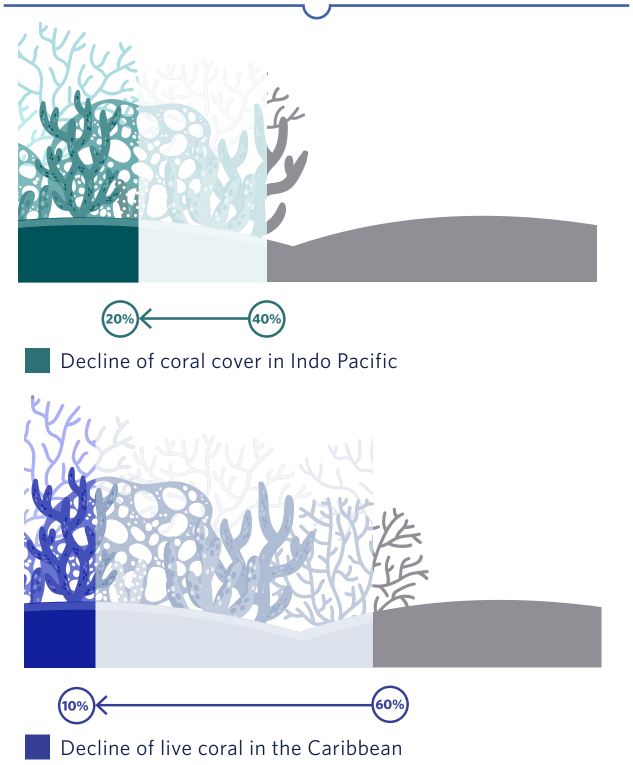
UNDERSTANDING THE RISKS FACED BY REEFS

Coral reefs are the most biodiverse marine ecosystems in the world – and they provide key ecosystem services that support human well-being, such as coastal protection, habitat for commercially important species, and sediment production (Moberg and Folke, 1999). These benefits are linked to the capacity of scleractinian corals to create complex three-dimensional structures by accumulating calcium carbonate (Woodhead et al., 2019). But increasing pressures on these ecosystems have led to rapid declines in reef health around the world in recent decades (Pandolfi et al., 2003; Bellwood et al., 2004): live coral cover declined from 40% to 20% in the Indo-Pacific (Bruno and Selig, 2007) and from 60% to 10% in the Caribbean, which included the significant loss of the reef-building coral genus *Acropora* (Jackson et al., 2014). As these live scleractinian corals decline, reefs lose topographic complexity and undergo major changes in community composition that can result in declining ecological functions and compromised ecosystem services (Alvarez-Filip et al., 2011a; Graham et al., 2014). Yet despite widespread coral decline and the many risks affecting coral reefs, there are still examples of reefs in excellent conditions (i.e., high coral cover, reef complexity, and high fish biomass) (Cinner et al., 2016; Lester et al., 2020). Whether these reefs will prevail depends on the prevalence of risks, or stressors, they face.

A variety of stressors have been responsible for reef degradation, encompassing anthropogenic activities such as water pollution and overfishing (Zaneveld et al., 2016), natural events such as cyclones (Hughes and Conell, 1999; Mellin et al., 2019), coral diseases (Hughes et al., 2010) and outbreaks of crown-of-thorns starfish or *Acanthaster* (Vercelloni et al., 2017), as well as natural phenomena exacerbated by human activities such as coral bleaching (Carpenter et al., 2008; Hughes et al., 2018), ocean acidification (Anthony et al., 2011), eutrophication (Brodie et al., 2005; Vega-Thurber et al., 2014), and storms (Ateweberhan et al., 2013; Patricola and Wehner, 2018).

Given the high biodiversity importance of coral reefs and the ecosystems services they provide (Spalding et al., 2017; Woodhead et al., 2019), understanding the impact of different stressors on reef integrity (coral cover and reef complexity) would help reef managers: 1) decide where and how to invest scarce resources to insure, protect and restore coral reefs (Secaira Fajardo et al., 2019); 2) prioritize management activities to mitigate their impacts; and, 3) if signs of stressors are detected early, take preventative action (Ban et al., 2014).

Coral reef ecosystems have declined rapidly in the last decades



Decline estimates from Jackson et al., 2014 and Bruno and Selig, 2007

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FRAMEWORK TO ASSESS RISKS FACED BY REEFS

FRAMEWORK TO ASSESS RISKS FACED BY REEFS

TYPE OF DISTURBANCE CAUSED BY THE STRESSORS

Stressors on reefs can be categorized as biological or physical disturbances. Biological disturbances (e.g., climate-induced coral bleaching, outbreaks of *Acanthaster* or crown-of-thorns starfish, and coral disease) may kill corals immediately, reducing coral cover. Physical disturbances (e.g., tropical storms, tsunamis, and anchor damage) break down, displace and/or overturn entire coral colonies, simultaneously reducing both live coral cover and structural complexity (Pratchett et al 2008). Although biological disturbances can have severe effects, these appear to be limited to organisms that are highly dependent on coral cover for food or shelter. In contrast, physical disturbances that cause a loss of structural complexity can have a wider range of effects for biodiversity and ecosystem services. For example, the loss of structural complexity might rapidly affect the richness, abundance and biomass of associated fish communities (Alvarez-Filip et al., 2011a; Darling et al., 2017; Espinosa-Andrade et al., 2020) and therefore fisheries productivity (Rogers et al., 2014). Furthermore, immediate loss of reef complexity due to severe physical impact can affect the reef's capacity to modulate wave energy (Franklin et al., 2018) and therefore might also have consequences for shoreline structure and the protection of coastal infrastructure (Eliff et al., 2017; Zepeda-Centeno et al., 2018). In the absence of coral recovery following a biological disturbance, the consequences in the mid to long term (years to decades) are likely to be similar to those caused by physical disturbances, as coral skeletons will gradually breakdown due to destructive forces such a biological and chemical erosion (Kleypas and Langdon, 2006; Molina-Hernández et al., 2020), or the subsequent impact of risks such as tropical cyclones (Harmelin-Vivien, 1994; Crabbe et al., 2008).

TIME AND SPATIAL SCALE OF THE DISTURBANCES

The stressors that affect coral reefs vary inherently in intensity, extension (geographic scale of a disturbance), and frequency (Figure 1; Jackson et al., 1991; Nyström and Folke, 2001; Nyström, 2006). Their spatial scales range from centimeters to global and their temporal scales range from days to decades. Today, most coral reefs exist in an environment dominated by humans, where natural disturbance regimes, such as storms, are exacerbated by anthropogenic stressors. This prolongs the duration and increases the frequency of natural disturbances, hence transforming what were once pulse events into more persistent and even chronic stressors. These changes in frequency, magnitude, duration, and spatial distribution of natural disturbance regimes can be devastating for the dynamics and development of coral reef communities (Nyström and et al., 2000).

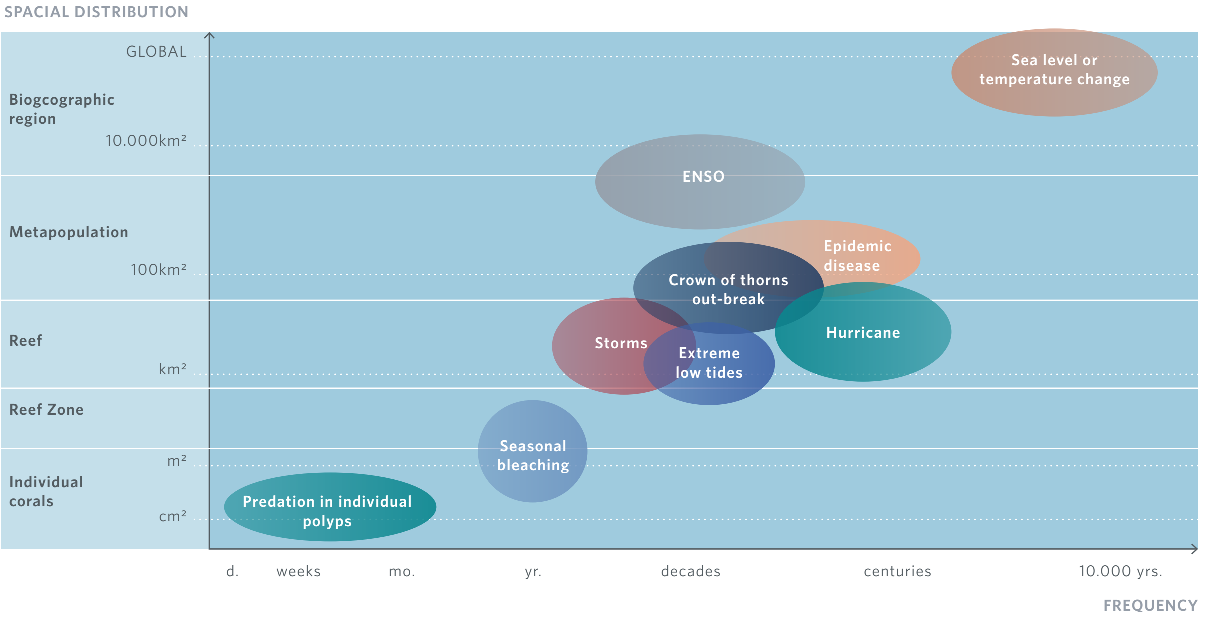

FIGURE 1. Spatial and temporal distribution of natural disturbance regimes in coral reefs. Global representation of the frequency (how long does a risk-event take to occur) and damage extension (how much surface does the impact cover) for risks faced by the world's coral reefs. Figure modified from Nyström and Folke (2001).

Impacts of anthropogenic stressors can range from local to global spatial scales (Gayle et al., 2017). Pollution, overfishing, sedimentation and eutrophication linked to coastal development, unsustainable tourism, and habitat conversion cause localized declines and phase shifts from coral-dominated to algal-dominated systems (Roff and Mumby, 2012; Suchley et al 2016; Rioja-Nieto and Alvarez-Filip, 2019). At the global scale, increases in greenhouse gases have resulted in ocean warming and acidification, which compromise carbonate accretion of coral reefs, resulting in less diverse reef communities (Hughes et al., 2003; Hoegh-Guldberg et al., 2007).

DISTURBANCES HAVE DIFFERENT EFFECTS ON REEFS DEPENDING ON THE SPECIES AND CHARACTERISTICS OF CORALS

Reef managers must consider the characteristics of their reef and how they have impacted by different risks to forecast how future and new risk may impact locally.

Coral reef' distribution is limited by its ability to adapt to physical and chemical conditions (Guam et al., 2020). Factors specific to a region (e.g., currents, nutrients) shape its coral communities, including tolerance thresholds to a disturbance (Chollet et al., 2012; Bahr et al., 2015; Birkeland, 2019). The resilience of coral reefs to disturbance is determined by characteristics such as genetic variability, species richness, and morphological characteristics or life-history traits of the corals that constitute the community (Darling & Cote 2018, McWilliams et al., 2018; González-Barrios et al 2021).

For example, coral communities dominated by branching or tabular morphologies are more susceptible to physical disturbances, such as tropical cyclones, which cause the dislodgement or fragmentation of the colonies (Madin and Connolly, 2006; Bozec et al., 2015). In contrast, biological disturbances, such as mass coral bleaching events, are less selective (Hughes and Connell, 1999), as there are no taxonomic differences in susceptibility to mass bleaching, and corals can die immediately or die slowly from heat stress (Hughes et al., 2018).

The impact of coral disease outbreaks depends on which species they affect. Impacts can be especially severe when they affect key reef-building and dominant species. For example, the widespread mortality of acroporids in the Caribbean during the 1980s was catastrophic, killing 90% of colonies and flattening the reefs (Aronson and Precht, 2001). Diseases can affect multiple species from key functional groups (massive and submassive species, hard and soft corals), as evidenced by the Stony Coral Tissue Loss Disease in the Caribbean, which has had widespread impacts affecting both reef integrity and growth potential (Estrada-Saldívar et al., 2020, 2021).

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METHODS

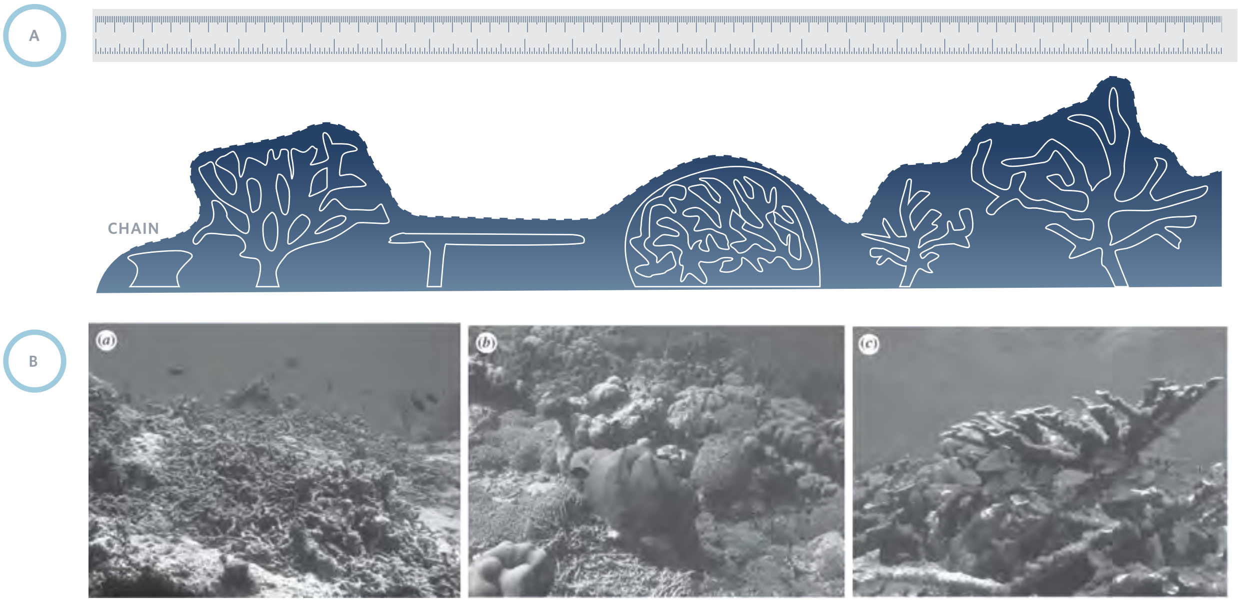
METHODS

4.1 INDICATORS TO ESTIMATE THE SEVERITY OF DAMAGES ON CORAL REEFS

The indicators used were live coral cover and structural complexity (i.e., rugosity index). These quantifiable indicators are commonly used worldwide to assess reef health (Gardner et al., 2005; Alvarez-Filip et al., 2009a; Claar et al., 2018) and are widely reported in the literature.

- ***A.*** Live coral cover is used to estimate the status of coral reefs and is expressed as a percentage resulting from dividing the living coral among all the organisms or substrates analyzed. Despite a range of common methods to assess coral cover are video-transects, quadrants or linear transects (Hill & Wilkinson, 2004) on the ground, all report using the same indicator.
- ***B.*** Rugosity index is expressed as the ratio of the total length of a chain to the length of the chain itself when molded on the surface of the studied reef (Figure 2A) (Hill & Wilkinson, 2004). A perfectly flat surface would have a rugosity index of 1, while a surface with a greater degree of architectural complexity would have a higher index, e.g., 2.5 (Figure 2B) (Álvarez-Filip et al., 2009).

FIGURE 2. A) Chain methodology to determine the rugosity index. Figure from Hill & Wilkinson, 2004. B) Examples (from left to right) of low rugosity, medium rugosity and high rugosity reef. Modified figure from Alvarez-Filip et al., 2009.



4.2 RISKS ASSESSED

Our research identified 16 risks to coral reefs which could be analyzed with the data compiled. There are other threats but with no appropriate information to conduct the analysis. The risks were classified by their effect on the coral community, extension, duration and frequency:

- **Severity of the risk** is the change in coral cover or rugosity caused by a disturbance.
- **Type of effect** is the kind of impact that a disturbance has on coral reefs:
    - **Biological** disturbances kill the tissue but not in the structure.
    - **Physical** disturbances effect the reef structure, breaking branches and disengaging coral from the substrate).
- **Extension of the risk** is the scale that a disturbance impacts, which can range from meters to thousands of kilometers (Jackson et al., 1991; Nyström and Folke, 2001; Nyström, 2006).
- **Duration** is the length of time that the disturbance affects the reefs.
- **Frequency of the risk** is how often the disturbance occurs, which can range from a few days to decades (Jackson et al., 1991; Nyström and Folke, 2001; Nyström, 2006). Note that the frequency of disturbances caused by human activities depends on the location of the reef and the activities happening around them. The frequency of disturbances stated here is for those sites close to human activities which cause them.

Specific terms were used to describe well known and identifiable risks (e.g., anchoring, cyclones), where risks had similar effects but different sources, we grouped them by their effects (e.g., flood events, coastal runoff). The risks assessed in this study are defined in Table 1.

TABLE 1. Description, type, extension, duration, and frequency of the risks assessed in this study, based on Jackson, 1991; Nyström and Folke (2001) and Nyström (2006).

RISK	Description	Type	Extension	Duration	Frequency
Scuba	Damage caused by inappropriate diving and snorkeling practices that harm coral colonies by breaking corals or generating sediments on the reef (Jackson et al., 2014).	Physical	**<1 km**	days	weeks-days
Dredging	Removing silt and other material from the bottom of water bodies, in this case from the seafloor. Dredging can cause direct and indirect damage to coral reefs through coral breakage and suspended sediments (Jones et a., 2016).	Physical		days	years
Anchoring	Damage caused by anchors when dropped on reefs, which can break coral colonies. Generally, anchoring impacts a limited area, but in some cases, the boat or ship drags the anchor causing damage across hundreds of meters (Forrester et al., 2015; Byrnes and Dunn, 2020).	Physical		days	months-years
Grounding	Refers to accidental ship groundings or strandings on coral reefs, which cause physical damage of coral reefs (Byrnes and Dunn, 2020).	Physical		days-weeks	months-years
Predators	Outbreaks of coral predators (other than *Acanthaster* sp, which has its own category) such as snails, sea stars, and corallimorphs, which directly affect the coral tissue and also represent a persistent force in structuring coral communities by contributing to directional shifts in species composition of coral assemblages (Quinn and Kojis, 2003). Although they can disperse across much larger areas in a timeframe of years, for this study we are measuring the effect of the outbreak at short temporal scales (months).	Biological		days	decades-years
Flood events	Generally, high rainfall induces flood events that lead to persistent turbidity in nearshore environments. Reefs near landmasses are affected by extreme weather events that result in masses of fresh water, suspended solids, and sediments flowing onto or over coral reefs. These events bring abrupt change in water temperature, reduction in light availability, and excess sediments that can smother and kill reefs (Wilkinson, 1999). In addition, nutrient loading caused by terrestrial runoff, and sediment resuspension associated with storms can lead to an increase in macroalgae cover.	Biological		days	decades
Competition	Competition refers to the ability of other organisms to displace coral colonies, affecting coral tissue. Although we acknowledge that a variety of organisms can be competing with corals (e.g. tunicates, zoanthids), we only found a few studies assessing these stressors before and after the disturbance. We did not consider macroalgae as competition since they are not competing with corals per se; rather, they encroach upon space when the coral dies (Chadwick and Morrow, 2011).	Biological		days	decades-years

RISK	Description	Type	Extension	Duration	Frequency
Low tides	Refer to conditions when coral heads in shallow water are exposed for long periods of time due to low tides. Coral surfaces overheat and their tissues can dry out, causing physiological stress that can lead to bleaching and eventually death (Loya et al., 1972).	Biological	1-10 km	days	decades
Acanthaster	This disturbance refers to the high and moderate densities of the crown-of-thorns starfish (*Acanthaster* sp). This predator has the potential to greatly modify coral community structure by selectively feeding on certain corals and has had a devastating effect on coral reefs on Indo-Pacific reefs reefs (Pratchett, 2014). Multiple outbreaks in the region have been linked to an increase in nutrients (Brodie et al., 2005). Although they can disperse across much larger areas in a timeframe of years, for this study we are measuring the effect of the outbreak at short temporal scales (months).	Biological	10 - 100 km	days	years
Disease	Coral diseases injure the living tissues and often result in the death of part or the whole of the colony. Although diseases are natural and commonly found in coral reefs, there are events that can be considered as outbreaks, such as the Stony Coral Tissue Loss Disease in the Caribbean (Harvell et al., 2007; Precht et al., 2016). An outbreak is a sudden increase of occurrences within a particular time and place. An increasing number of diseases have been attributed to land-based sources of pollution or global climate issues. (Vega-Thurber et al., 2014). Although disease can disperse a cross much larger areas with the pass of years and decades, for this study, we compared data with less than four years of interval before and after the outbreak.	Biological		years	decades
Oil spill	Leakage of petroleum onto the sea surface. These events can kill coral depending on species and exposure, as heavy oil gets mixed with sand or sediment and can become dense enough to sink below the ocean surface and smother corals below. Chronic oil toxicity also impedes coral reproduction, growth, behavior, and development (Turner and Renegar, 2017).	Biological		weeks-months	decades-years
Plankton bloom	Increased density of marine plankton within an area. This can cause the smothering of corals by anoxia, due to the high increase of plankton or macroalgae (Burke et al., 2011).	Biological		weeks	years
Earthquake	Violent shaking of the ground as a result of tectonic plate movement. Earthquakes can cause a coral reef avalanche, shatter or overturn coral colonies, and move large sections of coral reefs above sea level or to deeper below water (Aronson et al., 2012). Earthquakes can also cause tsunamis that can damage the reefs.	Physical		days	centuries
Tsunami	A tsunamis is a series of waves caused by a large and sudden displacement of the ocean, usually the result of an earthquake below or near the ocean floor. The wave force can break coral colonies, as can the tons of heavy debris waves carry with them as they recede back into the ocean. The waves also carry sludge, which can bury and suffocate coral (Majumdar et al., 2018).	Physical		days	centuries

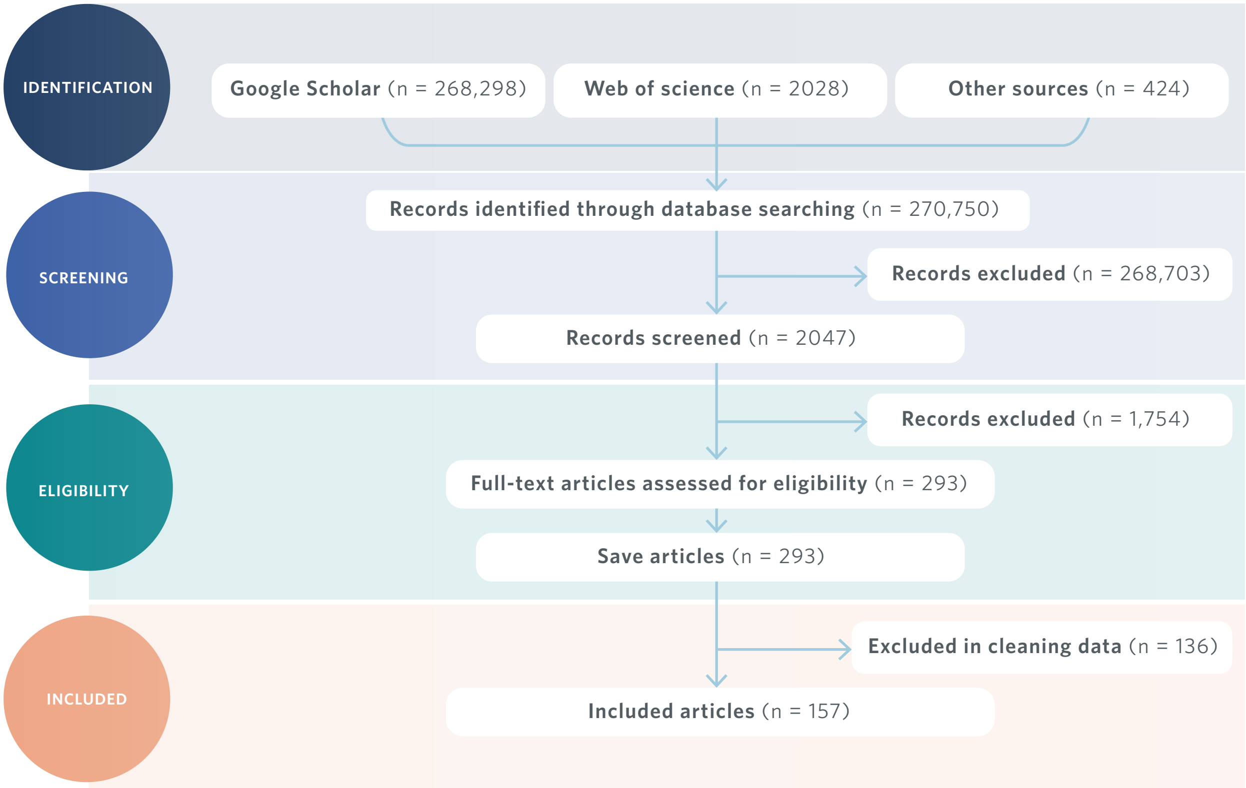
RISK	Description	Type	Extension	Duration	Frequency
Cyclones/ Hurricanes/ Typhoons	Formed over warm tropical oceans, these systems of winds rotate around a low-pressure center. They affect coral reefs by generating debris and sedimentation (Burke et al., 2011). Those formed over the South Pacific and Indian Oceans are called cyclones; those formed over the Northwest Pacific Ocean are called typhoons; and those form over the North Atlantic and Northeast Pacific Oceans are called hurricanes.	Physical	**100 - 1000 km**	days	decades
Bleaching	When corals are stressed by changes in conditions such as temperature, light, or nutrients, they expel the symbiotic algae living in their tissues, causing them to turn completely white or bleach (Hoegh-Guldberg, 1999). Bleaching events are largely caused by the increase of seawater temperature exceeding the coral tolerance threshold (Hughes et al., 2017). Corals can survive a bleaching event. However, if the period of stress is intense or last for long-periods of time this can result in coral mortality, ranging from few colonies to mass mortality events.	Biological	**> 1000 km**	weeks-months	decades

4.3 DATA COLLECTION AND SYSTEMATIZATION

To assess which risks have the greatest impact in the different regions of the world, we conducted a systematic search to compile studies that evaluated the damage to coral reefs using coral cover or rugosity as indicators, before and after a risk event. We conducted an extensive review of the existing scientific literature, including synthesis papers (e.g. Wilkinson, 1999; Hughes et al., 2003; Burke et al., 2011; Ban et al., 2014). Within this search, we identified chronic stressors (e.g., coastal development, land-based pollution), which continually affect coral reef communities, however, these were not included in the study because the pressure is permanent, non-stop, therefore they do not have an initial or end date needed for this analysis. We systematized all the information into a database, which was assiduously curated.

To ensure proper research for meta-analysis, we followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009; Figure 3). Our search identified 270,326 documents and screened 2,047 of them with data for this study. We then systematically assessed the 2,047 documents by reading the abstract to determine the relevance to our research questions (Figure 3). We included only field-based studies, and we did not include any laboratory, or experimental studies. In total, we saved 293 documents to extract data from. In addition to these, we used information from the project "Hurricane damage to coral reefs in the Caribbean and its correlation with hurricane and reef characteristics" (Pérez-Cervantes et al., 2020), integrating 424 data sets that met our criteria. For additional information on the search process see the extended report.

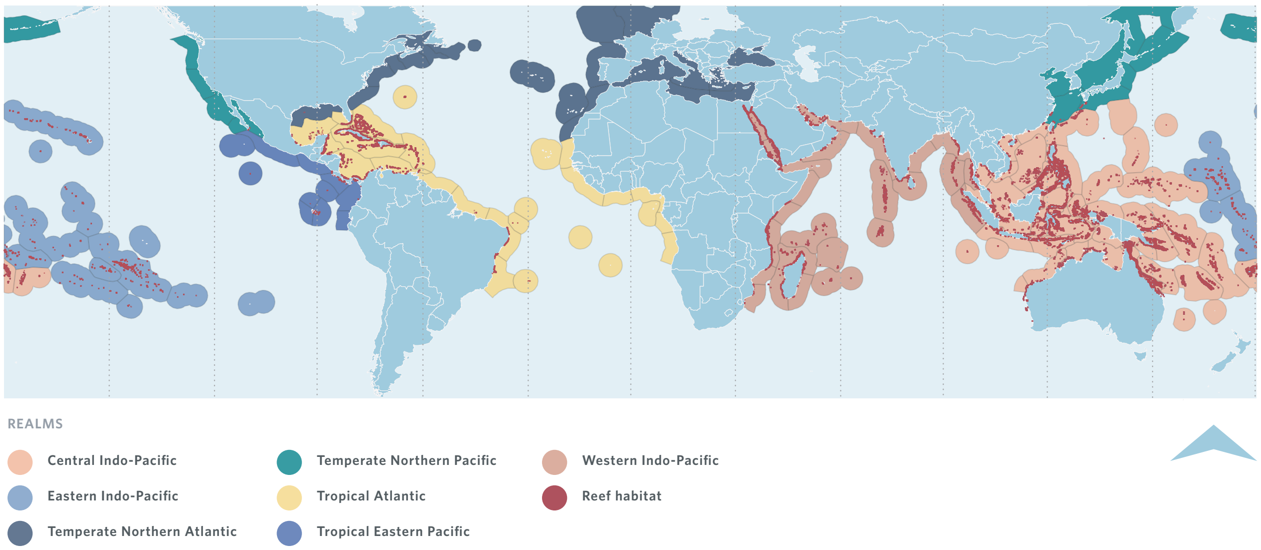
FIGURE 3. PRISMA 2009 flow diagram showing the starting and excluding steps from studies returned from the full Web of Science and Google Scholar literature search.



The database containing information from the 293 studies was carefully curated and systematized and many data sets had to be eliminated. As part of this systematization, we established a process to eliminate duplicate data, correct typos and coordinates, and homogenize terms. We also removed risk-sets with very low coral cover, low sample size, unusually high increase of coral cover and/or those with no clear correlation to a passing tropical cyclone. As a result, the final database has information from 157 documents including Pérez-Cervantes et al., 2020. The database is divided in two parts: one with information on coral cover and rugosity indicators (e.g., site, methodology, average, survey, and risk dates) and the other with information on risks (e.g., name of risk, year, duration, and indicators of intensity). For detailed information on the organization of the databases, see extended report.

For the spatial distribution of the risk-sets, we used the Marine Ecoregions of the World (Spalding et al., 2007). This hierarchical system at three spatial levels – realm, province and ecoregion – identifies 14 realms around the world. We found information in 7 realms: Eastern Indo-Pacific, Tropical Eastern Pacific, Temperate Northern Atlantic, Tropical Atlantic, Western Indo-Pacific, Central Indo-Pacific and the Temperate Northern Pacific (Figure 4). For the purposes of this report, we are exploring the effect at two spatial levels: global and realm to estimate the coral area (km²) for each realm we used the information from Hoekstra et al., (2010). The spatial representation of the results was made on a geographic information system using the QGIS software.

FIGURE 4. Biogeographic realms from the Marine Ecoregions of the World by Spalding et al., (2007). In total, there are 14 realms around the world, but only 7 realms have data: Eastern Indo-Pacific, Tropical Eastern Pacific, Temperate Northern Atlantic, Tropical Atlantic, Western Indo-Pacific, Central Indo-Pacific and the Temperate Northern Pacific.

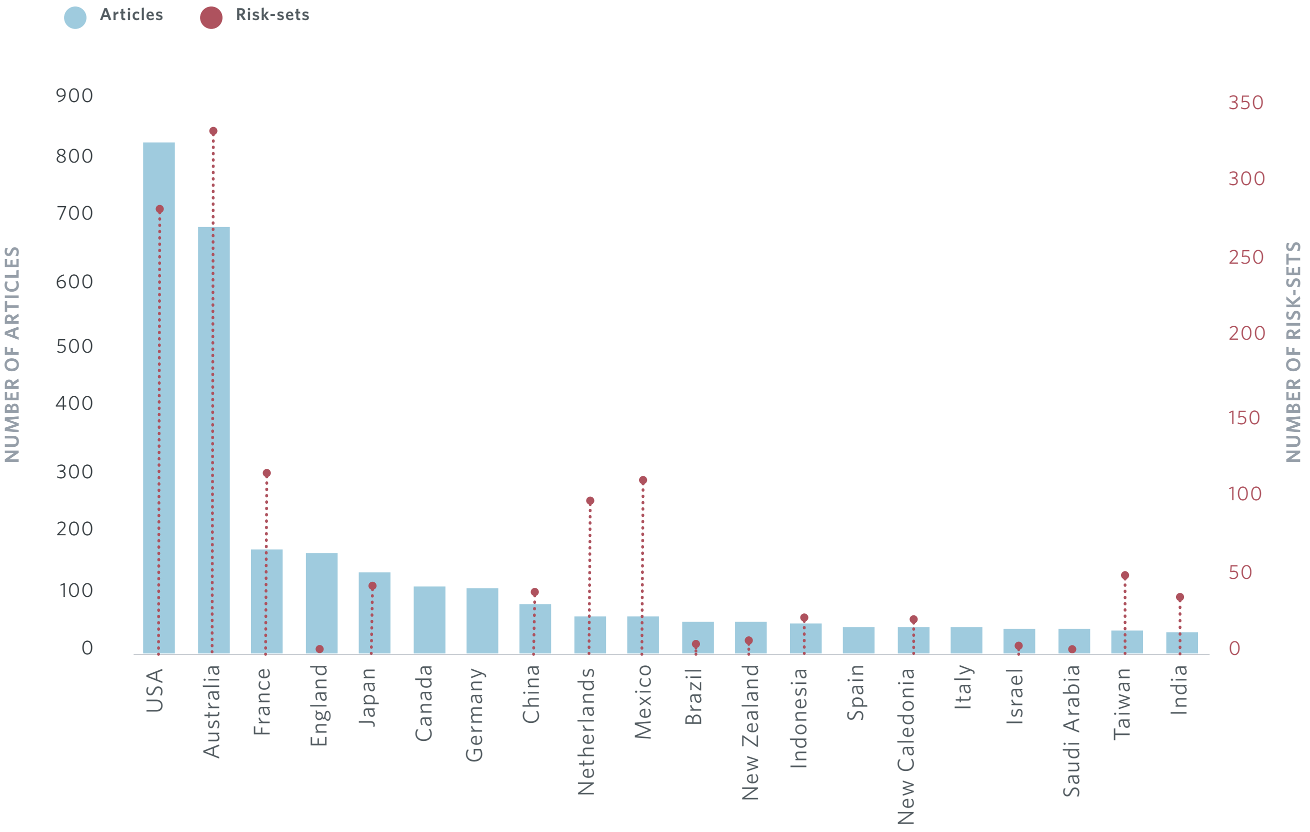


We recognize that the disturbances used in this analysis are not the only ones that may affect coral reefs, especially when we focus at the realm level. For this, we identified two main obstacles, the language, and the scientific input. Regarding the language, all of our searches were made through Web of Science and Google Scholar with terms in English, so the majority of the resultant documents were in English, although we also retrieved some studies in Spanish. The searches only yielded some documents in a different language (e.g. Spanish, French, Japanese or Chinese), some studies have identified that most of the primary coral reef data for some countries are not detectable through Web of Science (Hughes et al., 2013).

As for the scientific input, we identified that some risks have been better studied than others, as we have more data for the climate change-driven risks (i.e., bleaching and tropical cyclones), than of important local anthropogenic threats (i.e., ship grounding or dredging). It is important to emphasize that the same happens with information at regional level, since the regions with the highest number of data (e.g. Central Indo-Pacific and Tropical Atlantic) correspond to the countries with the highest number of publications (Figure 5). Another challenge was the quality of the data retrieved, we had different and, sometimes, unclear reporting of methods, and results. For example, some of the documents did not report the sample size used (number of transects) or an associated variance of the mean.

Furthermore, the time required for sourcing data from the literature, and the subsequent data organization, cleaning and manipulation should not be underestimated, so we highly recommend a structured method for this type or searches (i.e., Claar et al., 2018).

FIGURE 5. Articles found using the term "coral reefs" published in the 20 top journal in Web of Science, per country of submission. Most risk-sets use information published by United States and Australia, as those countries published most of the data.



4.4 A UNIT OF ANALYSIS: RISK-SETS

Each data set needs at least four pieces of information: 1) a site, 2) an event of any risk occurring in that site, 3) information on the condition of the coral before the event and 4) information on the condition after the event. We named this group of data a risk-set, which formed the sampling unit of our analyses (Figure 6). Generally, risk-sets are associated with one event only, and therefore to one risk. However, many sites had been impacted by several events, either from different risks or the same, and have information prior and after the events. We included these risks sets in the analysis and classified accordingly.

FIGURE 6. Example of a site with risk-sets. La Bocana, México has information for 2004, 2007, 2020, and 2021. Between 2004 and 2007 an event caused by EVENT 1 occurred, and with the data of the event, the data for 2004 (pre-risk) and for 2007 (post-risk) we formed one risk-set. This combination of pre-risk, risk and post-risk is defined as risk-set A (in blue). Next, we have two risks (EVENT 2 and EVENT 3) that occurred between 2007 and 2020, with pre-risk data (2007) and post-risk data (2020) resulting in risk-set B (in orange). Finally, between 2020 and 2021 two events of the same risk (EVENT 4) struck the site, with pre-risk data (2020) and post-risk data (2021) becoming risk-set C (in red).

Many studies reported information on reef condition for multiple years, typically referred to as a 'time series' (e.g. Gardner et al 2003; Bruno and Selig, 2007; Alvarez-Filip et al 2009), and in some cases, the same time series reported the effect of different stressors in different times. For these cases, the closest data point available prior to the event was included as pre-event and the data point following the event was considered as post-event. If another event occurred in the same site, a new risk-set was created. Risk-sets were then classified according to the type of risk and the number of events that were captured in the set. When several types of risk occurred in the risk-set, it was not possible to quantify the effect of a single risk and we categorized those risk-sets as "multiple risks" and showed them for illustrative purposes.

4.5 CLASSIFYING BLEACHING EVENTS BY INTENSITY

Depending on their duration and intensity, bleaching events have varying impacts on coral cover. To categorize the intensity of bleaching events that coral colonies may have experienced, we used "Degree Heating Weeks'' (DHW), which provides a measure of accumulated thermal stress experienced by corals and has been widely used for the evaluation of heat stress events on reef systems (Eakin et al., 2010; Hughes et al., 2018). DHW is calculated by summing HotSpots of 1 °C or greater above the highest summertime mean from the preceding 12-

week period, and is expressed in the unit °C-weeks (Liu et al., 2014). Thus, DHW represents the cumulative measure of thermal stress intensity and duration over the most recent 12-week period (i.e., the most recent 84 days).

The DHW has been directly correlated with bleaching occurrence and severity (Liu et al., 2014). The Coral Reef Watch DHW product accumulates prolonged periods of thermal stress and has been shown to be more predictive than HotSpots of mass coral bleaching (Glynn and D'Croz, 1990). We obtained DHW values for the 485 risk-sets from the National Oceanic and Atmospheric Administration (NOAA) Coral Reef Watch product (CRW, V 3.1) and processed them to estimate the intensity of the event at each and every site and moment. The CRW V 3.1 product consists of rasters with satellite information of DHW observation polygons of 5 km since 1986; this product is also known as CoralTemp (Skirving et al., 2020).

Using a geographic information system environment in QGIS, V 3.16, the DHW raster layers were intersected with the geographic location of all risk-sets for every year from 1987 to 2017. In some cases, the sites registered in risk-sets coincide with cells without DHW information. In this situation, the DHW value of the cell closest to the point was taken. We classified the DHW data for the 485 risk-sets using the Liu et al. (2014) system to visualize the relationship between DHW values and the severity of coral bleaching (Table 2).

TABLE 2. Bleaching event intensity level based on Liu et al., (2014)

DHW INTENSITY	Definition
Low	0 < DHW < 4
Medium	4 < DHW < 8
High	8 ≤ DHW

4.6 CLASSIFYING CYCLONES BY INTENSITY

It is well documented that cyclone intensity is correlated with the severity of the damages to reefs (Gardner et al, 2005; Pérez-Cervantes et al 2020). Cyclones were classified using the Saffir-Simpson Hurricane Wind Scale (Table 3). Information was obtained from the International Best Track Archive for Climate Stewardship (IBTrACS) v.4, provided by NOAA (Knapp et al., 2010).

TABLE 3. Tropical cyclones intensity level based on the Saffir-Simpson Hurricane Wind Scale (Knapp et al., 2010)

CATEGORY	Range of storm's "maximun wind speed" (knots)	
Td	< 34	
Ts	34 or	< 64
1	65 or	< 83
2	83 or	< 96
3	96 or	< 113
4	113 or	< 137
5	137 or	more

The IBTrACS has information dating back to 1980 at a spatial resolution of ~10km, temporal resolution at 3-hour intervals, coverage from 70° North to 70° South and 180° West to 180° East in the form of a shapefile and an excel database (Knapp et al., 2018; Knapp et al., 2010). The IBTrACS has six-hour storm snapshots, which provide an insight of the intensity along the hurricane track. We used a geographic information framework to make a 100-km radius buffer from our shapefile of risk-sets, then interpolated this layer with the IBTrACS shapefile to identify all the cyclones that passed within a radius of 100 km from the risk-set. With this intersection, we manually identified the highest intensity snapshot (i.e., category of the cyclone) within the 100 km for the 710 risk-sets associated with cyclone events. For 25 risk-sets, we did not identify a hurricane passing within 100 km of the site; however, because the study reported that the site was affected by a hurricane, we expanded the radius to 200 km and found the cyclone associated with those particular risk-sets.

4.7 MEASURING CHANGE IN CORAL COVER AND RUGOSITY

A common approximation to assess the damage caused by a disturbance is to estimate the change before and after of any given event (Côté et al., 2006; Gardner et. al., 2003, Gardner et. al., 2005; Suchley et al., 2016; Álvarez-Filip et al., 2011b; Gonzalez-Barrios et al., 2021).

In this study, we calculated the annual percentage of change between measures of coral cover or rugosity before and after the disturbance as: $X = (\log (End) - \log (Start) / t)$, in which Start represents the initial value and End represents the post-disturbance value of both coral cover or rugosity and t is the number of years elapsed between the two measures. Thus, we considered the t in order to estimate the rate of change by year. This metric better suits the non-linearity of the time series due to the different resources and methodologies that data were collected (Côté et al., 2006).

The annual percentage of change was estimated for each risk-set and then a mean (± standard deviation) was calculated for each risk. The standard deviation allows us to know how much the data vary around the mean. The analyses were carried out at the global level using coral cover and rugosity and at the realm level using coral cover data (Spalding et al., 2007). To evaluate whether the number of years between the pre- and post-disturbance could influence the interpretation of our data, we compared the results of the global analysis of coral cover using risk-sets from the analysis and using risk-sets with less than three-year intervals between pre- and post-disturbance (see Figure 8).

We also used a weighted meta-analytic approach to estimate annual rates of change in the live coral cover after a disturbance. This method has been previously used in studies of ecological change on coral reefs (Côté et al. 2006; Paddack et al.2009) and its properties, such as the best fit mean estimate (i.e., effect-size), and the approach have been thoroughly investigated (Côté et al. 2005). To represent the robustness of each effect-size estimate in our meta-analyses, we used the inverse of the sample variance, as risk-sets with higher samples have higher robustness (Rosenberg et al., 2000). All the statistical processes followed the methodology of Alvarez-Filip et al., (2011b). See results in Table 8.

05

CHARACTERISTICS OF COMPILED RISK-SETS

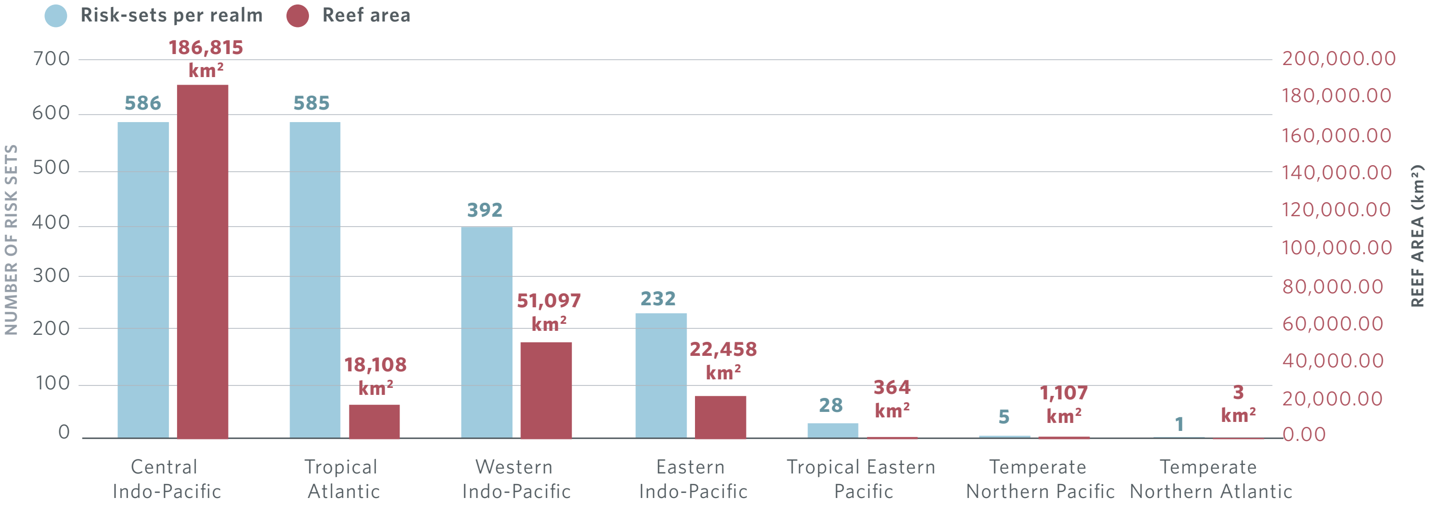
CHARACTERISTICS OF COMPILED RISK-SETS

For this study, we compiled 1,829 risk-sets associated with 1,097 sites with coral cover data. The vast majority of risk-sets (98.2%) are found in four realms, the Central Indo-Pacific (586), Tropical Atlantic (585), Western Indo-Pacific (392) and Eastern Indo-Pacific (232) (Table 4). In contrast, 3 realms had only 34 risk-sets or 1.8%: the Eastern Tropical Pacific, the Temperate Northern Pacific and the Temperate Northern Atlantic. The low number of risk-sets is expected as reefs located in those realms account for only 0.5% of the reefs in the world. Except for the Tropical Atlantic, the number of risk-sets broadly corresponds with the reef area in each realm (Figure 7). The large number of risk-sets for the Tropical Atlantic reflects that this region had been widely study; although it might be disproportionally represented in our analysis as we incorporated data collected from a previous study (Pérez-Cervantes et al, 2020) conducted in the Caribbean region by this team (see section 4.3).

TABLE 4. Compiled risk- sets associated with coral cover data.

REALMS	Risk-sets	Reef area (km²)
Central Indo-Pacific	586	186,815
Tropical Atlantic	585	18,108
Western Indo-Pacific	392	51,097
Eastern Indo-Pacific	232	22,458
Tropical Eastern Pacific	28	364
Temperate Northern Pacific	5	1,107
Temperate Northern Atlantic	1	3

FIGURE 7. Total number of risk-sets by realm (blue) and the area of coral reef (red circles) found within each realm. The coral reef area by realm was retrieved from Hoekstra et al., 2010.



Of the 1,829 risk-sets, 89.3% represent one event associated with one risk, 4.0 % have two or more events associated with one risk (cyclones, bleaching and flood events), and 6.7% were associated with two or more different risks, such as the impact of a hurricane and an *Acanthaster* outbreak (Table 5). These risk-sets were pooled in multiple events class and multiple risks class as it was not possible to discern the relative damage caused by each risk, and they were all grouped in the "multiple risks" category (Figure 5).

TABLE 5. Number of risk-sets per category of event

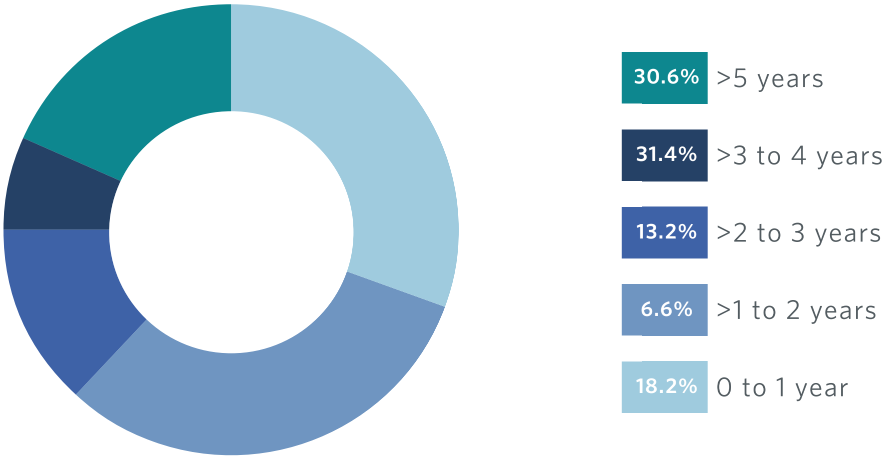
CATEGORY	Number of risk-sets	%
Single risk and single event	1,634	89.3%
Single risk with multiple events	73	4.0%
Multiple risks and multiple events	122	6.7%
Total	1,829	100%

The time interval between pre- and post-data collection is incorporated in the equation to estimate the annual percentage of change. Seventy five percent of the risk-sets have a time interval between data of 0 to 3 years, while others had up to 10 years (Figure 8; Table 6). The analysis of risk-sets with coral cover with 3 years or less did not show significant difference when using all data sets (see Table 9).

TABLE 6. Number of risk-set per interval pre and post event in years

YEARS RANGE	Number of risk-sets
0 to 1	560
>1 to 2	574
>2 to 3	242
>3 to 4	120
> 5	333
Total	1829

FIGURE 8. Distribution of time intervals between the pre- and post-year of each risk-set.



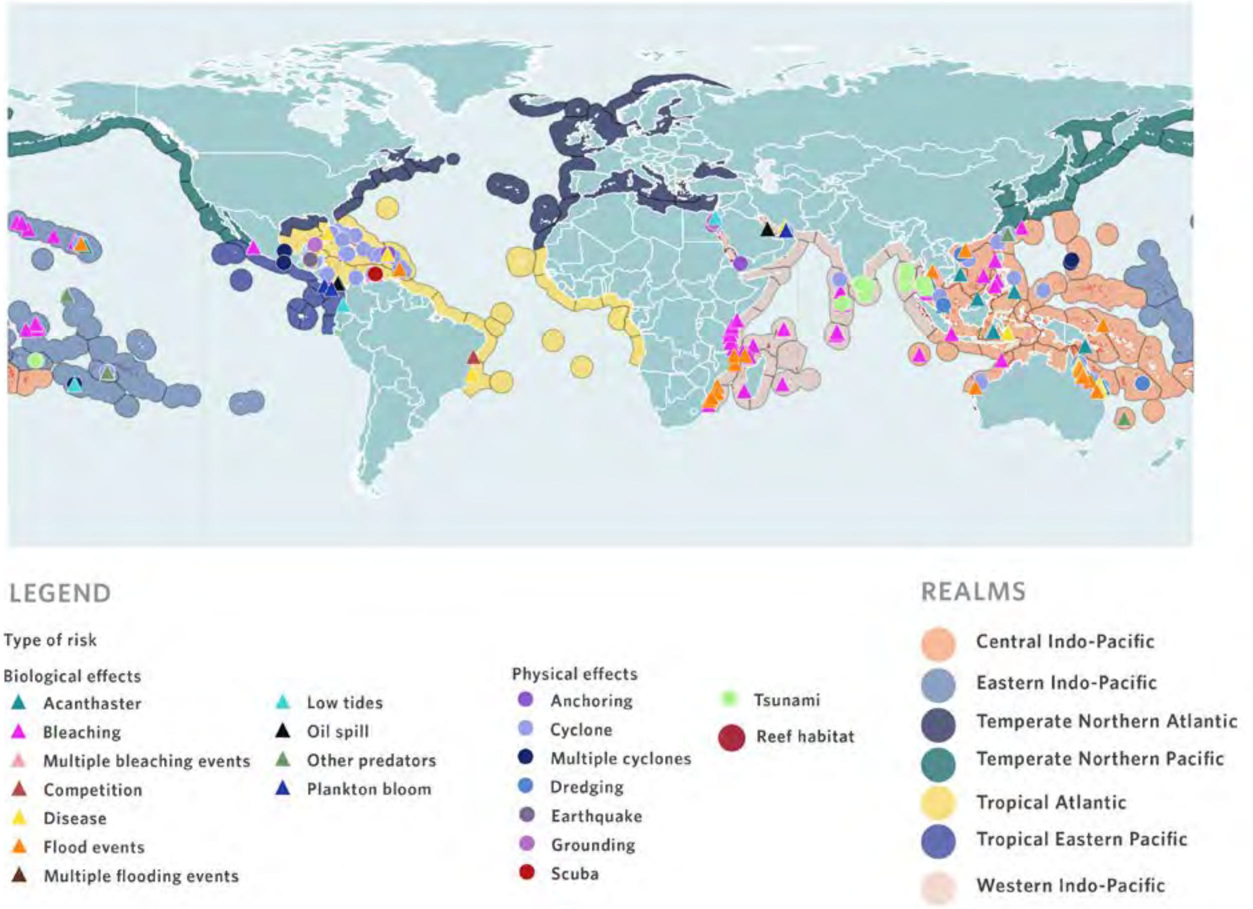
Time intervals can be considered as a weighting factor in future analyses as risk-sets with shorter time intervals between the pre- and post-data collection may better reflect the impact of the disturbance than longer time intervals.

The analysis encompassed 16 risks; not all risks occur in all realms; some are characteristic of certain realms (Table 7; Figure 9) and there were not data for others. For example, *Acanthaster* was found only in the Central, Eastern, and Western Indo-Pacific; the plankton blooms were found only in the Tropical Eastern Pacific and Western Indo-Pacific, and tsunamis were found only in the Eastern and Western Indo-Pacific. Cyclones were found in four realms with the an over-representation of risk-sets in this specific risk (n= 455 out of 655) in the Tropical Atlantic. Bleaching events occur in all realms and are well represented in the Central, Eastern, and Western Indo-Pacific, but underrepresented in the Tropical Atlantic.

TABLE 7. Number of total risk-sets and confidence levels (high=dark green, medium=medium green, low=light green) for each risk (row) and realm (column).

RISK	Central Indo-Pacific	Tropical Atlantic	Western Indo-Pacific	Eastern Indo-Pacific	Tropical Eastern Pacific	Temperate Northern Pacific	Temperate Northern Atlantic	Total	Ext
Multiple	34	12	28	45	2		1	122	
Scuba		6						6	< 1 km
Anchoring		2	6					8	
Dredging	25		15					40	
Grounding		1	6					7	
Multiple flooding			9					9	1-10 km
Other predators	8			7				15	
Flood events	73	2	10	16				101	
Low tides			21	3	2			26	
Competition		2	1					3	
Disease	36	12	1					49	10 - 100 km
Acanthaster	98		5	31				134	
Plankton bloom			2		20			22	
Oil spill		14	1					15	
Tsunami			65	2				67	100 - 1000 km
Multiple cyclones	19	31		1	4			55	
Cyclone	164	455	8	28				655	
Earthquake		1						1	
Multiple bleaching	4		4	1				9	> 1000 km
Bleaching	125	47	210	98		5		485	
Total	586	585	392	232	28	5	1	1829	

FIGURE 9. Spatial and temporal distribution of risk-sets. Colors and shapes indicate the risk type and associated frequency and extension.



5.1 SPATIAL DISTRIBUTION OF THE RISK-SETS

The spatial representation, across the world, of each of the 16 risks is presented in figures 10-24.

FIGURE 10. Spatial distribution of risk-sets associated with a bleaching event. Risk-sets, which only had one bleaching event in fuchsia and those with multiple events in pink. Multiple events were found in the Western and Eastern Indo-Pacific.

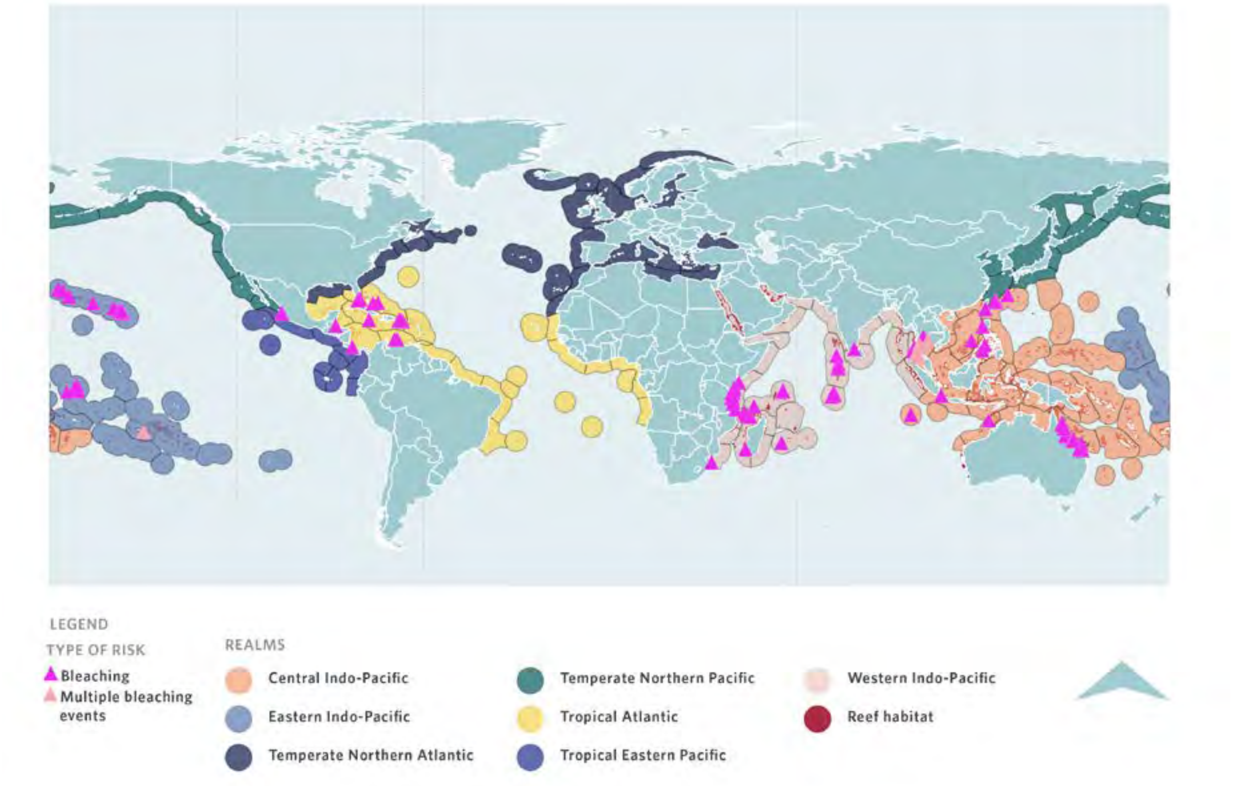


FIGURE 11. Spatial distribution of risk-sets associated with a cyclone event. Risk-sets, which only had one bleaching event in lilac and those that had multiple events in blue.

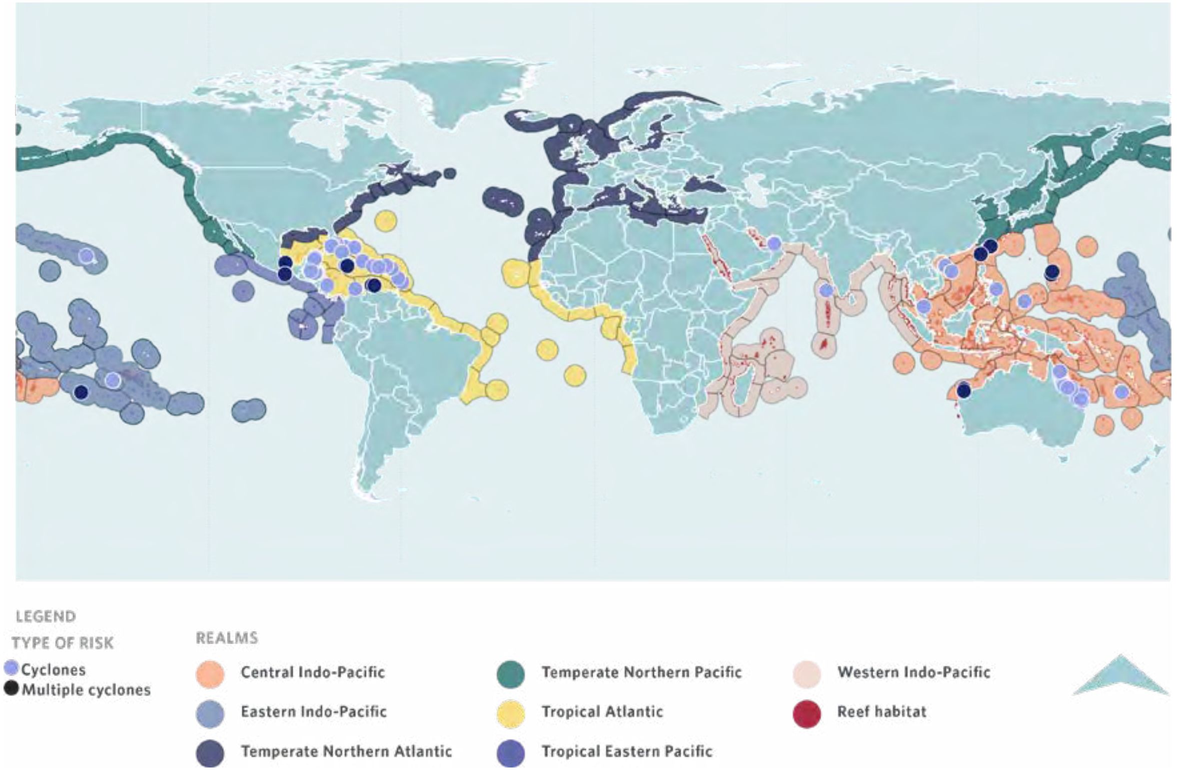


FIGURE 12. Spatial distribution of risk-sets associated with a predator's outbreak. We separate the *Acanthaster* outbreaks (blue) from the other predators (green), because it has an extremely important impact and is a recurring event in the realms of the Central and Eastern Indo-Pacific.

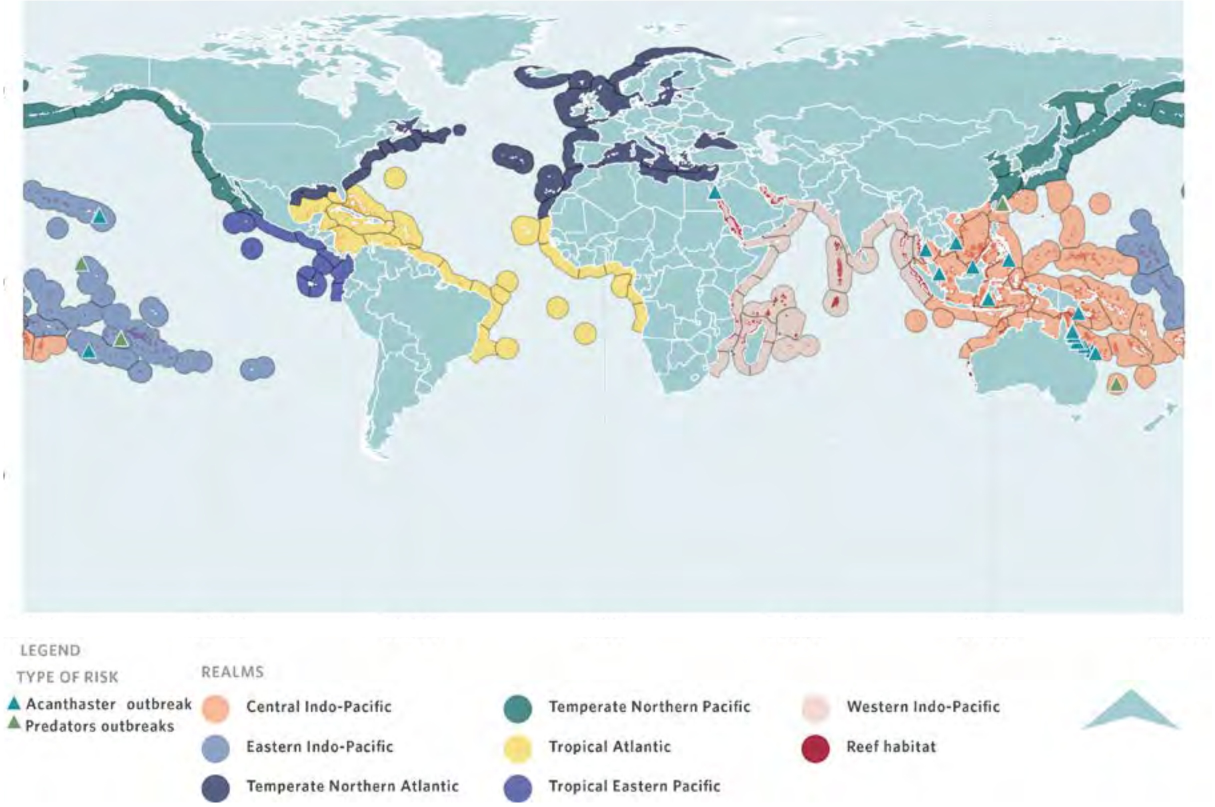


FIGURE 13. Spatial distribution of risk-sets associated with the damage of anchors. Impacts found in the Tropical Atlantic and Western Indo-Pacific.

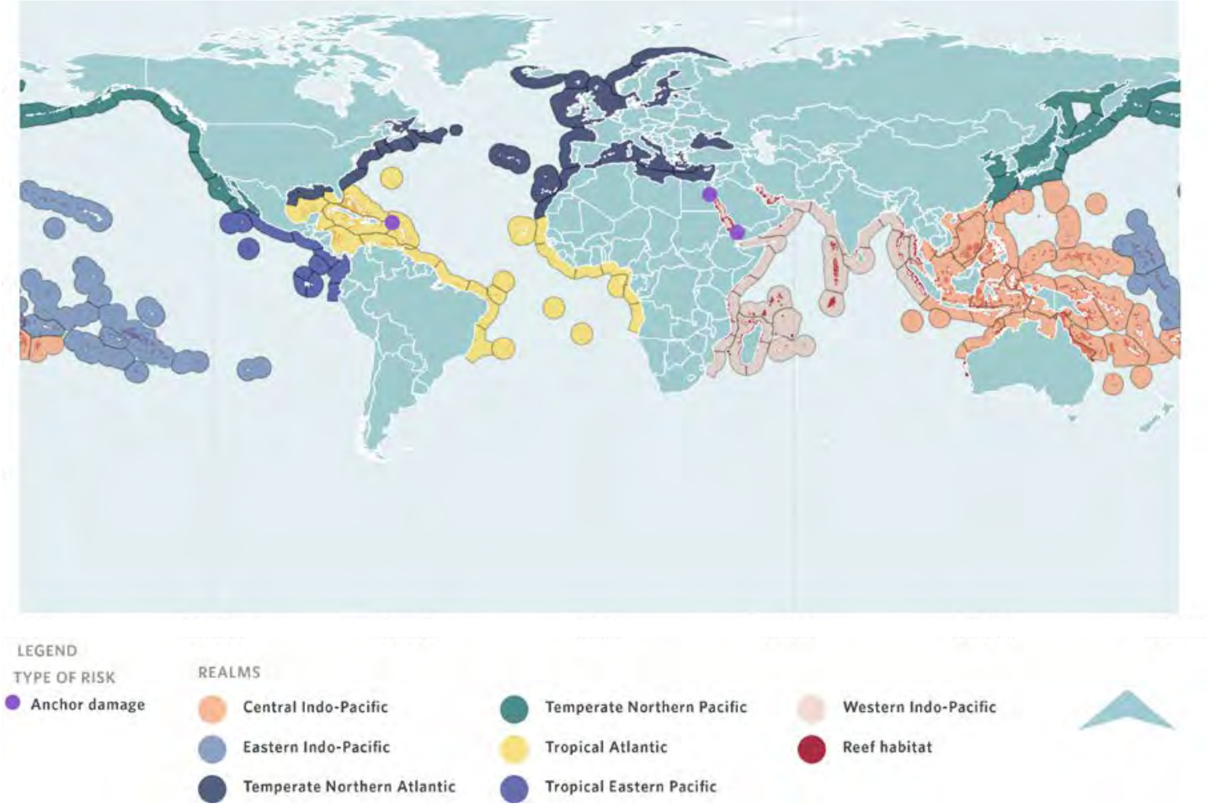


FIGURE 14. Spatial distribution of risk-sets associated with coral disease outbreaks.

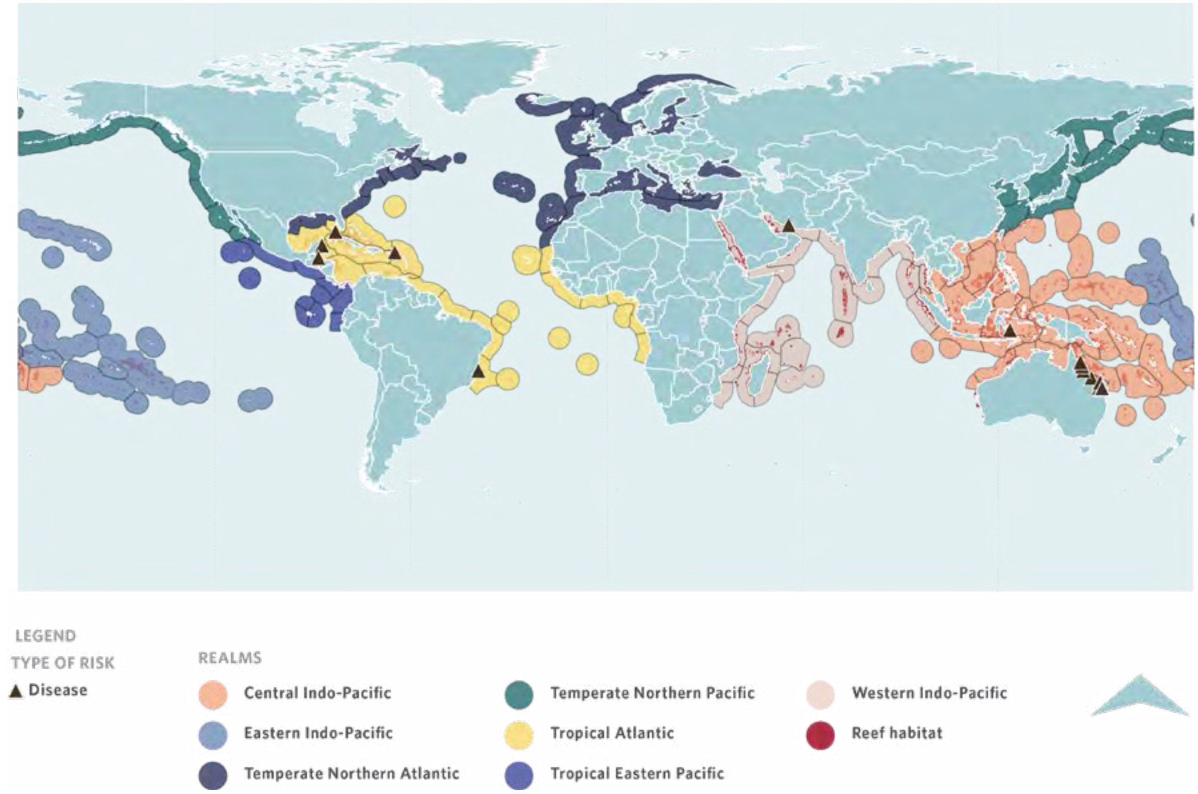


FIGURE 15. Spatial distribution of risk-sets associated with dredging activities.

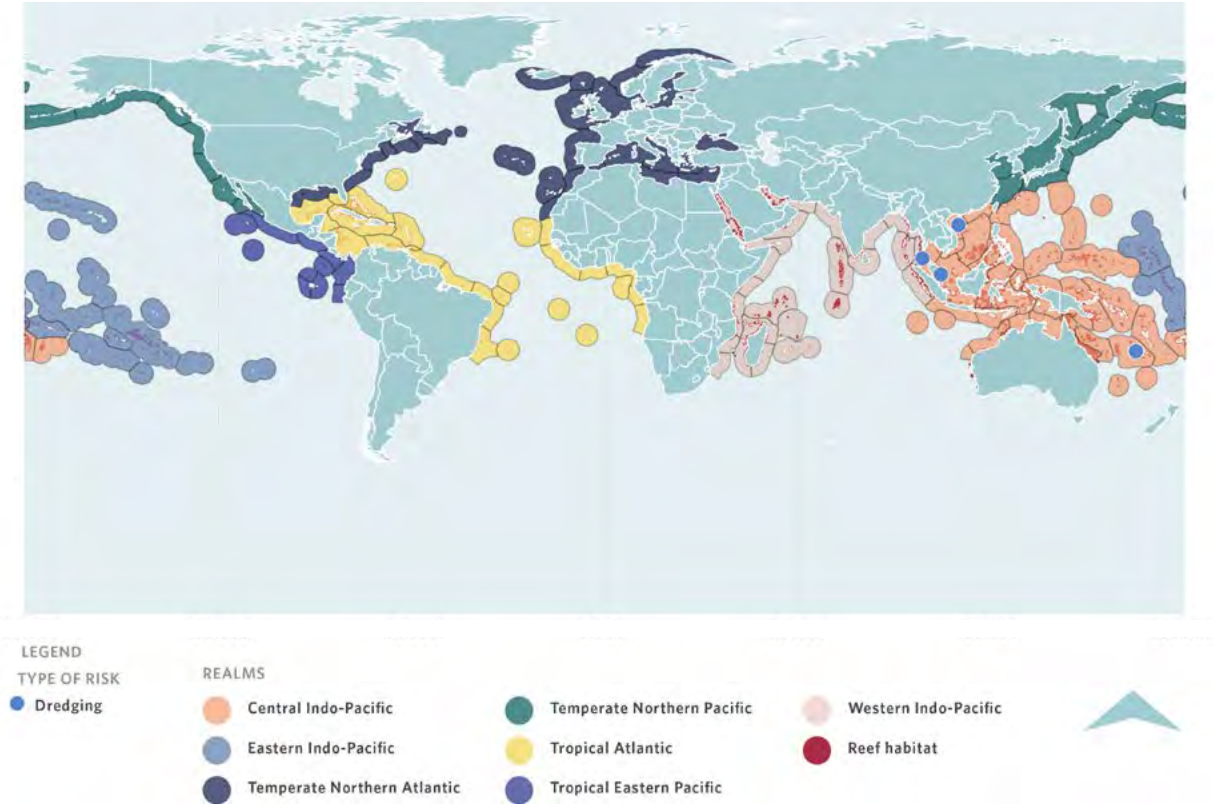


FIGURE 16. Spatial distribution of risk-sets associated with earthquake damage. The only risk-set is located in Belize.

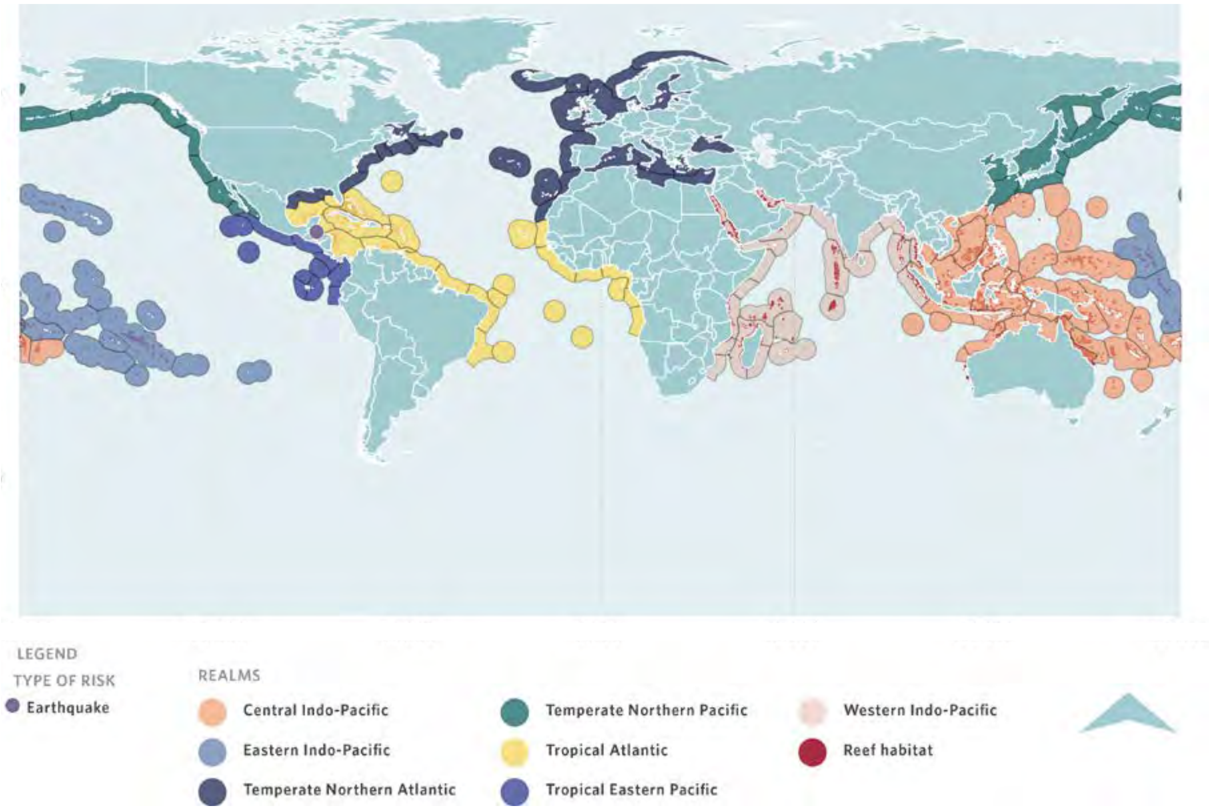


FIGURE 17. Spatial distribution of risk-sets associated with flooding events. This category includes events such as increased rainfall, increased river level, runoff, among others. Risk-sets with only one flood event are in orange and multiple events in dark brown.

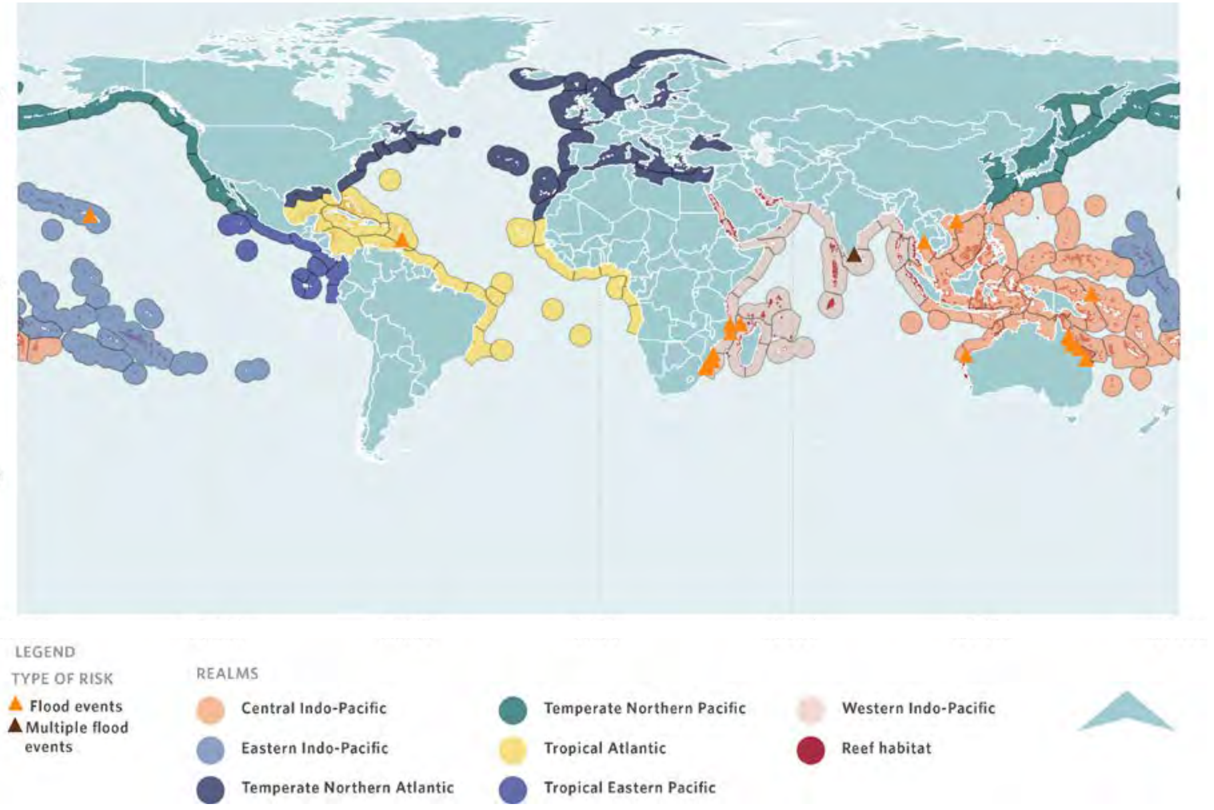


FIGURE 18. Spatial distribution of risk-sets associated with ship groundings. These risk-sets are located in the Tropical Atlantic and Central Indo-Pacific.

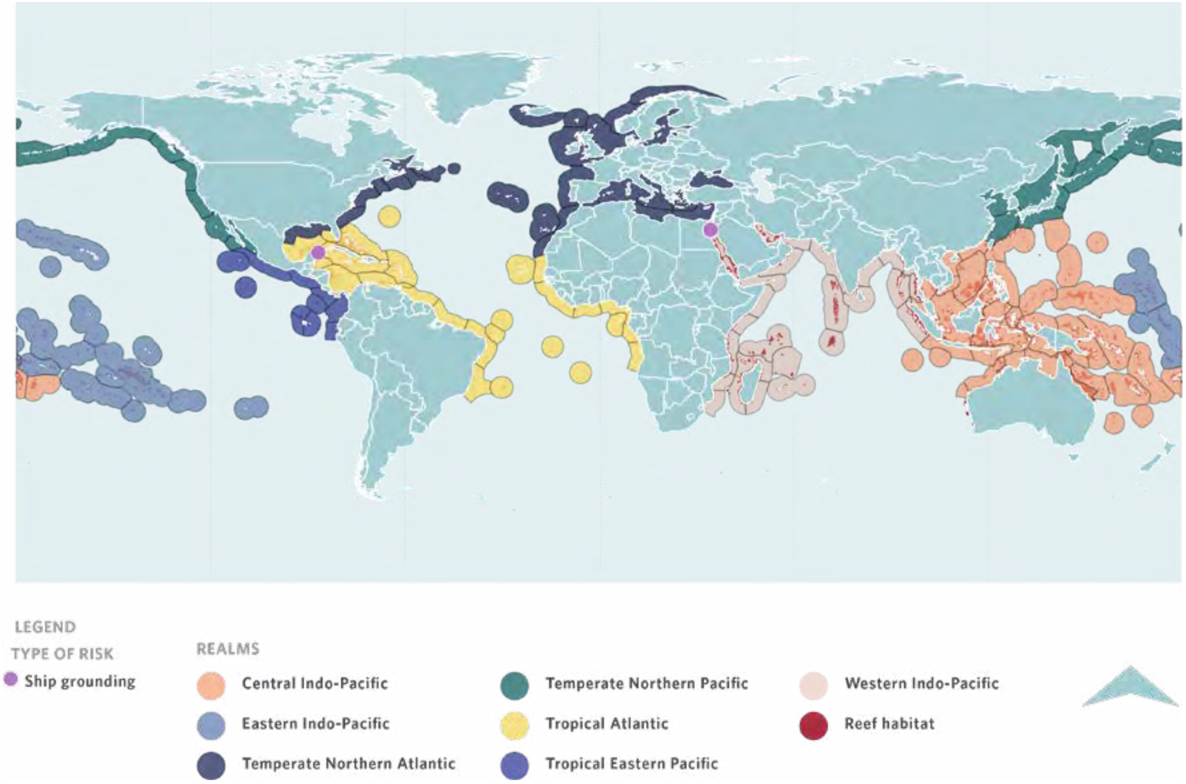


FIGURE 19. Spatial distribution of risk-sets associated with low tides.

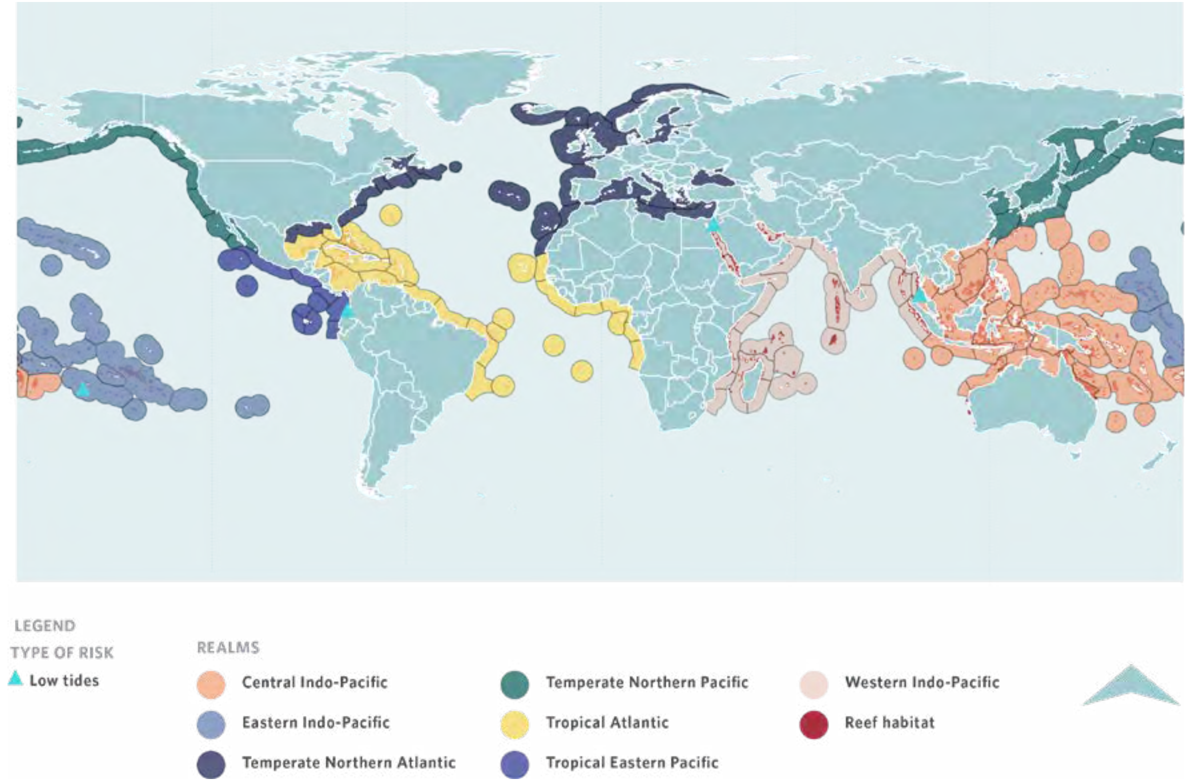


FIGURE 20. Spatial distribution of risk-sets associated with oil spills. These risk-sets are found mainly in the Tropical Eastern Pacific and the Western Indo-Pacific.

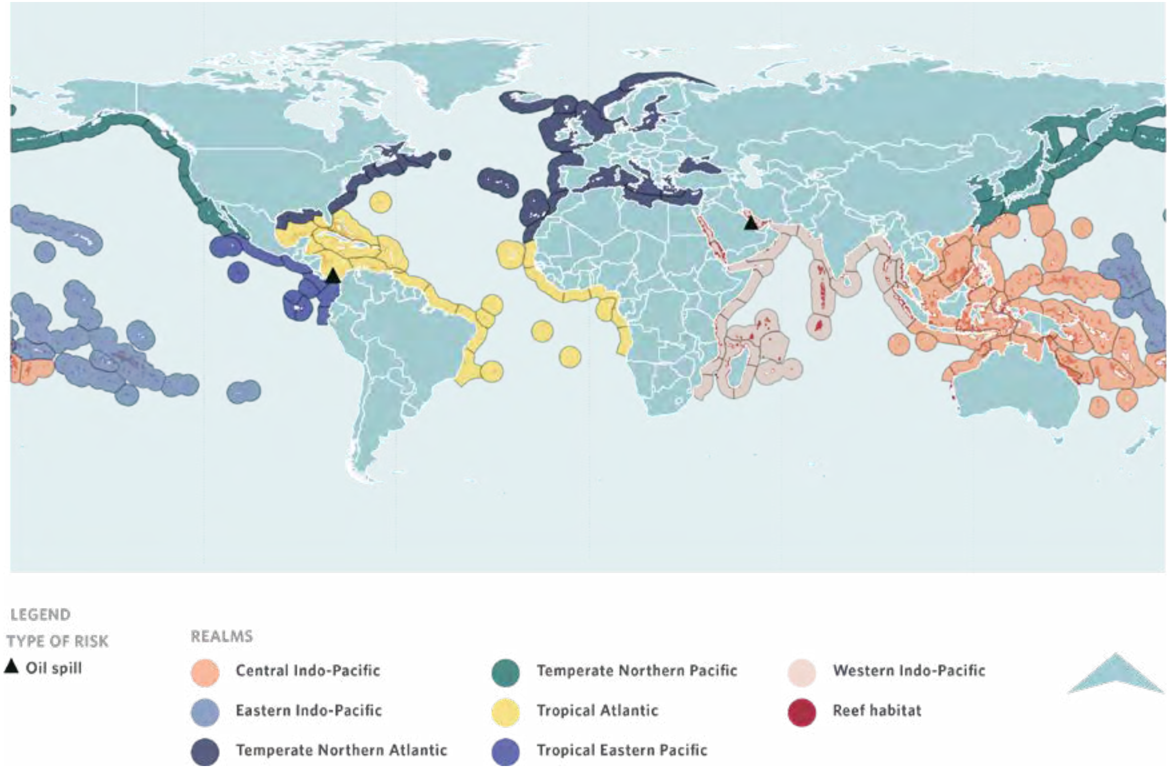


FIGURE 21. Spatial distribution of risk-sets associated with plankton bloom. These risk-sets are found mainly in the Tropical Eastern Pacific and the Western Indo-Pacific.

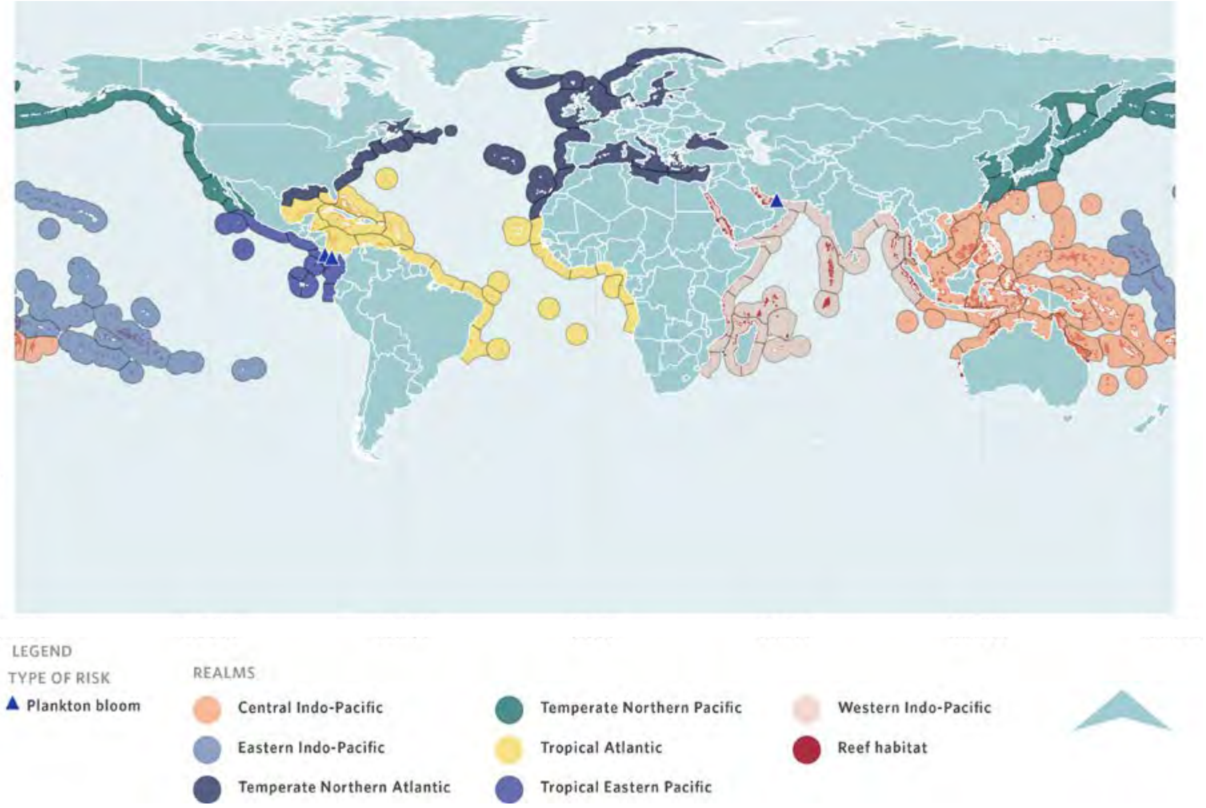


FIGURE 22. Spatial distribution of risk-sets associated with scuba damage. This only risk-set is located in Bonaire, Tropical Atlantic.

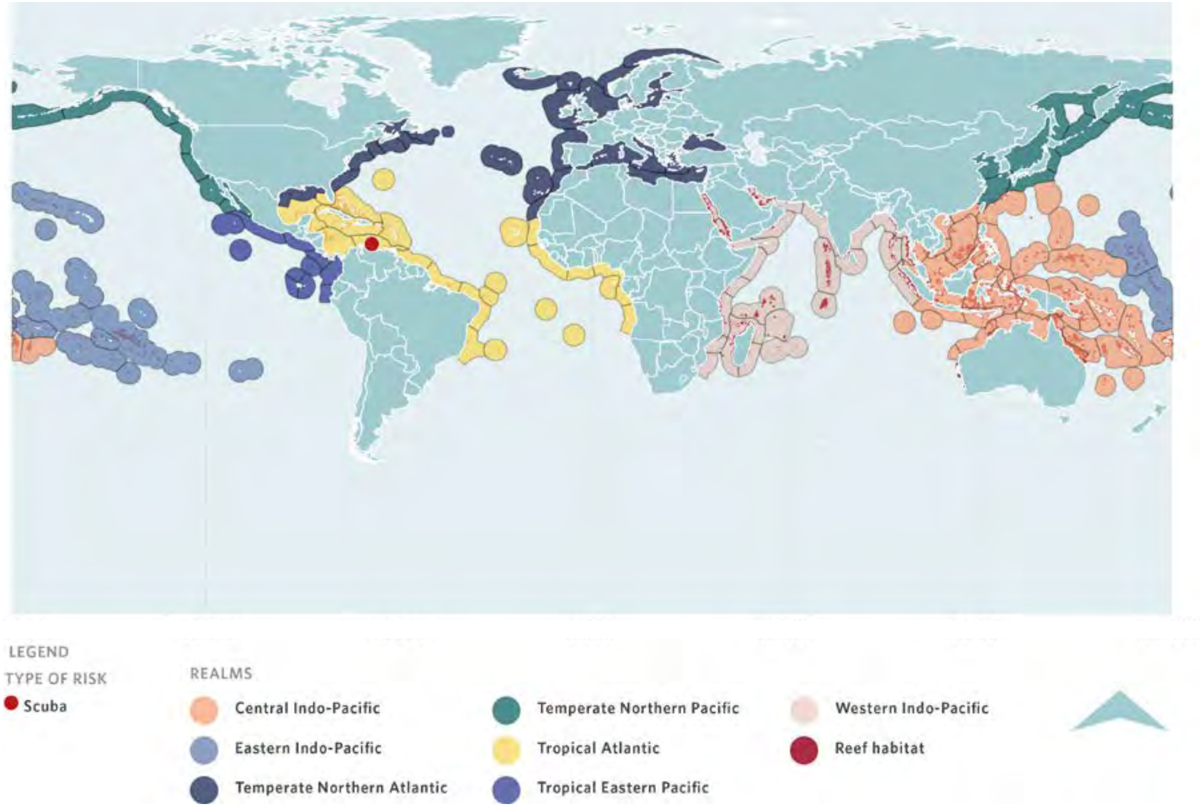


FIGURE 23. Spatial distribution of risk-sets associated with tsunamis. The Indo-Western Pacific region is where the greatest number of risk-sets are concentrated.

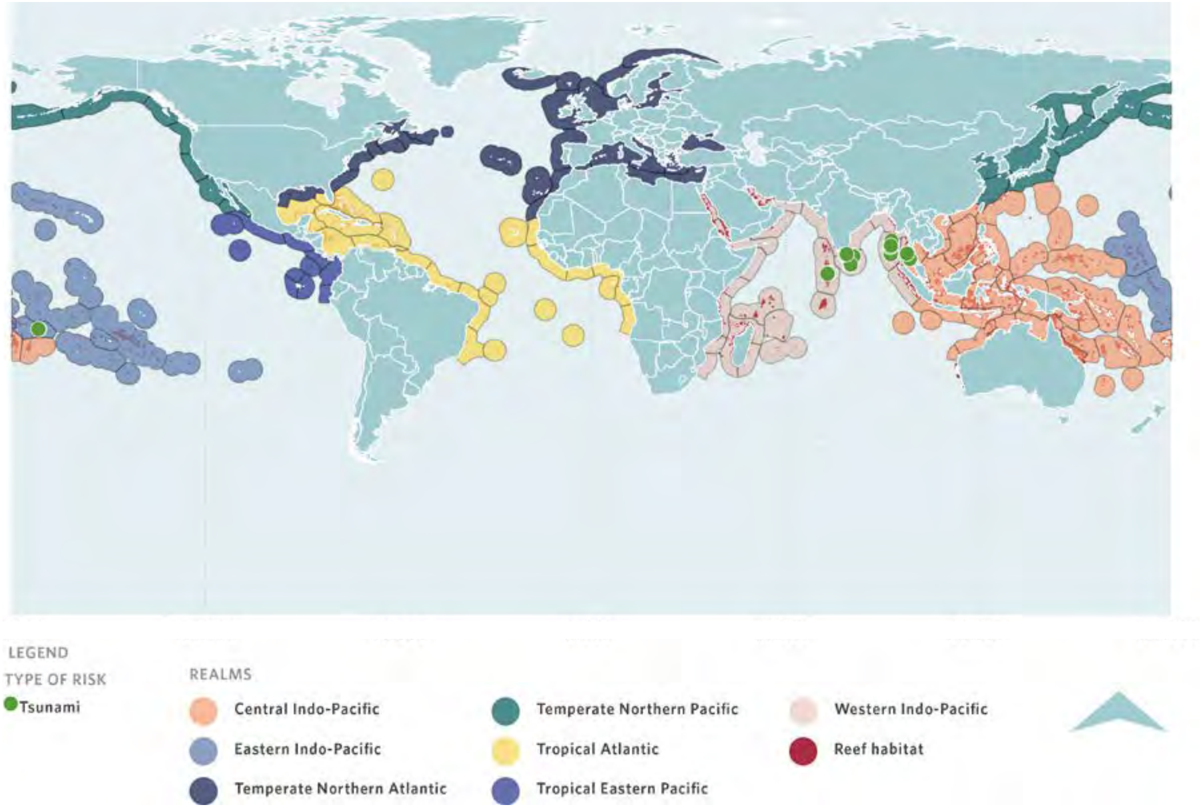
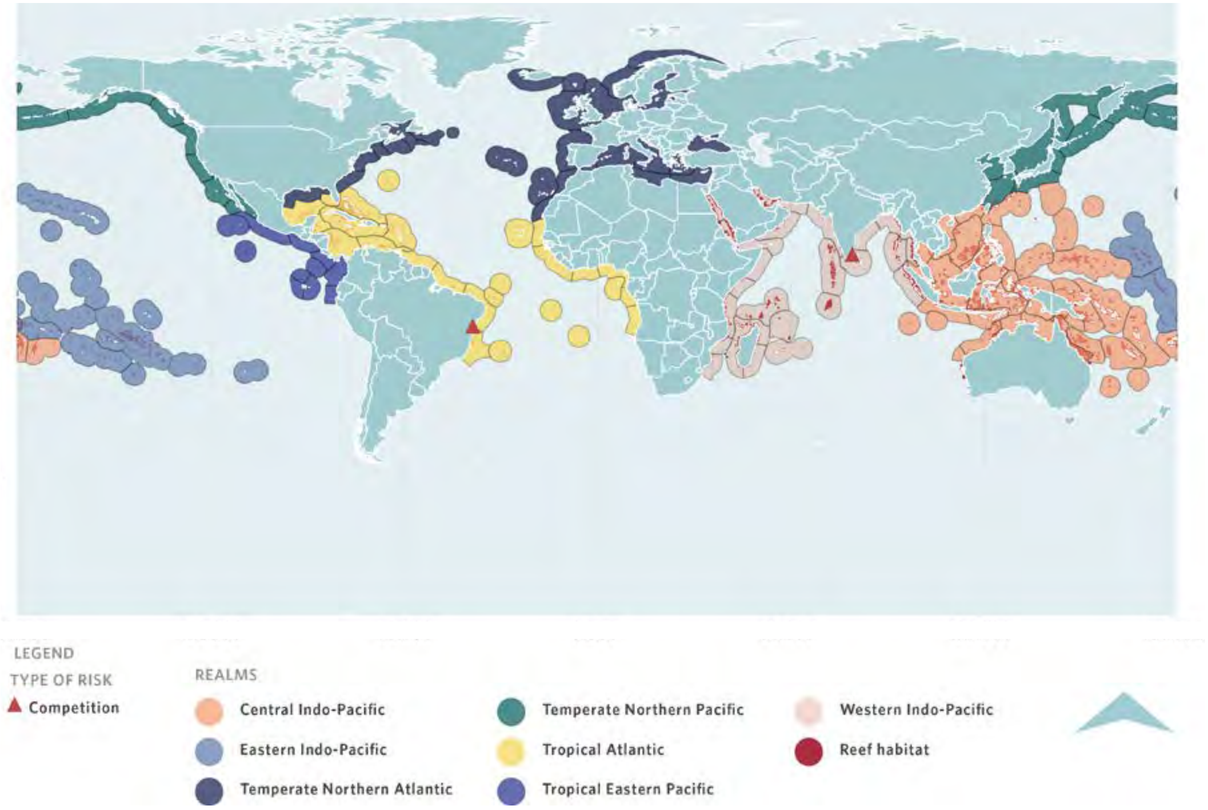


FIGURE 24. Spatial distribution of risk-sets associated with competition relationships between corals and zoanthids (*Epizoanthus gabrieli*) or between corals and sponges (*Terpios hoshinota*).



5.2 DATA LIMITATIONS

Although we have information for 16 risks, data is scarce for many, especially when analyzing per realm. We have high confidence in the mean results of risks per realm with good representation (>98 risk sets). Conclusions for risks per realm with fair representation (30-98 risk-sets) were considered to have medium confidence, while conclusions for risk-sets per realm with low representation (<30) were considered as low confidence as this information is insufficient to draw conclusions from the mean value or to estimate future damages (Martinez-Abrain, A. 2014).

There are sufficient risk-sets to draw conclusions for cyclones (655), bleaching (485), *Acanthaster* breakouts (134) and flood events (101) with high confidence levels across some realms; these four risks represent 70% of all risk-sets. Diseases (49), tsunamis (67) and dredging (40) have enough risk-sets to draw conclusions at the global scale. However, 65 out of 67 risk-sets for tsunamis are in the Western Indo-Pacific, so conclusions can be drawn for that realm only.

With only 0.5% of the world's coral reef area, the Tropical Eastern Pacific, Temperate Northern Pacific, and Temperate Northern Atlantic have only 34 risk-sets; therefore, no conclusions can be drawn for those realms.

06

GLOBAL IMPACTS ON CORAL COVER

GLOBAL IMPACTS IN CORAL COVER

We found an overall reduction of coral cover associated with most of the risks at the global level (Figures 25). Sixty nine percent of the risk-sets (n=1,234) showed a decrease in coral cover and 59% showed a decline in rugosity (Figure 25). On the contrary, 28% of the risk-sets (n=503) showed an increase in coral cover and 31% increase in rugosity. Lastly, 3% and 10% of risk-sets show no change in coral cover and rugosity, respectively. In summary, overall, for all our risk-sets there was an evident shift in the proportion of coral cover towards lower covers following disturbance by the different risks (Figure 26).

FIGURE 25. Annual percentage of change for coral cover and rugosity in risk-sets.

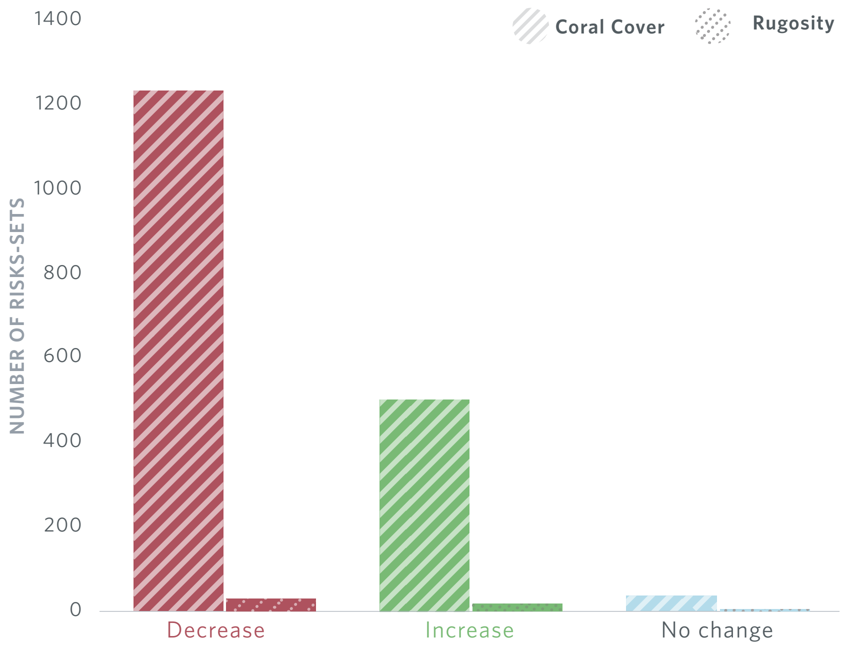
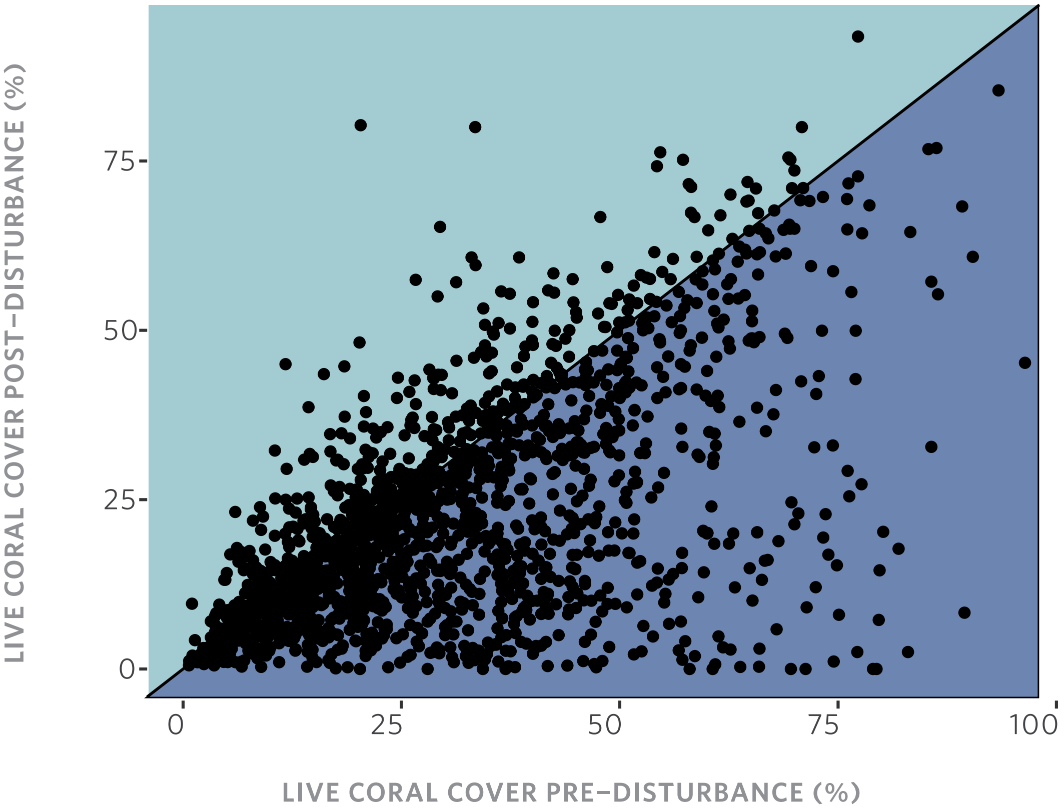
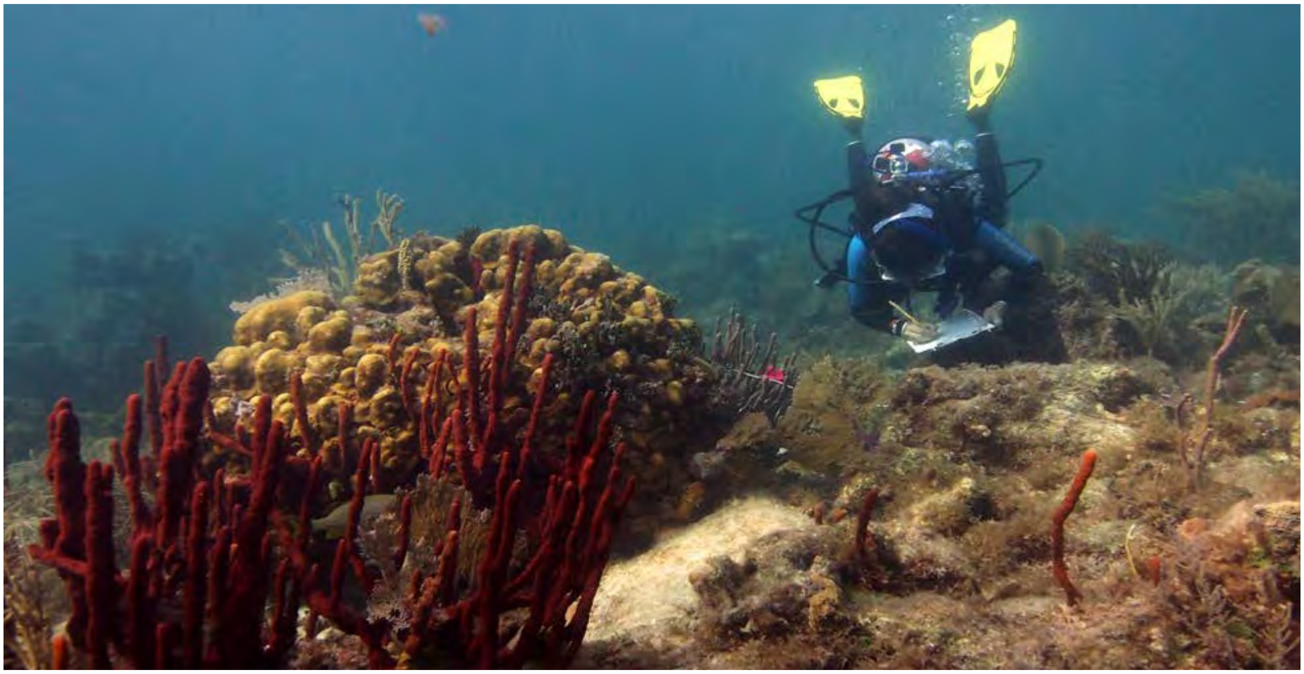


FIGURE 26. Percentage of coral cover pre- and post-disturbance. The black line marks where there is no change in coral cover pre- and post-disturbance. The risk-sets that had a decline in coral cover post-disturbance appear below the line and the risk-sets that had an increase in coral cover appear above the line.





6.1 COMPARING THE IMPACT OF RISKS GLOBALLY

For this section of the analysis, we present 28 risk classes of risks built from the 16 risks we processed in this study. We considered the 7 levels of intensity of cyclones and the 3 levels of intensity for bleaching as different classes of risk; risks-sets with multiple events (floods, cyclones and bleaching) were also considered different classes.

The impact from risks varies greatly. Most risks classes (25 out of 28) showed a negative mean annual change varying from a low impact (-2%) to a catastrophic impact (-95%). Five risks (scuba, other predators, tropical depressions, cyclones 1 and low bleaching) cause moderate damages (-6% to -10%); most of the risks (20) cause severe and catastrophic damages (Fig 27).

Only 3 risks (multiple flood events, tropical storms, and multiple bleaching) showed a positive mean annual change; however, the variability of the data for those risks indicates that many events caused negative impacts (Fig 27).

FIGURE 27. E) Spatial representation of coral reefs across the four realms.

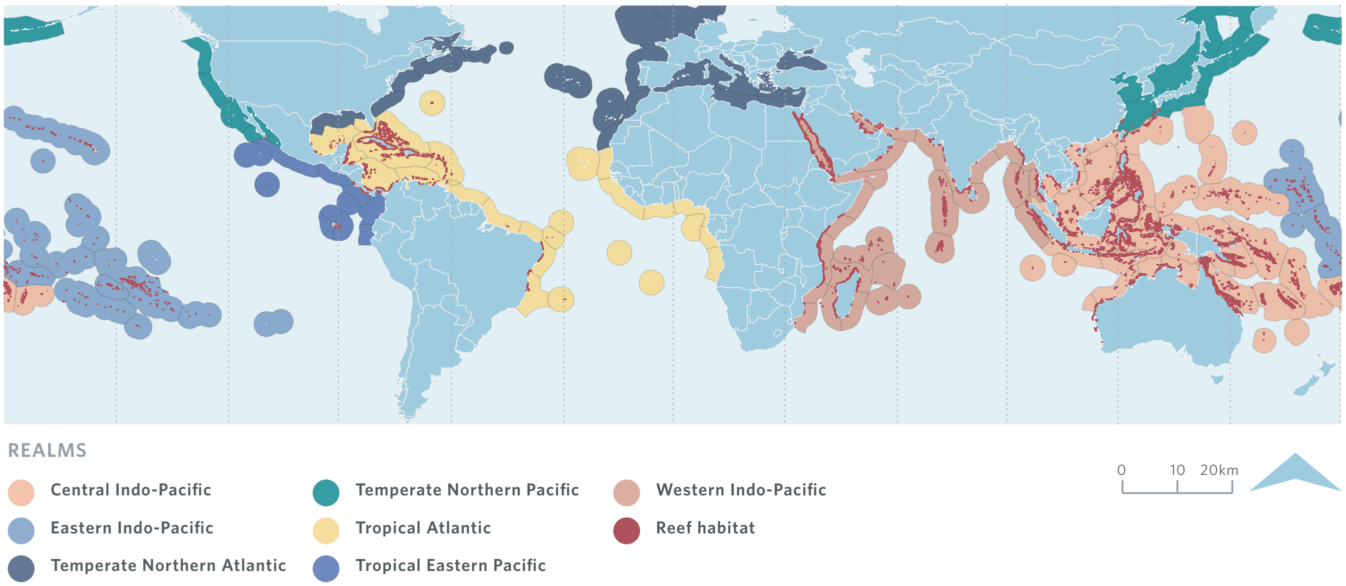
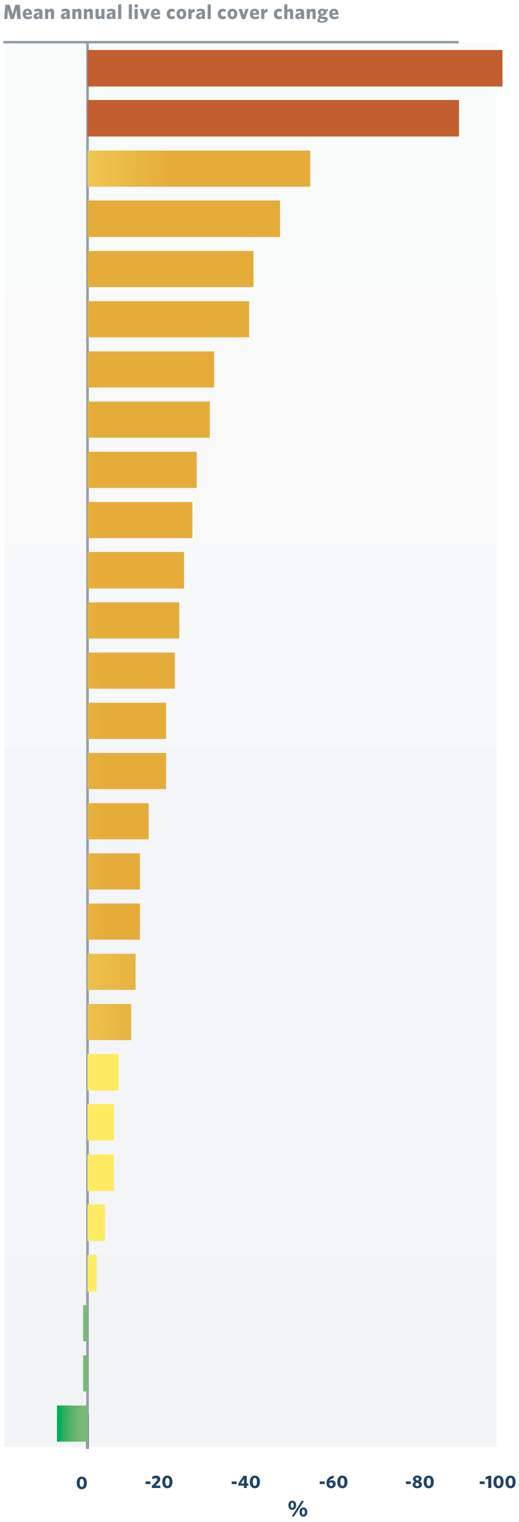


FIGURE 28. Risk organized by severity of the impact on coral cover. Risk, mean, standard deviation (SD), number of risk sets (n) and mean annual change (%)

Order	RISK	Mean	SD	n
1	**Earthquake**	-95	0	1
2	**Grounding**	-85	11	7
3	**Cyclone 5**	-51	20	3
4	**Competition**	-44	20	3
5	**Plankton bloom**	-38	44	22
6	**High bleaching**	-37	33	78
7	**Oil spill**	-29	19	15
8	**Medium bleaching**	-28	26	113
9	**Low tides**	-25	39	26
10	**Cyclone 4**	-24	30	106
11	**Acanthaster**	-22	18	123
12	**Flood events**	-21	35	101
13	**Cyclone 3**	-20	25	40
14	**Dredging**	-18	29	40
15	**Cyclone 2**	-18	26	35
16	**Multiple risks**	-14	26	122
17	**Disease**	-12	19	45
18	**Multiple cylones**	-12	19	55
19	**Anchoring**	-11	17	7
20	**Tsunami**	-10	18	67
21	**Low bleaching**	-7	21	293
22	**Tropical Depression**	-6	22	176
23	**Cyclone 1**	-6	20	53
24	**Other predators**	-4	10	15
25	**Scuba**	-2	11	6
26	**Tropical Storm**	1	25	205
27	**Multiple bleaching**	1	8	9
28	**Multiple flooding**	7	10	9



The severity of the damage caused by different hazards varies greatly. Risks (earthquakes, groundings, cyclone 5 and competition) which cause catastrophic damage (95%, 85%, 51% and 44%), however, they have a low number of risk-sets (1, 7, 3 and 3). Risks which cause severe damages (25% to 38%) have higher number of risk-sets and higher confidence on the results.

Risk can be organized by the geographic scale of the disturbance and the consequent impact they have on reefs (see Table 8).

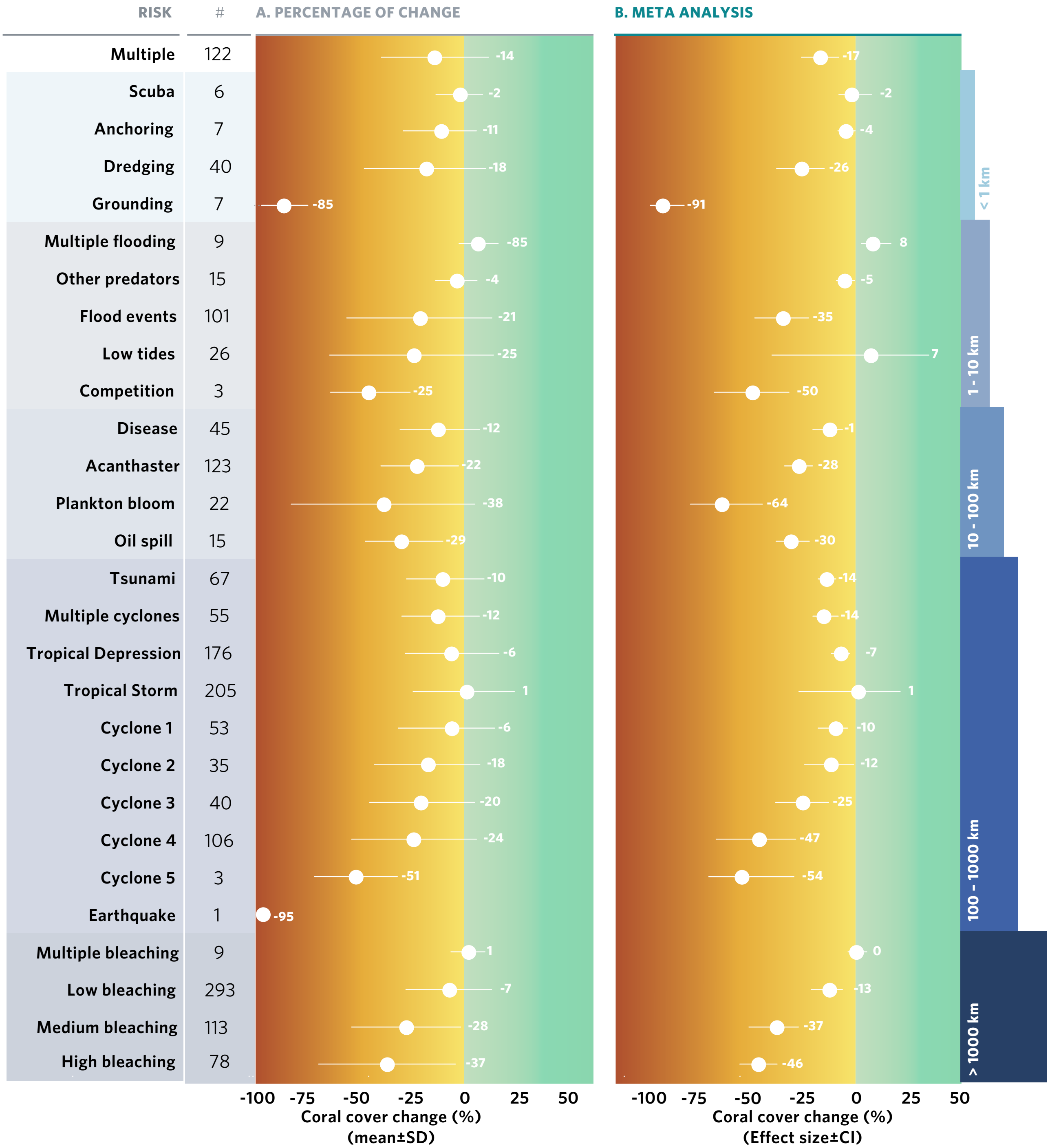
TABLE 8. Annual rates of change and effect size of the meta-analysis. Risk, number of risk-sets, mean, standard deviation (SD), effect size of the meta-analysis (E+), confidence intervals (CIS1 and CIS2), and spatial extension of damage (Ext).

RISK	Number of risk-sets	Annual rate of change (%)		Meta-analysis			
		Mean	SD	E+	CIS1	CIS2	Extension
Multiple	122	-14	26	-17	-9	-8	
Scuba	6	-2	11	-2	-6	-10	< 1 km
Anchoring	7	-11	17	-4	-4	-3	
Dredging	40	-18	29	-26	-12	-11	
Grounding	7	-85	11	-91	-6	-10	
Multiple flooding	9	7	10	8	-6	-9	1-10 km
Other predators	15	-4	10	-5	-4	-4	
Flood events	101	-21	35	-35	-13	-13	
Low tides	26	-25	39	7	-47	-27	
Competition	3	-44	20	-50	-17	-18	
Disease	45	-12	19	-13	-8	-6	10 - 100 km
Acanthaster	123	-22	18	-28	-7	-7	
Plankton bloom	22	-38	44	-64	-15	-21	
Oil spill	15	-29	19	-30	-8	-8	
Tsunami	67	-10	18	-14	-5	-4	100 - 1000 km
Multiple cyclones	55	-12	19	-14	-6	-5	
Tropical Depression	176	-6	22	-7	-5	-4	
Tropical Storm	205	1	25	-2	-4	-4	
Cyclone 1	53	-6	20	-10	-8	-6	
Cyclone 2	35	-18	26	-12	-12	-11	
Cyclone 3	40	-20	25	-25	-13	-11	
Cyclone 4	106	-24	30	-47	-19	-18	
Cyclone 5	3	-51	20	-54	-15	-24	
Earthquake	1	-95					
Multiple bleaching	9	1	8	0	-3	-5	> 1000 km
Low bleaching	293	-7	21	-13	-8	-6	
Medium bleaching	113	-28	26	-37	-13	-10	
High bleaching	78	-37	33	-46	-9	-9	

Comparison of meta-analysis and annual percentage of change.

The meta-analysis shows a similar decline pattern as the annual percentage of change analysis. However, the interpretation with the meta-analysis is different, as it evaluates the certainty of the estimates around the mean effect size of the risks. We found a significant effect in the severity of the change of live coral cover E+ (Figure 29, panel B) compared with the mean annual percentage of change (Fig 29, panel A) for certain risks. For example, the impact of cyclones has a mean of -24% and E+ of -47. Plankton bloom has a mean of -38% and a E+ -64. Only low tides showed a change from negative mean -25% to positive impact with an E+ of 7.

FIGURE 29. Percentage change of coral cover among the different risks at the global level. Panel A shows the mean of the annual percentage of change (circle) and standard deviation (line). Panel B shows the effect size of change of coral cover (E+) (circle) from the meta-analysis and the 95% bias corrected bootstrapped confidence intervals (line). Risks are organized by the spatial extension of impacts from small scale (top) to large scale (bottom). Numbers at the right of the risks indicate the number of risk-sets included in the analysis for each group, and numbers near the error lines show the mean and E



Influence of time-interval of risk-sets on the results

TABLE 9. Annual rates of change of all the risk-sets and the risk-sets with 3 year periods. Risk, number of risk-sets, mean, standard deviation (SD) and spatial extension of damage (Etx)

RISK	Annual rate of change (%)			Annual rate of change % (3 year periods)			
	Number of risk-sets	Mean	SD	Number of risk-sets	Mean	SD	Extension
Multiple	122	-14	26	75	-16	31	
Scuba	6	-2	11	6	-2	11	< 1 km
Anchoring	7	-11	17	6	-12	19	
Dredging	40	-18	29	34	-21	30	
Grounding	7	-85	11	7	-85	11	
Multiple flooding	9	7	10	9	7	10	1-10 km
Other predators	15	-4	10	9	-1	10	
Flood events	101	-21	35	78	-27	38	
Low tides	26	-25	39	15	-53	24	
Competition	3	-44	20	1	-67		
Disease	45	-12	19	32	-13	22	10 - 100 km
Acanthaster	123	-22	18	70	-21	19	
Plankton bloom	22	-38	44	22	-38	44	
Oil spill	15	-29	19	14	-20	19	
Tsunami	67	-10	18	48	-14	19	100 – 1000 km
Multiple cyclones	55	-12	19	34	-18	21	
Tropical Depression	176	-6	22	139	-7	25	
Tropical Storm	205	1	25	161	3	28	
Cyclone 1	53	-6	20	53	-6	20	
Cyclone 2	35	-18	26	35	-18	26	
Cyclone 3	40	-20	25	39	-21	25	
Cyclone 4	106	-24	30	91	-24	31	
Cyclone 5	3	-51	20	3	-51	20	
Earthquake	1	-95		1	-95		
Multiple bleaching	9	1	8				> 1000 km
Low bleaching	293	-7	21	201	-9	24	
Medium bleaching	113	-28	26	86	-35	24	
High bleaching	78	-37	33	73	-38	33	

In Figure 29, we can observe a clear pattern of increasing severity with event intensity. Category 5 cyclones tend to cause ten times more damage (51% ± 20%) than Category 1 cyclones (6% ± 20%). We observed the same pattern with bleaching events, where high DHW coral bleaching tended to cause six times more damage (-37% ± 33%) than low DHW coral bleaching (7% ± 21%) (Table 8).

When combining the severity of the impact with the scale of the disturbance, we can conclude that cyclones and bleaching have the greatest impact of all risks. Cyclones can severely reduce coral cover (19% to 51%), have a frequency in the order of decades to centuries and impact large areas (100 to 1,000 kms). High and medium bleaching events can reduce coral cover from 24 to 36% in very large areas (100 to 1,000 km or even beyond) and nowadays occur every few decades

To evaluate if the time interval between pre-event and post-event had an effect with the interpretation of the results, we carried out an analysis considering only information from risk-sets that had up to three years of time interval. Results did not change significantly between all risk-sets and those with 3 years interval (Table 9).

6.2 COMPARING THE IMPACT ON REEFS BY REALM

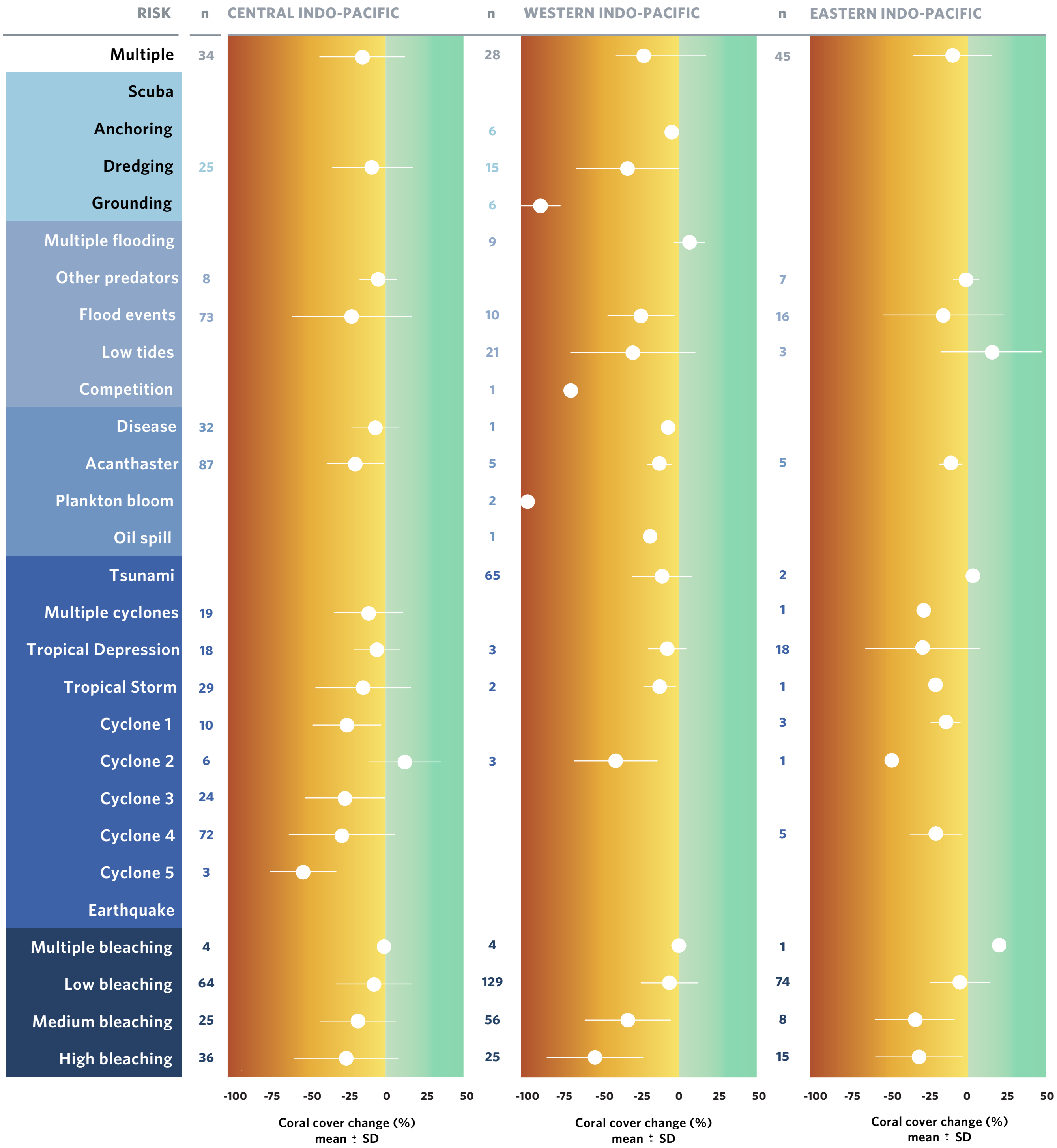
We found that most risk-sets for coral cover show a negative annual change associated with risks across realms, although, the severity of specific risks varies greatly (Table 10; Figure 30). For example, disease tends to have more acute effects in the Tropical Atlantic (-25 % ± 26) than in the Central Indo-Pacific (-8% ± 14).

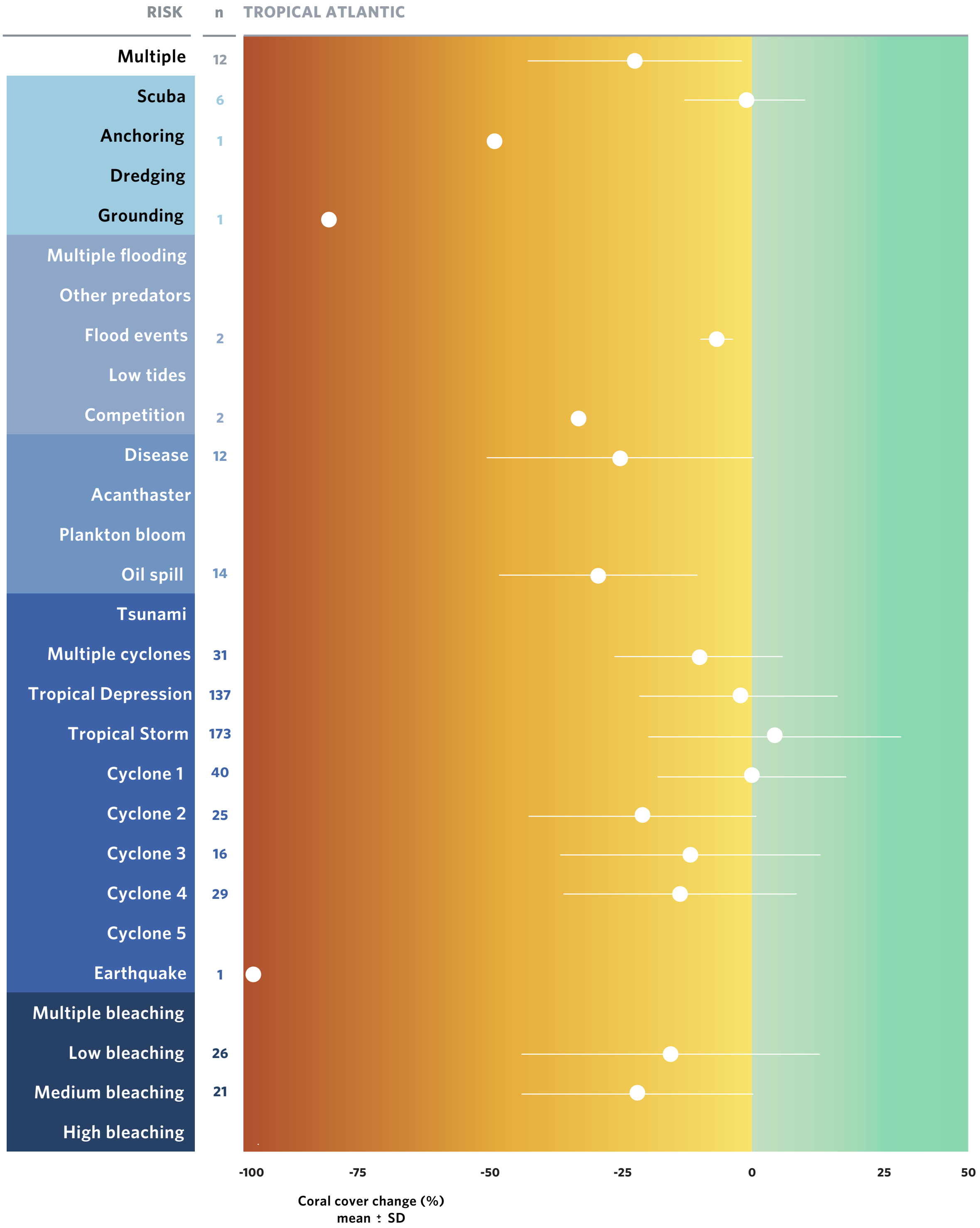
As stated, the lack of data at the realm level limits our ability to reach conclusions or generalizations. Some risks have a very small number of risk-sets. For example, anchoring and grounding in the Tropical Atlantic have only one set each, and plankton blooms and cyclones in the Western Indo-Pacific have two and three sets, respectively. On the other hand, cyclones and bleaching are significant stressors to coral reefs across four realms. The Eastern Tropical Pacific, Northern Tropical Atlantic and Northern Tropical Pacific realms have a small number of risks and few risk-sets associated with each, limiting the interpretation of such data. Results for these 3 realms are presented in section 6.2.5.

TABLE 10. Changes in coral cover for each risk across realms with sufficient data. Mean change of coral cover with the standard deviation (SD), number of risk-sets (N), and spatial extension of damage (Ext). See other realms in Table 11

RISK	Tropical Atlantic			Western Indo-Pacific			Central Indo-Pacific			Eastern Indo-Pacific			
	Mean	SD	n	Mean	SD	n	Mean	SD	n	Mean	SD	n	Extension
Multiple	-23	20	12	-11	28	28	-16	26	34	-11	26	45	
Scuba	-2	11	6										< 1 km
Anchoring	-50		1	-4	4	6							
Dredging				-32	32	15	-10	24	25				
Grounding	-81		1	-86	12	6							
Multiple flooding				7	10	9							1-10 km
Other predators							-6	11	8	-2	9	7	
Flood events	-7	3	2	-23	21	10	-22	36	73	-17	40	16	
Low tides				-29	39	21				15	34	3	
Competition	-33	2	2	-67		1							
Disease	-25	26	12	-6		1	-8	14	32				10 - 100 km
Acanthaster				-12	7	5	-20	17	87	-28	21	31	
Plankton bloom				-94	2	2							
Oil spill	-30	19	14	-18		1							
Tsunami				-10	19	65				3	3	2	100 - 1000 km
Multiple cyclones	-10	16	31				-12	21	19	-30		1	
Tropical Depression	-3	19	137	-7	11	3	-7	14	18	-30	37	18	
Tropical Storm	4	24	173	-12	10	2	-15	29	29	-22		1	
Cyclone 1	0	18	40				-25	20	10	-15	10	3	
Cyclone 2	-21	22	25	-39	26	3	10	22	6	-51		1	
Cyclone 3	-12	25	16				-26	24	24				
Cyclone 4	-14	22	29				-28	32	72	-22	17	5	
Cyclone 5							-51	20	3				
Earthquake	-95		1										
Multiple bleaching				0	5	4	-2	4	4	20		1	> 1000 km
Low bleaching	-16	29	26	-6	18	129	-8	23	64	-6	20	74	
Medium bleaching	-22	22	21	-32	27	56	-18	23	25	-35	26	8	
High bleaching				-52	30	25	-25	32	36	-33	29	15	

FIGURE 30. Percentage change in coral cover for different risks at the realm level. Circles show the mean of the annual rate of change, lines indicate standard deviation in A) Central Indo-Pacific, B) Tropical Atlantic, C) Western Indo-Pacific and D) Eastern Indo-Pacific.




RISK
n
TROPICAL ATLANTIC
Multiple 12
Scuba 6
Anchoring 1
Dredging
Grounding 1
Multiple flooding
Other predators
Flood events 2
Low tides
Competition 2
Disease 12
Acanthaster
Plankton bloom
Oil spill 14
Tsunami
Multiple cyclones 31
Tropical Depression 137
Tropical Storm 173
Cyclone 1 40
Cyclone 2 25
Cyclone 3 16
Cyclone 4 29
Cyclone 5
Earthquake 1
Multiple bleaching
Low bleaching 26
Medium bleaching 21
High bleaching
-100
-75
-50
-25
0
25
50
Coral cover change (%)
mean ± SD

6.2.1 BLEACHING

- High bleaching events caused greater damage in the Western Indo-Pacific (-52%) than in the Central Indo-Pacific (-25%) or Eastern Indo-Pacific (-33%). There were no records of high bleaching with that severity for the Tropical Atlantic.
- Medium bleaching events have been reported in all four realms, causing more damage in the Eastern Indo-Pacific (-35%) and Western Indo-Pacific (-32%) than in the Tropical Atlantic (-22%) and Central Indo-Pacific (-18%).
- Low stress bleaching events had low negative impacts on reefs in all four realms (-6% to -16%).

6.2.2 CYCLONES

- Cyclones are more prevalent in the Tropical Atlantic and Central Indo-Pacific, supported by N= 451 and 181 respectively, compared with only nine risk-sets in the Eastern Indo-Pacific and three in the Western Indo-Pacific.
- Category 5 cyclone cause catastrophic damages (-51%) in the Central Indo-Pacific, the only realm with data.
- Category 2, 3 and 4 cyclones caused negative effects (-21% to -28%) in the Central Indo-Pacific and Tropical Atlantic. There is not enough data for the other realms (12 risk-sets).
- Tropical Depressions have the lowest impact on coral reefs, except for the Eastern Indo-Pacific, which had a catastrophic negative effect (-30%).

6.2.3 *ACANTHASTER* OUTBREAK

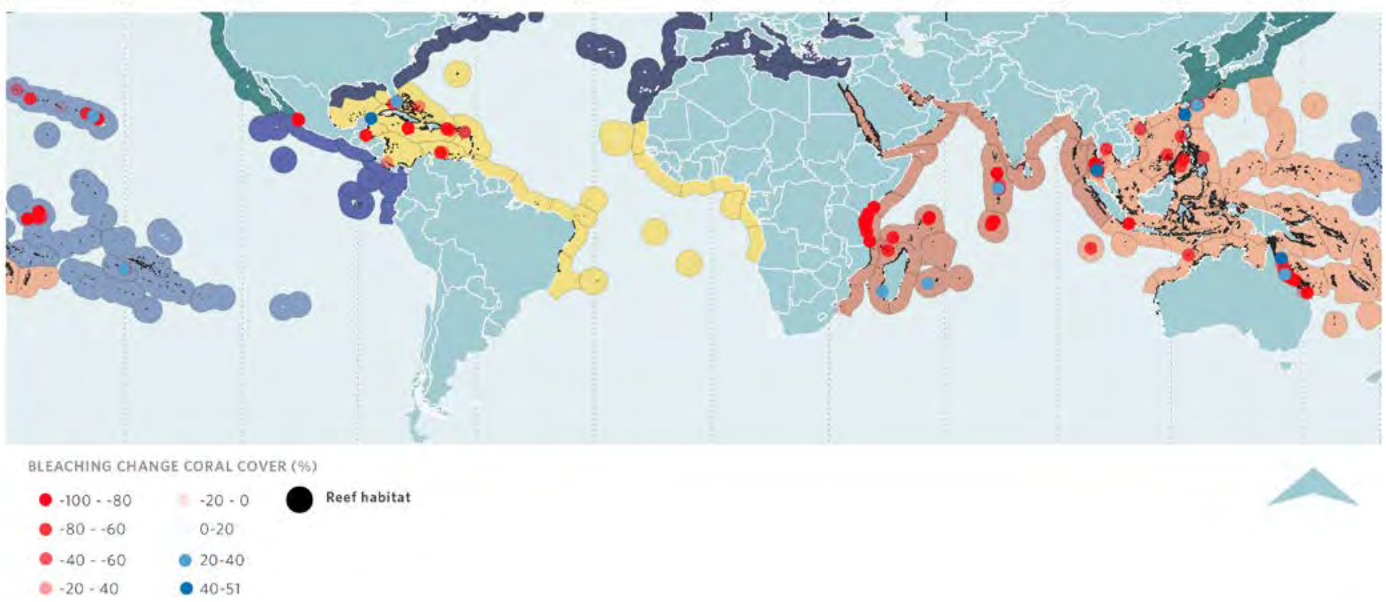
- The outbreaks of crown-of-thorns starfish (Acanthaster sp) are a significant threat across all Indo-Pacific reefs. The Eastern and Central Indo-Pacific have the largest impact, in contrast to the Western Indo-Pacific where the negative impacts appear to be lower (Figure 18). For the Tropical Atlantic there is no registered presence for Acanthaster sp.

6.2.4 OTHER RISKS

- The highest impact for flood events is found in the Central Indo-Pacific (-22%). The lowest impact is found in the Tropical Atlantic (-7%).
- Most tsunamis were reported in the Western Indo-Pacific (N=65) and had low negative impact (-10%). Note that the two risk-sets in the Eastern Indo-Pacific did not register a negative impact for the reefs (Figure 25).
- Plankton blooms cause catastrophic damages in Western Indo-Pacific (-94%). Although they occur in other realms, we did not find data to include in this analysis.

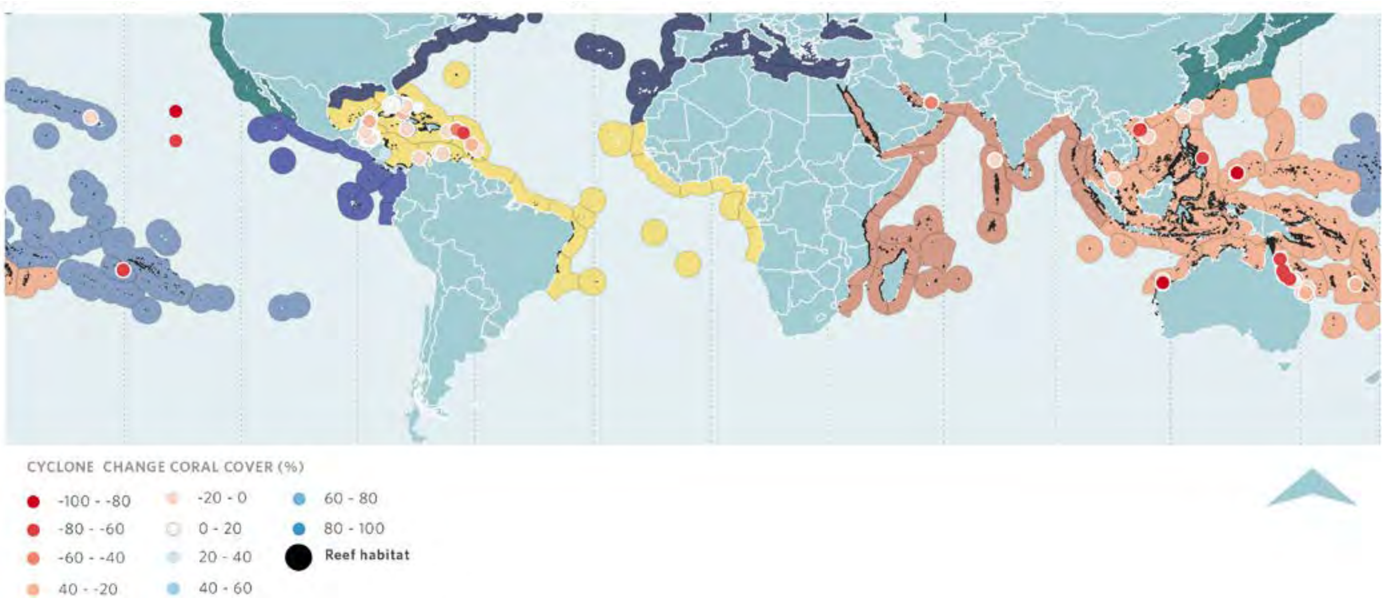
BLEACHING

FIGURE 31. Spatial representation of the coral cover changes (%) due to bleaching events across the realms. Each color dot represents a risk-set and the color gradation represents the annual change, with a negative impact represented in orange and red and a positive impact in blue. Seven realms are shown in the map: Central Indo-Pacific, Eastern Indo-Pacific, Western Indo-Pacific, Tropical Eastern Pacific, Tropical Atlantic, Temperate Northern Atlantic, Temperate Northern Pacific.



CYCLONE

FIGURE 32. Spatial representation of the coral cover changes (%) due to cyclones across the realms. Each color dot represents a risk-set and the color gradation represents the annual change, with a negative impact represented in orange and red and a positive impact in blue.

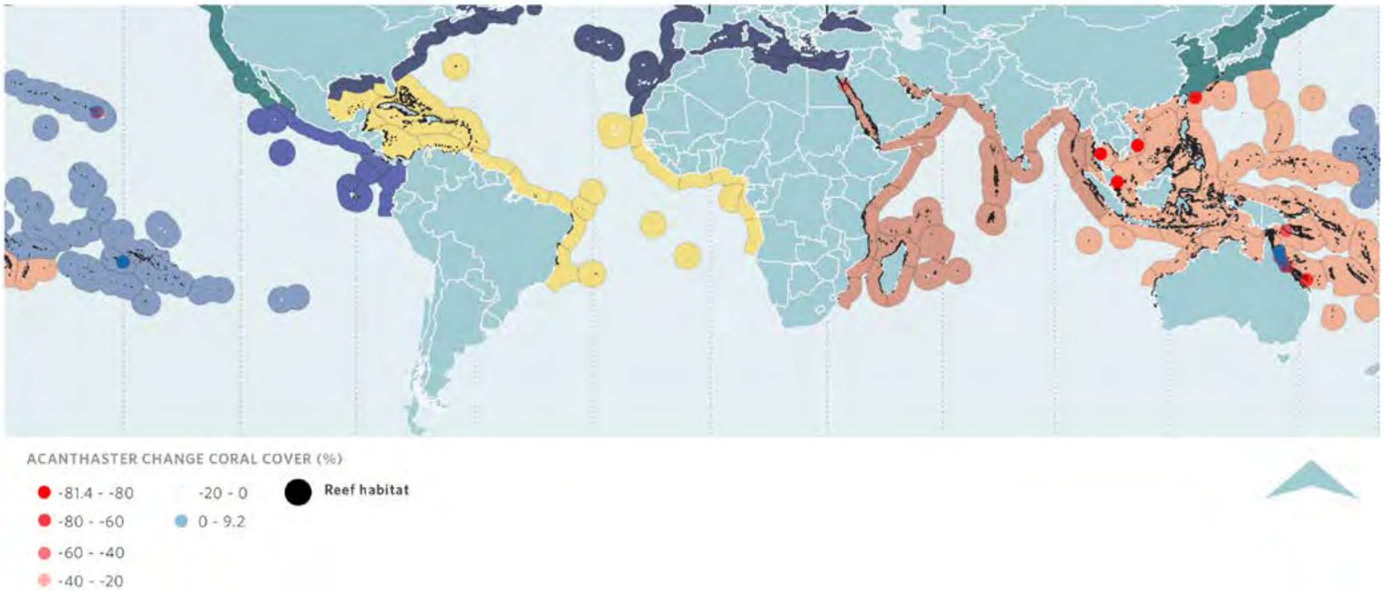


CYCLONE

FIGURE 33. Tropical cyclone tracks from 1980 to 2020. Seven realms are shown in the map: Central Indo-Pacific, Eastern Indo-Pacific, Western Indo-Pacific, Tropical Eastern Pacific, Tropical Atlantic, Temperate Northern Atlantic, Temperate Northern Pacific.

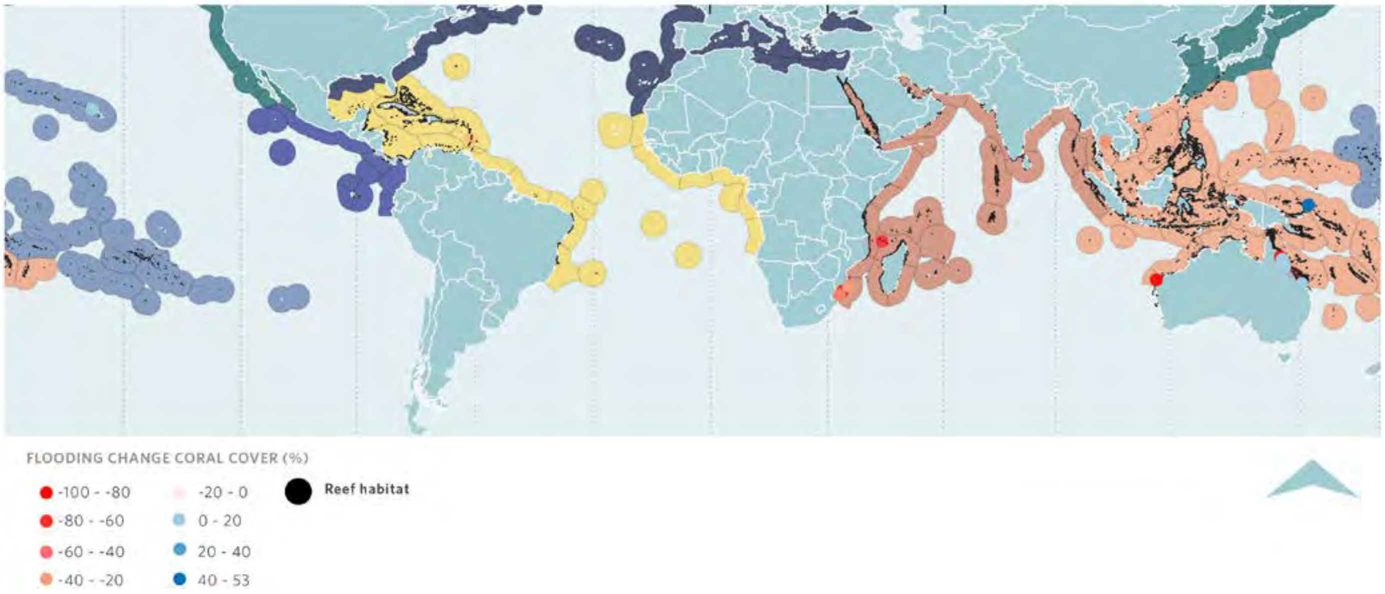
ACANTHASTER

FIGURE 34. Spatial representation of the coral cover changes (%) due to *Acanthaster* sp. across the realms. Each color dot represents a risk-set and the color gradation represents the annual change, with a negative impact represented in orange and red and a positive impact in blue. Seven realms are shown in the map: Central Indo-Pacific, Eastern Indo-Pacific, Western Indo-Pacific, Tropical Eastern Pacific, Tropical Atlantic, Temperate Northern Atlantic, Temperate Northern Pacific.



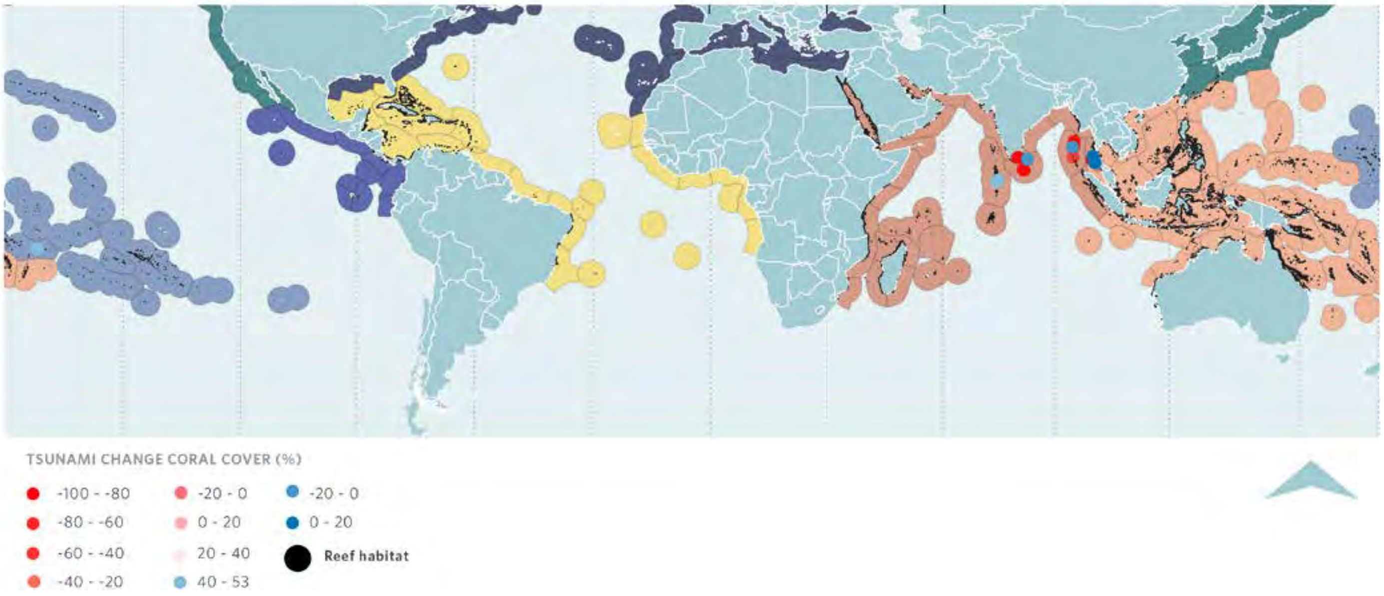
FLOODING

FIGURE 35. Spatial representation of the coral cover changes (%) due to flood events across the realms. Each color dot represents a risk-set and the color gradation represents the annual change, with a negative impact represented in orange and red and a positive impact in blue. Seven realms are shown in the map: Central Indo-Pacific, Eastern Indo-Pacific, Western Indo-Pacific, Tropical Eastern Pacific, Tropical Atlantic, Temperate Northern Atlantic, Temperate Northern Pacific.



TSUNAMIS

FIGURE 36. Spatial representation of the coral cover changes (%) due to tsunamis across the realms. Each color dot represents a risk-set and the color gradation represents the annual change, with a negative impact represented in orange and red and a positive impact in blue. Seven realms are shown in the map: Central Indo-Pacific, Eastern Indo-Pacific, Western Indo-Pacific, Tropical Eastern Pacific, Tropical Atlantic, Temperate Northern Atlantic, Temperate Northern Pacific.



DISEASE EVENTS

FIGURE 37. Spatial representation of the coral cover changes (%) due to disease events across the realms. Each color dot represents a risk-set and the color gradation represents the annual change, with a negative impact represented in orange and red and a positive impact in blue. Seven realms are shown in the map: Central Indo-Pacific, Eastern Indo-Pacific, Western Indo-Pacific, Tropical Eastern Pacific, Tropical Atlantic, Temperate Northern Atlantic, Temperate Northern Pacific.

6.2.5 IMPACT ON CORAL COVER IN DATA-POOR REALMS

The Tropical Eastern Pacific realm was impacted by low tides, plankton blooms and multiple cyclones (Table 11), with only 28 risk-sets. The Temperate Northern Pacific realm had only five risk-sets of bleaching events. The Temperate Northern Atlantic realm had only one risk-set that encompassed multiple risks (i.e., bleaching, cyclones and flooding) (Table 11).

TABLE 11. Mean annual change of coral cover per risk for each realm. Mean of change of coral cover with the standard deviation (SD), number of risk-sets (N) and spatial extension of damage (Ext).

RISK	Tropical Eastern Pacific			Temperate Northern Pacific			Temperate Northern Atlantic			
	Mean	SD	n	Mean	SD	n	Mean	SD	n	Extension
Multiple	-13	6.7	2				-48		1	
Low tides	-46	8.4	2							1-10 km
Plankton bloom	-33	42.1	20							10 - 100 km
Multiple cyclones	-23	27.5	4							100 - 1000 km
Medium bleaching				-58	13.6	3				> 1000 km
High bleaching				-75	31.1	2				

07

GLOBAL IMPACT ON REEF RUGOSITY

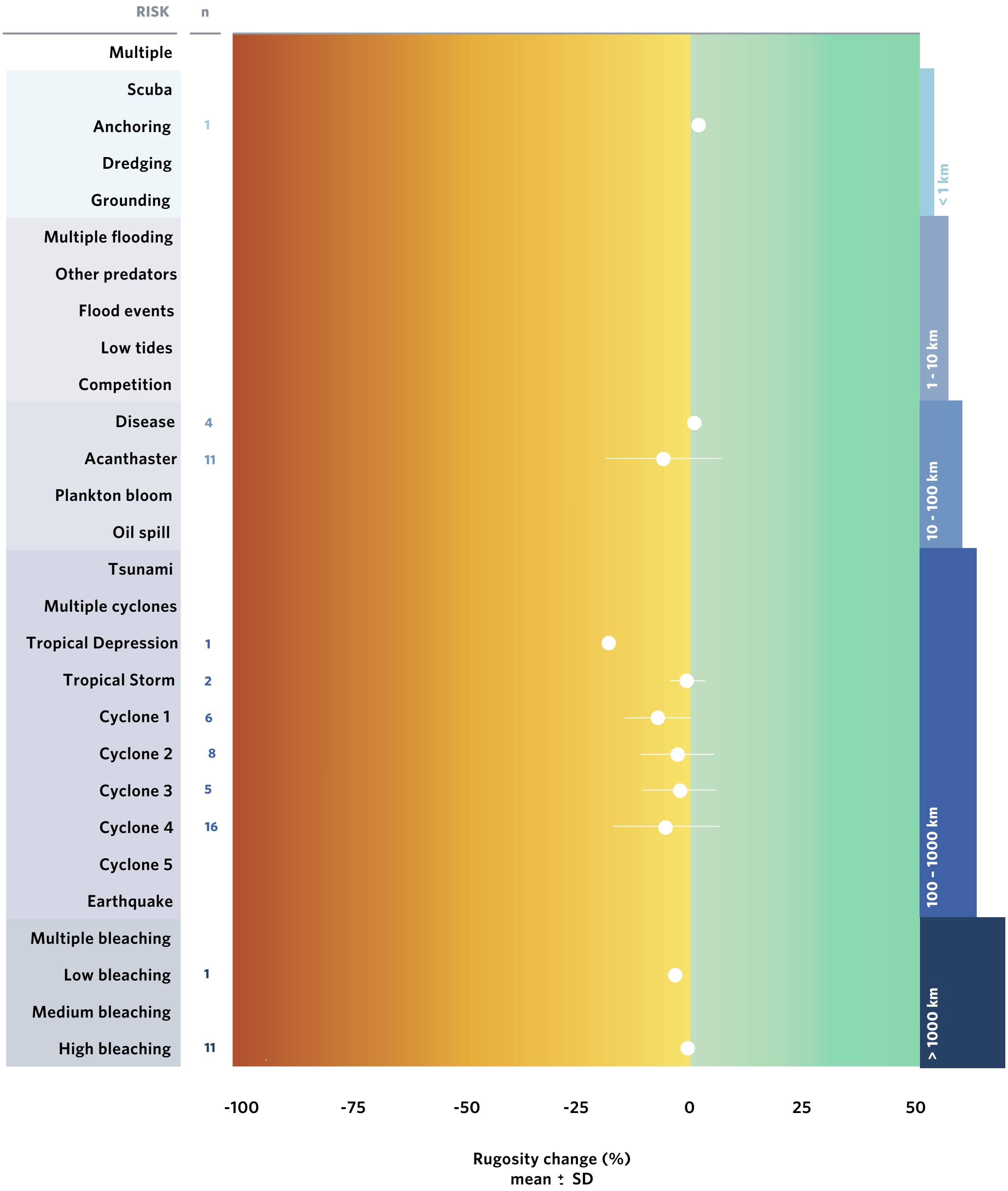
GLOBAL IMPACT ON REEF RUGOSITY

The analysis of the impact of risk on reef rugosity (Table 12; Figure 38) had far fewer risk-sets (71) than the analysis of coral cover (1876); cyclones are the only risk with good representation (n=43). When sorted by realm, none had enough risk-sets (minimum of 20) to analyze impacts on reef rugosity at the realm level, hence, we conducted a global level analysis only. Most of the risk-sets show a negative annual change, which is associated with the effect of the different risks (Figure 22). Although tropical depressions showed the largest impact (-15.8%) with one risk-set, the most significant negative change is caused by Category 1 cyclones (-6.2% ± 6.5) with six risk-sets. In contrast to the relationship data showed between cyclone and bleaching severity and damages to coral cover, the data showed no relationship between cyclone intensity and damages to rugosity. However, as the number of risk-sets available for each category limited the analysis, this result should be taken with caution.

TABLE 12. Data on rugosity per risk for each realm with mean of change of coral rugosity, standard deviation (SD), number of risk-sets (N) and spatial extension of damage (Ext).

RISK	Realm	Mean	SD	n	Extension
Anchoring	Tropical Atlantic	2.2		1	**< 1 km**
Disease	Central Indo-Pacific	0.9	1.2	4	**10 - 100 km**
Acanthaster	Central Indo-Pacific	-5.0	11.7	11	
Tropical Depression	Tropical Atlantic	-15.8		1	**100 - 1000 km**
Tropical Storm	Tropical Atlantic	-0.2	3.6	2	
Cyclone 1	Tropical Atlantic	-6.2	6.5	6	
Cyclone 2	Tropical Atlantic	-2.1	7.4	8	
Cyclone 3	Tropical Atlantic	-1.0	7.9	5	
Cyclone 4	Central Indo-Pacific	-4.4	10.8	16	
Low bleaching	Eastern Indo-Pacific	-2.8		1	**> 1000 km**
Medium bleaching	Western Indo-Pacific	-5.3	2.2	11	

FIGURE 38. Percentage change in coral rugosity among the different risks at the global level. Risks are listed in order of the spatial extension of damage from limited extension (top) to more vast extension (bottom). Numbers at the right of error bars indicate the number of risk-sets included in the analysis for each group. Cyclones include tropical depressions, tropical storms, and Category 1-5 hurricanes. Low bleaching is equivalent to <4 DHW, medium from 4 to 8 DHW, and high >8 DHW.



08

ASSESSING THE FREQUENCY OF EVENTS AND EXTENSION OF IMPACTS

ASSESSING THE FREQUENCY OF EVENTS AND EXTENSION OF IMPACTS

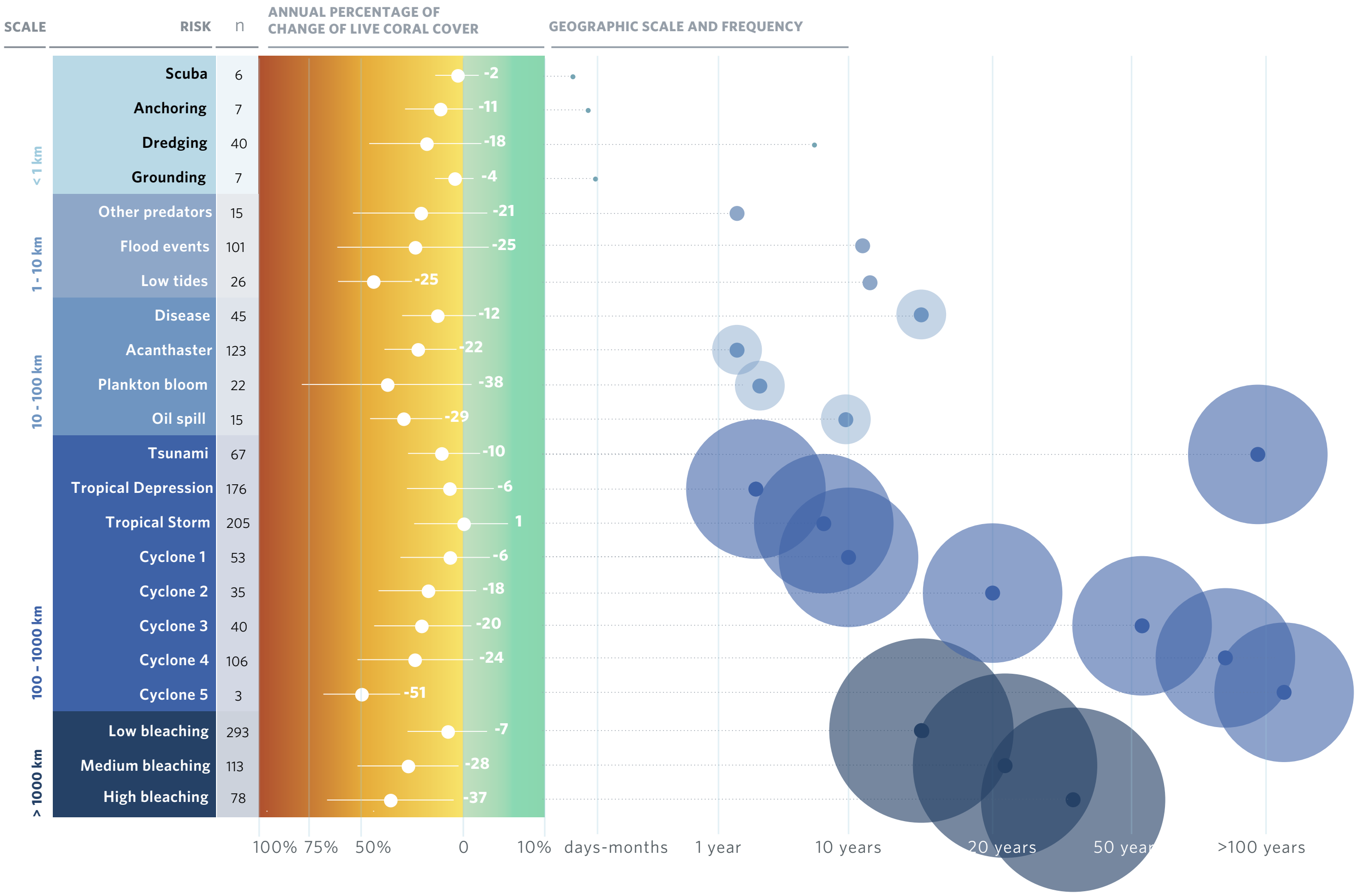
Coral reefs are exposed to a wide range of threats (Nystrom and Folke, 2001). Overall, our analysis of changes in coral cover and rugosity following a disturbance showed evident declines. To compare risks faced by the world's coral reefs, it is essential to consider: 1) the severity of damage the event produces, 2) the extent or scale of the impact, and 3) the frequency at which the events occur (Fig.1; Jackson, 1991; Nystrom & Folke, 2001; Nystrom, 2006). The severity of the impact varies according to: 1) the nature of the risk that affects a particular reef site, 2) the type of damage (biological damage that kills coral tissue or physical damage that dislodges coral from the colony or substrate), and 3) the intensity of the event.

This study was focused on measuring the severity of damage by accounting for reductions in either coral cover or reef rugosity and generated the mean estimates (annual percentage of change) of severity in our analysis. We used the conceptual framework proposed by Nystrom and Folke (2001) to incorporate frequency and extension.

Frequency is expressed in return periods of days, months, years, decades, and centuries. The extent of the impact is classified in order of spatial magnitude: less than 1 km, 1 to 10, 10 to 100, 100 to 1,000, and more than thousand kilometers. Though these frequency and extent metrics are commonly used and accepted, impacts from anthropogenic activities vary greatly depending on specific locations (e.g., near a city, navigation route or oil operation). Moreover, the frequency of natural events also vary depending on the region of the world (e.g., cyclones are prevalent in the Tropical Atlantic and Central Indo-Pacific, but do not generally impact the Western Indo-Pacific). Nevertheless, generalization from Jackson, 1991; Nystrom & Folke, 2001; Nystrom, 2006 can be useful to compare the extent and frequency at the global level.

To visualize the results, we plotted the severity of each risk according to its extent and frequency (Figure 39).

FIGURE 39. Global representation of the frequency (how often a risk occur), damage extension (spatial scale of the damage) and intensity (percent change of coral cover) for risks faced by the world's coral reefs. The information on frequency and spatial extension is based on Jackson, 1991; Nystrom & Folke, 2001; Nystrom, 2006. The circle indicates the order of magnitude of the geographic scale of a typical disturbance of the risk. The location of the center of the circles indicates the gross estimate of the return period of the disturbances. The return periods for human activities are expressed for sites in areas of influence of those activities; many sites are impacted less frequently or not affected at all.



We considered this categorization to assess the frequency and extent of risks:

1. Small extent (less than 1 km) and high frequency (days-months): scuba diving, predators like snails or sea-urchins, damage by anchors or ship groundings.
2. Medium extent (1 to 10 km) and low frequency (years): flood events, low tides, dredging.
3. Large extent (10 to 100 km) and medium frequency (years to decades): plankton boom, *Acanthaster*, oil spills.
4. Very large extent (100-1000 km and more) and low frequency (decades to centuries): all types of cyclones, bleaching events and tsunamis.

Based on the figure 39 we can state that:

- Category 3, 4, and 5 cyclones and bleaching events have the greatest impact on reefs, as they can reduce coral cover between -20% and -51% and affect areas of 100 to 1,000 km.
- Oil spills and plankton blooms follow in importance, with an mean impact of -29% and -38%, respectively, affecting areas from 10 to 100 km.
- Dredging and Category 2 cyclones have the same mean damage on coral reefs (-18%) but at very different spatial scales, with dredging limited to <1 km and cyclones 2 affecting areas of 100 to 1,000 km.
- Ship groundings have great impact on coral cover (-85%) and affect reefs around the world, but the damage they cause is limited to areas of <1 km.).
- Oil spills occur very frequently in areas near oil exploitation and transportation, in the order months to years, and the severity and extent of each event varies greatly.
- Earthquakes and tsunamis affecting reefs are the least frequent of all, in the order of centuries.

09

ILLUSTRATIVE EXAMPLES OF RISKS TO CORAL REEFS

ILLUSTRATIVE EXAMPLES OF RISKS TO CORAL REEFS

The lack of risk-sets for analysis in this study is not indicative of a lack of risks or a lack of damage. Rather, in many cases, the risks and damages were reported using different metrics (visual, density of colonies) than used for this study or the incidents were reported but damage was not evaluated. The examples below reflect events and impacts that severely affected coral reefs – including oil spills, grounding and anchoring damage from ships, low tides, and earthquakes – but could not be included in this study due to the use of different metrics or insufficient data.

9.1 OIL SPILLS

The impacts of large and abrupt spills of petroleum in pristine water are severe, as they overwhelm organismal capacity to respond to the threat (Turner and Renegar, 2017). Petroleum pollution comes from three main sources: extraction (e.g., operational discharges or ballast water); transportation (e.g., oil spills), and consumption (e.g., land-based runoff). Annually more than 1.3 × 106 metric tons of crude and refined oil enter the marine environment (NRC, 2003; Turner and Renegar, 2017). Regardless of the source of contamination, this is a major environmental concern that, unfortunately, has not been properly reported. Moreover, the absence of pre-spill baseline data makes it difficult to discern between negative impacts of the oil spill and other pre-existing stressors (Turner and Renegar, 2017).

There have been many oil spills, with some resulting in major deterioration of the reef community. For example, on 3 June 1979, the Ixtoc I exploratory well in the Bay of Campeche blew out, resulting in one of the largest oil spills in history. The well was finally capped 290 days later – after 475,000 metric tons of oil had spilled into the Gulf of Mexico (Figure 40). Because of the chemical toxicity (near the well) and physical properties (stickiness), this blowout acutely affected species and ecosystems along the coast and in a large offshore area (Jernelöv and Lindén, 1981).

FIGURE 40. 1979 oil spill in the Bay of Campeche (Photo from NOAA, Incident news, 2007).

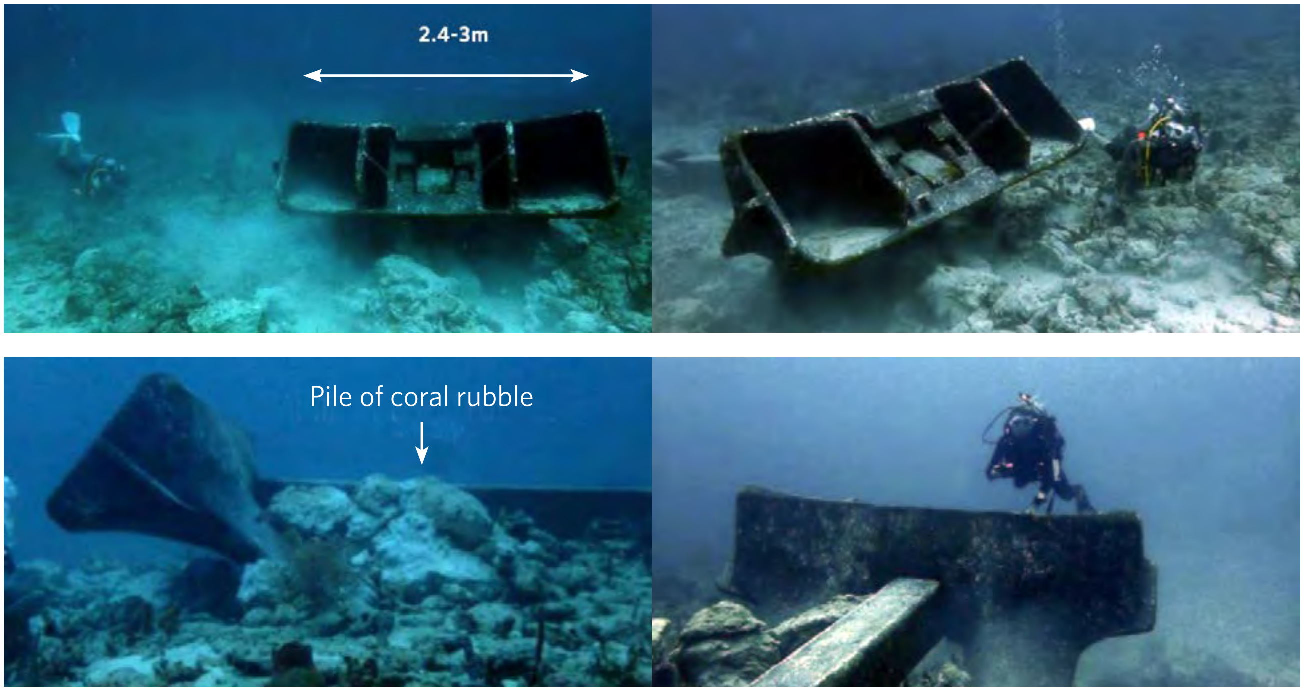
Caused by an explosion on the drilling platform on 20 April 2010, the Deepwater Horizon oil spill was the largest in history. By the time it was capped 87 days later, the well had discharged more than 4.1 million barrels of crude oil (McNutt et al., 2011; 2012). The oil slick and dispersants floated for weeks above coral reefs located more than 100 km from the spill, including three Pinnacle Trend reefs closest to the wellhead. These reefs showed major declines after the spill and have continued to deteriorate in the years since, suggesting recovery of injured corals is unlikely.

9.2 SHIP DAMAGE

The physical damage from ship groundings is acute and catastrophic for corals as ships break and displace coral colonies, fracture reef structure, and generate debris fields. Remaining coral communities may also be impacted by contaminants leaking from grounded ships (Negri et al., 2002), which can extend the footprint of the damage and impede recovery.

There are very few studies about this risk (Flynn and Forrester, 2019), but there are reports of damage on coral reefs due to specific ship groundings or anchoring. For example, during the COVID-19 pandemic, the Barbados Government allowed 29 cruise ships in the Bridgetown Port to anchor along the west and south coasts of the island from 1 March to 1 September 2020. Many of the ships anchored more than once, which led to 132 anchor drops taking place in relatively shallow water (< 50 m) on sandy areas, hard coral patch reefs, and hard coral reefs (Figure 28; Small & Oxenford, 2021). Approximately 1,000 square meters were visually confirmed to have been damaged, and it is estimated that the area impacted is closer to millions of square meters (Small & Oxenford, 2021).

FIGURE 41. Anchoring damage in Carlisle Bay, Barbados, during the COVID pandemic in 2020. (Photos from Small & Oxenford, 2021).



9.3 DESTRUCTIVE FISHING

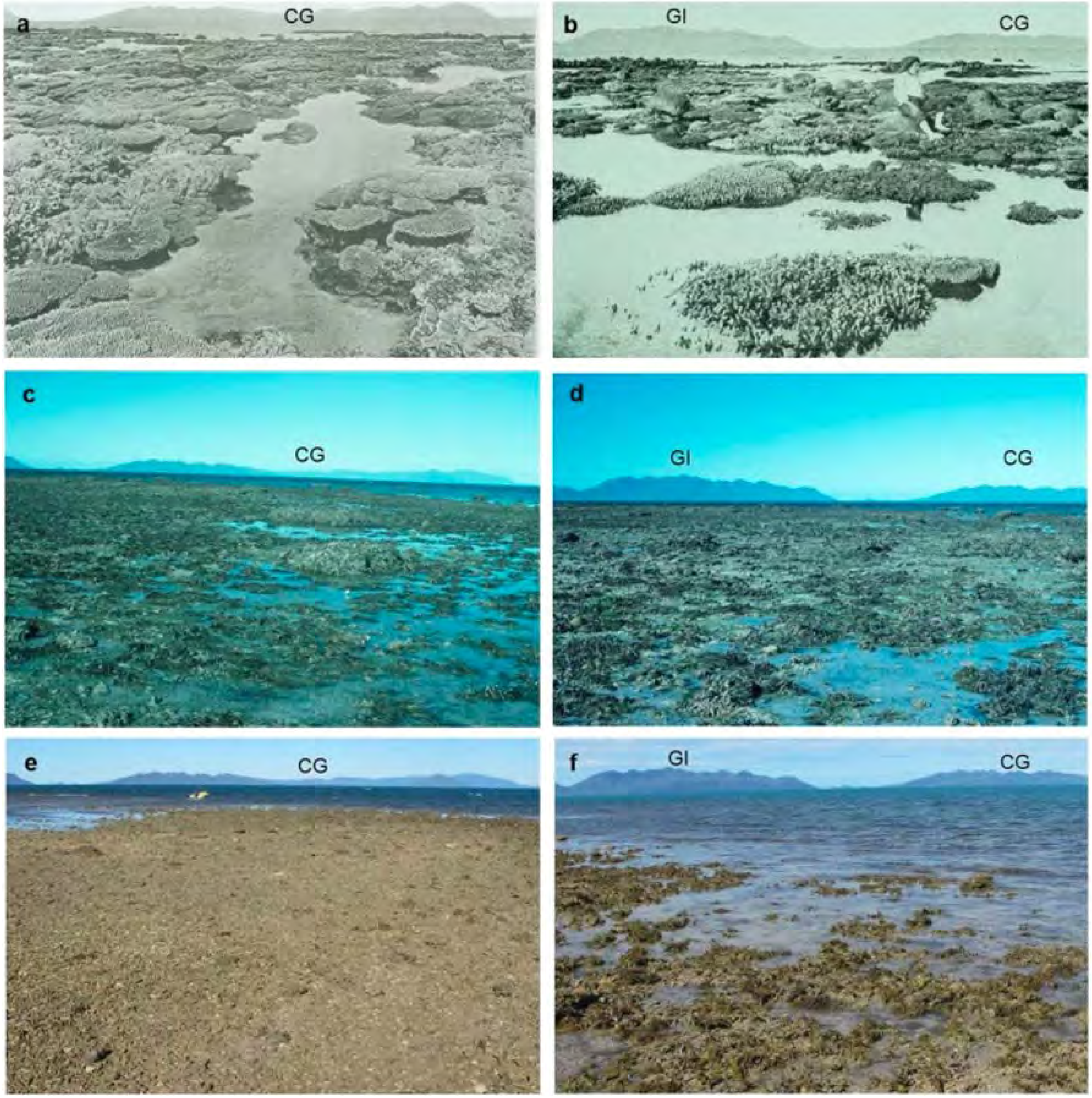
Various destructive fishing techniques continue to be a major risk, causing significant damage to reefs in the Indo-Pacific (Magdaong et al., 2014; Zhao et al., 2016; Kennedy et al., 2020). These harmful fishing practices include dynamite or blast fishing and cyanide fishing (McManus et al., 1997). These practices not only remove the resource itself (fish and invertebrate stocks), but also destroy the habitat. Dynamite fishing inflicts maximum damage to the entire coral ecosystem, as the detonated bomb and shock waves pulverize coral skeletons within a one-meter radius (Nuridin et al., 2016). Cyanide fishing has been used to collect selective fish species to supply the marine aquarium and live reef fish food trades since the 1960s. While the cyanide only stuns the fish, it has toxic effects on other marine life and can kill coral (Magdaong et al., 2014). Despite bans on these practices, they are still widespread in more than 30 countries (across Southeast Asia, the South Pacific, Eastern Africa, and the southern part of the Red Sea) due to low operational costs and quick results (Nzali et al., 1998; Riegl and Luke 1998; Burke et al., 2002; Kennedy et al., 2020). Several reefs have been affected by dynamite, reducing coral cover through coral breakage; overfishing occurs in damaged areas continuously fished as coral cover and structure recover very slowly (Magdaong et al., 2014).

9.4 LOW TIDES

Although some coral reefs are used to natural tidal changes and being exposed a couple of hours throughout the day, many studies have demonstrated that corals are affected during extreme low tides, which can last for several days or weeks. During these events, corals are exposed to solar radiation, wind, rain, extreme temperature, and desiccation. The stress caused by this exposure has devastating effects, including bleaching and the partial or total mortality of the colony (Castrillón-Cifuentes et al., 2017). One case of extreme low tide was reported in 1970 in the Red Sea's Gulf of Eilat, where the reef was exposed at low tide during five consecutive days. This exposure to the sun and air temperatures of 34°C-38.4°C for 3-4 hours every day caused the death of approximately 80%-90% of the corals (Figure 41; Loya, 1972).

Another example is the Stone Island reef, in the central part of the Great Barrier Reef in Australia. With a series of historical photographs Clark et al., (2016) documented the loss of coral cover due to a series of low tide events. In 1890 and 1915 the reefscape was dominated by branching Acropora and other coral general (Figure 29a,b); whereas in 1994 after a low tide event, the reef was covered in a mixture of coral rubble and algae with no living Acropora and very few massive coral colonies present (Figure 29c,d). By 2012, another low tide event of 0.25 m was registered (Figure 29e,f).

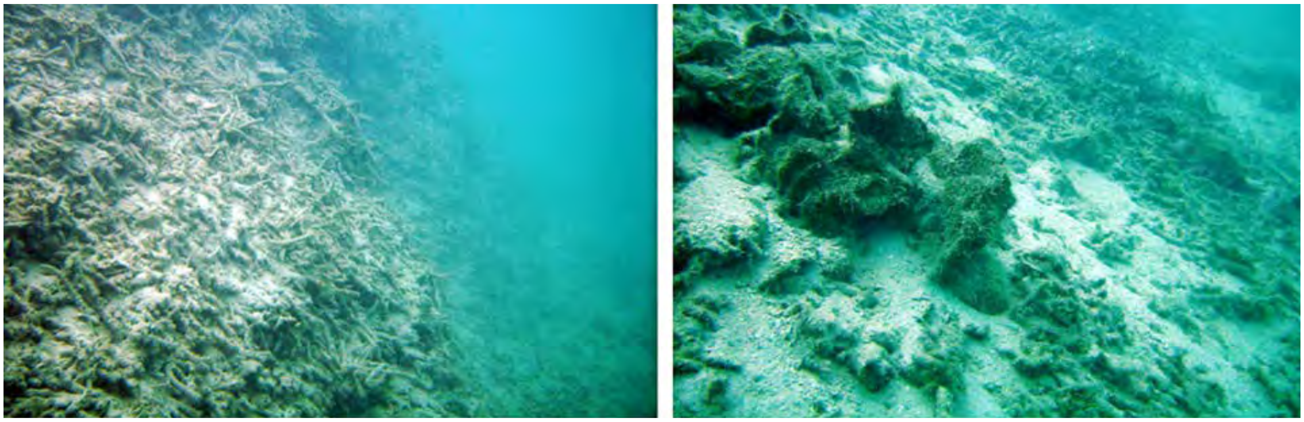
FIGURE 42. Low tides that expose corals to air can be damaging for coral reefs.s. Historical photographs of Stone Island in the central Great Barrier Reef: (a) photograph in 1980 high coral cover, (b) photograph in 1915, (c, d) Photograph of Stone Island taken in 1994 and (e, f) photographs on July 2012. (Clark et al., 2016).



9.5 EARTHQUAKES

Earthquakes have been recognized as natural disturbances that affect coral reefs (Wilkinson, 1999), but their effects are normally caused by or associated with resulting tsunamis. Though few studies have been focused on the localized damage associated with earthquakes, a well-documented event in Western Caribbean in 2009 had a catastrophic impact on the coral reefs in the shelf lagoon of the Belize Barrier Reef (Aronson et al., 2012). The collapse of the reefs was triggered by fractures caused by the earthquake and all benthic organisms migrated, were displaced, or were buried, leaving only sediment and the skeletal debris of corals (Figure 41; Aronson et al., 2012). According to the authors, the recorded damage from the tectonic event extended over an area of hundreds of square kilometers, making it an unprecedented event on a scale of millennia.

FIGURE 43. Showing the effects of the May 2009 earthquake on the coral reef at Channel Cay, Belize (Photos from Aronson et al., 2012)



9.6 PLANKTON BLOOM EVENTS

The increase in coastal eutrophication and changes in oceanic climate can result in massive blooms of plankton and phytoplankton (Landsberg, 2002). These blooms decompose and cause oxygen depletion in the water and eventually can cause the mortality of different species, including corals, attributed to anoxia (Baas Becking, 1951; Guzman, 1990), toxicity, and reduction of light penetration (Guzman et al., 1990). One case of coral death associated with dinoflagellate bloom occurred from 3 June to 12 July 1985 in Caño and Uva Islands in Panama, which caused near 100% mortality of Pocillopora coral colonies (Guzman et al., 1990).

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COMPARATIVE ANALYSIS
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