# How Modeling Can Be Used to Predict the Effects of Climate Change on Philippine Coral Reef Ecosystems

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## ABSTRACT

Climate change will amplify the effects of ocean acidification and coral bleaching, the two main threats to the health of coral reef ecosystems. However, it is uncertain as to what extent climate change will harm coral reef ecosystems within the next decade. Modeling studies have been conducted to understand the future possibilities to predict the effects of climate change on coral reef ecosystems and evaluate the outcome. Here I conduct a literature review on predictive studies that could be used to examine the effects of climate change on coral reef ecosystems in the Philippines. These studies show that while predictive modeling has been used to guide climate policies, they are ultimately limited by the inability to account for factors external to each model. These studies work for specific trends, such as observing the increase in species biomass in a given study area but are ultimately unable to realistically reflect the future on a larger scale due to the unpredictable nature of climate change and its effects.

## KEYWORDS

ocean acidification, coral bleaching, emissions scenarios, predictive study, literature review

## INTRODUCTION

Climate change is a phenomenon characterized by changes in temperature and weather patterns across the globe (Abbass et al. 2022). These changes to the Earth's climate have amplified over the past 50 years as a result of anthropogenic activity, specifically the combustion of fossil fuels. Carbon dioxide emissions have trapped atmospheric gases to enhance the greenhouse effect, causing the Earth's climate to warm (Cassia et. al 2018). To understand this warming, the Intergovernmental Panel on Climate Change (IPCC) has created various scenarios known as representative concentration pathways (RCP). Each RCP is associated with a different carbon emissions scenario; RCP4.5 is where emissions slow down by 2040 while RCP8.5 is where emissions continue to rise until the end of the 21st century. These emissions scenarios have been used to guide climate research and assessments for at least 30 years and have influenced climate policies both on a national and international level (Pedersen 2022). Although these scenarios have proven to be helpful, their application in accurately predicting the impacts of climate change on marine ecosystems remains a challenge.

Coral reef ecosystems are one of many ecosystems undergoing stress due to climate change. They are highly dynamic (Spalding and Brown 2015) due to their constant exposure to natural and anthropogenic stressors, but the amplification of these stressors has provided new challenges. A primary threat to coral reef health is coral bleaching, which occurs when sea temperatures warm because of climate change (van Woesik et al. 2022). The warm waters cause coral reefs to expel photosynthetic symbionts, making them appear white and ultimately more prone to mortality (van Hooidonk et al. 2020). Bleaching events are increasing in frequency (Goreau and Hayes 2021), thus decreasing the ability of coral reefs to recover between events. Some corals, under repeated exposure to changes in temperature, can develop tolerance to thermal stress (Sully et al. 2019); however, coral reef ecosystems are also impacted by ocean acidification, preventing reef growth and recovery. As anthropogenic carbon emissions have increased, the ocean has become more acidic over the past decades. This increased acidity occurs because the ocean is Earth's largest carbon sink with a great capacity to absorb large amounts of carbon dioxide (Findlay and Turley 2021). Ocean acidification impedes the ability of reef-building organisms to produce calcium carbonate, which corals are made of, resulting in a decline in the formation and repair of reefs. The increased frequency of bleaching events that prevent reef recovery coupled with ocean acidification will make it difficult for coral reefs to survive in the long term under current climate conditions (van Hooidonk et al. 2020).

The destruction of coral reef ecosystems will impact species diversity and interactions within them. These ecosystem changes are not unprecedented but the rate at which it is happening is much faster than it was over geological time (Pinsky et al. 2020). To cope with the changing environmental conditions, marine organisms are more likely to experience geographical range shifts as they can migrate and colonize new territory more easily compared to land animals (Pinksy et al. 2020). The movement of species to different marine environments, or gene flow, will lead to the distribution of phenotypes to other populations, altering the composition of many coral reef ecosystems. This movement has already been observed in the past decade, with Tropical reef species observed to be shifting towards higher latitudes (Pandolfi 2015). Certain species have phenotypic plasticity, or the ability to express different phenotypes under various environmental conditions. Under climate change-induced conditions, these species may slow down the pace of adaptation by shifting the mean phenotype of the population (Donelson et al. 2019). Whether species are forced to migrate or can remain within their original environments, the compositions of these ecosystems are expected to change due to climate change, bringing in novel species interactions.

In this study, I will be using literature reviews to examine existing predictive studies and models and evaluate their use in the context of Philippine coral reef ecosystems. I will be examining studies on three different scales: (1) predicting changes in environmental conditions, (2) predicting changes in physical characteristics, and (3) predicting changes in species interactions. I expect to find that the change in environmental conditions is the most easily predictable because of the cause-and-effect nature of climate change on coral reef ecosystems. I expect that predicting changes in physical characteristics such as reef size, and species interactions is more difficult as these require very specific inputs and calculations.

## METHODS

In this study, I compiled and reviewed past studies to evaluate the use of modeling to predict the impacts of climate change on coral reef ecosystems in the Philippines. Predictive modeling is based on trends that are observed historically and in the present day, making these studies somewhat comprehensive and potentially useful to address future climate change impacts. However, models have challenges as they cannot fully account for factors such as changes in climate policies and new research in related fields that could help mitigate effects sooner (Meehl 2023). I made comparisons between multiple studies to evaluate their predictive modeling methods, which range from large-scale models like the IPCC emissions scenarios, to established ecosystem modeling programs such as Ecopath with Ecosim (EwE), to proposed modeling methods. The models I present here were chosen by recognizing their use across multiple studies in a variety of ecosystems, not only coral reefs. I compiled the literature for this paper by sorting into five categories:

**Table 1. Categories for literature collection** are sorted, and described, with associated keywords and time frame

| | **Category Name** | **Description** | **Keywords/phrases** | **Time Range** |
|---|---|---|---|---|
| 1 | Broad literature (B) | Literature to provide context, general research on climate change, the Philippines, and coral reef ecosystems | Climate change, coral reef ecosystems, coral bleaching, ocean acidification, Philippines, coral reef ecosystems, IPCC | Any |
| 2 | Predictive modeling literature (PM) | General literature on predictive modeling and its use for climate-related studies | Predictive modeling, modeling, predicting climate change, climate change | Any |
| 3 | Environmental conditions (EC) | Studies on changes in an ecosystem's surrounding environmental conditions and applications of predictive modeling | Predictive modeling, climate change, environment, Philippines | 2018-Present |
| 4 | Physical characteristics (PC) | Studies on changes in an ecosystem's physical characteristics and applications of predictive modeling | Predictive modeling, climate change, coral reef ecosystems, marine ecosystems, Philippines | 2018-Present |
| 5 | Species interactions (SI) | Studies on changes in an ecosystem's species interactions and applications of predictive modeling | Predictive modeling, climate change, species interactions, food web, migration, predator, prey, Philippines | 2018-Present |

I decided to not limit categories 1 and 2 by time to provide as much contextual information as possible. Alternatively, I limited categories 3-5 to a year range of 2018-2024 to ensure that all predictive modeling studies were recent and relevant to the current state of the world. As the purpose of this paper is to offer guidance as to which predictive modeling methods are most effective in the context of Philippine coral reef systems and climate change, more recent methods are more effective as they are also likely to reflect the limits of current technology. Most literature in categories 4 and 5 was limited to studies in aquatic or marine ecosystems to remain as close to coral reef ecosystems as possible.

**Study Site**

This study evaluated all predictive modeling methods in how they could be used in the Philippines and its coral reef ecosystems. The Philippines is located in the coral triangle region (CTR), known to be a marine biodiversity hotspot. It has the third largest reef area size in the world with the highest coral species diversity (Licuanan et al. 2019). It is one of many countries that are dependent on ecosystem services provided by coral reefs, hence why it is important to anticipate how climate change will impact reefs located in this region.

**Predictive Modeling Methods**

*Modeling Changes in Environmental Conditions*

The increasing amount of greenhouse gases in the atmosphere has resulted in an enhanced greenhouse effect, causing warming on the Earth's surface. The average temperature of oceans across the globe has risen by about 0.74ºC and the average acidity by 0.1pH in the past two decades alone (Findlay and Turley 2021). These have severe consequences for coral reef ecosystems, which undergo mass coral bleaching events in which symbiotic algae are expelled from corals (van Hooidonk et al. 2020), leading them to become vulnerable and prone to death.

Many methods exist for the predictive modeling of environmental conditions in response to climate change, the most comprehensive one being the Intergovernmental Panel on Climate

Change (IPCC)'s emissions scenarios. The IPCC created the Representative Concentration Pathways (RCPs) in the early 2000s. This was the first large-scale predictive model of climate change, including a simulation of how emissions were expected to change up until the $24^{th}$ century. This model is distinctively important as each emission scenario also integrates the implementation of policies, to an extent (Meehl 2023). For example, the worst-case RCP8.5 scenario can be interpreted as countries failing to implement or find effective climate policies and mitigation strategies, thus leading to a future where emissions continue to rise until the end of the $21^{st}$ century (Meehl 2023).

The IPCC's research completely revolutionized the field of climate science though it was also scrutinized by scientists who doubted the magnitude of future sea level rise (Meehl 2023), as older studies were less comprehensive and thus, yielded less extreme results. Earlier studies only accounted for thermal expansion, or the warming of seawater, as a cause for sea level rise and neglected the possibility of glaciers melting, which is now known to be one of the primary drivers of sea level rise (Siegert et al. 2020). The inability of the IPCC to accurately predict sea level rise is an example of how predictive modeling can sometimes be limited by a lack of knowledge or the inability to incorporate more factors into a model. Although modeling methods have significantly improved, they are still yet to be developed to their full potential.

The United Nations Environment Programme (UNEP) published a study in 2020 where that used the IPCC CMIP6 (Coupled Model Intercomparison Project) climate models to present projections of coral bleaching conditions and publicize their findings to inform new research (van Hooidonk et al. 2020). The study is an updated version of the 2017 report, where the CMIP5 model was used. Although the CMIP5 model used Representative Concentration Pathways (RCPs), which focused more on greenhouse gas emissions, the CMIP6 model introduced the Shared Socioeconomic Pathways (SSPs), which take socioeconomic factors such as population and economic growth into account. The SSPs are a more realistic approach that emphasizes the connectivity between climate change and anthropogenic activity and is also more favorable for policymakers.

In this study, researchers were able to model the expected changes in sea temperatures for SSP 2-4.5 and SSP5-8.5. SSP 2-4.5. SSP2-4.5 is a realistic scenario that "represents the current rates of emissions" (van Hooidonk et al. 2020), which continue to rise at a moderate level through the year 2100. It is equivalent to the RCP4.5 scenario, which implies that emissions could slow down by 2040 but will continue, nonetheless. SSP5-8.5 is the worst-case scenario, similar to RCP8.5 where it is assumed that there are little to no efforts to stop climate change. It was also created to reflect a scenario in which fossil fuels are the primary source of energy, with the world undergoing mass socioeconomic and technological development. The report concludes that, under the SSP5-8.5 scenario, annual severe bleaching (ASB) is expected to impact all of the world's reefs (van Hooidonk et al. 2020). Among the countries with the largest (>25%) reef area, the Philippines is expected to experience ASB at a faster rate.

As these studies have already been explored multiple times in the context of Philippine coral reef ecosystems, they can be used to guide future research in subsequent changes in physical characteristics and species interactions.

*Modeling Changes in Physical Characteristics*

Modeling changes in the physical characteristics of coral reefs is important as their physical characteristics are very indicative of their health. "Physical characteristics" could be defined as the size of a coral reef ecosystem or the ratio of healthy coral to bleached coral in a chosen study site. Thus, a coral reef ecosystem that is observed to decrease in size over time, whether due to bleaching events, destruction, or sedimentation, is a clear indicator of poor health and management. Through the predictive modeling of changes in these physical characteristics, conservation efforts can be made concerning sites that are predicted to be more susceptible to the effects of climate change.

Browne et al. (2021) conceptualizes a model (see Appendix B1) that predicts geo-ecological coral reef ecosystem responses to climate change. Researchers organized coral reef systems into "smaller sub-system modules". The disaggregation of these complex ecosystems into individual components allowed researchers to observe each component qualitatively. An example of a component would be calcium carbonate ($CaCO_3$) production, which is necessary in the process of reef-building. $CaCO_3$ production is also a metric that has been historically measured and can be predicted in response to climate change. Six sub-system modules are defined as such: calcification, coral community, reef accretion, bioerosion, carbonate sediments, and sediment transport/island change. These modules do not only account for the physical characteristics of the reefs but the surrounding environment as well, reflecting the complex nature of coral reef ecosystems. Although many studies focus on the cause-and-effect relationship between climate change and coral reef ecosystems, the conceptual model created by Browne et al. (2021) uniquely integrates geological factors such as bioerosion and sediment transportation.

Sedimentation is determined as one of the largest threats to Philippine coral reef ecosystems that aren't directly caused by climate change, occurring when pollution and runoff settle on top of coral reefs. Sedimentation is primarily caused by coastal development and results in light attenuation, or a decrease in light intensity (Valino et. al 2021). The inability of coral reefs to receive light hinders the productivity of important symbiotes such as *zooxanthellae*, a photosynthetic organism that takes sunlight and converts it into nutrients essential to the growth and sustenance of corals.

Nutrient pollution as a result of agricultural runoff is also integrated into the model. It is another factor that is important if researchers want to accurately simulate a Philippine coral reef ecosystem through modeling. Nutrient pollution is a threat as it can reduce rates of calcification in high amounts (Browne et. al 2021), negatively impacting the health and growth of new corals, similar to sedimentation. Thus, the consideration of sediment and nutrient factors is required to realistically reflect changes in a coral reef ecosystem as many are located along the Philippines' coastlines where sedimentation occurs and often impacts the health of adjacent reefs.

For predictive studies on changes in the physical characteristics of coral reefs, it could be said that existing models cannot be used, though they can be referenced as guidelines for new models. Such as in Browne et al. (2021), it would be useful to create a model unique to study sites in the Philippines where an ecosystem could be similarly disaggregated into different components but more specific to factors observed in Philippine coral reef ecosystems. One component that is more unique to these coral reef ecosystems is how they are often located in Marine Protected Areas (MPAs), which vary in how they are managed (Savage et al. 2020).

### *Modeling Changes in Species Interactions*

Species interactions may be the most complex to predictively model. Ecosystem modeling programs exist to track changes in species biodiversity and interactions, such as *Ecopath with Ecosim* (EwE). The US National Oceanographic and Atmospheric Administration (NOAA) has acknowledged EwE as "one of the ten greatest scientific breakthroughs" (Villasante et al. 2016) for the diverse ways in which it can be used. The program was created in the early 1980s by researchers at NOAA as *Ecopath*, its static modeling component, and has since developed to include *Ecosim*, which can produce long-term simulations and models. It combines software to analyze trophic mass balance and dynamic modeling software, allowing users to predict various environmental effects (Christensen and Walters 2004). EwE allows users to input data on any species, such as biomass, birth rate, and mortality rate.

Clores et al. (2023) published a study on the food-web dynamics of seagrass in the Caramoan Peninsula, Philippines. EwE was used in this study to model three different seagrass ecosystems to analyze the effect of biomass changes on food-web dynamics. Researchers calculated biomass from different seagrass ecosystems in the Philippines between October 2021 and October 2022. Each study site possessed unique characteristics with site A being isolated, site B located next to mangroves, and site C next to a coral reef ecosystem. After a year of collecting samples, the researchers input the data into EwE where they utilized existing features such as the ability to identify predators, prey, consumption patterns, and diet. They determined these factors through the combination of their observations and existing literature and applied them to their simulation to reconstruct the seagrass ecosystem in the program. The study concluded that site A needed more conservation efforts due to its lack of naturally occurring support from adjacent ecosystems; site B needed special management to improve its ability to be a refuge for economically important species; and site C was the least likely to be impacted by stress-induced changes, so conservation efforts should be relatively less.

The study uses the main integrated features of EwE: Ecopath and Ecosim. Ecopath is used to model mass balance, which is examined through the relationships of predator and prey. Ecopath acts more as a static snapshot of an ecosystem, whereas Ecosim is more temporally dynamic, meaning that it is used to model ecosystems over time (Christensen and Walters 2004).

The primary equation used in Ecopath to measure production is:

$$Production = catch + predation + net\ migration + \\ biomass\ accumulation + other\ mortality$$

The formula to calculate production not only includes naturally occurring mechanisms, such as predation and migration but also accounts for some human interactions, such as catch rate in fisheries. Inputs from Ecopath and historical data can be used in Ecosim to simulate how an ecosystem has or is expected to change over time. This program has been used to influence policymaking, especially in fisheries, where its application is very straightforward. This study would be an example of how EwE could be used in a predictive manner, and how it can be used to observe something as dynamic and volatile as species interactions within a complex ecosystem.

In Chapman et al. (2020), EwE was used to model the effect of climate change on marine ecosystem food webs in three study sites in Maine. Researchers designed scenarios to simulate the effects of climate change and modeled them using Ecopath to create snapshots for each scenario. The scenarios were dependent on other predictive studies, where they found that ocean acidification and sea temperature increase would lead to the disruption of energy flow between trophic levels. This would then increase detrital and bacterial biomass. They translated these scenarios in Ecopath by decreasing the biomass of higher trophic levels by 25%, 50%, and 75% and increasing bacterial biomass by 200%. Their results showed that altering the biomass levels would significantly impact food web energy flow.

The use of EwE in Chapman et al. (2020) is comprehensive as they were able to incorporate findings from other predictive studies and turn them into inputs that fit EwE. As this study was conducted on marine ecosystems, it could be easily translated into one specific to Philippine coral reef ecosystems. There are existing predictive studies on how climate change is expected to affect the Philippines' coral reef ecosystems without the use of EwE so employing the same technique of using related studies and creating scenarios using the program could yield similar results.

## DISCUSSION

The purpose of this study was to reflect on different models that can be used to predict the effects of climate change on Philippine coral reef ecosystems. Through this literature review, I conclude that the most effective models are those that can accurately reflect the complexities of climate change and coral reef ecosystems as best as possible. These models disaggregate complex systems into smaller components that are described qualitatively and can be measured quantitatively, allowing for the input of existing or measurable data. Through examining and evaluating the effectiveness of different modeling methods in the Philippine coral reef ecosystem, I have determined that no matter how comprehensive or precise each method was, the models do not fully replicate reality requiring discussion of this limitation and whether it is possible to overcome.

*Modeling Changes in Environmental Conditions*

The IPCC's emissions scenarios are currently the most important set of climate predictions not only for their large-scale implications but also for how they have been used to guide many existing climate policies today. Despite their significance, some studies suggest that at the rate at which emissions are being produced, researchers have determined that what will happen to the climate in the upcoming years will exceed the IPCC's scenarios (Siegert et al. 2020). IPCC has acknowledged that the effects of climate change could surpass the conditions described in their emissions scenarios because of factors and mechanisms that were not taken into account when making their climate assessment (Siegert et. al 2020), which reintroduces the primary limitation of predictive modeling methods being their inability to perfectly reflect real life.

For sea-level rise, researchers write that using historical data does not work "beyond simple extrapolations that very rapidly become inadequate under enhanced global warming" (Siegert et. al 2020). Computer models are more reliable when it comes to predicting changes in the environment as they allow researchers to incorporate large-scale environmental mechanics and quantify their effects. They can also account for differences across regions that possess unique environmental traits that make it difficult to evaluate under the same standards. This study highlights the importance of using recent technological advancements to improve predictive modeling, which could be applied in the case of the IPCC emissions scenarios. The improvement of technology and modeling programs could enhance the IPCC's findings in the upcoming years, allowing for the incorporation of mechanisms not included before.

*Modeling Changes in Physical Characteristics*

The methods used to predict changes in physical characteristics of coral reef ecosystems, such as changes in reef size, should be more localized and applicable on a medium-to-small scale. The method proposed by *Browne et al. (2021)* is an example of a modeling method that can be localized as it incorporates the reef ecosystem and its adjacent land environment. This can be applied to many coastal coral reef ecosystems around the Philippines. Furthermore, the model is newly synthesized and made specific to the chosen study site. The researchers systematically broke down an ecosystem to study the effects of climate change on different components and went far and beyond to incorporate geo-ecological aspects such as sedimentation.

As the study features a conceptual model, the researchers were able to identify the limitations of each identified variable. Some of these include a lack of knowledge/understanding, site access, methodological limitations, time, money, and expertise. In Browne et al. (2021), it is emphasized that there is a large amount of research, and resources required to make such a complex model into reality; furthermore, there is a need for collaborative and genuine efforts to do so. While conceptual models can be created for Philippine coral reef ecosystems, the same limitations will be encountered and might be harder to overcome due to the overall lack of funding for climate-related research and efforts in the country (Savage et al. 2020).

*Modeling Changes in Species Interactions*

More precise and quantitative predictive modeling methods are needed to measure the effects of climate change on coral reef biomass and species interactions. Employing an established ecosystem modeling program such as Ecopath with Ecosim (EwE) is highly effective for this purpose. The program uses precise data inputs to simulate real ecosystems, making it very dynamic and applicable to various ecosystems. However, there are still limitations to the program, especially in how it is used for predictive studies. Chapman et al. (2020) identifies that, although EwE was very accessible and easy to use, it had many limitations, such as how the program is not as complex as it could be due to the lack of funding for it. Additionally, its use in the context of Philippine coral reef ecosystems could not be very beneficial as predictive studies on a larger scale are still underdeveloped. It could be said that a program like EwE would be more beneficial when looking at the Philippines' fisheries and how climate change is expected to affect them as it yields more practical results.

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**REFERENCES**

Abbass, K., M. Z. Qasim, H. Song, M. Murshed, H. Mahmood, and I. Younis. 2022. A review of the global climate change impacts, adaptation, and sustainable mitigation measures. Environmental Science and Pollution Research 29:42539–42559.

Browne, N. K., M. Cuttler, K. Moon, K. Morgan, C. L. Ross, C. Castro-Sanguino, E. Kennedy, D. Harris, P. Barnes, and A. Bauman. 2021. Predicting Responses of Geo-ecological Carbonate Reef Systems to Climate Change: A Conceptual Model and Review. Page Oceanography and Marine Biology. CRC Press.

Chapman, E. J., C. J. Byron, R. Lasley-Rasher, C. Lipsky, J. R. Stevens, and R. Peters. 2020. Effects of climate change on coastal ecosystem food webs: Implications for aquaculture. Marine Environmental Research 162:105103.

Cassia, R., M. Nocioni, N. Correa-Aragunde, and L. Lamattina. 2018. Climate Change and the Impact of Greenhouse Gasses: CO2 and NO, Friends and Foes of Plant Oxidative Stress. Frontiers in Plant Science 9.

Christensen, V., and C. J. Walters. 2004. Ecopath with Ecosim: methods, capabilities and limitations. Ecological Modelling 172:109–139.

Cornwall, C. E., S. Comeau, N. A. Kornder, C. T. Perry, R. van Hooidonk, T. M. DeCarlo, M. S. Pratchett, K. D. Anderson, N. Browne, R. Carpenter, G. Diaz-Pulido, J. P. D'Olivo, S. S. Doo, J. Figueiredo, S. A. V. Fortunato, E. Kennedy, C. A. Lantz, M. T. McCulloch, M. González-Rivero, V. Schoepf, S. G. Smithers, and R. J. Lowe. 2021. Global declines in coral reef calcium carbonate production under ocean acidification and warming. Proceedings of the National Academy of Sciences 118:e2015265118.

Donelson, J. M., J. M. Sunday, W. F. Figueira, J. D. Gaitán-Espitia, A. J. Hobday, C. R. Johnson, J. M. Leis, S. D. Ling, D. Marshall, J. M. Pandolfi, G. Pecl, G. G. Rodgers, D. J. Booth, and P. L. Munday. 2019. Understanding interactions between plasticity, adaptation and range shifts in response to marine environmental change. Philosophical Transactions of the Royal Society B: Biological Sciences 374:20180186.

Dygico, M., A. Songco, A. White, and S. Green. 2013. Achieving MPA effectiveness through application of responsive governance incentives in the Tubbataha Reefs. Marine Policy 41:87–94.

Findlay, H. S., and C. Turley. 2021. Chapter 13 - Ocean acidification and climate change. Pages 251–279 *in* T. M. Letcher, editor. Climate Change (Third Edition). Elsevier.

Goreau, T. J. F., and R. L. Hayes. 2021. Global warming triggers coral reef bleaching tipping point. Ambio 50:1137–1140.

Intergovernmental Panel On Climate Change, editor. 2014. Long-term Climate Change: Projections, Commitments and Irreversibility Pages 1029 to 1076. Pages 1029–1136 Climate Change 2013 – The Physical Science Basis. First edition. Cambridge University Press.

Licuanan, W. Y., R. Robles, and M. Reyes. 2019. Status and recent trends in coral reefs of the Philippines. Marine Pollution Bulletin 142:544–550.

Meehl, G. A. 2023. The Role of the IPCC in Climate Science. Page Oxford Research Encyclopedia of Climate Science.

Muallil, R. N., M. R. Deocadez, R. J. S. Martinez, and P. M. Aliño. 2019. Data on the biomass of commercially important coral reef fishes inside and outside marine protected areas in the Philippines. Data in Brief 25:104176.

Pandolfi, J. M. 2015. Incorporating Uncertainty in Predicting the Future Response of Coral Reefs to Climate Change. Annual Review of Ecology, Evolution, and Systematics 46:281–303.

Pedersen, J. T. S., D. van Vuuren, J. Gupta, F. D. Santos, J. Edmonds, and R. Swart. 2022. IPCC emission scenarios: How did critiques affect their quality and relevance 1990–2022? Global Environmental Change 75:102538.

Pinsky, M. L., R. L. Selden, and Z. J. Kitchel. 2020. Climate-Driven Shifts in Marine Species Ranges: Scaling from Organisms to Communities. Annual Review of Marine Science 12:153–179.

Pulhin, J. M., and M. A. Tapia. 2022. Climate Change Adaptation in the Philippines. Pages 129–173 in J. J. Pereira, M. K. Zain, and R. Shaw, editors. Climate Change Adaptation in Southeast Asia. Springer, Singapore.

Savage, J. M., M. D. Hudson, and P. E. Osborne. 2020. Chapter 18 - The challenges of establishing marine protected areas in South East Asia. Pages 343–359 in J. Humphreys and R. W. E. Clark, editors. Marine Protected Areas. Elsevier.

Siegert, M., R. B. Alley, E. Rignot, J. Englander, and R. Corell. 2020. Twenty-first century sea-level rise could exceed IPCC projections for strong-warming futures. One Earth 3:691–703.

Spalding, M. D., and B. E. Brown. 2015. Warm-water coral reefs and climate change. Science 350:769–771.

Sully, S., D. E. Burkepile, M. K. Donovan, G. Hodgson, and R. van Woesik. 2019. A global analysis of coral bleaching over the past two decades. Nature Communications 10:1264.

Valino, D. A. M., M. V. Baria-Rodriguez, R. M. Dizon, and P. M. Aliño. 2021. Responses of Buluan Island turbid fringing reefs, southern Philippines to the 2016 thermal anomaly. Regional Studies in Marine Science 43:101704.

van Hooidonk, R., J. Maynard, G. Grimsditch, G. Williams, J. Tamelander, J. Gove, H. Koldewey, G. Ahmadia, D. Tracey, and K. Hum10. 2020. Citation: UNEP 2020. Projections of future coral bleaching conditions using IPCC CMIP6 models: climate policy implications, management applications, and Regional Seas summaries.

van Woesik, R., T. Shlesinger, A. G. Grottoli, R. J. Toonen, R. Vega Thurber, M. E. Warner, A. Marie Hulver, L. Chapron, R. H. McLachlan, R. Albright, E. Crandall, T. M. DeCarlo, M. K. Donovan, J. Eirin-Lopez, H. B. Harrison, S. F. Heron, D. Huang, A. Humanes, T. Krueger, J. S. Madin, D. Manzello, L. C. McManus, M. Matz, E. M. Muller, M. Rodriguez-Lanetty, M. Vega-Rodriguez, C. R. Voolstra, and J. Zaneveld. 2022. Coral-bleaching responses to climate change across biological scales. Global Change Biology 28:4229–4250.

Villasante, S., F. Arreguín-Sánchez, J. J. Heymans, S. Libralato, C. Piroddi, V. Christensen, and M. Coll. 2016. Modelling marine ecosystems using the Ecopath with Ecosim food web approach: New insights to address complex dynamics after 30 years of developments. Ecological Modelling 331:1–4.

**APPENDIX A: Intergovernmental Panel on Climate Change (IPCC) Scenarios**

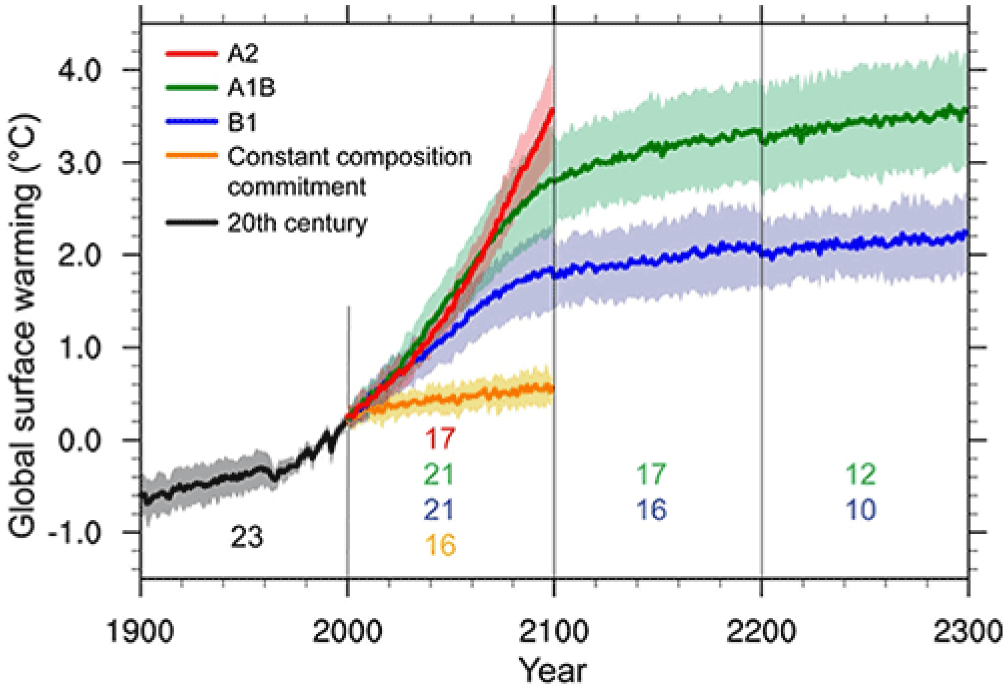


**Figure A1. First Representative Concentration Pathways (RCPs)** by the Intergovernmental Panel on Climate Change (IPCC).

**Table A1. Representative Concentration Pathways (RCPs)** and Associated Surface Temperature (ºC) and $CO_2$-eq Concentration (ppm) increase by 2100.

| Scenario Name | Surface Temperature Increase by 2100 (ºC) | $CO_2$-eq concentration (ppm) by 2100 |
|---|---|---|
| RCP2.6 | 0.4-1.7 | 430-480 |
| RCP4.5 | 0.9-2.6 | 530-580 |
| RCP6.0 | 0.8-3.1 | 720-1000 |
| RCP8.5 | 1.4-4.8 | >1000 |

**Table A2. Shared Socioeconomic Pathways (SSPs)** and associated descriptions and Radiative Forcing (W/m²) increase by 2100.

| Scenario Name | Description | Representative Concentration Pathway (RCP) Counterpart | Radiative Forcing (W/m²) |
|---|---|---|---|
| SSP126/ Sustainability | Sustainable development; the preservation of natural resources and the environment; improving income inequality; minimizing the consumption of natural resources and energy usage | RCP2.6 | 2.6 |
| SSP245/Middle of the road | Some environmental degradation; some improvements to income inequality; some cooperation between countries; moderate population growth | RCP4.5 | 4.5 |
| SSP370/ Regional rivalry | Conflict between states; policies are more focused on national and regional security; less focus on environmental and other global issues; large environmental changes due to lack of climate efforts | RCP6.0-RCP8.5 | 7.0 |
| SSP585/Fossil-fueled development | Fossil fuels lead global development; an increase in technological advancements; socioeconomic development requires the exploitation of fossil fuels; mass development worldwide | RCP8.5 | 8.5 |

## APPENDIX B: Models Used in Browne et al. (2021)

**Table B1. Six sub-system modules were** created by Browne et al. (2021) detailing module names, dominant mechanisms, associated variables, drivers, and module outputs.

| Module | Dominant process (P) or system element (E) | Number of variables | Dominant driver | Module output |
|---|---|---|---|---|
| 1. *In situ* carbonate production | Calcification (P) | 28 | Local environmental drivers (e.g. temperature, light) | Total calcification rate |
| 2. Acute disturbance events on coral reef communities | Coral community (E) | 36 | Physical erosion (e.g. cyclones) and local environmental drivers (e.g. temperature, DHW) | Total calcification rate |
| 3. Coral reef response to sea level rise | Reef accretion (P) | 27 | Sea level rise | Reef framework density and reef accretion |
| 4. Bioerosion | Bioerosion (P) | 23 | Environmental drivers (e.g. nutrients, temperature) and benthic cover | Net sediment production and reef framework density |
| 5. Net carbonate sediment production | Carbonate sediments (E) | 28 | Environmental drivers (e.g. temperature, nutrients) and physical erosion | Net sediment production |
| 6. Carbonate sediment transport and depositional sinks | Sediment transport (P) and island change (P) | 21 | Reef hydrodynamics | Shoreline position and elevation |

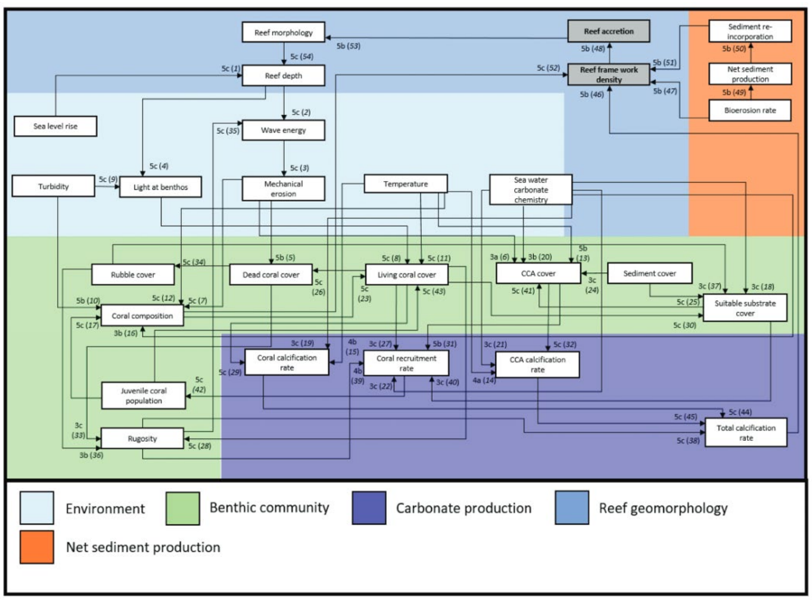


**Figure B1. Conceptual model detailing the relationships between 27 variables in a coral reef ecosystem.** The focus of the model is coral reef accretion and how it is impacted by climate-induced sea level rise. The incorporation of arrows to signify relationships of different strengths (labeled 1-5; 1 being the weakest and 5 being the strongest) between different variables reflects the complexity of coral reef ecosystems.