# Effects of Sea Level on Reef Habitats of Papahānaumokuākea Marine National Monument during the Last Glacial Maximum

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We certify that we have read this thesis and that, in my opinion, it is satisfactory in scope and quality as a thesis for the degree of Bachelor of Science in Global Environmental Science.

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## DEDICATION

I dedicate this paper to my family for their support over the years and the sacrifices they made to allow me to return to school.  I would also like to dedicate this, and future works to my nephew Luke and his generation. This scientific research is aimed to maintain a healthy environment so he, and future generations will be able to enjoy the natural beauty and resources as our ancestors have.

Mahalo Nui.

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A special thanks goes out the Cori Kane whom brought me on as a safety diver for my first research cruise to Papahānaumokuākea Marine National Monument (PMNM), it was a very special cruise for me being a native Hawaiian and as a scientist. I would also like to thank Randy Kosaki, Chief Scientist, and the rest of the scientist at PMNM for making me feel welcome. I'd also like to thank Richard Pyle whom first sparked my curiosity into trying to explain the extraordinarily high rate of endemism in the monument.

Mahalo Nui

## Abstract

Mesophotic Coral Ecosystems (MCE) (50-100m) are not as well understood as their shallower counter-part, the Photic Reef Ecosystem (PRE) (0-50m). The disparity in the level of understanding between the two regions is mainly due to the difficulty in getting observations from these depths. This study used Geographic Information System (GIS) software to calculate habitat increases of 88.53% (5605.34 $km^2$) in the PRE from the Last Glacial Maximum (LGM), when the sea level was 120m below the present day sea level. A statistically similar amount of habitat gain was found between the MCE and PRE (Show stat values). Understanding habitat changes will allow scientists to deduce causes of important differences in ecosystem characteristics between these two environments, such as endemism rates. PRE endemism rates for fish in Papahānaumokuākea Marine National Monument (PMNM) are 20.6% (DeMartini, Friedlander, 2004) while several dives in MCE habitat on Midway atoll recorded endemic fish rates above 90% (NOAA 2010, Unpublished). Similar changes in area between PRE and MCE, coupled with drastically different fish endemism rates suggests a continuous MCE habitat regime while the PRE experienced dramatic changes inducing extinctions or sever loss of biota. Rate of sea level rise may have had the most detrimental impact on the PRE, increasing as much as 25mm/yr during meltwater pulse episodes which lasted as long as 1000 years (Fletcher, Sherman, 1995). These relatively rapid rates are faster than the accretion rate of corals in PMNM, subsequently leading to drowning of the ecosystem. As MCE are not heavily light dependent and probably cover a wider depth range than

PRE, likely exhibit more continuity and habitat stability. A stable and long lasting isolated habitat is required for the evolutionary processes to produce unique animals that are found nowhere else in the world. The Continuous Marine Habitat (CoMaH) hypothesis explaining MCE endemism rates looks like the most plausible explanation of the historic events that shaped the current marine environments of the PMNM. CoMaH hypothesis supports the idea that the MCE habitat is able to endure the large fluctuations and rapid increase of sea level providing a continuous habitat for marine organisms to evolve into endemic species.

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# List of Abbreviations

CoMaH - Continuous Marine Habitat (hypothesis)

GIS - Geographic Information System

k yr - thousands of years

LGM - Last Glacial Maximum

MCE – Mesophotic Coral Ecosystem

PMNM - Papahānaumokuākea Marine National Monument

PRE – Photic Reef Ecosystem

PSL – Present Sea Level

SLIHC - Sea Level Induced Habitat Change

## 1. Introduction

This study presents a unique approach of analyzing historical changes in Photic Reef Ecosystem (PRE) and Mesophotic Coral Ecosystem (MCE) reef area using Geographic Information System (GIS) software. The effects of historic sea level change on reef habitat in the Papahānaumokuākea Marine National Monument (PMNM) were quantified by comparing habitat area for the Present Sea Level (PSL) and sea level during the Last Glacial Maximum (LGM). PREs are defined by some as a marine environment having a depth range between 0-30m and MCEs are defined as having a depth range of 30-150m (Lesser et al. 2009). These ecosystem boundaries were originally determined by analyzing spectral irradiance curves on MCEs in the Bahamas. In Hawaiʻi, however, the major reef building coral species, *Porites lobata*, is utilized to delineate the PRE from the MCE. 50m is shown to be the depth where a significant shift in coral cover begins to decline, from 3-23% above the 50m mark showing declines with increasing depth, effectively shifting the ecosystem to a sponge and algal dominated community (Liddell et al. 1997). The Darwin Point, the depth at which coral accretion rate is equal to the erosion rate, is 50m for *P. lobata* in the Au'Au Channel, Maui, Hawaii, and thus will determine the boundary between the two ecosystems in this study (Grigg 2005). 50m isobath is selected in this study in order to get a more accurate MCE for the marine environments of Hawai'i. The relatively clear water allows for deeper light penetration to allow the dominate *P. lobata* to grow in deeper ranges than in the studies conducted by Lesser. Until more research is done in Hawaii to delineate the depths at which the actual habitat changes the 50m division between ecosystems are adequate for the scope of this analysis. All analyses in this study applied the depth range of 0-50m for PRE and 50-100m for MCE (Figure 14).

Despite the defined boundaries applied to these ecosystems, many dynamic variations and relationships exist between PREs and MCEs (Slattery et al. 2011). The interaction between MCE and PRE are not well understood but some have proposed that MCE serve as a refuge for PRE fauna and may help to reseed PRE after disturbance events (Lesser et al. 2009). While PREs have been thoroughly examined, MCEs are significantly less understood due to the technical challenges of gathering ecological data in this deeper environment. This study aimed to investigate a possible link between high rates of biodiversity and endemism in the MCEs. A reef survey conducted on a MCE at Midway Atoll in 2010 found fish endemism rates in excess of 93% (Table 1) (NOAA 2010 Unpublished). It has been proposed that this extraordinarily high level of endemism is due to the greater stability across the Pleistocene glacial epochs (Slattery et al. 2011). With the large fluctuations of sea level throughout geologic history it is postulated that the PRE had either lost a large amount of area during the LGM while the MCE area remained relatively constant. Alternatively, due to PRE fragility, times of mass ecosystem extinctions and re-colonization occurred repeatedly throughout history as a result of the rapid rate of sea level rise (Pyle 2010). Multiple extinctions and re-colonization of coral habitats are believed to cause the relatively low rates of endemism (~20%) observed in PREs (Grigg R W 1988). This study proposes to classify this theory as the Continuous Marine Habitat (CoMaH) hypothesis. The CoMaH hypothesis was tested in this study by analyzing and comparing habitat areas between the PSL and LGM in both ecosystems. Showing similarities or differences in habitat change, an inference can be made relating to possibility of MCE being continuous. This continuous habitat would provide the necessary environment for high rates of endemism in deep biota.

Historically, sea-level fluctuations with estimated amplitudes of -120 to -140m are believed to have occurred throughout earths' history (Rooney, J., et al., 2008, Yokoyama, Y., et al., 2001). These fluctuations in Relative Sea Levels (RSL) are the result of glaciation periods in geologic history, the last of which occurred during the Pleistocene Era causing shifts ranging from 125 ± 4m decline from the present sea level (Yokoyama, Y., et al., 2001). Declines in RSL are believed to occur in cyclical patterns every 100 k yr, with the last maximum decline of RSL starting 22 k yr ago and lasting for ~3 k yr (Yokoyama Y. et al, 2001, Rooney et al. 2008). Understanding relationships between sea level and coral reef ecosystem habitat will provide necessary information to promote adequate management of these important resources.

Recent estimates suggest a potential .57 – 1.10m increase in sea level by the year 2100 and a subsequent rise of 1.84 – 5.49m by the year 2500 (Jevrejeva S et al. 2011). These changes could have some positive effects on coral reefs in regions like Thailand where a documented increase in sea level of 2.7 mm $y^{-1}$ from 1960 thru 2009 contributed to an increase in coral cover (Jevrejeva S et al. 2011). Atolls, unlike reef habitats located on continental shelves may face an unfortunate loss of reef habitat induced by sea level rise. In order to determine the impacts of sea level rise on reef habitat, this study also analyzed photic habitat area in relation to these predicted increases in sea level.

Papahānaumokuākea Marine National Monument (PMNM) is the chain of atolls that originated from the Hawaii hot spot currently located in the vicinity of Hawaii Island (Fletcher C H et al. 2008). The motion of the Pacific Tectonic Plate determines the spatial arrangement of PMNM; this Northwest movement has oriented the atoll chain in its current configuration (Moore 1987). The monument is comprised of atolls and sea banks located between Nihoa, the

Southern-most atoll, and Kure is the Northern most atolls. The Hawaiian archipelago is one of the most isolated island regions, located in the middle of the largest ocean in the world, making it an excellent study site to study the effects of habitat change on endemism and biodiversity.

# 2. Methods

## 2.1 Geographic Information Systems (GIS)

Geographic Information System (GIS) software was used in conjunction with reef area data collected by the National Oceanic and Atmospheric Administration (NOAA) and bathymetry data collected by the Pacific Island Benthic Habitat Mapping Center (PIBHMC). ESRI's arcGIS version 9.3.1 was used to calculate the area of each of the two reef habitats, PRE and the MCE, for the present day and LGM sea level. Due to the physical limitations of multibeam bathymetry data, the 20 - 30m region of the data set are sparse with large gaps, for this reason the present day photic reef area between 0 - 30 m was used for analysis. This area analysis was conducted using Shallow Water IKONOS Satellite Mapping NOAA's Biogeography Branch (Weiss et al., 2009). Combining the IKONOS habitat area with the GIS calculated area (between 30 – 50 m) enabled the present day area of PREs (0-50m) to be derived. The present day MCE was calculated utilizing the area between the 50 -100m isobaths. The estimations of 125m + or – 4m is the range of LGM fluctuations used frequently in the literature and will be the value used in this study to assess PRE changes (Yokoyama, et al., 2001). The 10m resolution bathymetry data doesn't allow 5m accuracy without interpolation of the data by the software so the sea level of 120m less than the present day sea level is used (Webster, 2006). The PRE area during the LGM was defined between the 120m and the 170m contour lines and the MCE was defined as the area between 170m and 220m contour lines.

## 2.2 Data Preparation

Bathymetry data was downloaded from the Pacific Island Benthic Habitat Mapping Center's (PIBHMC) website in 2011 (PIBHMC 2011). The data set for PMNM was divided into 4 georeferenced shape files that were used with the GIS software. In order to calculate the habitat area, each bathymetry contour line needs to be a closed loop. The gaps in the contour lines of interest were joined by underlying NOAA Nautical charts, then interpolating a path between the separated segments (NOAA 2011). The size of these gaps varied throughout the data set from a few meters to kilometers, with the available data and technology this is the most accurate way of processing and interpreting the bathymetry data. In general, the contours <30m were more disconnected and the deeper the bathymetry the more complete the contour line. This process was completed for the entire PMNM, 9 major atolls and 8 seamount/banks, for each of the 30, 50, 100, 120, 170, and 220m bathymetry lines.

## 2.3 GIS Analysis

Various functions of the ESRI arcGIS 9.3.1 software were used to analyze the spatial data. Spatial polygons were created using the polyline to polygon tool. This created an area bounded by the contour lines that could be clipped by the clipping tool to create a “doughnut” shaped region that represents the habitat area of interest. To create the habitat region, the upper bound was selected then the clipping tool subtracted that area from the lower bound creating the habitat region. The 30m polygons were subtracted from the 50m polygons creating the PRE area for present day sea level, the 50m polygon was then subtracted from the 100m polygon to get the present day MCE area. This process was completed for the entire chain for both present and LGM sea levels. The final step was to create a new area field in the attribute table, then use the calculated geometry function to get the area of each clipped polygon. The resulting area was then compared between the two depth ranges for each particular atoll or sea mount. A two-sample t-test was then performed between the change in area of the PRE and the MCE to compare the means in order to determine whether there is a significant difference in area between the two habitats.

## 2.4 Sea Level Induced Habitat Change (SLIHC) curve for Midway Atoll

The detailed analysis of Midway required a higher resolution of 5m for analyzing changes in habitat area induced by projected rises in sea level. In order to achieve this, interpolation of the bathymetry lines by the GIS software was necessary. Bathymetry data was transformed from a vector to a raster data set. Using the Feature to Raster tool, raster images where created and another set of contours were developed with a 5m resolution. This new set of 5m contour lines was then used to calculate the changes in area of the reef habitat caused by projected rises in sea level.

# 3. Results

## 3.1 Reef Habitat Analysis

Photic habitat area was calculated by combining GIS determined reef area (between 20-50m) with IKONOS derived habitat area within a depth range of 0-30m (Table 2). The Photic Reef Ecosystems (PRE) of the main atolls displayed increases ranging from 55.99 $km^2$ to 1275.03 $km^2$ in habitat area from the LGM to the Present Day (Table 3). The average increase in area for the 9 main atolls is 3477.26 $km^2$ of PRE habitat area. Individual area comparisons are represented in Figure 2. The PRE of the seamounts and banks of PMNM displayed a range of habitat area change including a decrease in area of 26.82 $km^2$ to an increase of 1664.38 $km^2$, with an increase of 2128.08 $km^2$. The combined habitat increase in PRE for PMNM is 5605.34 $km^2$.

The MCE displayed a range of habitat area change from the LGM to Present Day including a decrease of 100.93 $km^2$ on Maro reef to an increase of 479.23 $km^2$ on Laysan (Table 4). The total increase of MCE habitat area in the 9 main atolls is 1521.64 $km^2$ of additional area of mesophotic habitat, values for each individual atoll is shown in Figure 3. Increases in the seamount habitats range from 12.03 $km^2$ in the region of Nero Seamount to a 338.25 $km^2$ increase in habitat at Pioneer Bank. PMNM MCE habitat area displayed an increase of 2606.54 $km^2$. The results from the spatial analyses of the present and glacial time periods for the PRE and MCE are represented in Figures 4 through 12.

A two-sample t-test was performed to compare the PRE change vs. the MCE change. No significant difference was seen in habitat area change between the two ecosystems (N=17, T-Value = .82, P-Value = .419, DF=28). This analysis encompassed each atoll, seamount or bank in PMNM. Data was transformed using an arcsine transformation in order to meet the assumptions necessary for use of parametric statistical tests. Mean values and standard deviations for habitat area change are presented in Table 5.

### 3.2 Sea Level Induced Habitat Change (SLIHC) curve for Midway Atoll

For Midway Atoll a Sea Level vs. Photic Habitat Area graph was constructed to visualize the relationship between habitat area and sea level change (Fig 13). At LGM the habitat area was calculated to be 39.84 $km^2$, this area increased until sea level reached 60m below present day level. At this point the curve maintains an area in the mid to upper 120m range until sea level reaches +5m above present. This downward sloping curve continues until the maximum extent of the analysis with the sea level of +20, the area of the PRE is 95.5 $km^2$ at this point.

Benthic habitat analysis of the PRE during the LGM showed the total habitat area to be 39.84 $km^2$ when sea level was -120m below the present level compared to the present habitat area of 129.44 $km^2$ (Table 3, Figure 10). Utilizing the percent cover from data collected by NOAA, seven specified habitat types were estimated for the LGM. These categories of substrate types are Hardbottom with >10% live Coral, Hardbottom with >10% crustose coralline algae, Hardbottom (uncolonized), Hardbottom with >10% macro algae, Hardbottom with indeterminate cover, Unconsolidated with 10% or less macro algae or sea grass, and Unconsolidated with >10% macro algae or sea grass. The reduction of the PRE habitat area from present day to the LGM is 69.22%, translating to a similar loss of habitat for each of the specified substrate composition (Table 6). The coral habitat of > 10% live coral has a present day area of around 1.29 $km^2$ which is reduced in time of glacial maximum to an area of .39 $km^2$.

# 4. Discussion

## 4.1 Habitat Area Analysis

Large changes in area were seen for both PRE and MCE habitats, with percentage increases of 88.53% and 82.92%, representing habitat increases of 5605.34 $km^2$ and 2606.54 $km^2$ respectively (Table 2). These changes in habitat area may have led to re-colonization by corals from the Indo-West Pacific (IWP), resulting in taxonomic shifts in coral assemblages (Grigg R W 1988). The data derived from GIS analysis showed a statistically similar increase in habitat area from the LGM to the present sea level between PRE and MCE habitats (Table 5). This similarity between the two ecosystems change in area further supports the belief of greater MCE stability compared to PRE habitats by suggesting another biological phenomena to explain a more continuous habitat in the mesophotic realm (Slattery et al 2011). Higher rates of endemism in the MCE would require a continuous habitat needed to exist in order for adaptive radiation to occur. PRE fish endemism rates in PMNM are found to be 20.6% and the initial MCE fish surveys have endemism rates above 90%, it appears that something other than simply ecosystem area has contributed to the severe reduction of PRE endemism. Times of prolonged and relatively rapid sea level rise after the LGM inflicted stress to organisms occupying both ecosystems in the form of changing habitat area. An average sea level rise of 10mm/yr post LGM is a rate that the upper latitude scleractinian corals would not be able to cope with. These corals, having a growth rate much lower than the rate of rising sea level would result in corals being subjected to exist in depths beyond their optimal range (Davies P J 1983). There are also two glacial meltwater pulses that increased the raising sea level rate to 25 mm/yr for a nearly 1000 years per episode (Fairbanks R 1989). These rapid periods of sea level rise would cause dramatic shifts in the habitats of Hawaiian PREs. Another factor to support sea level induced changes to coral populations inhabiting PREs is the absolute depth range of the habitat. If the depth range of the PRE is 0-30m as suggested by Lesser et al. (2009), with a MCE of 30-150m, a physical advantage of having a larger depth range will increase the resilience of the coral occupying this habitat (Lesser et al., 2009). Because the depth range of the MCE is 4 times as deep as the PRE, logically it would take that much longer for the MCE to drown as opposed to the PRE. All these factors combined support the CoMaH hypothesis to explain a high endemism rate in the MCE of PMNM. This GIS analysis provides evidence for one small portion of a very complex relationship between endemism rates, vertical migration, interactions between the

PRE and MCE, and the effects of sea level rise on marine habitat. An MCE delineation study for PMNM should be conducted in order to more clearly define the ecosystems using biological characteristics. It seems logical that coral accretion rates vary throughout the monument and therefore the mesophotic region boundaries may not be consistent throughout the archipelago. Faster accretion of reef building corals would possibly extend the MCE where as a slow rate of accretion will raise the Darwin Point depth resulting in a regime change in substrate cover. With improvements in SCUBA technology greater depths can be explored in order to take substrate surveys to better understand the true range of the MCE.

## 4.2 Midway Sea Level Induced Habitat Change (SLIHC)

With the concerns and uncertainties of sea level rise induced by anthropogenic influences, PRE analysis is useful to determine when a typical Hawaiian atoll will begin to loose essential reef and terrestrial habitat. Shallow reef flats in Phuket, Thailand, displayed an increase of relative sea level of 2.7 mm/yr during the period of 1960-2009, where a positive correlation in coral cover was observed (Brown B E et al. 2011). In an effort not to misconstrue these observations as a positive effect of sea level rise an area analysis on Midway atoll will show at what level the PRE area will start to decline. The results of the analysis showed that an elevated sea level of 5m in 2500, the upper range of a sea level model by Jevrejeva, will result in a PRE area increase of 121.11 $km^2$ (Jevrejeva S et al. 2011). This is a decline from present day sea level area of 129.44 $km^2$, this decline in habitat continues to +20m relative to present sea level where it attains an area of 95.5 $km^2$ (Fig 12). The rate of sea level rise the Jevrejeva model predicts a high of 20 mm/yr and a low rate of 10 mm/yr (Jevrejeva 2011). Rapid increase in rates of sea level rise will eventually lead to loss of the PRE habitat, effectively drowning the atoll. The Sea Level Induced Habitat Change (SLIHC) curve can be used by resource managers to initiate a time frame for a relocation program for threatened species that depend on terrestrial habitat, such as monk seals and ground nesting birds that reside in PMNM.

## 5. Conclusion

An implication of this study is the utilization of GIS in the marine environment. Terrestrial applications are numerous and wide ranging allowing for a broad range of scientific study to be conducted from home range studies of elephants to hydrological studies, GIS is a powerful tool. Detailed studies of coral colony genetic linkages could be spatially analyzed to improve on this study furthering the understanding of the origin of modern reef ecosystems. Another implication of the habitat analysis of PMNM is a key component in determining the potential reef habitat area changes of Hawaiian MCEs. The similarity in habitat area gained from LGM to present suggests that rates of sea level rise may be the single most important factor in coral habitat changes during post-glacial periods. The rapid rise of sea level greatly out-paced the coral accretion rates in PMNM, which ultimately caused PRE corals to be subjected to MCE conditions, supporting the hypothesis of total extinction of the ecosystem during stages of rapid sea level rise. A deeper depth range for the MCE and the sheer resilience of the fauna and biota increase the likelihood of habitat survivability throughout this time of relatively rapidly increasing sea level. The CoMaH hypothesis is consistent with the observed high endemism rates in the MCE of the PMNM. Clearly understanding the relationship between sea level and the reef habitat will allow managers and communities to prepare for reductions in coral reef habitat. This will prove to be critical as sea level induced habitat reductions can have potentially detrimental impacts to the economic and sustenance value of these ecosystems.

**Table 1**: Fish count taken by NOAA diver Cori Kane at Midway Atoll on 8/04/2010. The recorded depth of the transect line is 185ft (56.388m). The 93.7743% endemism rate is calculated by fish count of endemics divided by the total number of fish.

| **Fish** | **Size** | **Count** | **Endemic?** |
|---|---|---|---|
| *Pseudanthias thompsoni* | 10 | 110 | Y |
| *Pseudanthias thompsoni* | 12 | 30 | y |
| *Pseudanthias thompsoni* | 8 | 70 | Y |
| *Chaetodon miliaris* | 15 | 10 | Y |
| *Chaetodon miliaris* | 12 | 3 | Y |
| *Coris flavovittata* | 18 | 1 | Y |
| *Parupeneus chrysonemus* | 12 | 1 | Y |
| *Parupeneus chrysonemus* | 10 | 1 | Y |
| *Heniochus diphreutes* | 15 | 2 | N |
| *Coris balleui* | 15 | 1 | Y |
| *Apolemichthys arcuatus* | 13 | 1 | Y |
| *Bodianus albotaeniatus* | 5 | 1 | Y |
| *Bodianus albotaeniatus* | 13 | 1 | Y |
| *Canthigaster coronata* | 8 | 1 | N |
| *Labroides phthirophagus* | 6 | 1 | Y |
| *Labroides phthirophagus* | 2 | 1 | Y |
| *Pseudojuloides ceracinus* | 8 | 1 | N |
| *Pseudojuloides ceracinus* | 10 | 1 | N |
| *Chaetodon fremblii* | 11 | 1 | Y |
| *Genicanthus personatus* | 13 | 1 | Y |
| *Genicanthus personatus* | 8 | 2 | Y |
| *Genicanthus personatus* | 6 | 1 | Y |
| *Bodianus sanguineus* | 8 | 1 | Y |
| *Bodianus sanguineus* | 12 | 1 | Y |
| *Xanthichthys mento* | 15 | 1 | N |
| *Xanthichthys mento* | 18 | 2 | N |
| *Centropyge interrupta* | 10 | 1 | N |
| *Centropyge interrupta* | 6 | 4 | N |
| *Centropyge interrupta* | 8 | 1 | N |
| *Enchelycore pardalis* | 40 | 1 | N |
| *Anampses chrysocephalus* | 12 | 1 | Y |
| *Chromis hanui* | 4 | 1 | Y |
| *Gymnothorax eurostus* | 40 | 1 | N |
| | | Total | Endemic |
| | | 257 | 241 |
| | | | % Endemic |
| | | | 93.7743 |

**Table 2:** Table of all GIS data and the IKONOS image derived Photic Reed Ecosystem (PRE) area. The PRE, present day sea level has two components, 0-30m IKONOS area and the 30-50m GIS data. These two values are combined to get the hybrid 0-50m reef area estimate for the present day sea level. All values are in $km^2$. The values are 0 for the 0-30m present day, seamounts area because they are all submerged or shallow data was not available for the area estimation. In the case of Gardner Pinnacles where there are land masses above sea level the area is inconsequential for the scope of this study and the habitat area will be larger by a small factor.

| | Photic Reef | | | | Mesophotic Reef | |
|---|---|---|---|---|---|---|
| **Location** | 0-30m | 30-50m | 0-50m | LGM | Present | LGM |
| Kure | 69.8 | 37.01466 | 106.8146 | 50.827 | 97.501068 | 12.2311 |
| Midway | 95.5 | 33.93808 | 129.4380 | 39.838 | 129.33174 | 11.1336 |
| Pearl and Hermes | 391.6 | 38.6486 | 430.2486 | 30.687 | 151.96158 | 14.1556 |
| Lisianski | 438.7 | 50.64483 | 489.3448 | 27.929 | 180.03193 | 15.0024 |
| Laysan | 127.2 | 3.183019 | 130.3830 | 29.913 | 491.26094 | 12.0259 |
| Maro Reef | 518.7 | 855.2779 | 1373.977 | 98.952 | 85.587342 | 186.518 |
| French Frigate Shoals | 417.6 | 93.67549 | 511.2754 | 52.997 | 98.553134 | 28.1279 |
| Mokumanamana | 227.6 | 107.1111 | 334.7111 | 52.182 | 136.49642 | 28.4293 |
| Nihoa | 74.1 | 314.2701 | 388.3701 | 33.980 | 476.34343 | 17.8066 |
| Nero Seamount (Z1) | 0 | 0 | 0 | 18.631 | 20.093602 | 8.06244 |
| Pioneer Bank | 0 | 18.33279 | 18.33279 | 45.155 | 348.24891 | 9.99993 |
| Northampton Seamounts | 0 | 108.9564 | 108.9564 | 30.831 | 188.45040 | 15.9140 |
| Raita Bank | 0 | 229.3478 | 229.3478 | 27.119 | 161.48141 | 28.2960 |
| Gardner Pinnacles | 0 | 1759.606 | 1759.606 | 95.222 | 302.45067 | 62.6604 |
| Brooks Banks & St. Rogatien Bank | 0 | 320.9404 | 320.9404 | 57.215 | 60.021905 | 71.9743 |
| Twin Banks | 0 | 0 | 0 | 14.997 | 19.52554 | 6.95111 |
| mystery rock | 0 | 0 | 0 | 19.930 | 96.181211 | 7.68859 |

## Photic Reef Ecosystem (PRE) Area in $km^2$

Present Sea Level (PSL) and Sea Level at Last Glacial Maximum (LGM)

| Location | PSL | LGM | Habitat Change | Percent Change |
|---|---|---|---|---|
| Kure | 106.81 | 50.83 | 55.99 | 52.42 |
| Midway | 129.44 | 39.84 | 89.60 | 69.22 |
| Pearl and Hermes | 430.25 | 30.69 | 399.56 | 92.87 |
| Lisianski | 489.34 | 27.93 | 461.42 | 94.29 |
| Laysan | 130.38 | 29.91 | 100.47 | 77.06 |
| Maro Reef | 1373.98 | 98.95 | 1275.03 | 92.80 |
| French Frigate Shoals | 511.28 | 53.00 | 458.28 | 89.63 |
| Mokumanamana | 334.71 | 52.18 | 282.53 | 84.41 |
| Nihoa | 388.37 | 33.98 | 354.39 | 91.25 |
| Main Atoll Totals | 3894.56 | 417.31 | 3477.26 | 89.28 |
| Nero Seamount (Z1) | 0 | 18.63 | -18.63 | --- |
| Pioneer Bank | 18.33 | 45.16 | -26.82 | -40.60 |
| Northampton Seamounts | 108.96 | 30.83 | 78.12 | 71.70 |
| Raita Bank | 229.35 | 27.12 | 202.23 | 88.18 |
| Gardner Pinnacles | 1759.61 | 95.22 | 1664.38 | 94.59 |
| Brooks Banks & St. Rogatien Bank | 320.94 | 57.22 | 263.73 | 82.17 |
| Twin Banks | 0 | 15.00 | -15.00 | --- |
| Middle Bank | 0 | 19.93 | -19.93 | --- |
| Seamount Totals | 2437.18 | 309.10 | 2128.08 | 87.32 |
| Total | 6331.75 | 726.41 | 5605.34 | 88.53 |

**Table 3**: The area calculations from the Geographic Information System (GIS) analysis are divided, first, into atolls then Seamounts. The Present Sea Level column shows the habitat area in $km^2$ of the Photic Reef Ecosystem (PRE), then the amount of change followed by the percent change. The totals are calculated for both the main atolls and the seamounts, followed by an accumulated total. Note that the percent change has been normalized and has been calculated by taking the Habitat Change divided by PSL Area, also, the totals are not an average of the percent change, but the percent change calculated from the total habitat area.

## Mesophotic Coral Ecosystem Area in km²

Present Sea Level (PSL) and Sea Level at Last Glacial Maximum (LGM)

| Location | PSL | LGM | Habitat Change | Percent Change |
|---|---|---|---|---|
| Kure | 97.50 | 12.23 | 85.27 | 87.46 |
| Midway | 129.33 | 11.13 | 118.20 | 91.39 |
| Pearl and Hermes | 151.96 | 14.16 | 137.81 | 90.68 |
| Lisianski | 180.03 | 15.00 | 165.03 | 91.67 |
| Laysan | 491.26 | 12.03 | 479.23 | 97.55 |
| Maro Reef | 85.59 | 186.52 | -100.93 | -54.11 |
| French Frigate Shoals | 98.55 | 28.13 | 70.43 | 71.46 |
| Mokumanamana | 136.50 | 28.43 | 108.07 | 79.17 |
| Nihoa | 476.34 | 17.81 | 458.54 | 96.26 |
| Main Atoll Totals | 1847.07 | 325.43 | 1521.64 | 82.38 |
| Nero Seamount (Z1) | 20.09 | 8.06 | 12.03 | 59.88 |
| Pioneer Bank | 348.25 | 10.00 | 338.25 | 97.13 |
| Northampton Seamounts | 188.45 | 15.91 | 172.54 | 91.56 |
| Raita Bank | 161.48 | 28.30 | 133.19 | 82.48 |
| Gardner Pinnacles | 302.45 | 62.66 | 239.79 | 79.28 |
| Brooks Banks & St. Rogatien Bank | 160.02 | 71.97 | 88.05 | 55.02 |
| Twin Banks | 19.52 | 6.95 | 12.57 | 64.40 |
| Middle Bank | 96.18 | 7.69 | 88.49 | 92.00 |
| Seamount Totals | 1296.45 | 211.55 | 1084.91 | 83.68 |
| Totals | 3143.52 | 536.98 | 2606.54 | 82.92 |

**Table 4**: The area calculations from the Geographic Information System (GIS) analysis are divided, first, into atolls then Seamounts. The Present Sea Level column shows the habitat area in $km^2$ of the Mesophotic Coral Ecosystem (MCE), then the amount of change followed by the percent change. The totals are calculated for both the main atolls and the seamounts, followed by an accumulated total. Note that the percent change has been normalized and has been calculated by taking the Habitat Change divided by PSL Area, also, the totals are not an average of the percent change, but the percent change calculated from the total habitat area.

**Table 5:** The Two-Sample T-Test was performed using MiniTab. The sample size was 17, this was all the atolls combined with the seamounts. The area change in the PRE was tested against the MCE, the resulting P-Value suggests a relationship between the two habitats in the amount of area gained from the LGM. The means and the standard deviation are listed under the Descriptive Statistics header.

## Two-Sample T-Test and CI: Change Transform (arcsin), Photic_1_Mesophotic_2

```
Two-sample T for Change Transform (arcsin)

Photic_1_Mesophotic_2   N    Mean  StDev  SE Mean
1                      17    0.04   1.23     0.30
2                      17  -0.261  0.834     0.20


Difference = mu (1) - mu (2)
Estimate for difference:  0.296
95% CI for difference:  (-0.443, 1.035)
T-Test of difference = 0 (vs not =): T-Value = 0.82  P-Value = 0.419  DF = 28
```

## Descriptive Statistics: Photic Change, Mesophotic Change

```
Variable            N  N*   Mean  SE Mean  StDev
Photic Change      17   0    330      113    466
Mesophotic Change  17   0  153.3     36.9  152.0
```

**Table 6:** Reef habitat composition of Midway atoll during the LGM and at PSL. The PRE of Midway atoll at the PSL is 129.44 km$^2$ and the reef area during the LGM is 39.84 km$^2$. Using reef area percentages of taken by NOAA, the PRE area from the LGM can be inferred. Due to some ambiguity, Hardbottom with >10% crustose coralline algae, and Unconsolidated with >10% macroalgae or seagrass, both reported as less than 1%, assigning a value of .5% to these two fields brings the composition % to just over 100%.

| **Habitat Type** | **% Composition** | **PSL Area** | **LGM Area** |
|---|---|---|---|
| Hardbottom with >10% live coral | 0.01 | 1.29 | 0.3984 |
| Hardbottom with >10% crustose coraline algae | 0.005 | 0.65 | 0.1992 |
| Hardbottom (uncolonized) | 0.16 | 20.71 | 6.3744 |
| Hardbottom with >10% macroalgae | 0.23 | 29.77 | 9.1632 |
| Hardbottom with indeterminate cover | 0.07 | 9.06 | 2.7888 |
| Unconsolidated with 10% or less macroalgae or seagrass | 0.53 | 68.60 | 21.1152 |
| Unconsolidated with >10% macroalgae or seagrass | 0.005 | 0.6472 | 0.1992 |

**Figure 1**: The sea level fluctuations from 500 ka BP with the Last Glacial Maximum (LGM) highlighted. The historic oscillations are direct results of glacial ice accumulations effectively reducing sea level (Webster J M et al, 2003). This table was modified to extract the sea level curve and highlight the area of interest.

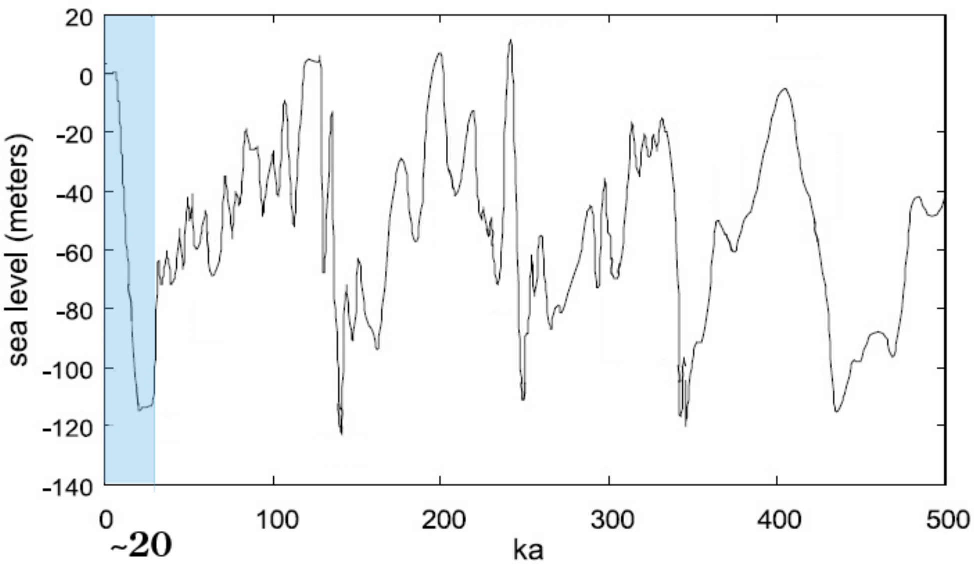



**Figure 2**: Photic Reef Ecosystem area bar graph with present sea level in black and Last Glacial Maximum (LGM) sea level in gray.

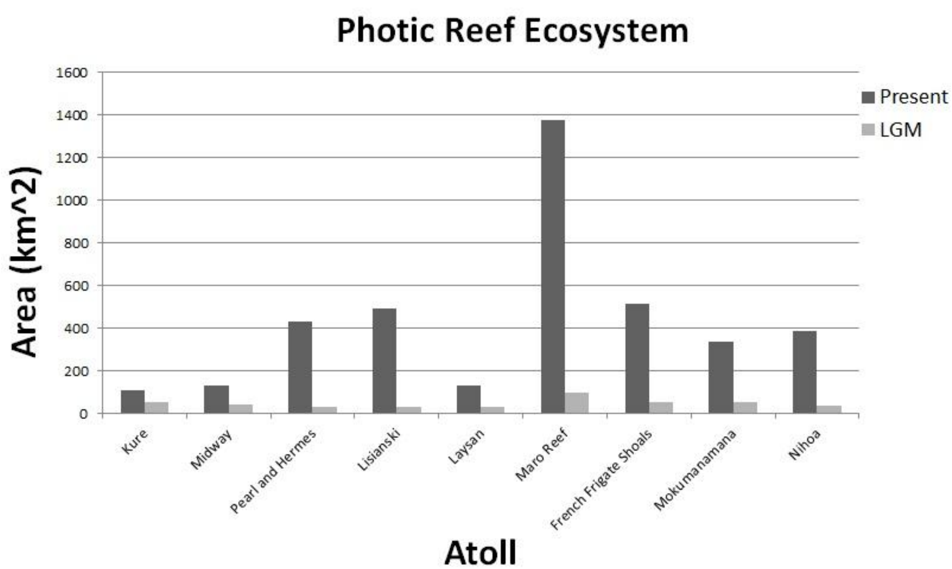
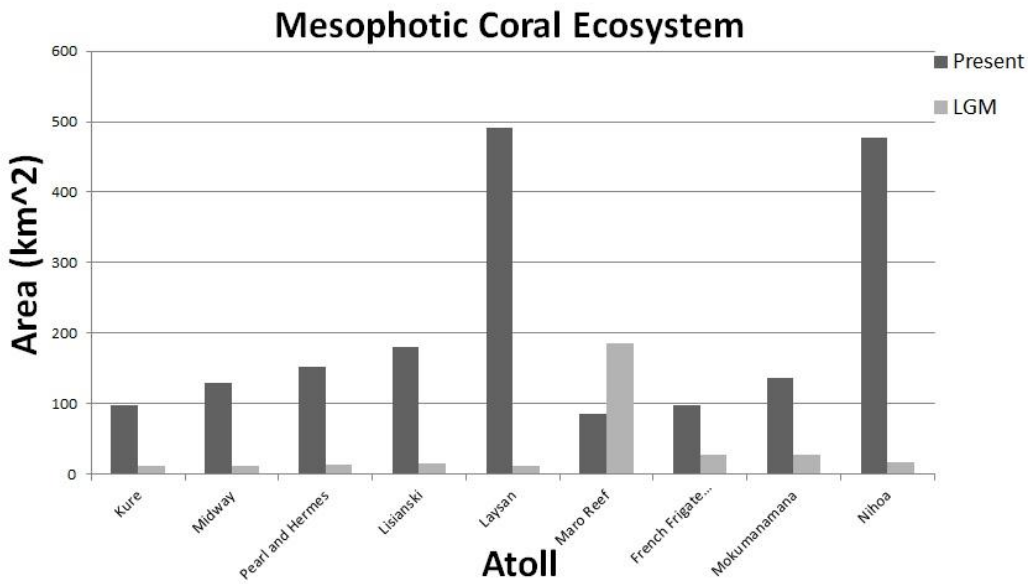


**Figure 3**: Mesophotic Coral Ecosystem (MCE) area bar graph with present sea level in black and Last Glacial Maximum (LGM) sea level in gray.



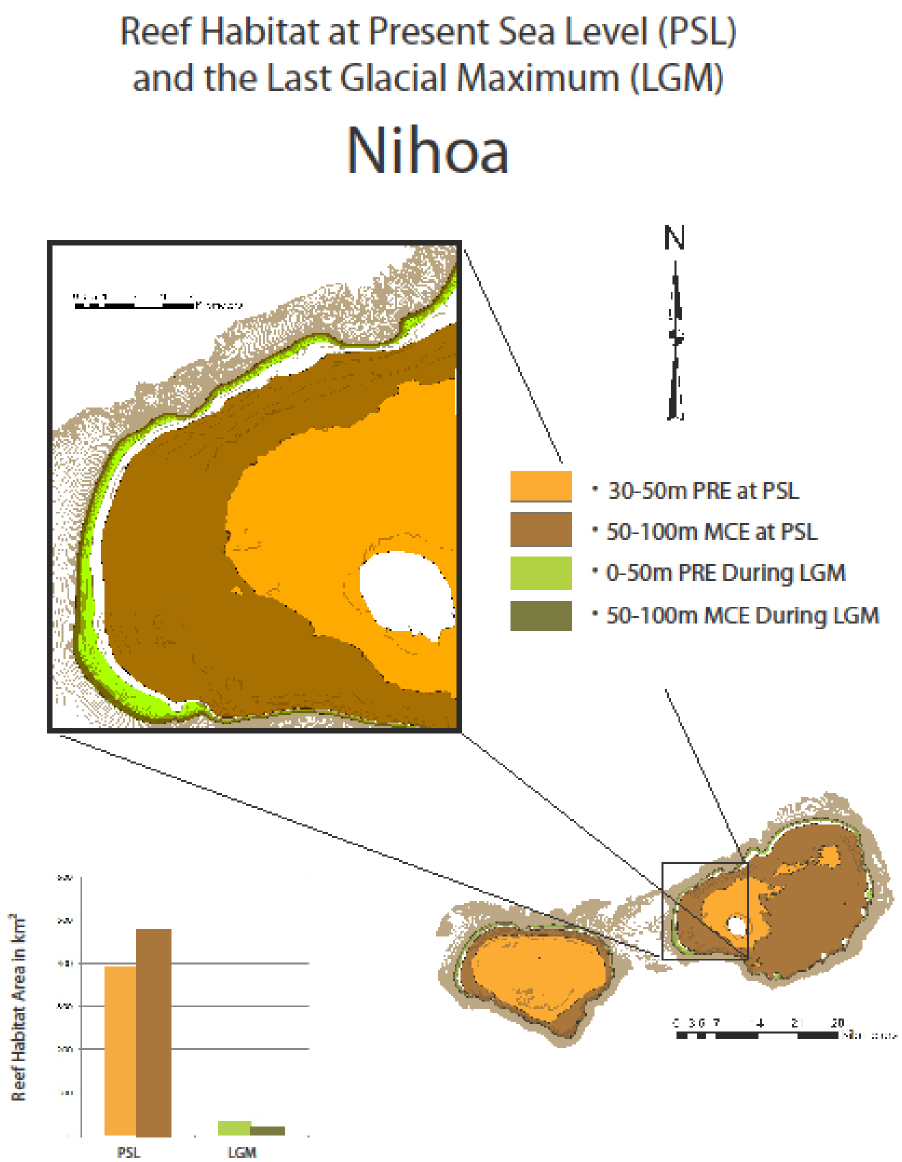



**Figure 4**: Nihoa is the closest atoll to the main Hawaiian Islands with a latitude and longitude of 23° 5'N, 161° 51'W (NOAA 2009). The spatial representation of the Photic Reef Ecosystem (PRE) and the Mesophotic Coral Ecosystem (MCE) for both the glacial maximum and the present sea level are shown on the same bathymetry contours in order to visually compare the differences in size. The 30-50m habitat is the area that was calculated with GIS and combined to the NOAA IKONOS area results from 0-30m. 0-50m PRE during LGM is the area at the maximum sea level decline of 120m. At both sea level heights the MCE is the next lower habitat.

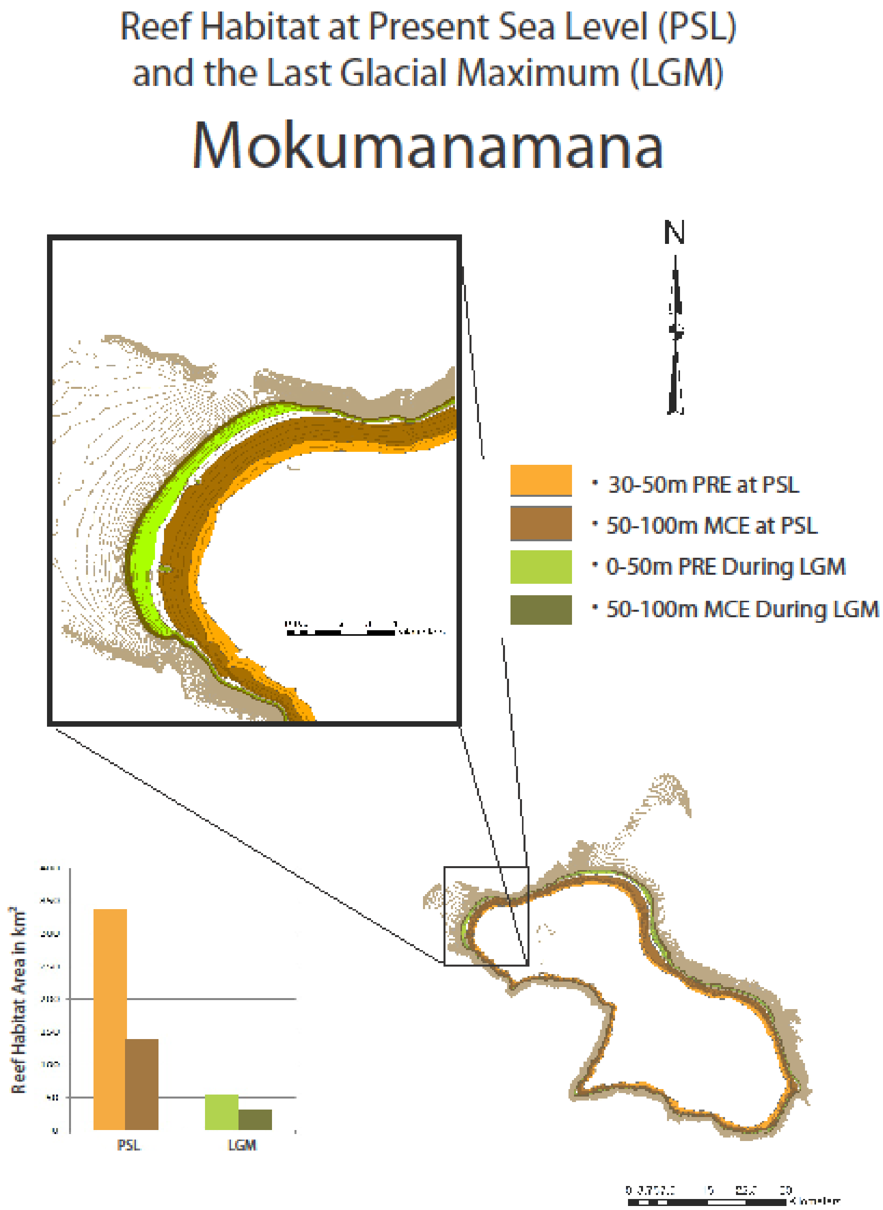



**Figure 5**: Mokumanamana has a latitude and longitude of 23° 27'N, 164° 31'W (NOAA 2009). The spatial representation of the Photic Reef Ecosystem (PRE) and the Mesophotic Coral Ecosystem (MCE) for both the glacial maximum and the present sea level are shown on the same bathymetry contours in order to visually compare the differences in size. The 30-50m habitat is the area that was calculated with GIS and combined to the NOAA IKONOS area results from 0-30m. 0-50m PRE during the LGM is the area at the maximum sea level decline of 120m. At both sea level heights the MCE is the next lower habitat.

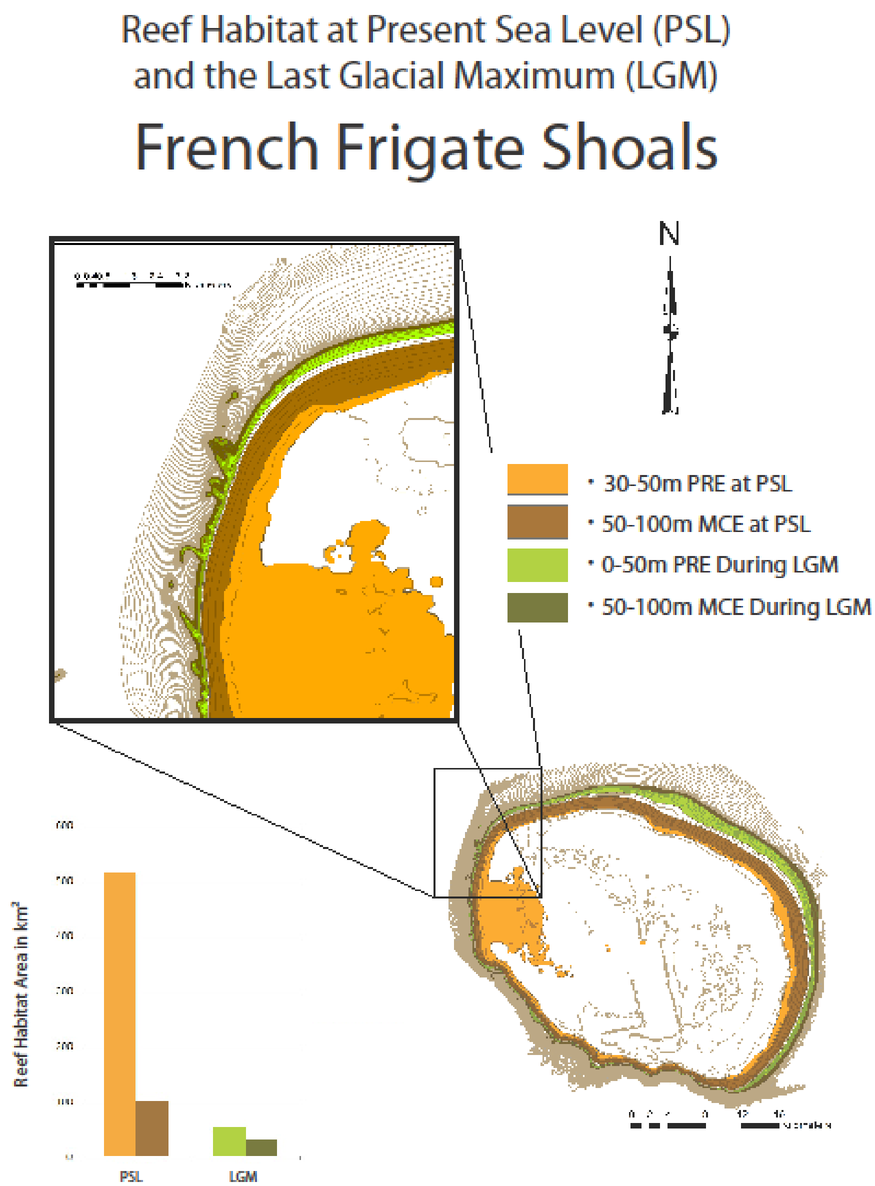



**Figure 6**: French Frigate Shoals has a latitude and longitude of 23° 46'N, 166° 12'W (NOAA 2009). The spatial representation of the Photic Reef Ecosystem (PRE) and the Mesophotic Coral Ecosystem (MCE) for both the glacial maximum and the present sea level are shown on the same bathymetry contours in order to visually compare the differences in size. The 30-50m habitat is the area that was calculated with GIS and combined to the NOAA IKONOS area results from 0-30m. 0-50m PRE during LGM is the area at the maximum sea level decline of 120m. At both sea level heights the MCE is the next lower habitat

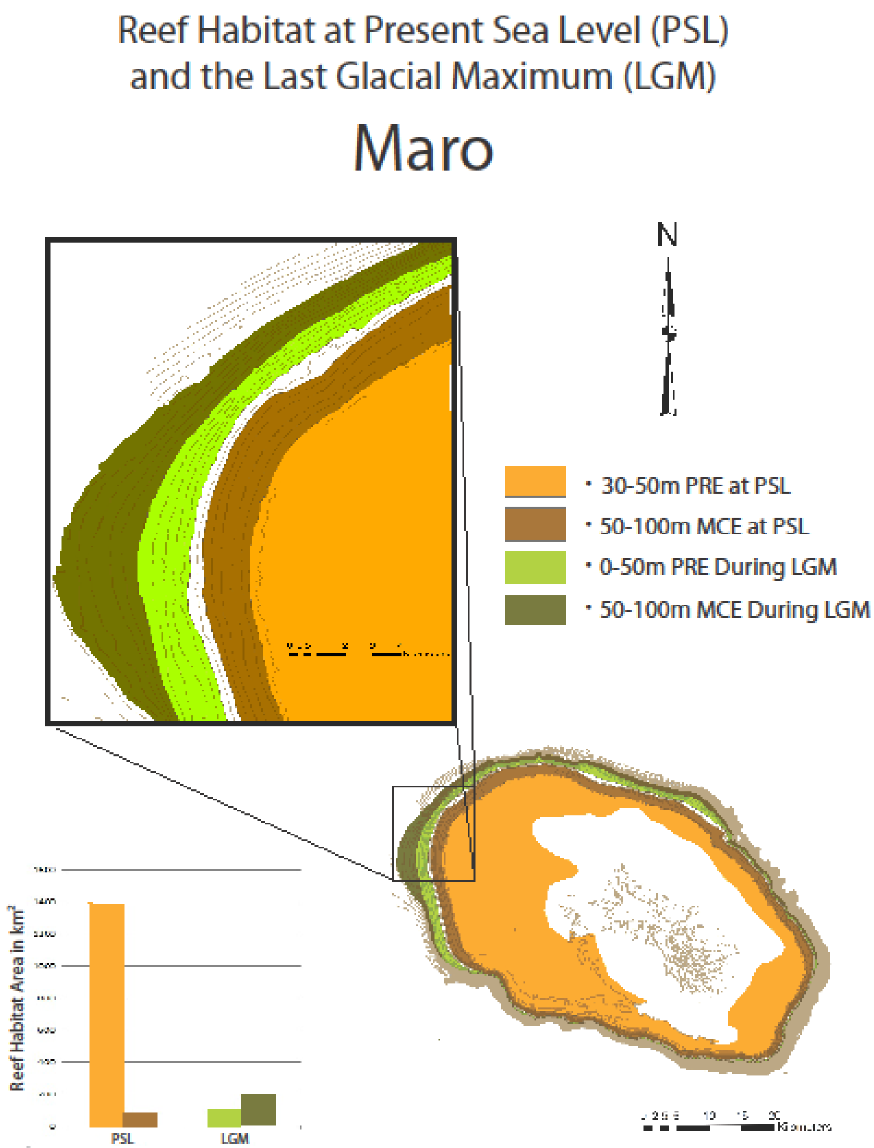



**Figure 7**: Maro Reef has a latitude and longitude of 25° 27'N, 170° 37'W (NOAA 2009). The spatial representation of the Photic Reef Ecosystem (PRE) and the Mesophotic Coral Ecosystem (MCE) for both the glacial maximum and the present sea level are shown on the same bathymetry contours in order to visually compare the differences in size. The 30-50m habitat is the area that was calculated with GIS and combined to the NOAA IKONOS area results from 0-30m. 0-50m PRE during LGM is the area at the maximum sea level decline of 120m. At both sea level heights the MCE is the next lower habitat.

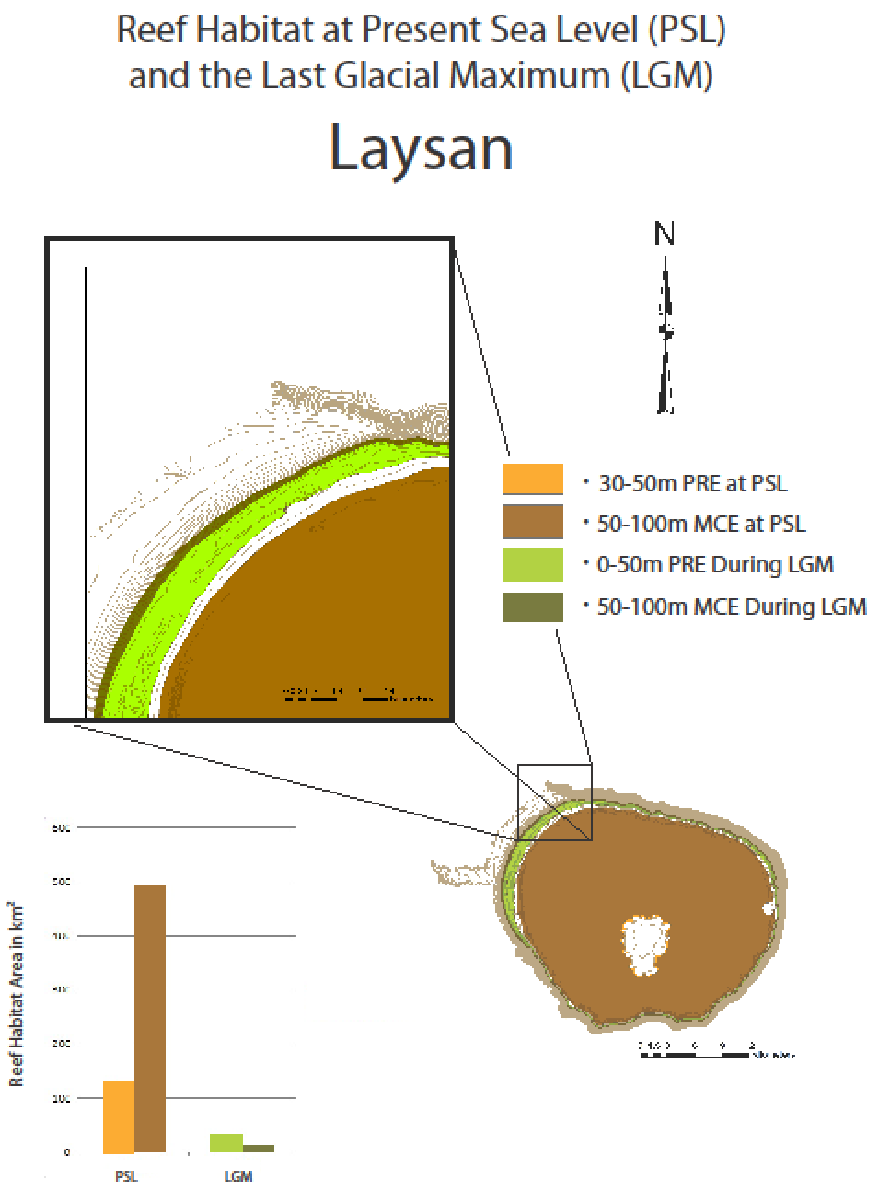



**Figure 8**: Laysan has a latitude and longitude of 25° 47'N, 171° 44'W (NOAA 2009). The spatial representation of the Photic Reef Ecosystem (PRE) and the Mesophotic Coral Ecosystem (MCE) for both the glacial maximum and the present sea level are shown on the same bathymetry contours in order to visually compare the differences in size. The 30-50m habitat is the area that was calculated with GIS and combined to the NOAA IKONOS area results from 0-30m. 0-50m PRE during LGM is the area at the maximum sea level decline of 120m. At both sea level heights the MCE is the next lower habitat.

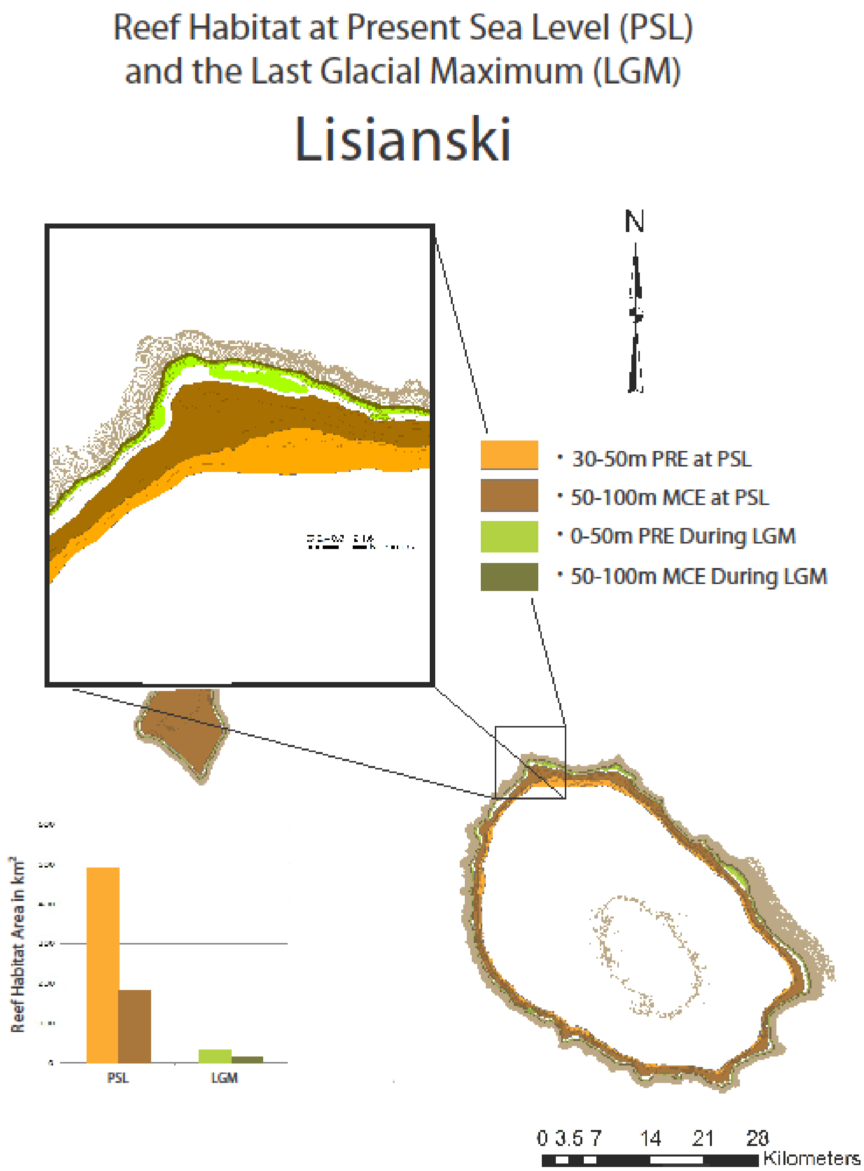



**Figure 9**: Lisianski has a latitude and longitude of 26° 3'N, 173° 58'W (NOAA 2009). The spatial representation of the Photic Reef Ecosystem (PRE) and the Mesophotic Coral Ecosystem (MCE) for both the glacial maximum and the present sea level are shown on the same bathymetry contours in order to visually compare the differences in size. The 30-50m habitat is the area that was calculated with GIS and combined to the NOAA IKONOS area results from 0-30m. 0-50m PRE during LGM is the area at the maximum sea level decline of 120m. At both sea level heights the MCE is the next lower habitat.

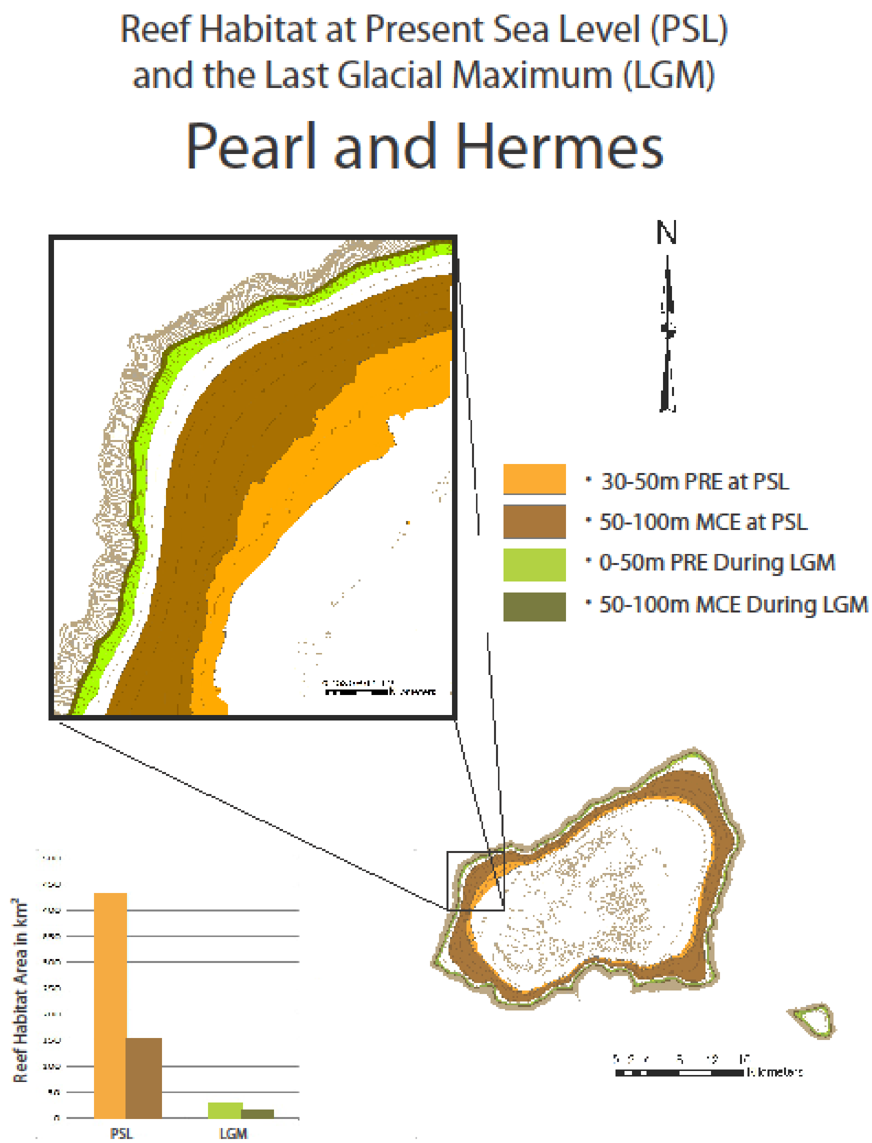



**Figure 10**: Pearl and Hermes has a latitude and longitude of 27° 51'N, 175° 51'W (NOAA 2009). The spatial representation of the Photic Reef Ecosystem (PRE) and the Mesophotic Coral Ecosystem (MCE) for both the glacial maximum and the present sea level are shown on the same bathymetry contours in order to visually compare the differences in size. The 30-50m habitat is the area that was calculated with GIS and combined to the NOAA IKONOS area results from 0-30m. 0-50m PRE during LGM is the area at the maximum sea level decline of 120m. At both sea level heights the MCE is the next lower habitat.

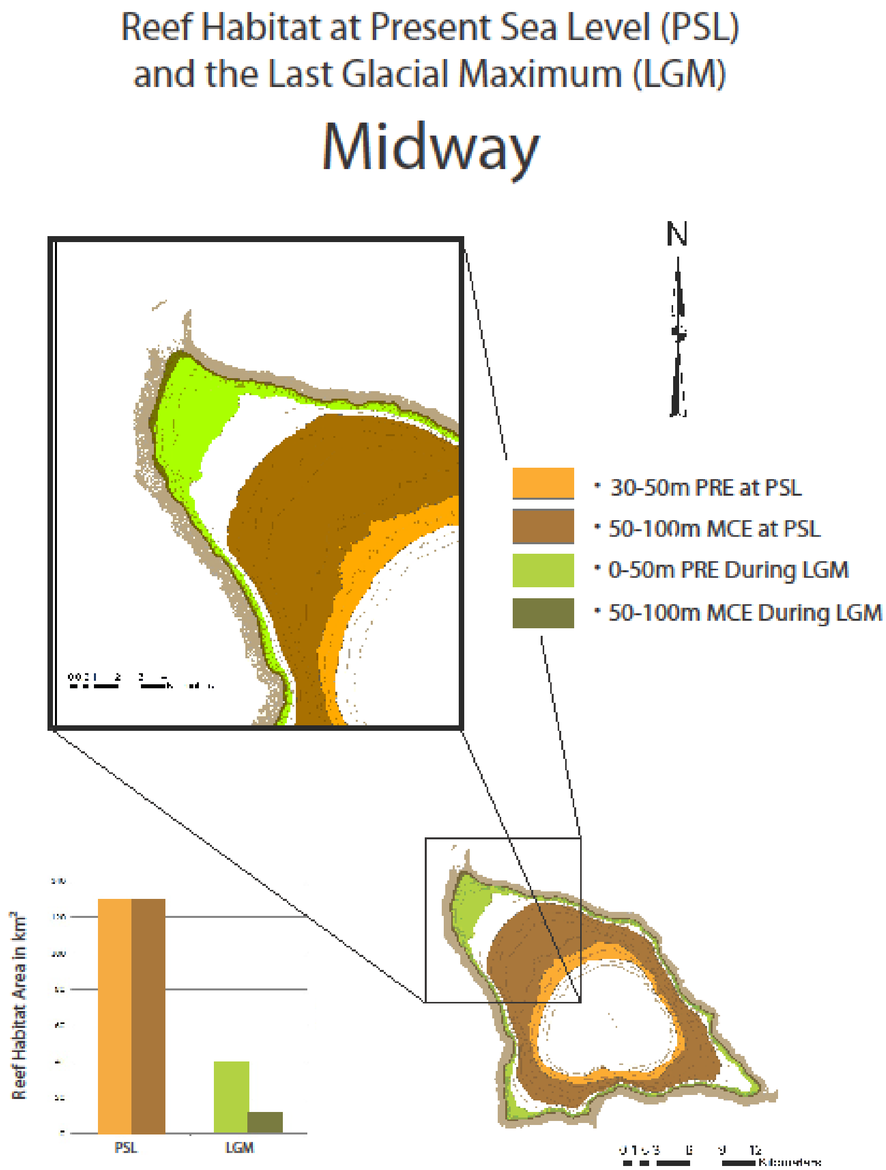



**Figure 11**: Historic Midway has a latitude and longitude of 28° 14'N, 177° 22'W (NOAA 2009). The spatial representation of the Photic Reef Ecosystem (PRE) and the Mesophotic Coral Ecosystem (MCE) for both the glacial maximum and the present sea level are shown on the same bathymetry contours in order to visually compare the differences in size. The 30-50m habitat is the area that was calculated with GIS and combined to the NOAA IKONOS area results from 0-30m. 0-50m PRE during LGM is the area at the maximum sea level decline of 120m. At both sea level heights the MCE is the next lower habitat.

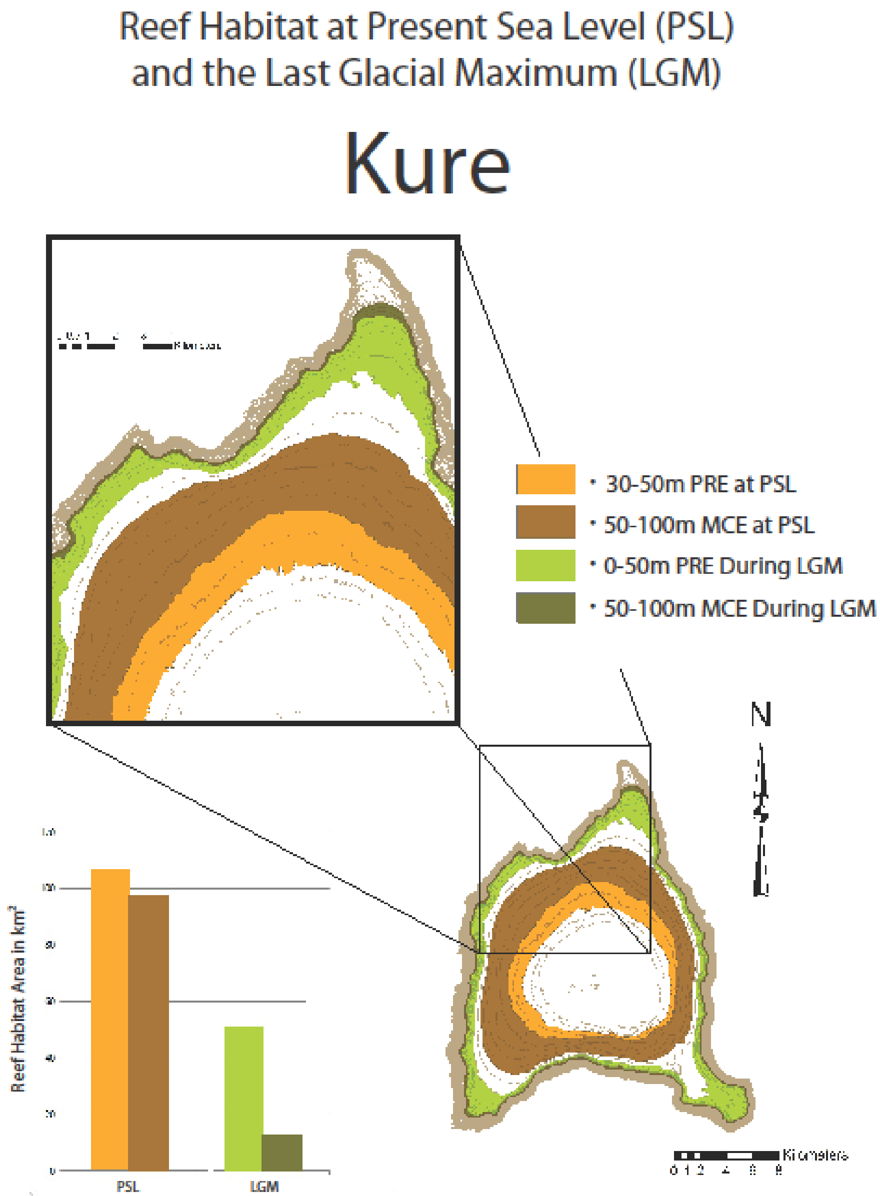



**Figure 12**: Kure is the furthest atoll in Papahanaumokuakea with a latitude and longitude of 28° 26'N, 178° 19'W (NOAA 2009). The spatial representation of the Photic Reef Ecosystem (PRE) and the Mesophotic Coral Ecosystem (MCE) for both the glacial maximum and the present sea level are shown on the same bathymetry contours in order to visually compare the differences in size. The 30-50m habitat is the area that was calculated with GIS and combined to the NOAA IKONOS area results from 0-30m. 0-50m PRE during LGM is the area at the maximum sea level decline of 120m. At both sea level heights the MCE is the next lower habitat.

| Sea Level Relative to Present in meters. | Photic Reef Ecosystem Area in km² |
|---|---|
| -120 | 39.84 |
| -110 | 61.11 |
| -100 | 72.10 |
| -90 | 81.43 |
| -80 | 94.29 |
| -70 | 104.31 |
| -60 | 125.26 |
| -50 | 129.03 |
| -40 | 128.98 |
| -30 | 123.87 |
| 0 | 129.44 |
| +5 | 121.11 |
| +10 | 112.78 |
| +15 | 103.14 |
| +20 | 95.5 |

**Figure 13:** The Sea Level Induced Habitat Change (SLIHC) curve is the habitat area in $km^2$ vs. Sea Level in meters. The Last Glacial Maximum (LGM) is to the left of the chart at -120m approximately 22 ka BP and the projected year of 2500 is at +5m (Yokoyama, Y. et al. 2001)(Jevrejeva S et al. 2011).

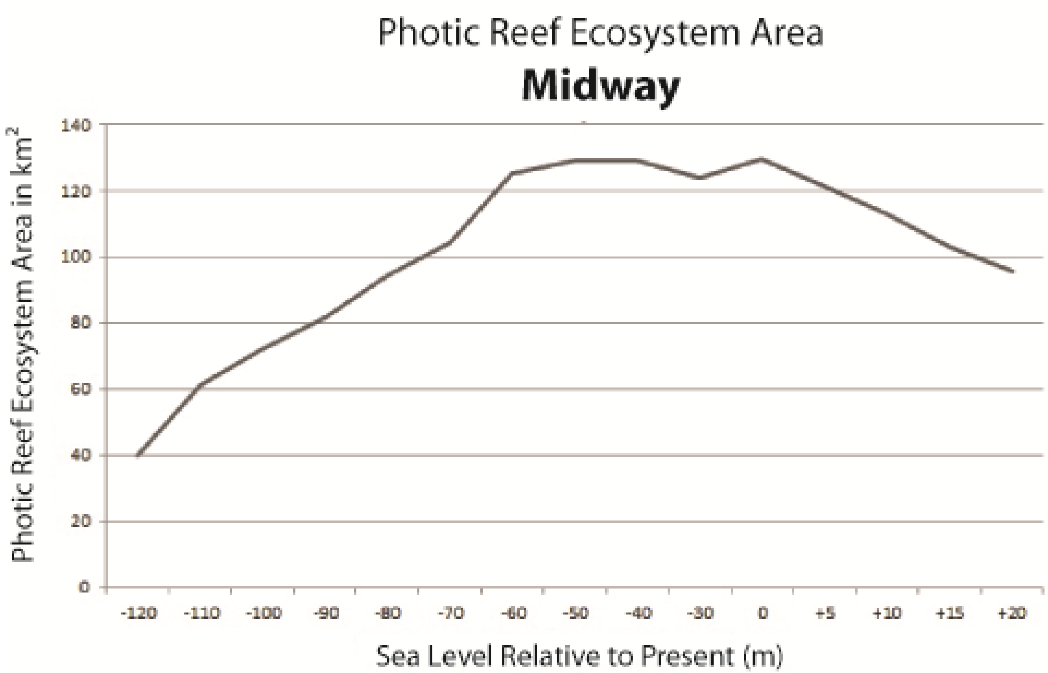
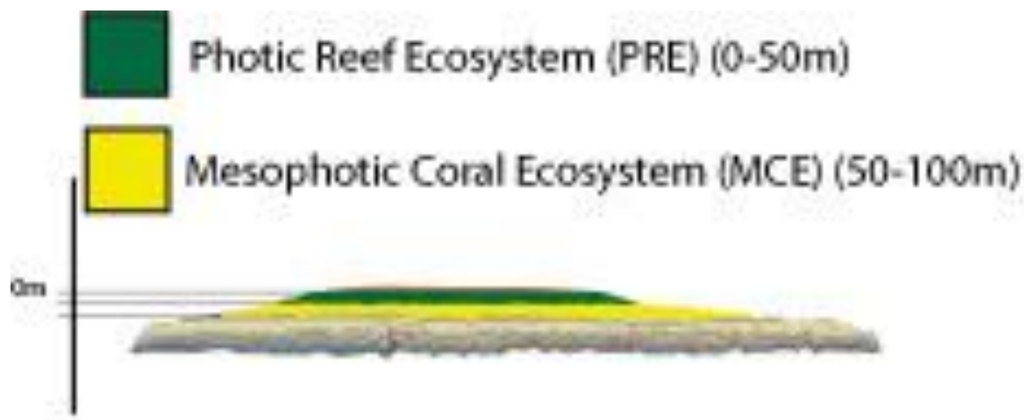


**Figure 14:** Elevation view of Midway atoll with the divisions of the PRE (0-50m) and the MCE (50-100m).



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