

What can evolutionary modelling of coral reef diversity in the past tell us about how anthropogenic climate change will affect coral reef diversity today?



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2 ABSTRACT

For millions of years, the earth's climate has manipulated and shaped the biodiversity of the planet's vibrant biota. The ever-changing environmental conditions have had a profound effect on speciation rates of all organisms. This has become a topic of paramount importance as anthropogenic activity accelerates global warming at unprecedented rates, threatening extinction to millions of organisms. The following report analyses how changing prehistoric environmental conditions affected a coral taxon, Scleractinia, millions of years ago. First appearing in the early middle Triassic era, Scleractinia are marine animals of the phylum Cnidaria. They are stony corals which build a hard robust skeleton. As with all coral species present today, Scleractinia are under threat of extinction due to rapid species decline because of climate change. This report aims to address this decline in species and use prehistoric data to predict how present-day organisms will react to climate change. By investigating the impact climate change has had on extinct organisms it will allow us to understand the potential impact it has on surviving species. This report constructs a phylogenetic tree to undertake correlational analyses of speciation rates. Speciation rates will be analysed against temperature, sea level and atmospheric carbon dioxide data. The findings of this report suggest that upon global temperature increase, Scleractinia speciation rates decreased. It also showed that an increase in atmospheric CO₂ led to a decrease in speciation rates. However, no correlation between sea level and speciation was observed. The results conclude that anthropogenic climate change is likely to have an effect on modern day coral reefs.

3 INTRODUCTION

Over the next century, it is expected that global warming will rise by 2-4.8°C (O'Neill et al. 2017). This has the potential to be highly destructive to the biodiversity of millions of species, including coral reefs. Recent investigations into this have revealed that 50% of global coral reefs have already faced the detrimental consequences of anthropogenic climate change, and some predictions estimate a further 40% could be lost in the next 30 years (Munday et al. 2008). Coral reefs are some of the Earth's most diverse ecosystems, providing habitat and shelter for over 1 million species. They are crucial mechanisms in protecting the planet's coastlines from storms and erosion, as well as being economical hubs providing opportunities for tourism, employment, and the discovery of new medicine (Harris et al. 2018). Globally, around half a million people are dependent on coral reefs for food, income, and protection.

An essential step towards conserving coral reefs is developing a better understanding of the potential consequences of human-induced climate change. One way to approach this is to model

trends observed from the geological record, in which the Earth experienced a change in climate conditions similar to those we are seeing today. This will allow us to predict the probable effects of current and future climate change on coral reefs. The analysis of speciation rates in Scleractinia will allow for deeper insight into the effects of changing environmental conditions on coral reefs. In this investigation, a phylogenetic coral reef tree will be analysed against atmospheric CO₂, temperature, and sea level data to observe how coral reefs adjusted to changing conditions.

Previous investigations into the relationship between climate and biological diversification of aquatic species have found marine crustaceans, Anomura, exhibited increased speciation rates with cooler global temperatures (Davis et al. 2016). This therefore suggests that global cooling leads to increased biodiversity amongst marine species and alludes to the detrimental consequences that anthropogenic global warming could have on coral reefs. Therefore, this report aims to further build on these findings and investigate this correlation further by performing correlational analyses on prehistoric temperatures, as well as atmospheric CO₂, and sea level to Scleractinia.

First appearing 240 million years ago, Scleractinia are colonial corals comprising of multiple physiologically integrated polyps and branches (Veron et al. 2015). Today, 1500 extant species of Scleractinia remain, and are dominant (though not exclusively) reef-building corals which receive energy via symbiotic relationships with zooxanthellae algae. Scleractinia are widespread organisms inhabiting many of the world's oceans between 40°N and 40°S, as seen in Figure 1.0. Therefore, these corals are present across a wide range of water temperatures and depths which exhibits the complexity and vibrancy of the species. It is also due to the geography of the Scleractinia coral that it has been selected for this analysis, as it will appropriately exhibit the effect of climate change on a wider range of habitats.

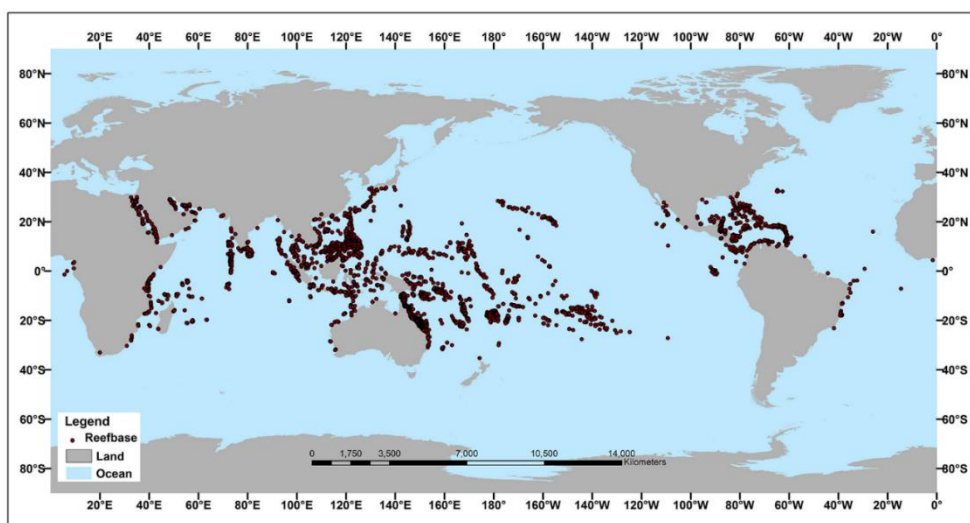


Figure 1.0, Map showing the modern distribution of Scleractinia coral reefs around the world. (NOAA 2022)

Similar investigations into prehistoric speciation rates of species under environmental stress have adopted a taxic heavy approach (Huang 2012). In these circumstances species, genera and families are differentiated independently and changes in taxonomic diversity are assessed through time. This study, however, will utilise a time calibrated phylogenetic tree of Scleractinia. Correlational analyses of paleo-climate conditions (Temperature, Atmospheric CO₂, and Sea Level) and subsequent speciation rates will be conducted to assess for the presence of a correlation between changing climate conditions and speciation rates.

The basis of this investigation surrounds the hypothesis that coral reef diversity in the past was negatively impacted by climate conditions that are like those the Earth is experiencing today, using my results to quantify how we might expect reef diversity to suffer under human-induced climate change. This hypothesis reflects the outcomes of previous work for other marine species and aims to build upon the understanding of how changing climates affects coral reefs.

4 METHODS

A phylogenetic tree was created for the Scleractinia data. This tree not only allowed the phylogeny to be viewed, but also allowed for the analysis of speciation rate. As seen in figure 2.0 the tree contains 943 nodes, 473 tips . Whilst this tree was used for analysis, an additional tree was produced using iTOL as it is easier to reference due to it being clearer (Itol 2022). Data was obtained from geological data of fossil and sequence records. Speciation rates were compared with global temperature data (Figure 3.0), global sea level data (Figure 3.0) and atmospheric CO₂ data (Figure 3.2) to determine the presence of correlations. A Wilcoxon signed-rank test allowed for the significance of these correlations to be analysed, this was done through a detrended cross correlation analysis (DCCA based) test. Correlation coefficients were generated in R Studio (RStudio Team 2020) using the BAMM package. (Rabosky et al. 2014).

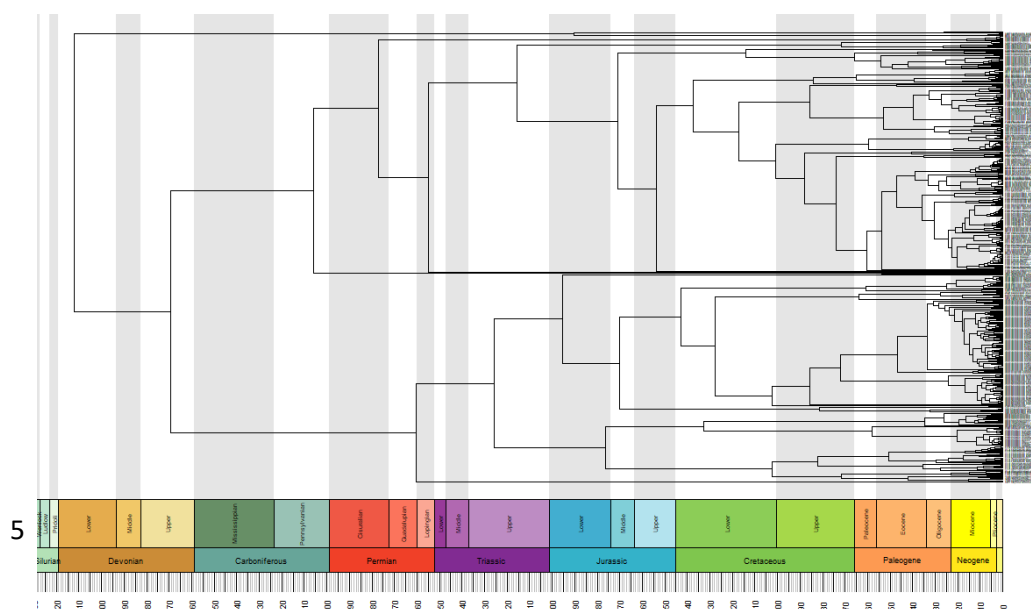


Figure 2.0, phylogenetic tree for Scleractinia data which was used for BAMM analysis.

id — Temperature
— Sea Level

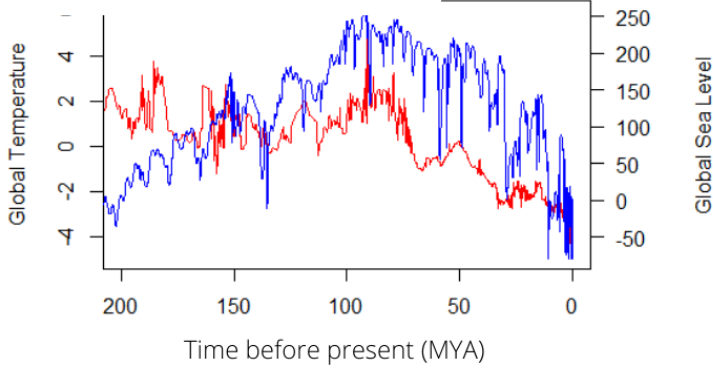


Figure 3.0, graphs showing fluctuations in global temperature and sea level throughout time.

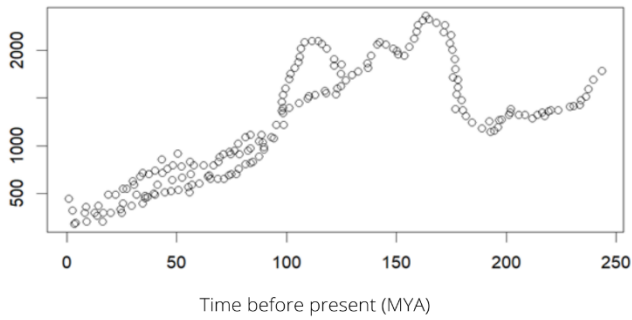


Figure 3.1, graph showing global atmospheric carbon dioxide concentrations from which data will be correlated.

Tree scale: 100

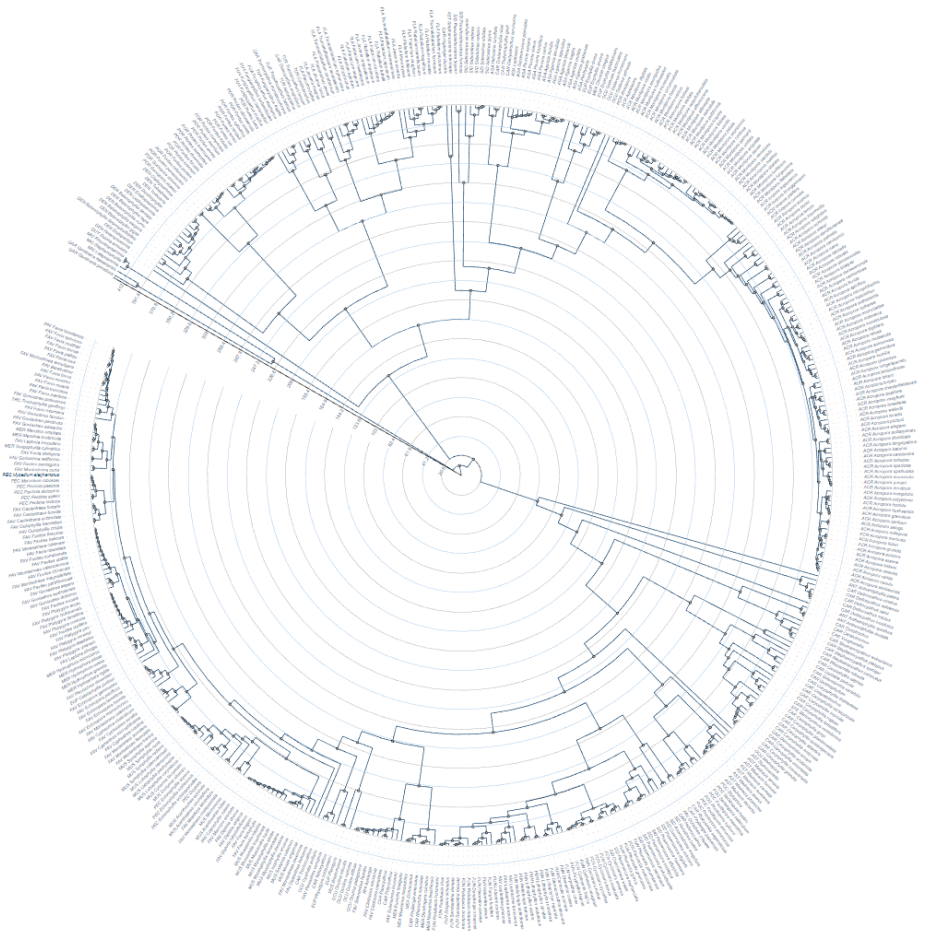


Figure 2.1, A complete phylogenetic tree created to allow easier visualisation of this dataset. Created using ItoL 2020.

5 TEMPERATURE

Hypothesis: Global temperature increase and speciation rates in Scleractinia will be significantly negatively correlated.

5.1 RESULTS

In Scleractinia, a significant negative correlation between temperature increases and speciation decrease was found in the incomplete tree, ($P = < 2.2e-16$) (Figure 4.0). The results provided a strong mean of -0.3038, and a small standard deviation. Therefore, confidence can be drawn from the observed negative correlation, and we can conclude that this distribution is significant.

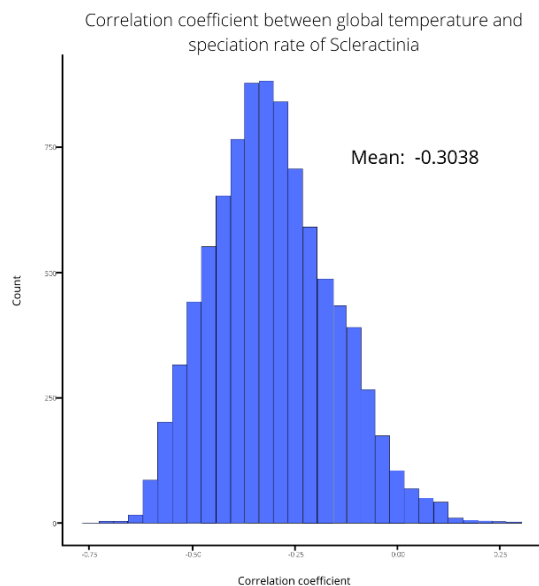


Figure 4.0

5.2 INTERPRETATION

There is a significant negative correlation between speciation and increase in global temperature. Therefore, we can accept the hypothesis for the effect of temperature on speciation. It is likely that Scleractinia favour cooler temperatures due to the damaging effects of increased temperature (Cirino 2019). This is due to the stress that rising temperatures have on coral polyps, causing the loss of algae within the polyp tissue. The algae within the polyps provides a mutualistic relationship in which the coral provides algae with protected environment and compounds required for photosynthesis (Douglas et al. 2003). The algae then provide the coral with a supply of oxygen and mechanism for waste removal. Therefore, the loss of this algae due to temperature increase would cause the eventual demise of the coral, leading to the observed decreased rate of speciation with higher temperatures.

Additionally, it is possible that it is favourable for the Scleractinia to reproduce at cooler temperatures thus leading to an increased speciation rate. Corals can reproduce via fragmentation, a process in which the coral breaks off into smaller pieces of 1-5 polyps (Okubo 2007). This allows the

coral tissue to reproduce asexually at rates up to 50 times faster than the average growth rate. It is possible that cooler temperatures are therefore favourable to the fragmentation process, as the smaller 1-5 polyp corals will be less tolerant to high temperatures and more susceptible to bleaching. Therefore, cooler temperatures increase the survival of coral offspring, thus increasing speciation rates. Therefore, it is possible that coral bleaching as a consequence of increasing global temperatures, is occurring at a rate which is too high for reproduction and subsequent speciation to occur.

Additionally, as detailed in Oliver's paper, it is to be noted the effect of rising temperatures has on oceanic currents (Oliver et al. 2011). Changes in temperatures disrupts currents causing an altered transportation system of nutrients, and disease. This is likely to have had detrimental consequences for the survival of corals. As increased warmer current movement will further contribute to coral bleaching. In contrast, it is possible that shifting ocean currents had a positive effect on more northerly located Scleractinia. This is because it is possible that the increased temperatures in previously cooler water increased the metabolic activity of inhabitant species. For example, Donelson, discusses how changing currents increased reproduction of reef fishes (Donelson et al. 2010). Warmer ocean temperatures favoured fish metabolic and reproductive rates. Increased fish larvae had a positive impact on coral reproduction as the presence of the fish caused increased rates of fragmentation.

Further research to investigate the effects of temperature on speciation rates of corals would benefit from isolating a select geographical location of corals and analysing how they reacted to changing temperatures. This is because it is likely that rising temperatures had a significantly more negative impact on tropical corals as opposed to cooler water corals. It is also possible that increased temperatures were beneficial to cooler water corals, therefore further research would benefit from analysing this select group. The research could aim to separate data by geographical latitude. This research would provide valuable insight into how some coral species are able to afford increased temperatures more successfully as opposed to others, gaining a deeper understanding of how coral species acclimate and adapt to environmental stress.

6 ATMOSPHERIC CO₂

Hypothesis: Hypothesis: atmospheric CO₂ and speciation rates in Scleractinia will be significantly negatively correlated.

6.1 RESULTS

A significant negative correlation between increases in atmospheric CO₂ concentration and speciation rate decrease of Scleractinia was found in the phylogenetic tree, ($P < 2.2e-16$) (Figure 5.0). The mean was -0.4475, and the standard deviation was low which allows a significant level of confidence to be drawn from the results. Therefore, it can be concluded that a significant negative correlation was observed.

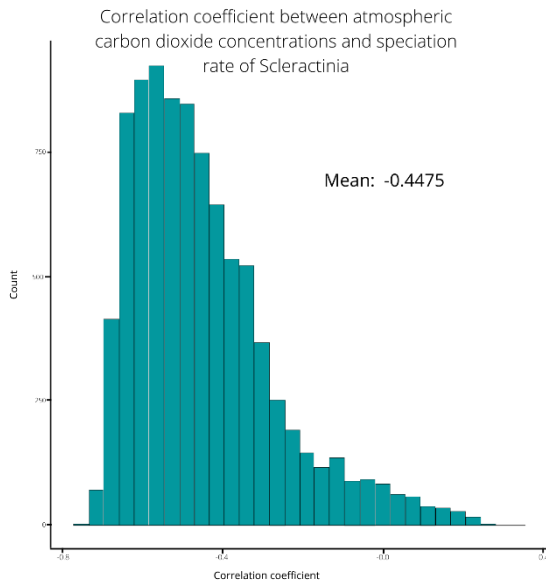


Figure 5.0

6.2 INTERPRETATION

There is a significant negative correlation between speciation and increase in atmospheric CO₂ concentrations. Therefore, we can accept the hypothesis for the effect of carbon dioxide on speciation. This alludes to the damaging effects that ocean acidification has on coral reefs. Ocean acidification occurs when increased levels of carbon dioxide emitted into the atmosphere are dissolved into the ocean. Carbon dioxide reacts with water molecules (H₂O) forming carbonic acid (H₂CO₃). This compound is broken down into a positively charged hydrogen ion (H⁺) and bicarbonate (HCO₃⁻). The presence of these ions decreases the pH of ocean water, causing acidification (Mumby et al. 2007). This has damaging effects on marine life as the delicate balance of pH is altered. Many coral species are highly sensitive to small changes in pH as it can impact chemical communication, reproduction, and growth. Sensitivity in corals is also accelerated as the construction of skeletons relies on the presence of carbonate ions within the water, and the process of ocean acidification decreases the abundance of carbonate ions thus limiting the formation of new corals. changes in pH also corrode existing coral skeletons causing the reef infrastructure to become weaker and increasing likelihood of erosion (Hoegh-Guldberg 2017). Previous studies estimate that within the next 60 years, ocean conditions will reach acidity levels that otherwise healthy coral reefs will erode at rates faster than they can rebuild. Therefore, it can be interpreted that the observed negative

correlation between carbon dioxide concentrations in the atmosphere and speciation rate is due to the acidification of oceans limiting the reproduction of coral reefs.

Other investigations into the effect of ocean acidification on coral reefs suggest that the impact will vary in significance depending on the coral species. This is because some species of coral reefs are able to use bicarbonate in place of carbonate to construct skeletons, thus allowing them to adapt to the acidifying oceans (Kleypas 2009). Additionally, few species of coral are able to survive without a skeleton for periods of time and return to skeletal construction once ocean conditions return to normal. Other species are able to maintain survival at wider ranges of pH. This report would be furthered by the investigation of how Scleractinia species react to pH changes, and samples of coral could be individually assessed to observe sensitivity.

7 SEA LEVEL

Hypothesis: Hypothesis: Sea level and speciation rates in Scleractinia will be significantly negatively correlated.

7.1 RESULTS

No correlation between sea level and speciation rates in Scleractinia was observed (figure 6.0) ($P < 2.2e-16$). A mean of -0.18632 was calculated which confirms a significant lack of correlation between these factors. The low P-value provides confidence that there is no correlation in these findings

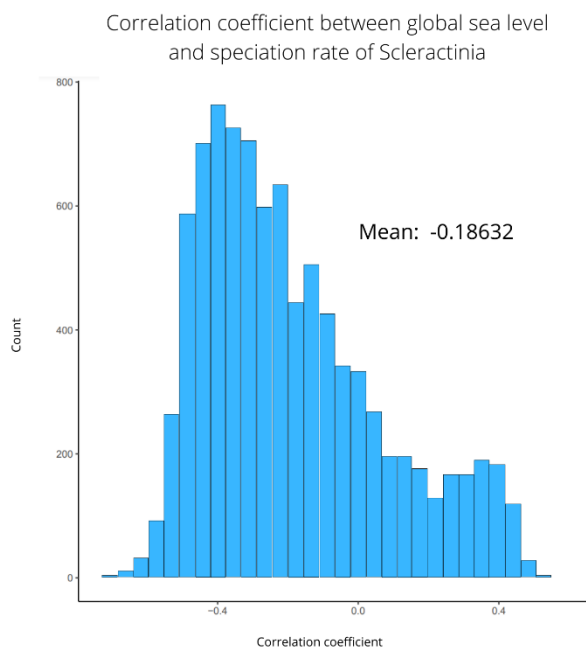


Figure 6.0

7.2 INTERPRETATION

There was no correlation observed between speciation rates of Scleractinia and changes in sea levels. Therefore, it cannot be concluded that sea level has an effect on speciation rate. The hypothesis that sea level and speciation rates in Scleractinia will be significantly negatively correlated is thus rejected, and we accept the null hypothesis. It is possible that the lack of correlation is due to a large sample size. The phylogenetic tree used corals found at a wide range of oceanic depths. Therefore, it is possible that fluctuating sea levels has less of an effect on deeper sea corals than shallow corals thus leading to the observed lack of correlation, this is supported by previous research (Muhs et al. 2011). Furthermore, it would be beneficial for further research to isolate groups of corals depending on oceanic depth they are found and correlating speciation rates of these against sea level to see how different species react to fluctuations.

Other research suggests that the lack of correlation observed is due to the capability of Scleractinia to adapt to changing sea levels more efficiently than they would to other environmental variables (e.g. temperature and CO₂). An paper by Camion revealed that the projected change of water depth by 2100, would limited damaging effects on Atlantic corals as the corals are able to adapt to this changing depth (Camion et al. 2015). It is however the increased destructive impact of waves on coral reef areas that would become detrimental to the survival of Scleractinia. Additionally, rises in sea level would cause an increase in run off sediment into areas near land based sources of sediment. This sedimentation runoff can lead to the something of coral. This is destructive to its survival as it limits nutrient and oxygen availability, ultimately killing the coral (Bartley et al. 2014).

It is possible that increasing sea level did not affect the survival of some Scleractinia coral as it increased potential habitats for corals. deeper water depth have cooler ocean temperatures, therefore, as discussed by Hunt, it is possible that rising sea levels made a large variety of habitats suitable for Scleractinia therefore counteracting the effects of global warming (Hunt et al. 2020). It is likely that no correlation was observed in this analysis due to the capability of Scleractinia coral to grow at depths of up to 40m. therefor ethe majority of coral which was sampled will not have been affected by fluctuating sea levels. Therefore, it would be important for future studies to focus on shallow species of Scleractinia to properly analyse how a rise in sea level will affect them.

8 CONCLUSION

The results of this analysis show that atmospheric CO₂ and temperature change had a significant impact on the speciation of Scleractinia. Speciation was driven by cooler temperatures and lower atmospheric carbon dioxide concentrations. Further research into the impact of temperatures

becoming similar to those estimated for future climate change would be necessary to draw reflections on the effect of present-day climate change on modern coral reefs. To further understand the effects of climate change on speciation of Scleractinia it would be necessary to investigate a wider range of environmental factors. This could for example include, tidal activity, weather patterns or tectonic movement. It would be beneficial to conduct this analysis on a smaller sample of Scleractinia and divide the data appropriately, for example between reef building and non-reef building corals. This would likely allow further insight into the lack of correlation between speciation and sea level changes which was observed. Excluding the sea level results, the results of the analysis are in line with findings from relevant literature. However, despite the conclusions drawn, valid predictions about the future of extant Scleractinia cannot be concluded.

Anthropogenic climate change is accelerating temperature increase, and sea level is rising at rates in which it is unlikely that modern-day Scleractinia will be able to adapt to in time. Therefore, it is relevant and appropriate to assume there will be severe negative impacts of global warming on Scleractinia, and modern day corals may not succeed in evolving at a rate fast enough to adapt to the unprecedented conditions.

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