Future Climate Change, Sea-Level Rise, and Ocean Acidification:



Implications for Hawai‘i and Western Pacific Fisheries Management

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Summary

The culture, subsistence, and welfare of tropical Pacific Island Nation people are all in some way tied to their proximate fishery resources. Many of these fisheries are already under considerable stress and duress due to human practices such as overfishing, pollution and runoff, habitat destruction and degradation, lack of proper management protocols, and coastal and global population pressures. Other human activities such as fossil fuel use, deforestation and changes in land use and consequent emissions of gases and particulates, such as carbon dioxide, sulfur dioxide, methane, etc., to the atmosphere are contributing to alteration of the global climate by a general overall warming of the planetary atmosphere. The warming of the overlying atmosphere in turn warms the underlying surface ocean. In addition to the surface ocean warming, there is also the problem of ocean acidification owing to absorption of anthropogenic carbon dioxide by the surface waters of the ocean. This input of atmospheric carbon dioxide into the surface ocean reduces the surface water pH, which is detrimental to calcifying organisms such as those that are integral to coral reefs or the planktonic calcareous coccolithophoridae and foraminifera. Climate change and ocean acidification both have the capacity to impact simultaneously all organism trophic levels and so the possible negative ramifications can and should not be underestimated. Because profound changes are needed to scale back greenhouse gas emission levels, such as carbon dioxide, to levels of even a few decades ago, it seems that for the short- and medium-term, the optimal approach to mitigating the harmful impacts of ocean warming and acidification on fisheries is to minimize the other human-related pressures on fishery resources, such as excess nutrient and suspended riverine loads to coastal ecosystems due to human activities on land. This results in the fisheries being as robust, healthy, and resilient as possible allowing them to better withstand the present and impending negative effects of short- and medium-term global change, while solutions for long-term control and reductions in atmospheric carbon dioxide and other greenhouse gas fluxes can be implemented and enforced.

We are just beginning to scratch the surface on our understanding of how the impending future warming and acidification of the surface ocean will negatively impact the recruitment, physiology, population dynamics, and ecology of various tropical-related fisheries along with the larger marine ecosystem. The purpose of this case study is to provide a brief overview of these issues by reviewing a wide range of related topics such as the economics of fisheries, the science of climate change and ocean acidification, how future climate change and ocean acidification may impact tropical marine fisheries, how global and coastal populations and future population growth place pressures on the fishery resource, importance of fisheries as a global food and protein source, etc. While this case study touches on a broad and diverse range of topics at the undergraduate level, it is not meant to be a definitive review of all these topics. At the end of each chapter, a short list of suggested readings is provided for those interested in further exploring the subject material.

I. Fisheries, Population, and Climate Change

A. Introduction

Local, coastal, and regional fisheries have played and continue to play an important role in Pacific Island communities. The local and regional fisheries serve as economic and dietary resources and embody cultural significance to local populations and endemic peoples of these island communities. Furthermore, the fishery environments (e.g., nearshore region, coral reefs, embayments, etc.) also serve as locations of recreation and leisure for the local population and can also attract tourism. Climate change and the accompanying sea level and temperature rise and ocean acidification will impact pelagic Pacific Ocean fisheries as well as nearshore coral reefs and associated reef fisheries. Some fishery and protected species resources likely to be affected by climate change first include both Solomon and Marshall Islands surface water tuna fisheries (e.g., skipjack) whose distribution and location are determined by the Western Pacific Warm Pool location and marine turtles and Hawaiian monk seals that depend on low-lying islands and temporally variant sand spits for habitat and breeding. The 2007 Intergovernmental Panel on Climate Change (IPCC) report states that for the next few centuries continued warming of the climate system is unequivocal, even if emissions of greenhouse gases are stabilized and that global sea level will continue to rise. Furthermore, as atmospheric CO_2 concentrations continue to increase due to anthropogenic emissions (e.g., from deforestation, fossil fuel burning, agriculture, cement production, etc.), the surface layer of the ocean will continue to absorb CO_2 from the atmosphere and become more acidic. The scope and effect of climate change impacts not just one or two species here and there, but rather entire ecosystems. This suggests that even if species (e.g., tuna) are the management focus and interest that ecosystem-based management approaches that are flexible to take into account how ecosystems and habitats shift with climate change are probably necessary to obtain favorable outcomes. Fortunately, the history and cultures of Pacific island communities are replete with holistic approaches to resource management that will serve them well as they adjust to the impending changes.

B. Fisheries as a resource

1. Global Fishery Production

Apart from bacteria, about 1% of the world's living biomass (as phytoplankton, zooplankton, fish, etc.) is contained in the oceans. At present, humans only harvest 0.2% of marine production. Fisheries can be generally categorized as (1) inland and (2) marine. Within these two categories, there are wild natural stocks and human manipulated aquaculture stocks. We will use data from the Food and Agriculture Organization of the United Nations (FAO) to frame discussion on global and regional fishery production. In 2009, the world's fisheries (inland and marine, wild and aquaculture) supplied approximately 117.8 million tonnes of food fish or a yearly per capita supply (using a population of 6.8 billion) of 17.2 kg (Table 1-1). Global capture fisheries production in 2008 was about 90 million tonnes representing a sale value of $US93.9 billion with 80 million tonnes from marine waters and 10 million tonnes from inland waters. To keep up with growing world demand for fish protein, aquaculture continues to be the fastest growing animal-food-producing sector. Aquaculture production in 2008 was near 52.5 million tonnes with a value of close to $US98.4 billion. World aquaculture production is heavily dominated by the Asia-Pacific region, which produces 89% of the total aquaculture production quantity and 79% of global value. This dominance is mainly due to China's role as a major aquaculture producer with 62% of the global production quantity and 51% of the global value. In Asia, about 1 billion people rely on fish as their primary source of protein. In 2008, 44.9 million people worldwide were directly engaged in the primary production of fish either in capture from the wild or in aquaculture. Furthermore, the entire fishing industry employs 180 million people worldwide. Ninety nine percent of the worldwide annual commercial ocean catch comes from coastal waters within 200 nautical miles of the coastline. These narrow coastal fringes are both the most productive and the most vulnerable.

Table 1-1. FAO World Fisheries and Aquaculture Production and Utilization including China in millions of metric tonnes. Reprinted from The State of World Fisheries and Aquaculture 2010. Table 1. 120pp. Permission from Food and Agriculture Organization of the United Nations.

World fisheries and aquaculture production and utilization

	2004	2005	2006	2007	2008	2009
			(Million tonnes)			
PRODUCTION						
INLAND						
Capture	8.6	9.4	9.8	10.0	10.2	10.1
Aquaculture	25.2	26.8	28.7	30.7	32.9	35.0
Total inland	33.8	36.2	38.5	40.6	43.1	45.1
MARINE						
Capture	83.8	82.7	80.0	79.9	79.5	79.9
Aquaculture	16.7	17.5	18.6	19.2	19.7	20.1
Total marine	100.5	100.1	98.6	99.2	99.2	100.0
TOTAL CAPTURE	92.4	92.1	89.7	89.9	89.7	90.0
TOTAL AQUACULTURE	41.9	44.3	47.4	49.9	52.5	55.1
TOTAL WORLD FISHERIES	134.3	136.4	137.1	139.8	142.3	145.1
UTILIZATION						
Human consumption	104.4	107.3	110.7	112.7	115.1	117.8
Non-food uses	29.8	29.1	26.3	27.1	27.2	27.3
Population (*billions*)	6.4	6.5	6.6	6.7	6.8	6.8
Per capita food fish supply (*kg*)	16.2	16.5	16.8	16.9	17.1	17.2

Note: Excluding aquatic plants. Data for 2009 are provisional estimates.

2. Exploitation of the Global Fish Resource

Many of the fisheries of the world have been overexploited to varying degrees. The proportion of overexploited, depleted, and recovering stocks have remained relatively stable for the past 10 to 15 years after the dramatic increase in fishing observed during the 1970's and 1980's. In 2008, 28% of all stocks were overexploited, depleted (3%), or recovering from depletion (1%). Fifty three percent of all stocks were fully exploited and only 15% of the global fishing stocks were moderately or under exploited (Table 1-2). Most of the top ten species, which in total account for 30% of the global marine capture production, are either fully or overexploited. Overall, more than 80% of the 523 selected world fish stocks for which data are available are reported to be either fully exploited, overexploited, depleted, or recovering from depletion.

The locations with the highest percentage of fully exploited stocks (71 to 80%) are the Northeast Atlantic, Western Indian Ocean, and Northwest Pacific (Figure 1-1). Relatively high proportions (20% or more) of under exploited or moderately exploited stocks can be found in the Eastern Indian Ocean, Western Central Pacific, Eastern Central Pacific, Southwest Pacific, and Southern Ocean. Figure 1-2 shows the capture fisheries production for principal marine fishing areas around the globe.

Table 1-2. Global fishery stocks and fishing pressure for 2008 as determined by FAO. Data from The State of World Fisheries and Aquaculture 2010. 120pp. Food and Agriculture Organization of the United Nations.

Fishing Pressure	% of Fishery stocks
Overexploited	28
Depleted	3
Recovering from depletion	1
Fully Exploited	53
Moderately or under exploited	15

Table 1-3. Growth in per capita world fish consumption (in kilograms). Data from The State of World Fisheries and Aquaculture 2010. 120pp. Food and Agriculture Organization of the United Nations.

Decade	kg per capita
1960s	9.9
1970s	11.5
1980s	12.5
1990s	14.4

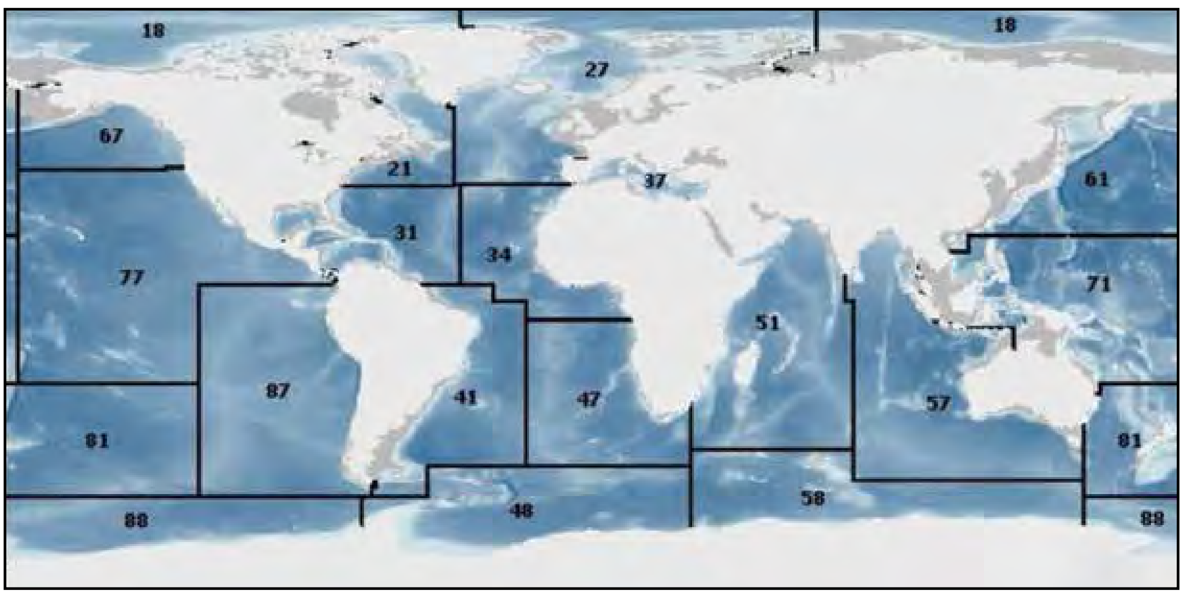

Figure 1-1. FAO defined geographical fishing areas. Area 77 (Eastern Central Pacific) includes Hawai'i and Area 71 (Western Central Pacific) includes many Western Pacific Island Nations.

3. Fish Consumption and Protein Source

During the past four decades, per capita fish consumption has increased with increasing demand for high quality protein from 9.9 kg in the 1960s to 11.5 kg in the 1970s, 12.5 kg in the 1980s, 14.4 kg in the 1990s and reaching 17.0 kg in 2007 (Table 1-3). In 2009, 117.8 million tonnes or more than 75% (Table 1-1) of world fish production was used for direct human consumption. The remaining 27.3 million tonnes of world fish production were used for non-food products such as fishmeal and fish oil. For human

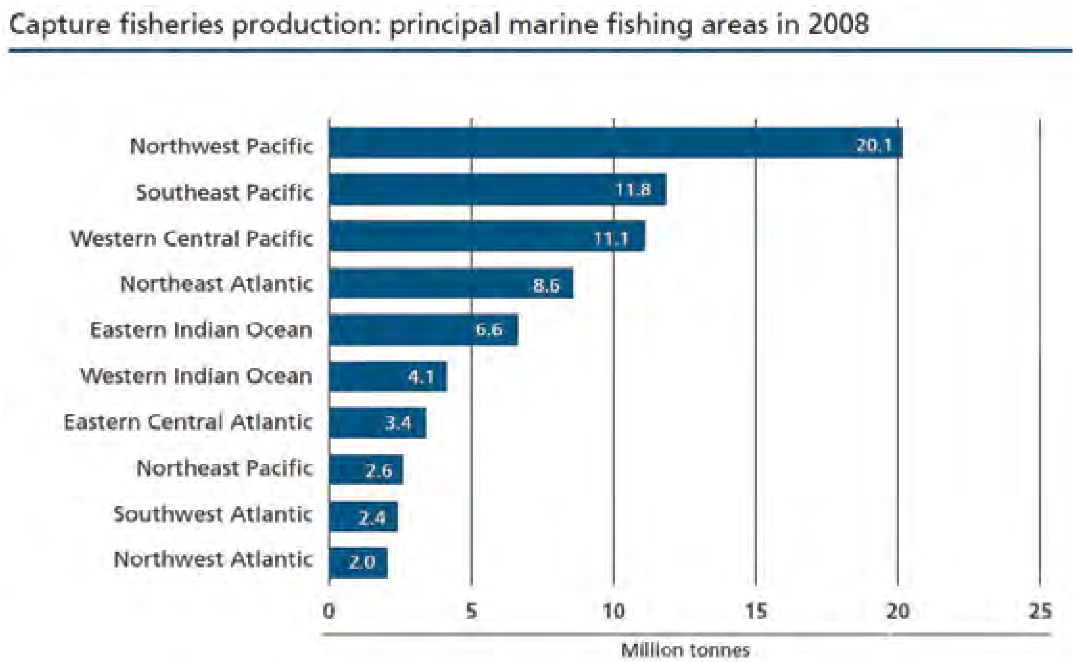

Figure 1-2. 2008 capture fisheries production (in millions of metric tonnes) based on geographical area as defined by the FAO in Figure 1-1. Reprinted from The State of World Fisheries and Aquaculture 2010. Figure 5. 120pp. Permission from Food and Agriculture Organization of the United Nations.

consumption, 49% was consumed live and in fresh form and the remaining 51% underwent some form of processing (e.g., freezing, canning, curing, etc.). On average, approximately 15.7% of per capita animal protein eaten by humans is from fish and another 5% of per capita protein comes indirectly via fish feed used to grow livestock. It is estimated for some small island nations that fish protein provides at least 50% of the total animal protein intake and 60% of global fish consumption is by the developing world's population. Figure 1-3 shows the average contribution of fish to animal protein supply from 2005 to 2007.

4. Central and Western Pacific Island Nations and Hawai'i

The Western Central Pacific geographic area as defined by the FAO is the third most productive fishing area of all regions making up 14% of the global marine catch with 11.1 million tonnes (Table 1-4). Tunas and tuna-like species make up about 24% of the total for this fishing area, with most species assessed as either fully exploited or moderately to fully exploited (Figure 1-4). The status of other species groups is highly uncertain. This region is highly diverse, its fisheries are mostly multispecies, and detailed data for reliable assessments are usually not available for most stocks. Analysis of survey information for some countries in the region (e.g., Malaysia, the Philippines, Thailand and Viet Nam) has shown considerable degradation and overfishing of coastal stocks, most dramatically in the Gulf of Thailand and along the east coast of Malaysia.

In contrast, Hawai'i's commercial fishing impact is relatively small compared to the FAO geographically defined area of the Western Central Pacific. In 2010, 29 million pounds, or 13,154 tonnes, of fish were caught by commercial fishermen in Hawai'i, which is three orders of magnitude less than the catch of the Western Central Pacific. The distribution of catch for 2007, 2008, and 2009 is shown in Table 1-5. Tunas, at 14.5 million pounds or almost 6,600 metric tonnes, make up 50% of the catch with billfish (i.e., marlin, swordfish, and spearfish) the next largest catch at 5.9 million pounds or 2,671 metric tonnes.

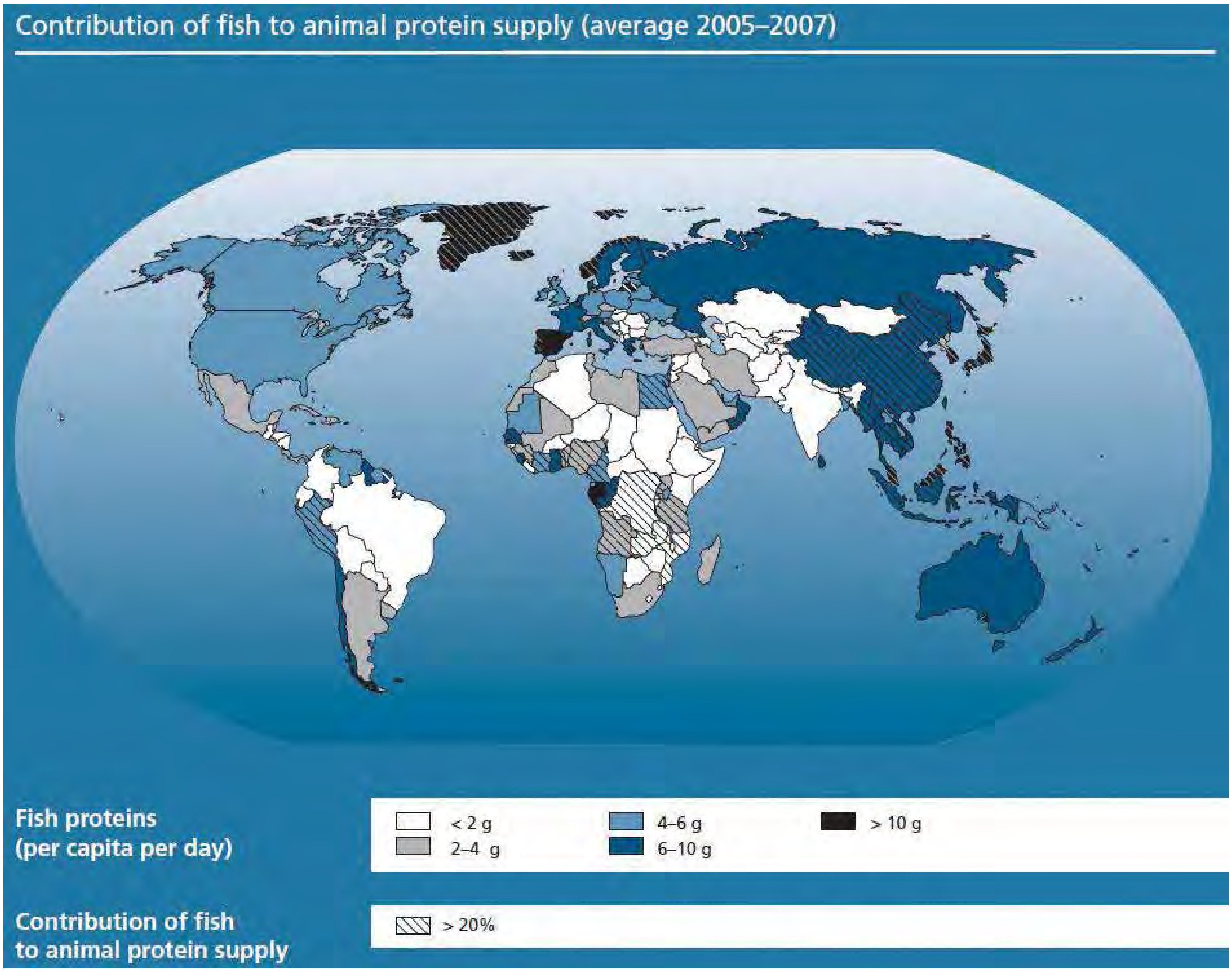

Figure 1-3. 2005 to 2007 Average Contribution of Fish to Animal Protein Supply. Reprinted from The State of World Fisheries and Aquaculture 2010. Figure 33. 120pp. Permission from Food and Agriculture Organization of the United Nations.

T*able 1-4. FAO geographic production of global marine catch (in millions of metric tonnes) from the top four regions. Data from The State of World Fisheries and Aquaculture 2010. 120pp. Food and Agriculture Organization of the United Nations.*

Location	Million Tonnes Catch	% of global marine catch
Northwest Pacific	20.1	25
Southeast Pacific	11.8	15
Western Central Pacific	11.1	14
Northeast Atlantic	8.5	11

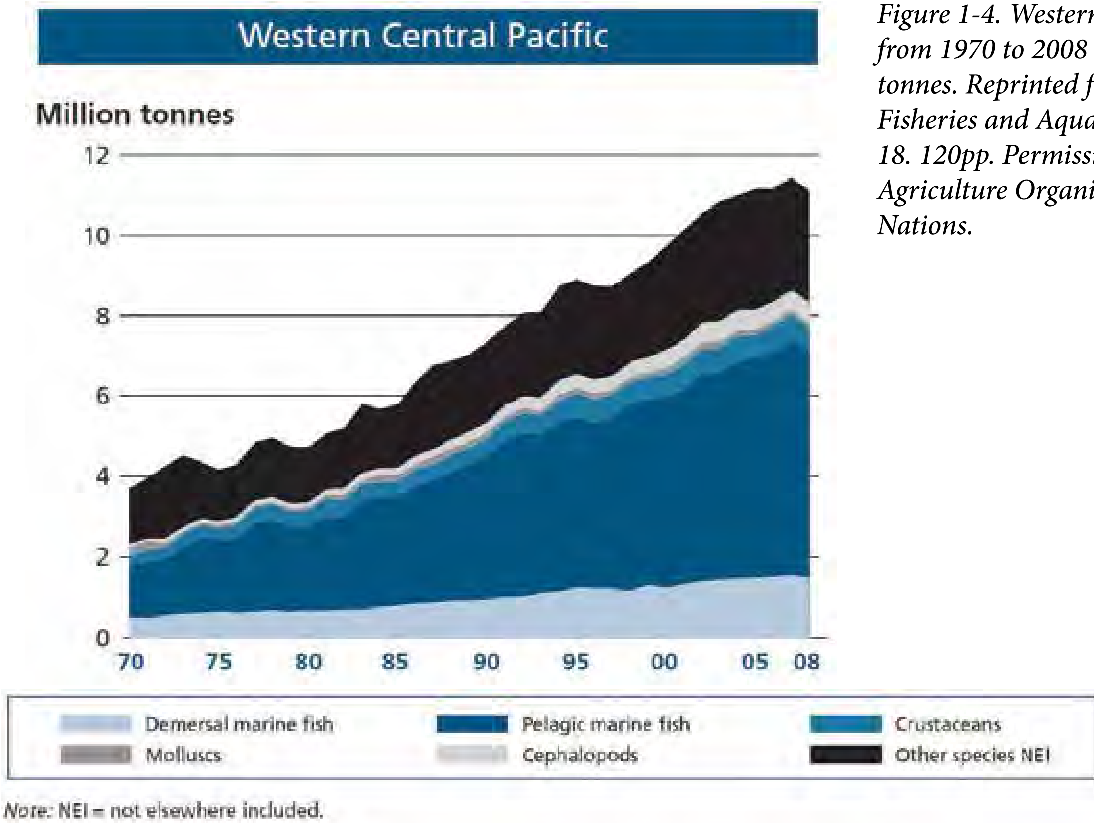

Figure 1-4. Western Central Pacific Catch from 1970 to 2008 in millions of metric tonnes. Reprinted from The State of World Fisheries and Aquaculture 2010. Figure 18. 120pp. Permission from Food and Agriculture Organization of the United Nations.

Species	2007	2008	2009
Total catch	26,563,127	33,310,542	26,527,158
Tunas	14,613,016	19,985,859	14,490,191
Aku (skipjack)	1,207,357	636,190	1,029,206
Tombo	620,324	1,014,455	452,609
Bigeye (ahi)	10,064,751	14,199,122	10,301,173
Yellowfin (ahi)	2,701,159	4,120,986	2,686,042
Billfishes	5,649,300	5,989,668	5,889,153
Blue marlin	913,889	787,524	1,122,715
Shortnose spearfish	239,763	577,794	244,129
Striped marlin	1,147,064	820,105	681,391
Swordfish	3,318,223	3,771,529	3,818,151
Miscellaneous pelagic species	4,088,145	5,240,266	4,269,125
Mahimahi	1,162,164	1,791,321	933,087
Monchong	548,693	659,001	646,282
Ono	816,292	992,558	709,195
Opah	1,134,802	1,283,863	1,513,867
Walu	399,729	481,862	444,514
Deep bottom fishes	474,387	439,182	489,974
Ehu	25,038	23,089	27,206
Hapuupuu	29,680	24,060	23,345
Opakapaka	116,966	112,136	146,083
Uku	151,778	157,147	124,517
Ulaula (onaga)	121,272	82,476	85,356
Akule/opelu	1,034,554	792,269	622,401
Akule	678,621	489,538	316,505
Opelu	355,933	302,731	305,877
Jacks	50,526	53,012	43,443
Inshore fishes	305,484	324,841	303,484
Sharks	266,860	374,942	293,649
Mako	191,951	273,945	222,946
Lobsters	8,838	9,059	18,385
Crabs	31,492	47,893	43,142
Shrimps	1/	1/	1/
Seaweeds	5,072	10,021	7,677
Unclassified / miscellaneous	35,453	43,530	56,534

Table 1-5. Commercial fish catch (in millions of pounds) by species from 2007 to 2009 for the State of Hawai'i. Reprinted from Hawai'i State Department of Land and Natural Resources, Division of Aquatic Resources, Commercial Fish Landings, State of Hawai'i- Fiscal Years 2007-2009 and records. Retrieved on 8 November 2010 (http://hawaii.gov/dbedt/info/economic/databook/2009-individual/20/200509.pdf).

C. Population Pressures

1. Global Population

Demography is the study of population and the causes for changes in its size and distribution. Estimates for world population around the Agricultural Revolution about 10,000 years ago are between 250,000 and 5 million (Figure 1-5). At the time of Christ, the world population was probably about 200 million people and by 1650 A.D. 500 million. It was not until 1850, that the world's population reached 1 billion. Eighty years later, 1930, the world's population had doubled again to 2 billion. 45 years later, 1975, the population had doubled again to 4 billion. By 1987, the world population reached 5 billion. Presently, the world population is estimated at 7 billion. The future of the world's populations is difficult to project because it is a function of a variety of factors such as future fertility and mortality rates that are tough to predict. Figure 1-6 depicts past and present populations of the underdeveloped, developed, and total world and their future growth based upon current best population growth projections.

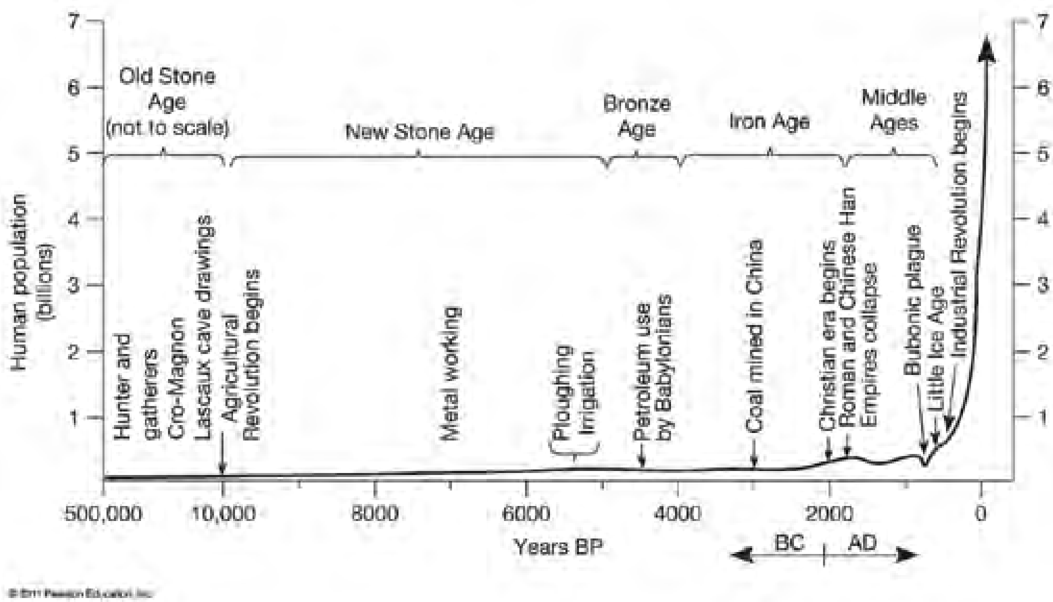

Figure 1-5. Growth of the world population over the past 500,000 years.

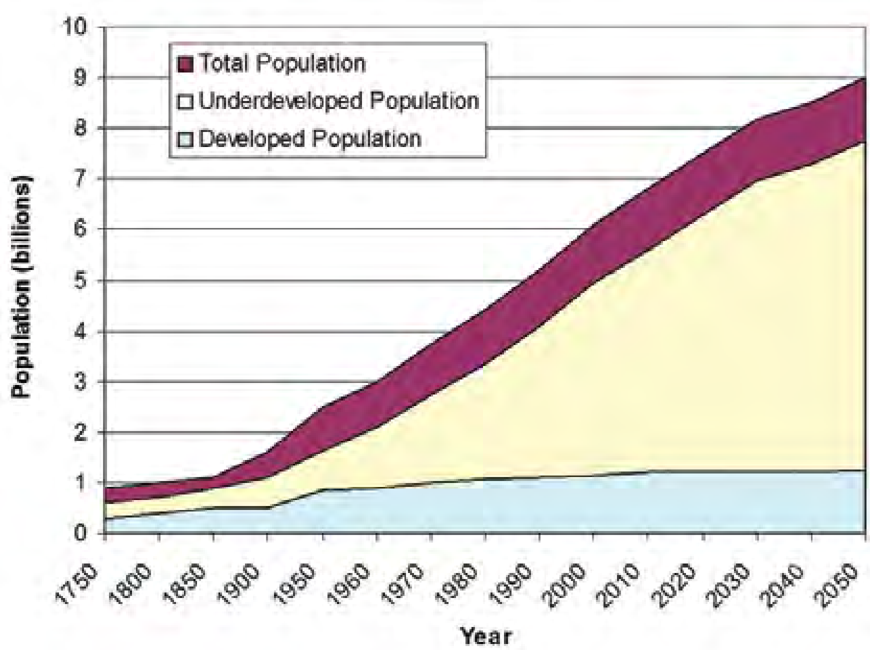

Figure 1-6. Past, Present, and Future Undeveloped, Developed, and Total World Population.

The growth rate of the world's population peaked in the late 1960s and early 1970s above 2.0% per year and has since fallen to presently around 1.2% per year. The doubling time of human population is an example of exponential growth. Exponential growth at a constant growth rate (r) can be described by the following relationship:

$$N_{(t)} = N_{(0)}e^{rt}. \qquad (1)$$

$N_{(t)}$ is the number of people at time (t), $N_{(0)}$ is the number of people at some starting time = 0, *t* is time, and *e* is the natural logarithm with the value of 2.718. In a population experiencing exponential growth, the doubling time can be calculated by:

$$N_{(t)} / N_{(0)} = 2 = e^{rt}. \qquad (2)$$

Taking the natural logarithm of both sides gives:

$$0.69 = rt \quad \text{or} \quad t = 0.69\ (1/r) \qquad (3)$$

where t is the doubling time in years and r is the population growth rate. So for example, at the present and constant growth rate of the world's population of 1.2% per year, the time to double is:

$$t = 0.69 / (0.012) = 57.5 \text{ years.} \qquad (4)$$

The projected increase in world population will be distributed unevenly among the world's nations. The more affluent countries are generally experiencing slow rates of population growth, whereas the less affluent poorer nations are experiencing the greatest gains in population (Figure 1-6). What about the population trends for Hawaiʻi and Western Pacific island nations?

2. Central and Western Pacific Island Nations and Hawaiʻi

As mentioned in the previous section, population growth rates can vary from country to country, especially with respect to affluence level. Although world population is presently growing annually at 1.2%, is that the case for Hawaiʻi and Western Pacific Island nations? Figure 1-7 shows the most recent population growth rates for some western Pacific Island nations. Hawaiʻi's most recent estimate of population growth, from 2009, is 0.6 % and is less than the population growth rates of the western Pacific Island nations shown in Figure 1-7. For example, if American Samoa's future population growth rate stays constant at 2.3%, then the population will double in 30 years. In comparison, at a present growth rate of 1.2% the global population will double in 57 years. This suggests that local population growth and subsequent increased calorie needs will increase fishing pressure on local marine resources (e.g., local reef and pelagic fish populations, etc.).

D. Climate Change Future

Climate change will impact fishery populations through a variety of direct and indirect pathways that operate on different temporal and spatial scales. Table 1-6 reviews how climate interactions with the environment affect fish populations. In addition to pelagic fisheries, climate change can also impact coral reefs, which are important as they serve as the habitat and structure for coastal reef fisheries and ecosystems.

Global sea surface temperatures, surface ocean pH, sea level, storm frequency, etc. are all expected to be impacted by the processes that drive global climate change. In turn, changes in these ocean properties can all have negative impacts on fisheries. As one example, a decrease in surface ocean pH due to ocean acidification processes can negatively impact the health of coral reefs and the associated fisheries. Decreasing pH can result in a deterioration of the calcareous organisms (corals, algae, etc.) and thus coral fishery habitat. pH changes can also lead to shifts in the distribution and selection of dominant reef building species abundance (e.g., shift from coral polyps to coralline algae). Climate change-driven species redistributions are also a possibility with redistribution of many pelagic species more towards the poles and away from the tropics with the future warming of global sea surface temperatures. The abundance of cod in the North Sea may decrease by 20% and there may be a 50% reduction in U.S. east coast cod population by 2050. These are just a few examples of how future climate change can impact fishery populations.

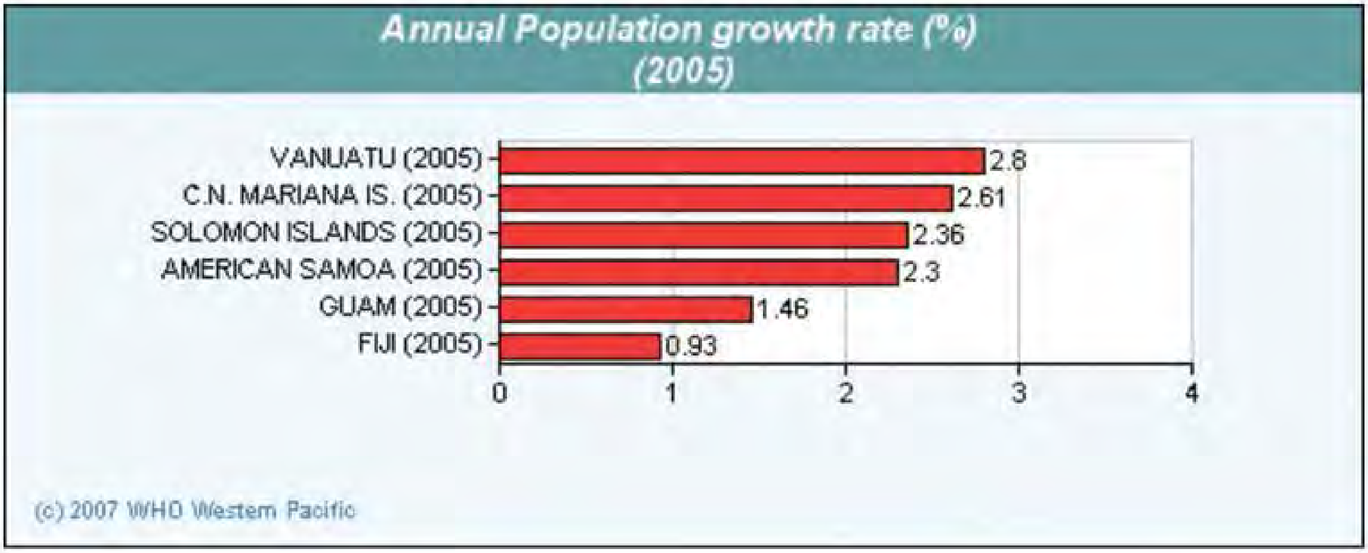

Figure 1-7. World Health Organization population growth rates for some Western Pacific Island Nations. Note that the growth rates are for 2005.

Table 1-6. Different ways in which climate affects fish populations. Reprinted from Journal of Marine Systems, 79, Ottersen, G., Suam, K., Huse, G., Polovina, J.J., and Stenseth, N.C., Major pathways by which climate may force marine fish populations, 343-360, 2010, with permission from Elsevier.

Process	Physical features	Biological feature	Species
Spawning and reproduction	Temperature	Age of sexual maturity	Atlantic cod
	Temperature	Time of spawning	Atlantic cod, capelin
	Temperature	Egg and larval size at hatch	Atlantic cod, Atlantic mackerel
	Temperature	Egg incubation time	Atlantic cod
	Small-scale turbulence	Larval feeding rates	Atlantic cod, Atlantic herring
Abundance and recruitment	Temperature	Larval feeding success, reduced predation risk	Norwegian spring-spawning herring, Atlantic cod, bluefin tuna, Atlantic salmon
	NAO	Not given	Eastern bluefin tuna, Northern Albacore tuna
	Upwelling	Primary production	Sardine
	Wind direction, advection	Larval retention on shelf, larval feeding success	Atlantic cod
	Entrainment of shelf waters by Gulf Stream rings	Transport of eggs and larvae off the shelf	Many groundfish stocks
Growth	Ambient temperature	Physiological processes (feeding, assimilation, metabolism, transformation, and excretion)	General feature
	Temperature	Length of feeding season	General feature
	Temperature	Food availability	Atlantic cod, capelin
Distribution and migration	Temperature		Habitat range
	Temperature	Migrational cue	Atlantic mackerel, Atlantic shad, Atlantic herring, Atlantic cod, Atlantic salmon
Natural mortality	Temperature (too low)		Sole, Atlantic cod, tilefish
	Temperature (too high)		Atlantic cod (larvae)
Catchability and availability	Temperature	Swimming speed	Atlantic cod

1. Global Climate Change

For more than 20 years, the IPCC has provided assessments of climate change including the causes of climate change, impacts and vulnerability, and response strategies. In its latest assessment report (2007), the IPCC projects the following impacts of global climate change by the end of this century (Table 1-7). It is apparent that globally we will be experiencing elevated temperatures and sea levels. In addition, the level of greenhouse gases such as carbon dioxide will continue to rise. Carbon dioxide not only has a climate warming impact, but also influences ocean chemistry through ocean acidification. Thus we can also expect that global ocean acidification (i.e., lowering of the surface ocean pH) will increase in the future. Global models are useful in projecting large scale system response, but what about predictions at regional and local scales such as the western and central Pacific and Hawai'i, respectively? Many times globally averaged and integrated models can miss smaller scale variation and details at the regional and local levels and it is critical, whenever possible, to use regional-level models to better determine the regional climate impacts.

2. Hawai'i and the Central and Western Pacific Climate Change

In 2001, the Pacific Islands Regional Assessment Group (PIRAG) published the report *Preparing for a changing climate: The potential consequences of climate variability and change*. This report focused on climate variability and change and their impacts on the American Flag Pacific Islands including Hawai'i, Guam, American Samoa, and the Commonwealth of the Northern Mariana Islands (CNMI), and the U.S.-affiliated Pacific Islands, which include the Federated States of Micronesia (FSM: Yap, Pohnpei, Kosrae and Chuuk), the Republic of the Marshall Islands (RMI), and the Republic of Palau. The report specifically looked at the effects of changing climate on sea surface temperatures, precipitation, and sea level in the Pacific region using the United Kingdom's Hadley Centre for Climate Predication and Research regional model. Looking at Figures 1-8, 1-9, and 1-10, we see that the projected changes in sea surface temperatures, precipitation, and sea level are not uniform over the Pacific. However, even though the projected changes are not uniform, both surface temperatures and sea level are greater than present day at the end of the 21st century (Figures 1-8 and 1-10). Precipitation is projected to increase or decrease depending on the geographical location at the end of the 21st century (Figure 1-9). These changes in sea surface temperatures, rainfall patterns, and sea level all have implications for the health of the near shore environment and coral reef ecosystems and thus related fisheries.

Table 1-7. IPCC 2007 projected global average surface warming and sea-level rise at the end of the 21st century from different climate models. Although the model outputs vary, it is important to note that they all project increases in ocean temperatures and sea level heights by the end of the 21st century.

Case	Temperature change (°C at 2090-2099 relative to 1980-1999) [a, d]	(m at 2090-2099 relative to 1980-1999)	Sea level rise
	Best estimate	*Likely* range	Model-based range excluding future rapid dynamical changes in ice flow
Constant year 2000 concentrations[b]	0.6	0.3 – 0.9	Not available
B1 scenario	1.8	1.1 – 2.9	0.18 – 0.38
A1T scenario	2.4	1.4 – 3.8	0.20 – 0.45
B2 scenario	2.4	1.4 – 3.8	0.20 – 0.43
A1B scenario	2.8	1.7 – 4.4	0.21 – 0.48
A2 scenario	3.4	2.0 – 5.4	0.23 – 0.51
A1FI scenario	4.0	2.4 – 6.4	0.26 – 0.59

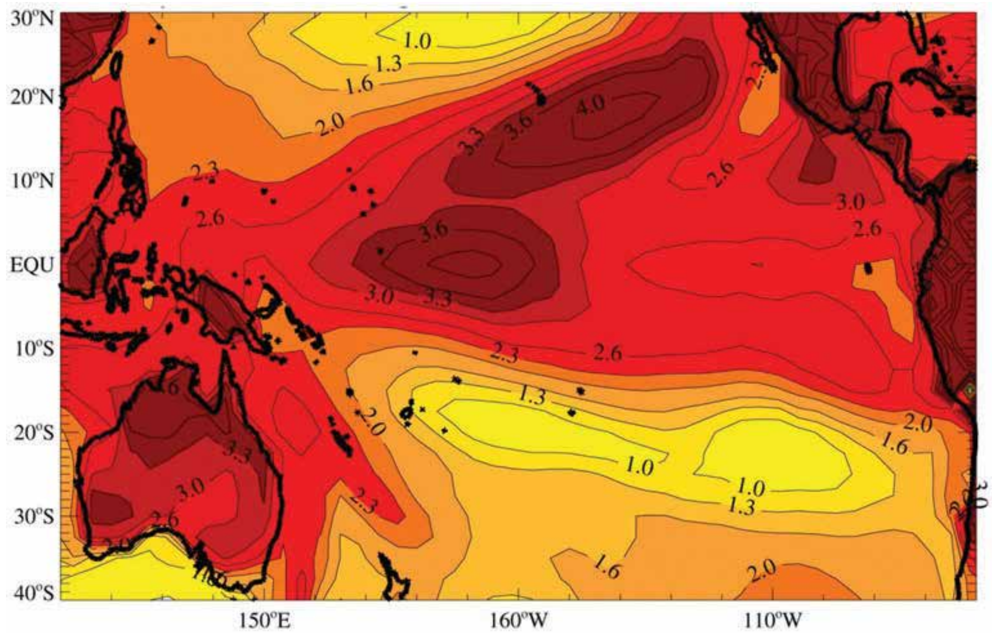

Figure 1-8. Model projected increases in surface temperature changes (in °C) for the late 21st century. Note the spatial non-uniform projected increases in temperature with the range of increase between 1.0 to 4 °C with some of the largest increases for the Hawaiian Islands (approximately 20°N and 160°W). Reprinted from Shea, E.L., Dolcemascolo, G., Anderson, C.L., Barnston, A., Guard, C.P., Hamnett, M.P., Kubota, S.T., Lewis, N., Loschnigg, J., and G. Meehl. Preparing for a changing climate. The potential consequences of climate variability and change. A report of the Pacific Islands Regional Assessment Group. East-West Center. 102pp.

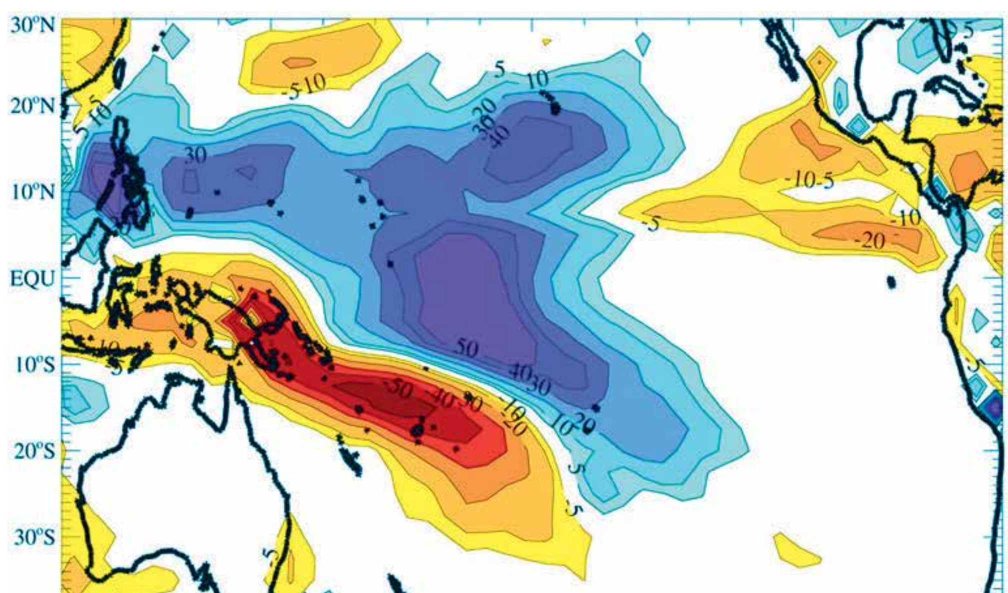

Figure 1-9. Model projected rainfall changes for the late 21st century in units of millimeters per day. Note the spatial non-uniformity in both projected increases and decreases in precipitation with an increase between 20 to 40 mm for the Hawaiian Islands (approximately 20°N and 160°W) and a decrease of -30 to -50 mm for some Western Pacific Islands such as American Samoa. Reprinted from Shea, E.L., Dolcemascolo, G., Anderson, C.L., Barnston, A., Guard, C.P., Hamnett, M.P., Kubota, S.T., Lewis, N., Loschnigg, J., and G. Meehl. Preparing for a changing climate. The potential consequences of climate variability and change. A report of the Pacific Islands Regional Assessment Group. East-West Center. 102pp.

E. Summary

The world population, presently at 7 billion is set to double before the end of the 21st century. This increase in population will require more natural resources – fuel, water, food – to provide for its needs. Currently, many natural resources are already stressed or stretched past their sustainable levels of use. The use of carbon-based fuels (e.g., oil, natural gas, coal, etc.), industrial practices (e.g., cement manufacturing), and land-agricultural practices (e.g., methane derived from livestock) all continue to result in emissions of greenhouse gases to the atmosphere. These emissions have implications for long-term global temperatures, rainfall, and sea level. The steady increase of carbon dioxide concentration in the Earth's atmosphere also results in surface ocean acidification, which is problematic for ecosystems and fisheries that are connected to the near-shore and coral reef environments. As with global population, populations of island nations such as the Solomon Islands, Fiji, Guam, American Samoa, Vanuatu, the Northern Marianas, and the state of Hawai‘i are all projected to increase (some at greater rates than the global average) for the rest of the 21st century. These local and regional population increases, in conjunction with climate-induced pressures, will only tax fisheries of which more than 80% are already fully exploited, overexploited, or depleted. Given that fish consumption is an important protein source, especially for coastal communities, a comprehensive approach to fisheries management taking into account all these pressures will be necessary to make the best of the future difficulties that await Pacific Island communities.

Some suggested readings:

Bell, J.D., Johnson, J.E., and Hobday, A.J. 2011. Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change. Secretariat of the Pacific Community, Noumea, New Caledonia. [Accessed 19 November 2011]. http://cdn.spc.int/climate-change/fisheries/assessment/e-book/indexcdn.html.

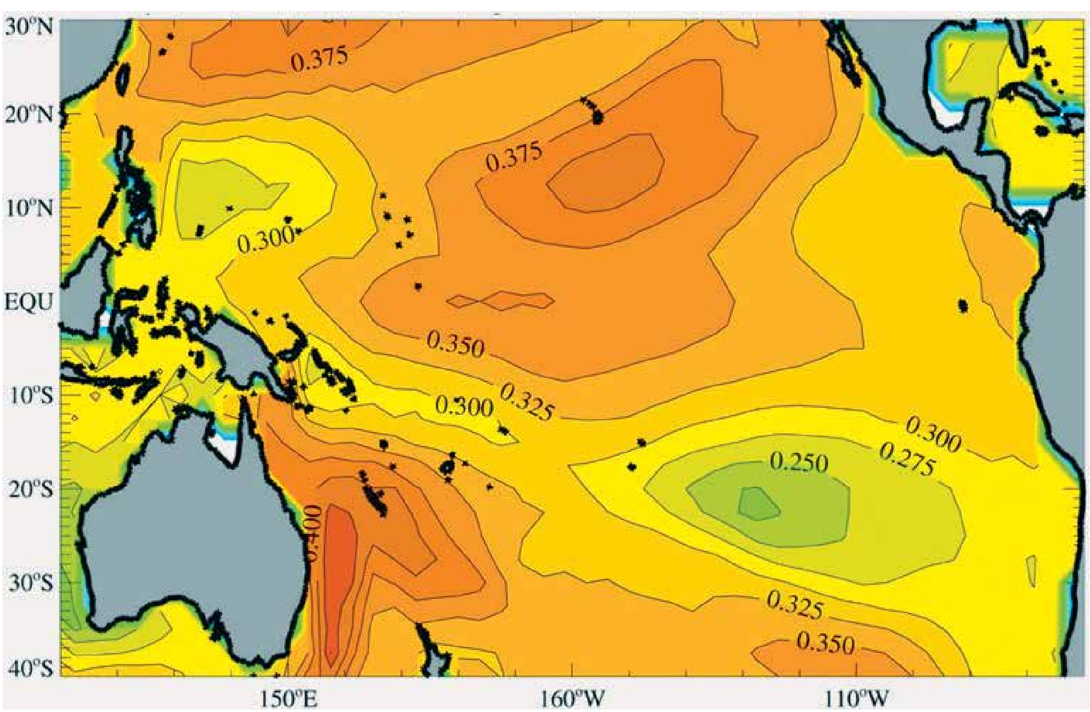

Figure 1-10. Model projected sea level changes for the late 21st century in units of meters. Note the spatial non-uniform projected increases in sea level with the largest range of increase of 0.4 meters, with some of the largest increases (0.35 to 0.375 meters for the Hawaiian Islands approximately 20°N and 160°W). Reprinted from Shea, E.L., Dolcemascolo, G., Anderson, C.L., Barnston, A., Guard, C.P., Hamnett, M.P., Kubota, S.T., Lewis, N., Loschnigg, J., and G. Meehl. Preparing for a changing climate. The potential consequences of climate variability and change. A report of the Pacific Islands Regional Assessment Group. East-West Center. 102pp.

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Ottersen, G., Kim, S., Huse, G., Polovina, J.J., Stenseth, N.C. 2010. Major pathways by which climate may force marine fish populations. Journal of Marine Systems. 79. p. 343-360.

Polovina, J.J., Dunne, J.P., Woodworth, P.A., and Howell, E.A. 2011. Projected expansion of the subtropical biome and contraction of the temperate and equatorial upwelling biomes in the North Pacific under global warming. ICES Journal of Marine Science. DOI: 10.1093/icesjms/fsq198

Shea, E.L., Dolcemascolo, G., Anderson, C.L., Barnston, A., Guard, C.P., Hamnett, M.P., Kubota, S.T., Lewis, N., Loschnigg, J., Meehl, G. 2001. Preparing for a changing climate. The potential consequences of climate variability and change. A report of the Pacific Islands Regional Assessment Group. East-West Center. 102pp.

II. Coral Reefs and Climate Change

A. Introduction

Coral reefs are underwater structures created by the calcareous secretions of various organisms including corals, coralline algae, and mollusks. Coral reefs form some of the most diverse ecosystems on Earth and serve a variety of functions including, but not limited to, coastal habitat for reef-related organisms and as a coastline physical barrier to waves and storms. Globally reefs have an estimated area of 600,000 km^2 (Figure 2-1) and are the key source of food, income, and near shore coastal protection for approximately 500 million people worldwide – which is approximately 8% of the global population. Coral reefs are critical for the inhabitants of small tropical and subtropical nations providing many benefits including, but not limited to, recreation and tourism, building materials, food, coastal storm protection and sand for beaches. Reefs are among the most biologically diverse ecosystems on the planet and serve as the infrastructure, habitat, spawning, and nursery grounds for coral reef fisheries.

Coral reefs have a global annual economic benefit of almost $US30 billion (Table 2-1) and yet cover less than 1% of the earth's surface. For the main Hawaiian Islands, coral reefs are estimated to provide an annual economic benefit of more than $US360 million. In American Samoa, the annual economic value is estimated at $US5 million for the coral reefs. This is a relatively low number compared to Hawai‘i, but tourism for American Samoa is not a major part of its economy like with Hawai‘i but the reefs still fulfill other important functions.

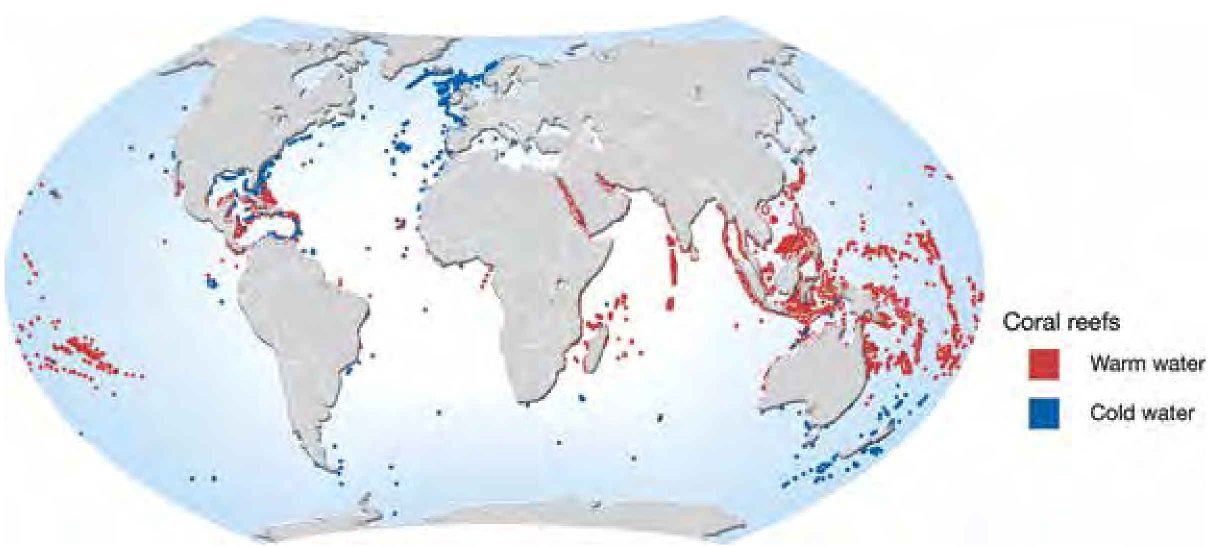


Figure 2-1. Global distribution of warm (and cold) water coral reefs. Reprinted with permission from distribution of cold water and tropical coral reefs. (February 2008). In UNEP/GRID-Arendal Maps and Graphics Library. Retrieved 8 October 2011 from http://maps.grida.no/go/graphic/distribution-of-coldwater-and-tropical-coral-reefs (Hugo Ahlenius, UNEP/GRID-Arendal).

Table 2-1. Annual economic benefit of the world's reefs.

Activity	Economic Impact ($US Billion)	Percentage of total economic impact
Tourism	9.6	32%
Coastal Protection	9	30%
Fisheries	5.7	19%
Biodiversity	5.5	19%

Climate change and accompanying impacts of sea-level rise, ocean acidification, increased sea surface temperature, alteration in ocean circulation, increased storm intensity, etc. are all potentially deleterious to coral reefs and their associated fisheries on the whole. Additionally, these impacts may in turn exacerbate other pre-existing issues that are already contributing to a significant decline in coral reef ecosystem health over the past few decades (e.g., coral bleaching, disease outbreaks, coastal sediment and nutrient input, and destructive fishing practices).

Coral reefs are dynamic ecosystems that are resilient if healthy and fragile if stressed. The reef structure serves as a habitat and community for hundreds of thousands of reef-related species. The stresses on reefs brought on by sea-level rise, ocean warming, and ocean acidification are troubling and will almost certainly continue to facilitate the decline in the overall health of the world's reefs observed over the past few decades. Coral reefs are critical to the survival of tropical and subtropical marine ecosystems and the associated local human populations. Pollution and climate change have already negatively impacted more than 25% of the world's reefs and should current trends persist most of the world's reefs could be significantly damaged by the year 2020. The international conservation group World Wildlife Fund recently warned that 40% of the reefs in the Coral Triangle have already been lost (Figure 2-2). The Coral Triangle is an ocean area shared between Indonesia and five other South East Asian nations, is 6 million km^2 in area, and contains 75% of the world's coral reef associated biota and a third of the world's coral species. The Coral Triangle is likened to the Amazon rainforest in terms of biodiversity.

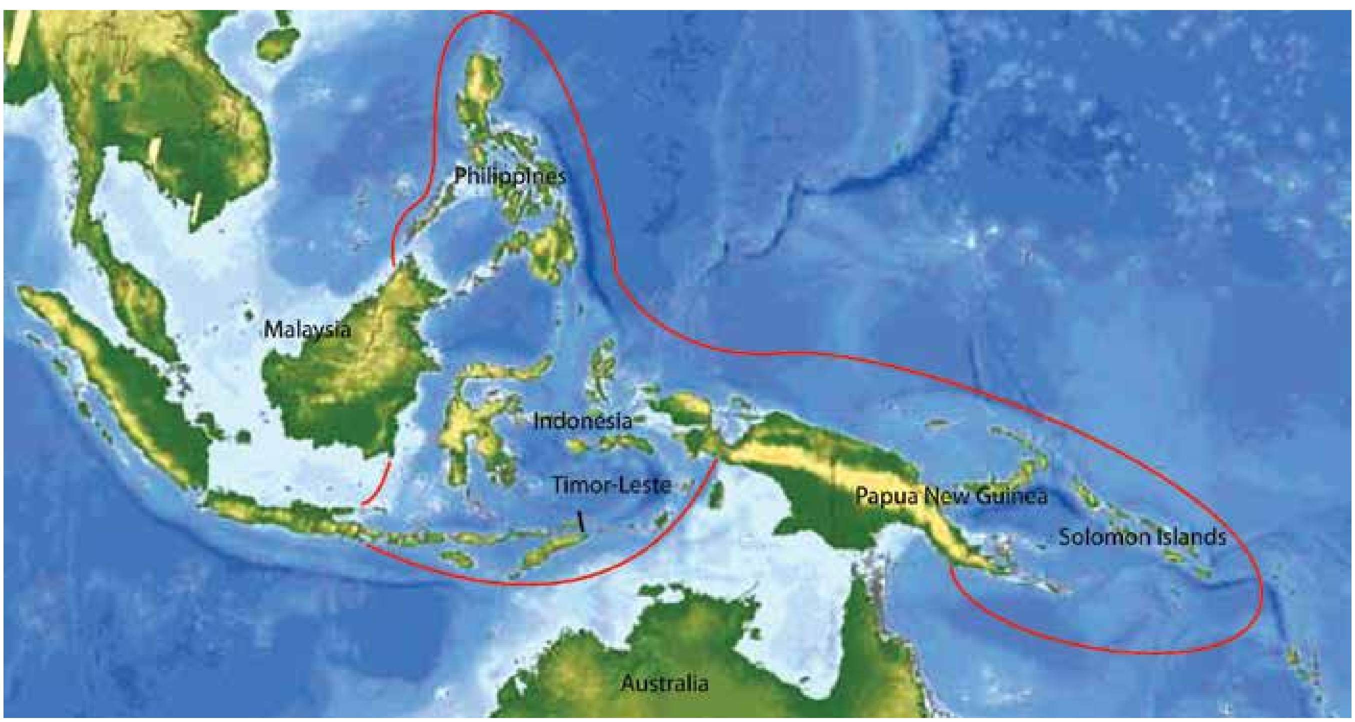


Figure 2-2. Map showing the coral triangle region (outlined in red), which is the most diverse and biologically complex marine ecosystem on the planet. The coral triangle covers 5.7 million km^2 and matches the species richness and diversity of the Amazon rainforest. Image courtesy of www.reefbase.org. Retrieved 20 December 2011 from http://oceanexplorer.noaa.gov/okeanos/explorations/10index/background/biodiversity/media/coral_triangle.html.

The future of the world's coral reefs appears so bleak that a proposal was announced at the 2009 United Nation Climate Change Conference in Copenhagen to freeze (in liquid nitrogen) samples of coral reefs as a last ditch effort to ensure genetic preservation of the world's reef biodiversity. Researchers at the University of Hawaiʻi at Mānoa in the Hawaiʻi Institute for Marine Biology partnered with scientists at the Smithsonian to create the first frozen bank for Hawaiian corals in an attempt to protect them from extinction and preserve their diversity in Hawaiʻi. It is clear that the death or severe deterioration of coral reefs and the associated organic communities that depend on them would have dire consequences for other marine resources (connected via the food web) and also for small tropical and subtropical island inhabitants dependent upon these resources. Future sea-level rise will have significant and profound effects on the economies and on the living conditions of the populations of coastal and island countries.

In this chapter we investigate the impacts of climate change on both the reef structure and the inter-related impacts to the reef fisheries. The impacts to the physical reef structure are reviewed first and include climate change effects on light, temperature, sea level, and ocean chemistry via acidification. After laying this foundation, we then review how the associated reef fisheries will be impacted by changes in the reef structure and near shore water conditions. Whenever possible, the influence on the reefs and reef fisheries of tropical Pacific Island nations will be included in the discussion.

B. Light and Sea Level

Coral reefs are the ocean equivalent of tropical rainforests in terms of biological production and biodiversity. Two-thirds of all marine fish species are associated with coral reef environments and these systems also exhibit a wide diversity of invertebrate life. For the purposes of this case study, we will focus on warm water reefs limited to tropical and subtropical waters. These reefs are not usually found in waters that are too deep, too muddy, too diluted by freshwater, or too extreme in temperature. Major warm water coral reefs do not occur in waters that are less than 18 °C or exceed 30 °C for extended periods of time. Many of the coral species living in the reef environments are near their upper thermal limit for survival during some months (i.e., summer) of the year. Coral reefs are dominated and primarily comprised of corals (animals with symbiotic algae called zooxanthellae) and coralline algae (plants). Corals and coralline algae form the living and dead framework of coral reefs along with contributions of skeletal and organic matter debris from mollusks, echinoderms, foraminifera, and other organisms (Figure 2-3).

Figure 2-3. Coral and coralline algae. Retrieved 20 December 2011 from http://ccma.nos.noaa.gov/products/biogeography/palau/htm/cover.aspx.

Active coral development and growth require several components and light is one of them. If corals are light limited (e.g., unable to get enough light for growth needs), then they stop growing and eventually will die. As an aside, the other primary component of the reef structure, coralline algae, is also light limited as plants. Light limitation can be due to a variety of factors, some related and some not, such as increased water turbidity and light attenuation as water depth increases. For corals, light is required for photosynthesis to take place by the endosymbiotic ("endo" meaning inside and "symbiotic" meaning mutual benefit) zooxanthellae (algae) that live within the coral polyps (Figure 2-4).

Zooxanthellae use light to convert carbon dioxide that is dissolved in seawater into energy rich sugars as represented by the simple equation [1]. Carbon dioxide is also generated by the production of calcium carbonate [2]. Zooxanthellae can provide up to 90% of the energy needs of the symbiotic coral. In return, the coral provides the zooxanthellae protection, shelter, and the nutrients necessary to carry out photosynthesis. Given this relationship and dependence of corals on zooxanthellae, coral growth

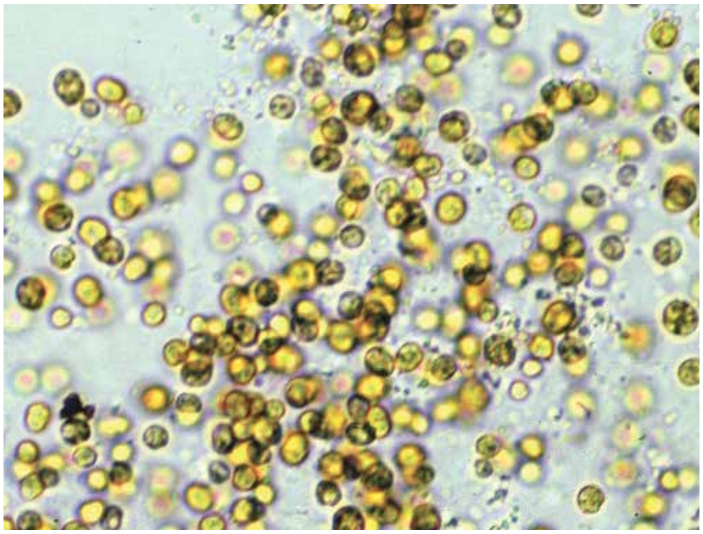


Figure 2-4. Zooxanthellae. Retrieved 20 December 2011 from http://coralreef.noaa.gov/aboutcorals/coral101/symbioticalgae/.

is limited to the photic or light zone. When stressed, corals can lose their zooxanthellae by either expulsion or digestion which is what happens during coral bleaching events. If zooxanthellae do not return within 6 months, the coral will die due to the lack of the energy source the zooxanthellae once provided.

Photosynthetic energy production

CO_2 (dissolved in seawater) + H_2O + light → CH_2O (sugar used for energy) + O_2 [1]

Calcium carbonate formation

$2HCO_{3^-} + Ca^{2+} \rightarrow CaCO_3 + CO_2 + H_2O$ [2]

Light also enhances oxygen production stimulating coral metabolism and leading to increased coral calcium carbonate deposition and thus coral reef growth. Corals are generally limited to water depths where light intensity is at minimum 1 to 2% of the light intensity at the water-air interface and therefore most, but not all, zooxanthellate corals are restricted to depths shallower than 70 m.

As corals are heavily dependent upon light to perform biological functions, future sea-level rise may reduce the amount of light reaching the reef. Changes in sea level can also impact the amount of wave energy that reefs experience and the amount of erosion from both regular wave events (e.g., trade wind driven waves) and storm events (e.g., hurricanes). As recent as within the past ten thousand years, the magnitude and rate of sea-level rise have been great enough to inhibit shoreward migration of reefs in both the tropical Pacific and the Caribbean. The latest IPCC Future report predicts a sea-level rise of 2 to 6 millimeters per year for this century depending on which model results are used. As the distance between the reef and overlying water surface becomes greater due to sea-level rise, the amount of light reaching corals is reduced. If coral reef growth and accretion rates do not match the rate of sea-level rise, then the result could be that the coral reefs can no longer sustain their upward and horizontal growth leading to "drowned" reefs. Another possibility is that the overall reef system might shift to become dominated by non-coral species (such as coralline algae), or some combination of the two, that is better adapted to lower light conditions. Slow growing coral species that are living at their physiological depth limit (i.e., they are already on the verge of being light limited) are especially susceptible to the consequences of rising sea level.

Once reefs are weakened, usually due to the combinatorial effects of multiple environmental stresses, they become more vulnerable to any subsequent stresses. Corals are relatively slow growing and so when large-scale damage occurs it can take more than 25 years for the smallest of coral colonies to repair and rebuild. For example, reef recovery from stress brought about by an El Niño Southern Oscillation (ENSO) event can take more than 100 years. Modeling of future climate change predicts that El Niño events will occur more frequently in the future. With more frequent events, corals may not have the time necessary to recover (between El Niño events) from previous damage resulting in a dramatic decline in coral abundance and distribution.

For corals, the negative impact of sea level change alone is perhaps less pressing compared to the more immediate problems of increases in sea surface temperatures and ocean acidification. As an example, the maximal coral reef growth rate for tropical reefs in Hawai'i is thought to be approximately 1 to 10 millimeters per year at a depth of 10 meters. The range in growth rate is latitude dependent with higher growth rates in warmer or lower latitude waters.
All things being equal, the rise in sea level may not be enough to drown the reefs. Although coral reef communities that are already weakened by increased

sea surface temperatures and ocean acidification (in addition to human activities of overfishing, etc.) resulting in reduced growth rates may become overwhelmed by sea-level rise. Researchers have demonstrated with computer modeling that Caribbean reefs in their degraded condition are presently unable to keep pace with expected sea-level rise. What about the Pacific reef communities such as those in Hawai'i and the Western Pacific?

Impacts on Tropical Pacific Reefs

Coral reefs in Hawai'i are impacted by a variety of processes that occur on different time and space scales. Nutrient and sediment runoff, volcanic activity, plate motion and eustacy, sea level change, species and ecosystem change, human activity, and many other processes operate on a variety of time and space scales that impact to varying degrees the environment in which coral reefs reside. Recent research by Dr. Jody Webster, while at the Monterey Bay Aquarium Research Institute, and colleagues suggests that coral reefs in Hawai'i have in recent geologic history (since the Last Glacial Maximum or LGM, which is roughly 18,000 years ago – see Figure 2-5) succumbed to "drowning" due to relatively rapid sea-level rise occurring over a period of several hundred years. This sea-level rise was brought on by a pulse of glacial meltwater resulting from the rapid rise in global temperatures since the LGM. Interestingly, the relatively rapid rise in sea level also resulted in a shift in reef species dominance. Before "drowning", the reefs were comprised primarily of a shallow reef-building coral species within the genus *Porites*. Upon "drowning", deep-water coralline algae became the dominant reef species and covered the top of the reef structure of pre-existing *Porites*.

Research done by Dr. Rick Grigg, who was one of the big-wave surfing pioneers on O'ahu's famed North Shore, demonstrated that Holocene (over the past 10,000 years) reef structure accretion from coral growth is limited by wave exposure and sea level. Coral growth and reef accretion were measured at four different wave energy sites around the island of O'ahu. The sites with the lower wave energy exposure (i.e., wave sheltered locations are in deep enough waters so that wave energy is dissipated) are the only sites to demonstrate long-term reef accretion and growth. The

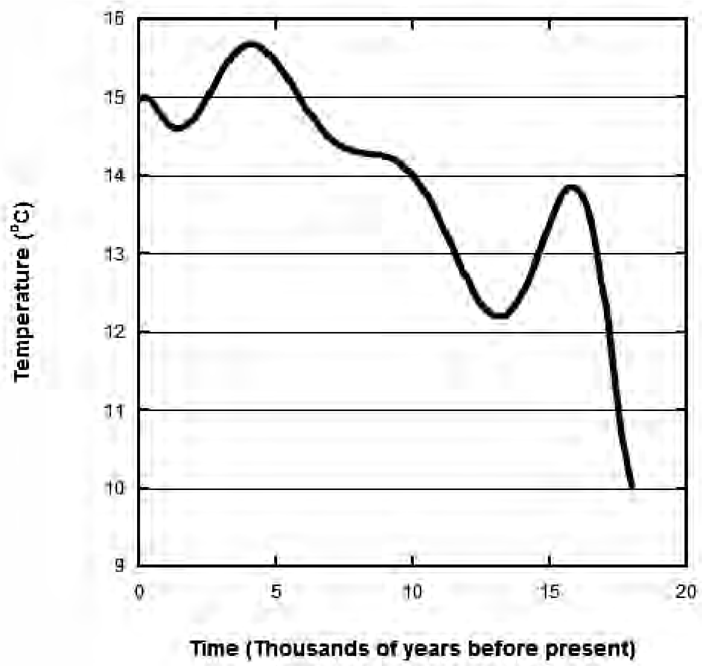


Figure 2-5. Average global temperature record since the Last Glacial Maximum (~18,000 years before present; pers. comm. with Dr. Abraham Lerman, Northwestern Univ.). Note the minimum temperature at the LGM coinciding with maximum glacial coverage of the earth. The coral reef drowning event in Hawai'i occurred right after that temperature minimum as the earth warmed, glaciers melted, and sea levels rose relatively quickly due to the rapid input and large volume of glacially-derived meltwater. It should be noted though that worldwide carbonate platforms expanded during this time as the rise in sea level inundated low-lying coastal areas providing additional area favorable for carbonate platform production.

breaking off of living coral and subsequent scouring and abrasion of living corals by coral pieces and rubble during high energy wave events result in enough reef mortality to limit coral reef growth and accretion. High energy wave events are derived from storms that are far away from Hawai'i (e.g., either generated in the distant North Pacific or the Southern Ocean around Antarctica) or by hurricanes and tropical storms that pass close to the islands. Computer modeling of future Pacific climate suggests that storm intensity and frequency will both increase and thus reefs will be at a higher risk of damage. The degree of sea-level rise though that is necessary to protect reefs from the negative impacts of the projected increase in storm-related high energy wave events is on the order of meters. Rapid, long-term sea-level rise over hundreds to thousands of years is necessary to generate meters of sea-level rise and thus we cannot expect sea-level rise in the next few decades to offset the negative impacts of increased frequency and intensity of high-energy storm-related wave events resulting from climate change.

Rapid sea-level rise over several hundred to thousands of years can negatively impact coral reefs, but what about the next century? The IPCC projected sea-level rise for the next century is between 2 to 6 millimeters per year. Even though that rate is relatively low compared to higher sea-level rise rates at times within the Holocene (e.g., 15 millimeters per year), it still can impact the fringing reef systems characteristic of those found in the tropical Pacific and Caribbean. If corals, due to other stresses, are unable to keep pace with rising sea level, then they will encounter increased turbidity (see Figure 2-6). Turbidity is a measure of cloudiness or haziness in the water. Increased turbidity occurs by the increase in wave energy suspending sediment in shallow reef areas and also eroding fine sediment deposits near the shoreline. Sedimentation and suspended sediment are leading contributors to reef degradation on fringing coral reefs in the Pacific and Caribbean. If reefs are unable to keep pace with sea-level rise, even small increases in sea level (relative to the top of the coral reef) will increase wave energy on reef flats and adjacent coasts. This increase in wave energy can potentially increase turbidity by increasing the resuspension of sediment in shallow reef areas and by erosion of fine sediment deposits on coastal plains that are adjacent to the reefs. A study of a shallow fringing reef off Molokai, Hawai'i demonstrated that sediment is suspended daily via waves generated by trade winds. Increased turbidity levels around the reef were correlated to wind velocity and water depth. Sea-level rise will increase wave energy and bottom stresses, which in turn will lead to an increase in both duration and magnitude of sediment suspension events. Sedimentation and suspended sediment already contribute to reef degradation on fringing coral reefs in the Pacific and Caribbean so rising sea level will increase this degradation.

In summary, we see that rapid changes in sea level within the recent past have resulted in negative impacts to reef growth via changes in light levels. We know that these past rapid changes in sea level are greater than what is projected to occur in this century. Drawing from this understanding, we see that the expected sea-level rise for the next century in itself will not be enough to outpace healthy coral growth rates. However, if the associated negative impacts occurring with sea-level rise (e.g., increased wave action energy, bottom stresses, and turbidity) are considered, then the projected rise in sea level is problematic. So it is possible that sea-level rise will serve as an environmental stress on coral reef health in the next century. We now shift our review from the impacts of future sea level changes to how future sea water temperature increases can impact coral reefs.

Figure 2-6. From left to right, turbidity standards 5, 50, and 500 Nephelometric Turbidity Units or NTUs. The higher the NTU value, the more turbid the standard. Notice how the far right sample is white (more turbid) than the far left standard (almost clear). Referenced from the U.S. Geological Survey.

C. Sea Surface Temperature

Water temperature impacts coral growth and distribution. Coral reefs are generally found between the latitudes of 30ºN to 30ºS as this is where water temperatures tend to stay relatively warm year round. Corals grow faster in warmer waters, but only up to an upper temperature limit. Corals prefer a mean annual temperature between 23 to 25 ºC (73 to 77 ºF), but some species can exist between 18 to 30 ºC (64 to 86 ºF). Once the water temperatures go above these upper limits, even for short durations, corals can be stressed.

In 2011, the concentration of CO_2 in the Earth's atmosphere exceeded 393 parts per million (ppm), which is more than 80 ppm above the maximum values for the past 700,000 years and perhaps the past 20 million years. The steady rise in atmospheric CO_2 and

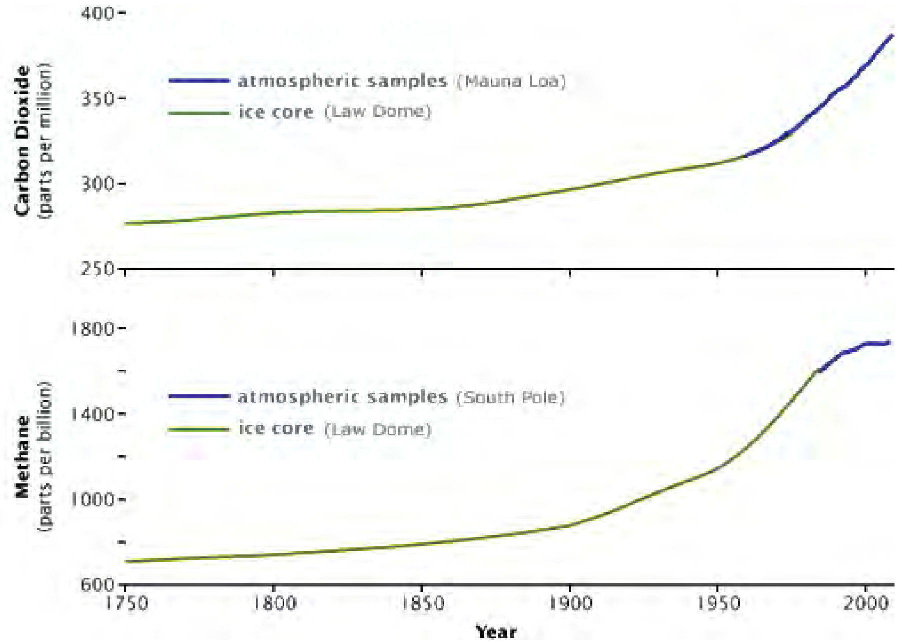


Figure 2-7. Rise in atmospheric CO_2 and CH_4 (two greenhouse gas concentrations) since the industrial revolution.

CH_4 (Figure 2-7) since the industrial revolution is in part responsible for a concurrent increase in global temperatures. This increase in global temperatures has resulted in the increase in global ocean heat content and surface seawater temperatures (Figure 2-8).

As previously discussed, corals have a narrow temperature tolerance range. Of all the climate change impacts on coral reefs, the long-term and consistent increase in seawater temperature may be the greatest problem. In some locations around the world such as the Caribbean and south and western Pacific, corals are currently living near, at, or beyond their temperature tolerance threshold as bleaching events indicate. Corals tend to not bleach permanently because of a rapid, short-term increase (e.g., days or weeks) in seawater temperatures. However, a large departure in seasonal (> 6 months) maximum seawater temperatures (3 to 4 °C) can be devastating. With shorter duration and smaller departures in maximum temperatures (1 to 2 °C), bleached corals can recover but their growth and reproductive capabilities may be significantly degraded. Figure 2-9 depicts the average maximum monthly sea surface temperature (SST) for the periods of 2000 to 2009 (top) and projected from computer modeling for 2050 to 2059 (bottom). Notice how the yellow (29 to 30 °C), red (30 to 31.1 °C), and dark red (> 31.1 °C) areas in the western and central tropical Pacific grow over the next fifty years with much of the central and western tropical Pacific at 30 °C or higher. The Hawaiian Islands are within a significantly cooler band of 24 to 29 °C SST for both time periods, but it is important to note that Hawaiʻi reefs have already experienced bleaching events in the past decade.

Impacts on Tropical Pacific Reefs

The Northwestern Hawaiian Islands (NWHI), which are in the Papahānaumokuākea Marine National Monument, are home to 69% of the coral reefs under U.S. jurisdiction (Figure 2-10). The NWHI coral reefs are exposed to large seasonal SST fluctuations of up to 10 °C per year, ranging from 18 °C in the winter to 28 °C in the summer. This SST difference between winter and summer months is large compared to most reef ecosystems around the world. The NWHI reefs experienced bleaching events in the years 2002, 2004, 2008, and 2010. Figure 2-11 represents the 2002 to 2003 SST data for Midway Atoll in the NWHI. The largest bleaching event occurred during the 2002 summer months of July, August, and September coincident with SSTs exceeding the bleaching threshold of 28 °C during August. During the 2004 bleaching event, the more northern islands and atolls had higher incidents of bleaching compared to more southern locations. At each location where SST was measured, the water temperatures were higher in shallow back reef and patch reef habitats and thus bleaching events were more frequent in these environments compared to the deeper and thus cooler fore reef environment. Additionally, depending on the

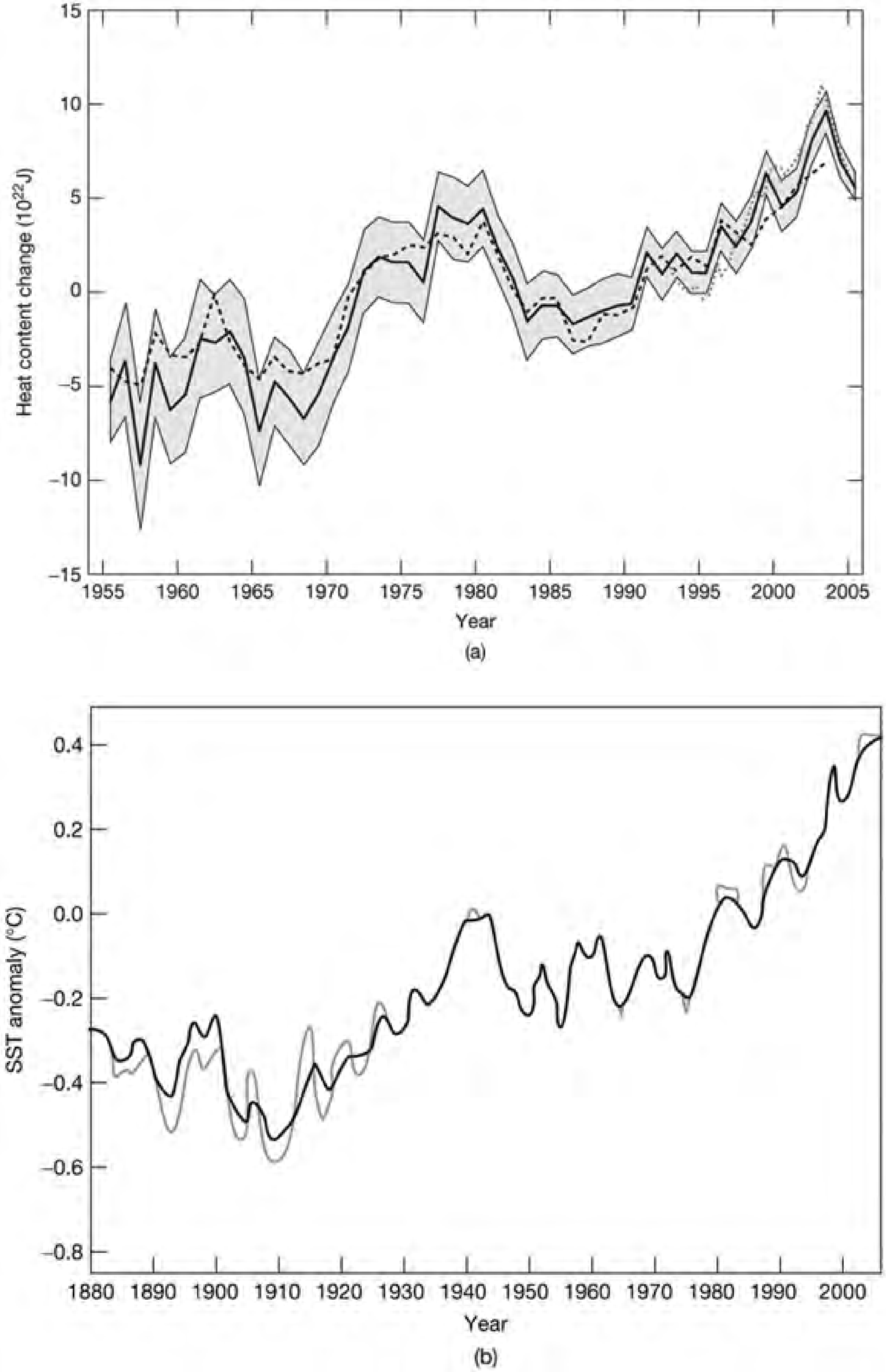


Figure 2-8. Estimates of (a) ocean heat content from 1955 to 2005 and (b) sea surface temperature (SST) from 1880 to 2000. Notice how both trends are increasing from the past into more recent times.

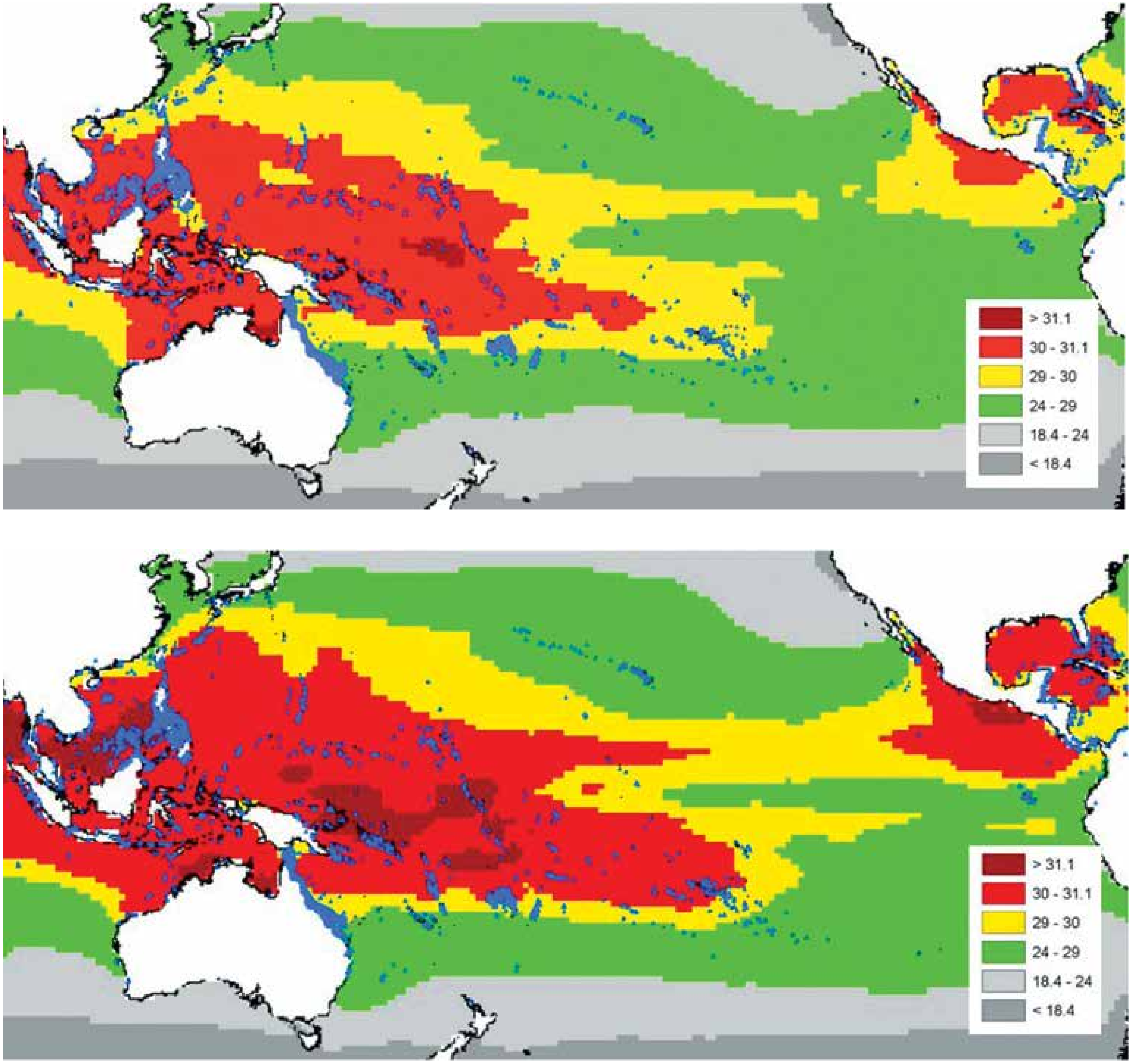


Figure 2-9. Maximum monthly SST for the years (top) 2000 to 2009 with pCO_2 = 375 ppmv and projected for years (bottom) 2050 to 2059 with pCO_2 = 492 ppmv. Reprinted from Coral Reefs, 22, Guinotte, J.M., Buddemeier, R.W., and Kleypas, J.A., Future coral reef habitat marginality: temporal and spatial effects of climate change in the Pacific basin, 551-558, 2003, with permission from Springer.

coral species and the reef environment, corals either recovered or were overgrown by macroalgae species during this event and subsequently.

Along with the NWHI reefs, Fijian reefs have experienced bleaching events in the previous decade (Figure 2-12). In 2000 during a La Niña and in 2002 during an El Niño, the waters around the Fiji Islands were unusually warm and the reefs suffered extensive hard coral stress and death due to bleaching in what was Fiji's first recorded mass bleaching event. From surveys it was estimated that Fiji's reefs experienced a total loss of between 40 to 80% of hard corals. With both the 2000 and 2002 events, SSTs remained above the long-term summer average of 28.3 °C for more than 3 months.

Fortunately, long-term biological monitoring of Fijian coral reefs was being carried out prior to, during, and after the 2000 and 2002 bleaching events that allowed for subsequent monitoring of reef recovery from these events (Figure 2-13). There was a decline in hard coral cover after the mass bleaching of 2000 with a drop of cover to the lowest point between the years 2001 to

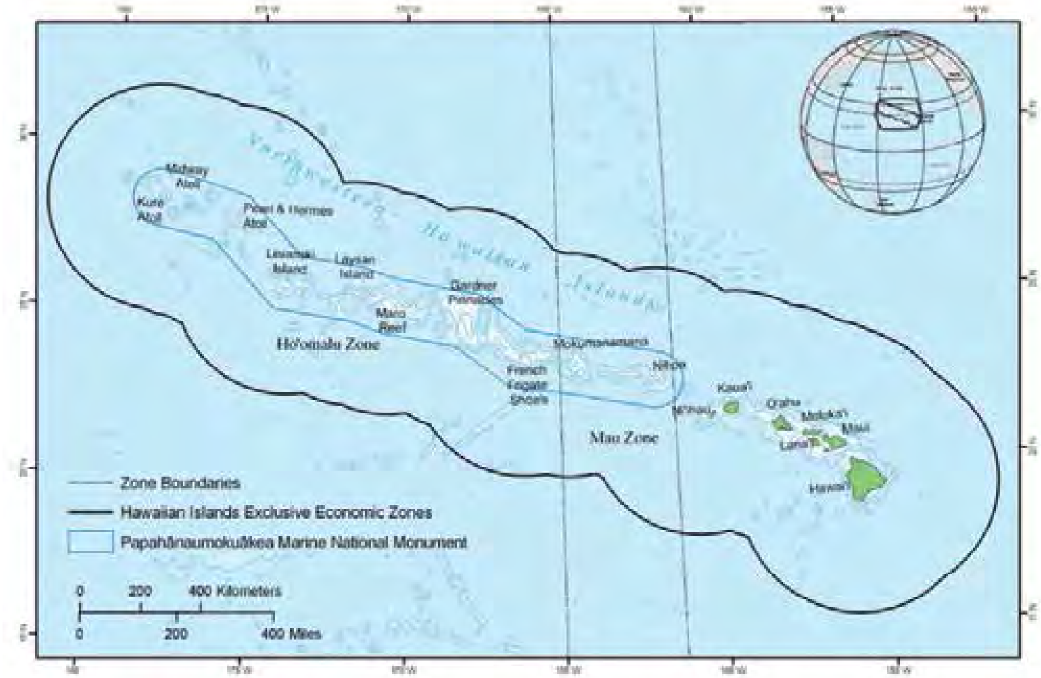


Figure 2-10. The Hawaiian Island chain with the Northwestern Hawaiian Islands or Papahānaumokuākea Marine National Monument. Retrieved 2 February 2011 from http://sanctuaries.noaa.gov/science/condition/pmnm/images/fig1_lg.jpg.

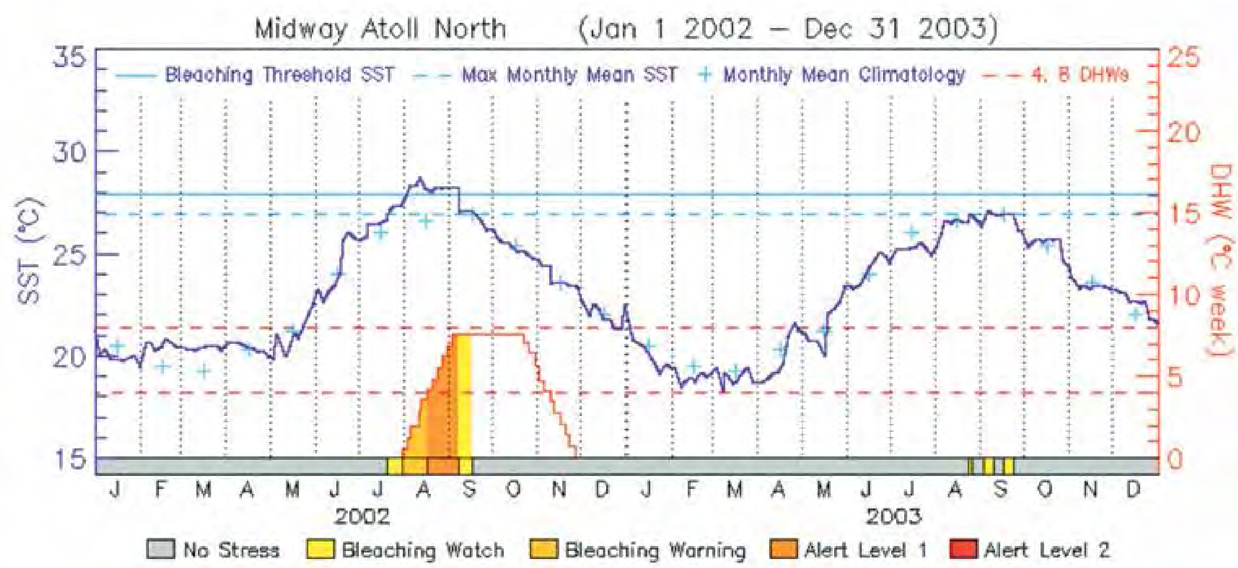


Figure 2-11. 2002 to 2003 Midway Atoll North station of the Northwestern Hawaiian Islands coral watch data. Notice the bleaching event in the months of July, August, and September 2002 coincident with SST above the bleaching threshold (28 °C). Retrieved 4 November 2010 from http://coralreefwatch.noaa.gov/satellite/vs/nwhi.html#.

2002. After that, coral cover increased and reached pre-bleaching levels by 2003 in the deep reef and 2005 in the shallow reef environments. Algal cover increased in the deeper reef zone while coral cover was depressed due to the bleaching and then decreased as corals recovered. This was assumed to be due to algal colonization of dead coral skeletons following bleaching events.

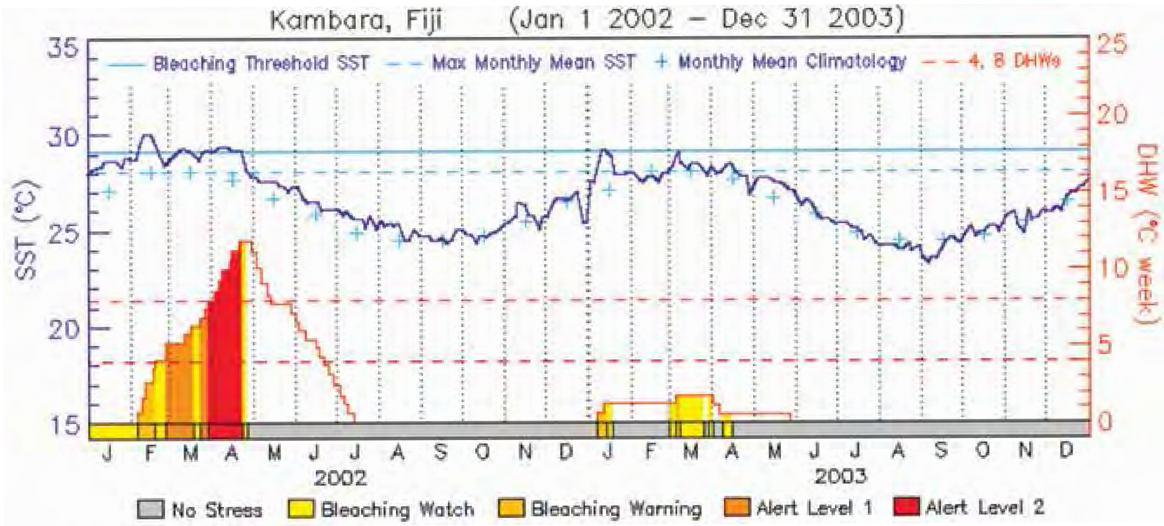


Figure 2-12. 2002 to 2003 Kambara, Fiji station coral watch data. Notice the elevated SST and the corresponding bleaching event during February, March, and April of 2002. Retrieved 4 November 2010 from http://coralreefwatch.noaa.gov/satellite/vs/melanesia.html#Kambara_Fiji.

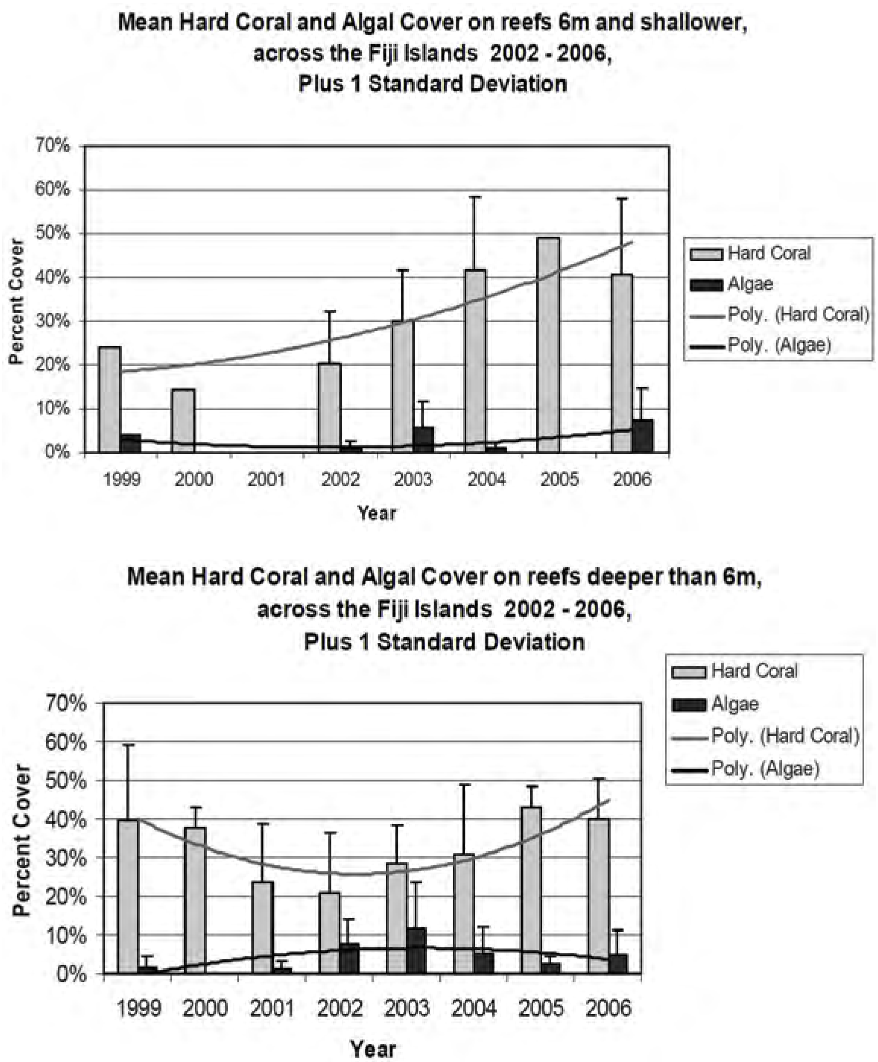


Figure 2-13. Mean hard coral and algal cover on reefs (top) 6 meters and shallower, and (bottom) deeper than 6 meters for Fiji from 2002 to 2006. Note how in the deeper reef algal cover increases when coral cover decreases after the 2000 and 2002 bleaching events indicating algal colonization of dead coral. Retrieved 10 November 2010 from http://www.crisponline.net/Portals/1/PDF/C2A2_MONITORING_REPORT_FINAL.pdf.

American Samoa has a relatively small range of SST throughout the year (2 °C from 27.5 to 29.5 °C). Mass bleaching occurred in American Samoa during the summers of 2002 and 2003 (Figure 2-14). American Samoa's Territorial Monitoring Program has been monitoring two back reef environments on Tutuila since the 2003 bleaching event. In these environments, staghorn coral is in abundance. The staghorn coral species tends to bleach more intensely on the top of branches compared to the sides or underneath. Figure 2-15 shows the correlation between SST and the percent of staghorn colony surface area partially bleached. Interestingly, although there is evidence that staghorn colonies have bleached every summer since 2002, little colony mortality has yet to occur. This however could easily change as the baseline summer average SST increases in the future, which in turn will be further exacerbated by stronger La Niña (SST warming for American Samoa) events. With this in mind, bleaching events are an impediment to coral growth and can also stop sexual reproduction. Corals that are bleaching annually are growing less compared to unbleached corals and not reproducing except asexually via fragmentation.

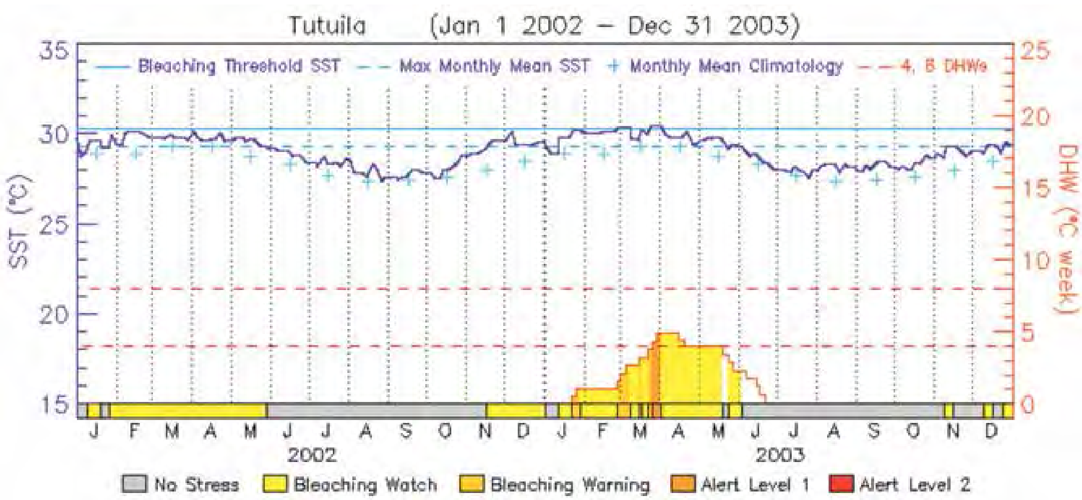


Figure 2-14. 2002 to 2003 Tutuila, American Samoa station coral watch data. Note the bleaching event in the months of February, March, and April 2003 coincident with SST at or above the bleaching threshold (30 °C). Retrieved 4 November 2010 from http://coralreefwatch.noaa.gov/satellite/vs/americansamoa.html#Tutuila.

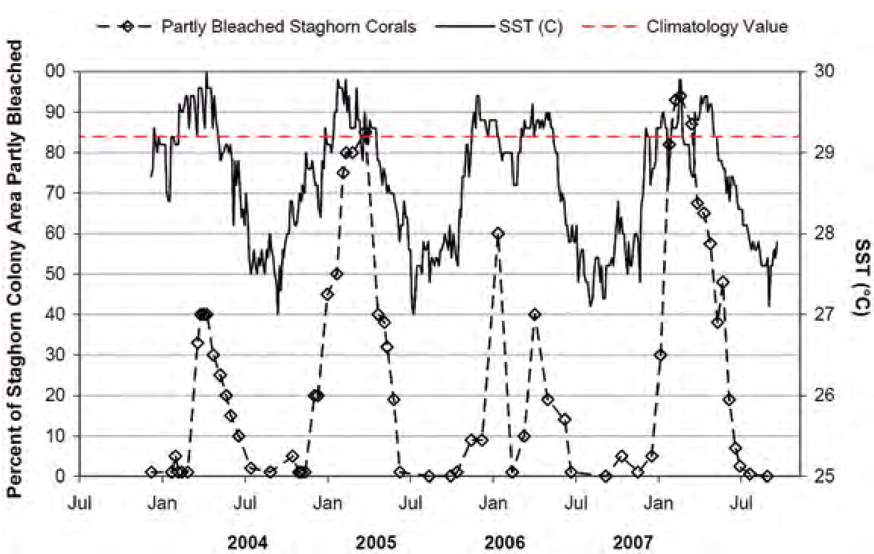


Figure 2-15. SST time series for a colony of staghorn coral during bleaching events from 2004 to 2007. The black line with diamonds is the percentage of partly bleached staghorn coral in the colony. The black line without symbols is the satellite measured SST in °C. The red dashed line is the projected summertime maximum temperature by NOAA's Coral Reef Watch, which is an effort to utilize remote sensing and in situ tools for real-time and long-term monitoring of coral reef ecosystems. Reprinted from The State of Coral Reef Ecosytems of the United States and Pacific Freely Associated States: 2008. National Ocean and Atmospheric Administration. p. 307-351.

Recently, stress-tolerant coral have been identified in higher maximum temperature habitats (e.g., warmer back reef environments versus cooler fore reef environments) of Vatia Bay, Faga'itua Bay, and Ofu Island in American Samoa. Up to 83% of the corals sampled in these three areas have a stress-tolerant variety of *Symbiodinium*, which are zooxanthellae. These American Samoan habitats do not exhibit higher sea surface temperatures compared to other distant locations that were sampled (e.g., Fiji, Philippines, and Palmyra Atoll). In these other distant locations, with higher sea surface temperatures, sampled coral populations were found to have much lower abundance (< 1%) of these stress-tolerant *Symbiodinium* compared to the three locations sampled in American Samoa. Symbiont switching (e.g., change of one zooxanthellae species for another within the host coral) does occur and offers a possible mechanism for corals to adapt, as has occurred in American Samoa, to changes in climate. This mechanism is relatively fast compared to other potential adaptive mechanisms such as acclimatization and host evolution via natural selection. The identification and protection of areas with high abundance of stress-tolerant *Symbiodinium*, such as those identified and fall under the US National Park in American Samoa, offer the opportunity to protect temperature resistant reef areas from human impacts such as runoff and overfishing so that reefs continue to be viable under warming.

D. Ocean Acidification Impact

Ocean acidification is the process by which the ocean becomes increasingly more acidic (or pH gets lower) due to atmospheric CO_2 dissolving into the surface water. This happens because the partial pressure or concentration of CO_2 in the atmosphere is greater than the partial pressure or concentration of CO_2 in the surface water layer, so CO_2 moves from higher (atmosphere) to lower (surface water) concentration. This increase in surface layer CO_2 increases the acidity of the surface ocean and also the deep ocean if the surface waters are subsequently subjected to downwelling into deeper waters. Since the Industrial Revolution, surface ocean pH has decreased by 0.1 pH units. Experimental studies show that a doubling of pre-industrial atmospheric CO_2 levels (from 280 to 560 ppm) may decrease coral calcification and growth by up to 40% through the inhibition of aragonite formation. An atmospheric CO_2 concentration of 560 ppm is expected by the middle of this century. Aragonite is the principal form of calcium carbonate deposited by coral polyps as their skeleton. Field studies confirm that calcium carbonate accretion on coral reefs approaches zero or becomes negative at aragonite saturation values (Ω: see Box 2.1) of 3.3 in today's oceans, which occurs when atmospheric CO_2 approaches 480 ppm and carbonate ion concentrations drop below 200 micromoles per kg solution in most of the global ocean.

Reef-building corals may exhibit several responses to reduced calcification. All these responses can have negative responses for not just the coral reef, but also the reef ecosystem. The first of these responses is a decreased growth rate and skeletal density of the coral colonies. Over the past 16 years, *Porites* colonies on the Australian Great Barrier Reef have shown an average reduction in skeletal growth rate and skeletal density of 20%. The second response is that corals may maintain their growth rate by reducing skeletal density, which makes them more brittle and thus more susceptible to erosion from grazing animals (e.g., parrotfish) and also storm damage. So if erosion rates are greater than calcification rates then the structural complexity and overall size of the coral reef will diminish, both of which may reduce reef fishery habitat and diversity. Finally, corals may maintain both skeletal growth and density under reduced carbonate saturation states (due to ocean acidification) by investing more energy into calcification. This takes away energy from other process – e.g., reproduction – which impairs the potential for recolonization following erosion or large scale disturbances (e.g., storm events).

Impacts on Tropical Pacific Reefs

Global atmosphere-surface ocean models are used in the attempt to predict how surface seawater pH will change as atmospheric CO_2 rises for at least the next century. Figure 2-16 displays the Pacific region output from one such model that calculates how changes in surface pH impacts the saturation state of the water with respect to aragonite, which is a $CaCO_3$ mineral. The top model output shows the aragonite saturation state for the period of 2000 to 2009 (pCO_2 = 375 ppm) while the bottom model output is from 2050 to 2059 (pCO_2 = 492 ppm). Optimal aragonite saturation states of > 4 are only maintained in a small part of the central tropical Pacific. The Hawaiian Islands and western

Box 2.1 Aragonite Saturation State of Seawater

The precipitation and dissolution of aragonite in seawater can be described by the chemical reaction:

$$CaCO_3 + H^+ = Ca^{2+} + HCO_3^- \qquad (1)$$

where Ca^{2+} is the dissolved concentration of calcium ions in seawater, CO_3^{2-} is the dissolved concentration of carbonate ions in seawater, and $CaCO_3$ is aragonite. The equation as read left to right is for the aragonite precipitation reaction and read right to left is for the aragonite dissolution reaction.

The saturation state of seawater with respect to aragonite can be defined as the product of the concentrations of dissolved calcium and carbonate ions in seawater divided by their product at equilibrium:

$$([Ca^{2+}] \times [CO_3^{2-}]) / [CaCO_3] = \Omega \qquad (2)$$

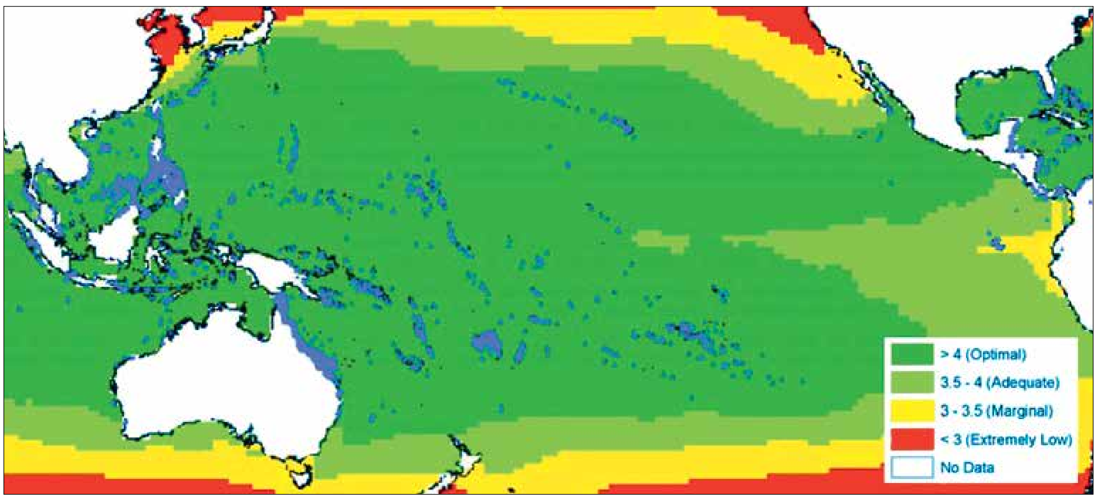
where dissolved calcium $[Ca^{2+}]$ is the seawater concentration of dissolved calcium ions, $[CO_3^{2-}]$ is the seawater concentration of carbonate ions, $[CaCO_3]$ is the solubility of aragonite in seawater, and Ω is the calculated saturation state.

When $\Omega = 1$, the seawater is exactly in equilibrium or saturation with respect to aragonite. In other words, the aragonite does not in a net way dissolve or precipitate. In relation to equation (1), equilibrium means that the forward precipitation reaction, left to right, and the backward dissolution reaction, right to left, are equal in their rate so there is no net precipitation or dissolution. When $\Omega > 1$, the seawater is said to be oversaturated with respect to aragonite. In this case, aragonite may precipitate or follow the left to right chemical reaction of equation (1). When $\Omega < 1$, the seawater is said to be undersaturated with respect to aragonite, which may result in the aragonite mineral dissolving or following the right to left chemical reaction of equation (1).

When carbon dioxide is added to surface seawater from the atmosphere, the acidity of the surface seawater increases. If the surface acidity increases, then there is relatively less carbonate ion (CO_3^{2-}) in seawater, and thus the value of Ω decreases and so does the saturation state of seawater with respect to aragonite.

tropical Pacific shift to marginal conditions. Field studies show coral reef carbonate accretion is severely retarded, even approaching zero or becoming negative, at aragonite saturation states of approximately 3.3.

A recent field study in Papua New Guinea gives a glimpse of how future acidification could impact marine reef ecosystems (Figure 2-17). Coral reefs, seagrasses, and sediment in the local "champagne reefs" are experiencing effects of seawater acidification due to natural volcanic CO_2 seeps that reduce seawater pH from the normal value of 8.1 to a value of 7.8. This decrease in pH is representative of surface waters in equilibrium with an atmosphere CO_2 value of 750 ppm, which is projected for the end of the 21st century at an atmospheric CO_2 value of 750 ppm. The reefs were found to have reduced coral diversity, recruitment, and abundances of structurally complex framework builders compared to reefs under higher pH conditions. Furthermore, there were shifts in the community composition as some organisms benefit, while others are negatively impacted, at the lower seawater pHs. This community shift is similar to how these communities respond to bleaching events. As a result of bleaching, macroalgae can flourish upon the loss or death of coral which provides space for macroalgal settlement. Extrapolating from this field study, reef development is predicted to cease when seawater pH drops below 7.7. Ironically, nearby "healthy" reefs (i.e., those not impacted by CO_2 seep



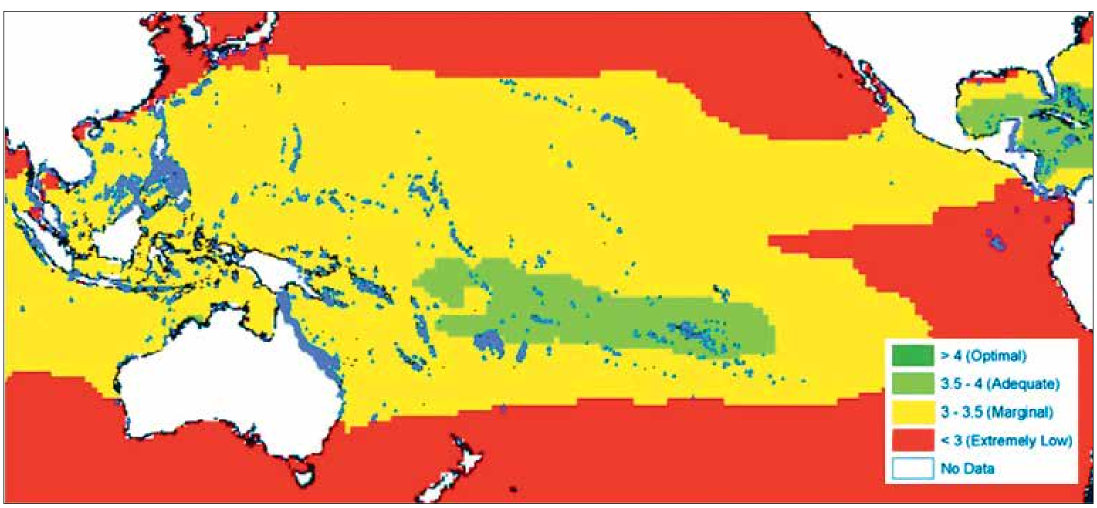


Figure 2-16. Aragonite saturation state for the years (top) 2000 to 2009 with pCO_2 = 375 ppmv, and (bottom) 2050 to 2059 with pCO_2 = 492 ppmv. Note how that for most of the western tropical Pacific and Hawai'i that saturation states go from > 4 (Optimal) to values between 3 to 3.5 (Marginal), which will provide additional stress to corals. Reprinted from Coral Reefs, 22, Guinotte, J.M., Buddemeier, R.W., and Kleypas, J.A., Future coral reef habitat marginality: temporal and spatial effects of climate change in the Pacific basin, 551-558, 2003, with permission from Springer.

driven seawater acidification) supply coral larvae that help replenish the reefs in the acidified regions. Without the supply of larvae, it is likely the reefs in the acidified areas would no longer be viable.

Figure 2-17. Champagne Reefs Papua New Guinea. Reprinted from Nature Climate Change, 1, Fabricius, K.E., Langdon, C., Uthicke, S., De´ath, G., Okazaki, R., Muehllehner, N., Glas, M.S., and J.M. Lough, Losers and winners in coral reefs acclimatized to elevated carbon dioxide concentrations, 165-169, 2011, with permission from Nature Publishing Group.

E. Management Implications

Marine protected areas (MPAs) are geographically defined areas with some level of restrictions placed on human activities with the intent of conserving and managing the natural marine environment and ecosystem. MPAs can be effective tools used to preserve coral reefs and their associated biodiversity and are found employed in various formulations throughout the world. Designing an effective MPA plan for coral reef preservation requires consideration and awareness of many factors. For instance, one important factor is accounting for the larval dispersal patterns of the corals and the associated fisheries. Preliminary evidence suggests that future changes in climate, ocean surface currents and circulation, SST, etc. could reduce the average dispersal distance of coral larvae. This reduction in dispersal reduces the spatial scale of larval connectivity between coral populations in, and between, protected areas. Incorporation of population connectivity, changes in viable habitat location and recruitment, anthropogenic pressures, etc. are examples of important considerations for the design and implementation of successful MPAs with respect to the negative impacts of future climate change and the sustainability and conservation of coral reefs.

F. Summary

Worldwide coral reefs are under tremendous strain. Table 2-2 summarizes some of the projected impacts of climate change on coral reefs. If current trends continue, by the year 2020 many of the world's reefs could be significantly deteriorated. Coral reefs are already being negatively impacted by human activities (e.g., overfishing, runoff and sedimentation, etc.). Additionally, we are beginning to see the first negative impacts of human-induced global climate change on the coral reef structure via increases in sea level, SST, and ocean acidification. These changes will only accelerate as the atmospheric CO_2 concentration increases due to human-related activities and emissions through the next century. Degradation of coral reefs also results in changes in community structure where non-coral species (e.g., macroalgae) become more prevalent to the point of dominating the reef environment. Now that we know how climate change potentially can lead to changes in the reef structure community, the next question is how will these changes impact associated reef fisheries? This is the focus of the next chapter.

Table 2-2. Summary of some present and future negative influences of climate change on coral reefs.

Variable	Effect
Light	Reduced light levels from sea-level rise reduces photosynthetic effectiveness of corals
Sea Level	Elevated sea level increases damage by storm waves and currents on reef structure
Ocean Acidification	Increased acidity negatively impacts the coral structure and thus habitat and community for reef fisheries
Temperature	Elevated temperature events, even for short periods, can result in bleaching events that kill

Some suggested readings:

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Bell, J.D., Johnson, J.E., and Hobday, A.J. 2011. Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change. Secretariat of the Pacific Community, Noumea, New Caledonia. [Accessed 19 November 2011]. http://cdn.spc.int/climate-change/fisheries/assessment/e-book/indexcdn.html

Burke, L., Reytar, K., Spalding, M., and Perry, A. 2011. Reefs at Risk Revisited. World Resources Institute. 130pp. Accessed 1 October 2011. <http://www.wri.org>

Carpenter, K.E., Abrar, M., Aeby, G., Aronson, R.B., and others. 2008. One-third of reef-building corals face elevated extinction risk from climate change and local impacts. Science. 321. p. 560-563.

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Denman, K., Christian, J.R., Steiner, N., Pörtner, H-O., and Nojiri, Y. 2011. Potential impacts of future ocean acidification on marine ecosystems and fisheries: current knowledge and recommendations for future research. ICES Journal of Marine Science. 68. p. 1019–1029.

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Hughes, T.P., Baird, A.H., Bellwood, D.R., Card, M., Connolly, S.R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J.B.C., Kleypas, J., Lough, J.M., Marshall, P., Nystrom, M., Palumbi, S.R., Pandolfi, J.M., Rosen, B., Roughgarden, J. 2003. Climate change, human impacts, and the resilience of coral reefs. Science. 301. p. 929–933.

Munday, P.L., Leis, J.M., Lough, J.M., Paris, C.B., Kingsford, M.J., Berumen, M.L., and Lambrechts, J. 2009. Climate change and coral reef connectivity. Coral Reefs. 28. p. 379-395.

Veron, J.E.N., Hoegh-Guldberg, O., Lenton, T.M., Lough, J.M, Obura, D.O., Pearce-Kelly, P., Sheppard, C.R.C., Spalding, M., Stafford-Smith, M.G., and Rogers, A.D. 2009. The coral reef crisis: the critical importance of 350 ppm CO_2. Marine Pollution Bulletin. 581. p. 428–1436.

III. Coral Reef Fisheries and Climate Change

In the previous sections of this study, we reviewed how future projected climate change and subsequent changes in light, sea level, sea surface temperature and sea water acidity can have negative impacts on the reef structure. The reef structure is home to an expansive biological community and many coastal human communities of the tropics and subtropics depend on the reef ecosystem to provide some level of subsistence. An important component of this subsistence is derived from the reef-related fisheries. If the coral reefs are negatively impacted by climate change, then it stands that the dependent reef fisheries will also be negatively impacted to some degree. In addition to climate change driven impacts on the coral reef itself, there are climate change driven impacts on coral reef fish and fisheries through effects on biodiversity, recruitment dynamics, population connectivity, and species performance. Other factors that impact reef fishery viability are those related to human activities such as fishing practices, coastal sediment and nutrient inputs, and overexploitation of the resource. These and other human-related processes are important as they contribute to the collective negative pressure on tropical and subtropical reef fisheries.

A. Human-Related Pressures on Reef Fisheries

The negative effects of climate change on coral reefs themselves will be compounded by other

Table 3-1. Some types, sources, and potential effects of pollution on the coastal marine ecosystem.

Type	Source	Effect
Nutrients	Runoff: approximately 50% from sewage; 50% from forestry, farming, and other land use. Also airborne nitrogen oxides from power plants, cars, etc.	Feed algal blooms in coastal waters. Decomposing algae depletes water of oxygen, killing other marine life. Can spur toxic algal blooms (red tides), releasing toxins that can kill fish and poison people.
Sediments	Erosion from mining, forestry, farming, and other land use; coastal dredging and mining.	Cloud water; impede photosynthesis below surface waters. Clog gills of fish. Smother and bury coastal ecosystems. Carry toxins and excess nutrients.
Pathogens	Sewage, livestock.	Contaminate coastal swimming areas and seafood, spreading cholera, typhoid, and other diseases.
Alien Species	Alien species are typically transported either by ballast water or hull fouling; also spread through canals linking bodies of water and fishery enhancement projects.	Outcompete native species and reduce biological diversity. Introduce new marine diseases. Associated with increased incidence of red tides and other algal blooms. Problem in major ports.
Persistent toxins (PCBs, DDT, heavy metals, etc.)	Industrial discharge; wastewater from cities; pesticides from farms, forests, home use, etc.; see page from landfills.	Poison or cause disease in coastal marine life, especially near major cities and industry. Contaminate seafood. Fat-soluble toxins that bioaccumulate in predators can cause disease and reproductive failure.
Oil	46% from cars, heavy machinery, industry, other land-based sources; 32% from oil tanker operations and other shipping; 13% from accidents at sea; also offshore oil drilling and natural seepage.	Low-level contamination can kill larvae and cause disease in marine life. Oil slicks kill marine life, especially in coastal habitats. Tar balls from coagulated oil litter beaches and coastal habitat. Oil pollution is down 60% from 1981.
Plastics	Fishing nets; cargo and cruise ships; beach litter; wastes from plastics industry and landfills.	Discarded fishing gear continues to catch fish. Other plastic debris entangles marine life or is mistaken for food. Plastics litter beaches and coasts and may persist for 200 to 400 years.
Radioactive isotopes	Discarded nuclear submarines and military waste; atmospheric fallout; also industrial wastes.	Hot spots of radioactivity. Can enter food chain and cause disease in marine life. Concentrate in top predators and shellfish, which are eaten by people.
Thermal	Cooling water from power plants and industrial sites.	Kill off corals and other temperature-sensitive sedentary species. Displace other marine life.
Noise	Supertankers, other large vessels, and machinery	Can be heard thousands of kilometers away under water. May stress and disrupt marine life.

Table 3-2. Metric tonnes of marine debris removed from the NWHI from the year 1996 to 2009 by NOAA and its partners. Amounts have been rounded to the nearest metric tonnes. 1MT is approximately 2,205 pounds.

Year	'96-'97	'98	'99	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09
MT	4	8	25	22	62	97	107	112	52	19	31	62	68

anthropogenic factors causing further reef, and subsequently reef-related fishery, degradation. Fishing practices that damage both the reef and associated fisheries and pollution have already caused large scale problems for the world's coral reefs. Pollution comes in various forms including land-derived sources, which include waste, chemicals (e.g., pesticides, heavy metals), nutrients (e.g., nitrogen and phosphorus), and sediment runoff (Table 3-1).

Pollution also includes marine debris – e.g., plastics, fishing nets, glass, metal, etc. – and has been a big problem for the Northwestern Hawai'i Islands (NWHI) and the health of its reefs, which are not heavily impacted by the various aforementioned forms of land-based pollution given they are mostly uninhabited. Table 3-2 shows the amount of debris removed from the NWHI by NOAA and its partners.

Overexploitation of reef fisheries (including reef-related fish, crustaceans, and mollusks) is also a large negative pressure on the health of current reef fisheries. Reef fishery diversity, function, structure, and ultimately resilience are all negatively impacted by overexploitation of the resource. One recent study calculated that approximately 55% of the world's island coral reef-related fisheries are being exploited at an unsustainable level. In fact, to maintain the present day catch demands on reef fisheries in a sustainable, non-exploitive manner would require an additional 75,000 km^2 of productive coral reef area somewhere in the ocean. This surface area is almost equivalent to the combined surface area of four Great Barrier Reefs of Australia. Island population per unit of coral reef area has been shown to be a good predictor and measure of fishing effort and the associated impacts of this fishing effort on reef fisheries. The degree to which reef fisheries are being exploited in the tropical and subtropical Pacific varies from location to location. American Samoa, Samoa, Fiji, Guam, and the Solomon Islands are all considered fully or overexploited while the Marshall Islands, Papua New Guinea, and Tonga are generally considered underexploited (Figure 3-1). Although coral reef fisheries only account for two to five percent of the global fish catch, their importance lies not just in their commercial value and financial impact on the local communities, but also in their contribution to the dietary and cultural needs of the coastal inhabitants. These pressures add to the impacts of climate change induced changes in SST, ocean acidification, sea-level rise, and ocean circulation on reef fisheries that we now review in further sections.

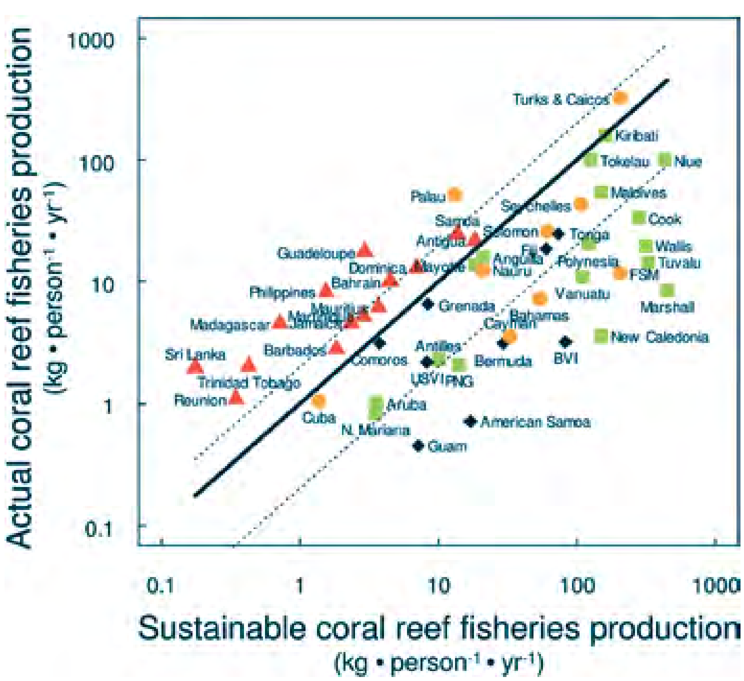

Figure 3-1. Current coral reef production versus sustainable coral reef fisheries production. Islands above and to the left of the solid black line are unsustainable at their current rate of coral reef fishery production. Present day island reef fisheries status is represented by four symbols. Green squares = underexploited. Orange circles = fully exploited. Red triangles = overexploited. Black diamonds = collapsed. Reprinted from Current Biology, 17, Newton, K., Côté, I.M., Pilling, G.M., Jennings, S., and N. Dulvy, Current and Future Sustainability of Island Coral Reef Fisheries, 655-658, 2007, with permission from Elsevier.

B. Sea Surface Temperature

The IPCC estimates that future global average surface atmospheric temperature will rise between 1.1 to 6.4 °C by the year 2100 with the range of 1.8 to 4.0 °C being most probable. With this projected increase in global average surface temperature, sea surface temperatures of tropical waters are expected to increase by 50 to 80% of the atmospheric temperature change. Using the lower 50% estimate, the result is an average sea surface temperature (SST) increase of 0.9 to 2.0 °C based on the 1.8 to 4.0 °C warming estimate. In addition, this increase will not occur uniformly geographically and there will be regional and local variability in this SST increase. For example, the equatorial western Pacific may warm more slowly than other tropical areas even though it is already one of the warmest parts of the equatorial Pacific.

In terms of the potential climate change effects on Pacific coral reef fisheries, we will discuss upper ocean water warming, ocean acidification, changes in ocean circulation, storm intensity and frequency, and sea level. Water temperature effects on fish species are likely the most understood although there is still much that is unknown. Many reef fish species, unlike coral species, are presently not at, or near, their lethal temperature limit threshold. The projected future increase in SST though could have significant impacts on species biomass and biodiversity. Fish are primarily ectotherms, which means that they cannot control their body temperatures through internal mechanisms. Instead their body temperatures match the temperatures of their environments and are thus externally controlled. Pelagic tunas are one exception as they are partially endothermic. Since most fish are ectotherms, small changes in water temperature can impact their physiological condition, development and growth rate, swimming ability, reproductive performance and behavior. Additionally, fish are poikilothermic (e.g., cold-blooded) and thus increasing environmental temperatures elevate their metabolic rates requiring greater amounts of food to sustain themselves. Many coral reef fish species have wide geographical ranges that in turn span large temperature gradients. In addition, these species have short generation times so it is possible that these species may be able to acclimate, to a certain extent, to future climate change or be able to genetically evolve rapidly enough to manage the temperature changes associated with climate change.

Fish are very sensitive to temperature change when they are developing early in their life history. Embryonic development rates for many non-tropical species increase as temperature increases rapidly enough so it is possible that tropical fish will have the same response. Once the embryo has hatched, increased temperature tends to result in an increase in larval growth rate and an increase in swimming ability. Elevated temperature has been show to shorten the larval duration and growth rates of anemone fish and wrasse species (Figure 3-2). While the decreased larval duration and increased growth rates may be a beneficial impact of increasing SST, the same temperature increase may also increase larval mortality rates. The effects of elevated temperatures on the life history stages of reef fish species are not well known and represent a significant gap in our knowledge.

Tropical reef fish species can be highly sensitive to temperature fluctuations and if the species is close to its thermal optimum for reproduction then small changes in temperature could have positive or negative effects. Tropical reef fish also often breed throughout large parts of the year and if their thermal maximum for reproduction is exceeded for long periods of time, then the long-term viability of the overall population is at risk. Some species breed once a threshold temperature has been reached and thus elevated temperatures could mean an earlier start to the breading season for those species, which could be beneficial or deleterious.

Figure 3-2. Red Tailed Wrasse (Photo Credit: USFWS).

1. Loss of Coral Cover, Habitat, and Shifts in Community Structure

Due to coral bleaching and ocean acidification from climate change, coral reefs will be further degraded in the future. Past coral bleachings have resulted in shifts in the benthic community structure, which in turn leads to changes in the reef fish communities (Figure 3-3). With bleaching events, coral reef fish species richness is seen to decrease immediately due to the loss of coral reef fish species that are heavily dependent on live coral. These coral, which are now dead, also physically degrade over the next several years reducing reef topographic complexity and thus habitat complexity. This loss in habitat complexity leads to a further decline in species richness. Initially after the bleaching process, there is also an increase of macroalgal cover as macroalgal species settle and colonize the dead coral surface. Although some herbivorous fish species can increase in numbers after a bleaching event in response to the short-term increase in macroalgal cover, they will eventually decline in population over the long-term, even below their pre-bleaching numbers, once the coral reef habitat structure is eroded. Overfishing of herbivorous fish can further exacerbate the post-bleaching impacts of macroalgal cover and the subsequent ability of the reef to recover because even healthy herbivore populations are not necessarily able to control rapid (e.g., after a bleaching event) macroalgae proliferation.

Although the relative proportion of reef fish assemblages vary, in terms of coral versus non-coral dependent fishes, from locale to locale and region to region, in general, approximately 10% of the general coral reef fish population is dependent on coral substrate. With the loss or damage of coral (e.g., bleaching) the coral dependent fish are the first and most severely impacted. Coral dependent species can require the physical structure and complexity of a coral reef for dwelling and habitat or actually consume coral. Corallivores, those fish that consume coral, are either obligate, which means they exclusively feed on coral, or are facultative, which means they feed on corals, algae, sponges, and mollusks. Coral reef fish species that are dependent on one species, for habitat or consumption or both, may bear the largest initial brunt of coral destruction and decline in coral cover as they are unable to adjust and use other available alternative coral resources. While only approximately 10% of the coral reef fish population is directly dependent on corals, up to 75% of the remaining coral reef fish species have been observed to drop in population abundance by up to 50% immediately after a reef is damaged.

Structural complexity tends to decline after a coral bleaching event as the damaged coral itself is eroded by physical (i.e., wave and current action) and biological processes. Reefs composed of coral species with greater structural complexity support a

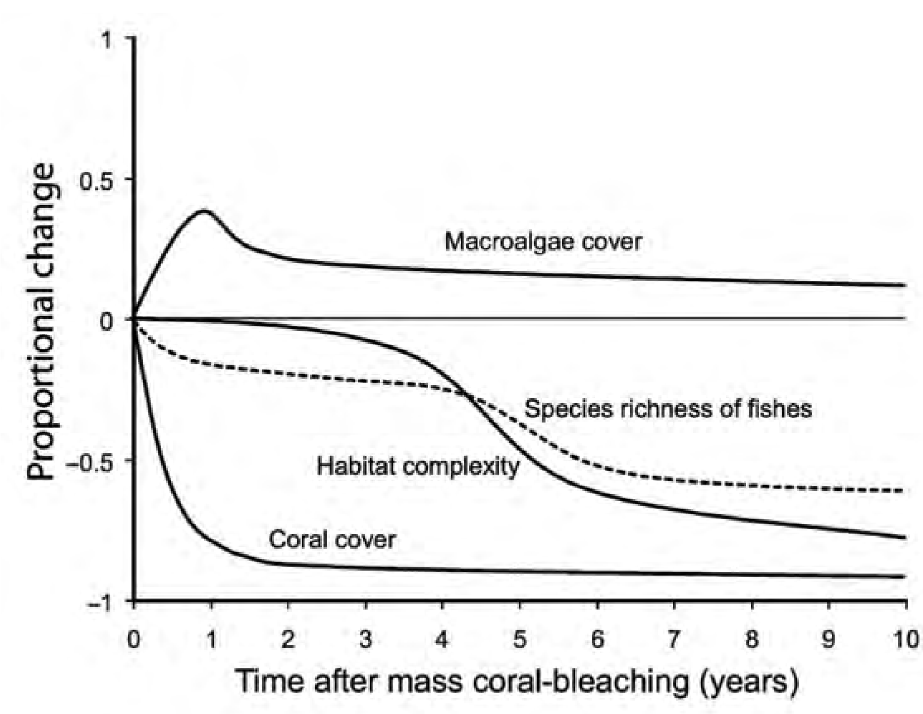

Figure 3-3. Conceptual diagram of changes in coral cover, fish communities, species richness, and macroalgae cover in response to a major bleaching event. Reprinted from Fish and Fisheries, 9, Munday, P.L., Jones, G.P., Pratchett, M.S., and A.J. Williams, Climate change and the future for coral reef fishes, 261-285, 2008, with permission from Blackwell Publishing Ltd.

greater diversity and abundance of reef fish species. In addition, coral species with greater structural complexity can have a greater propensity for bleaching versus structurally simple corals. Coral reef habitats such as those found offshore of most tropical island states with their relative abundance of hydrocoral (*Millepora* spp.), pocilloporid, and acroporids (*Acropora* spp.) species may be at additional risk. It is important to note that even between species within a genus that there is variability in damage due to a bleaching effect, so to determine the exact degree of impact from bleaching from location to location and even within the same location is difficult.

Reef fish communities have demonstrated the ability to rebound from habitat destruction and disturbance caused by storms, coral bleachings, and destruction by organisms (e.g., crown-of-thorns), if the coral reef structure and habitat ultimately can recover. One major concern is that the external pressures exerted by climate change and population growth will not allow for habitat resettlement and growth after regular large-scale destructive events. In American Samoa, live coral cover in the late 1970's was estimated at more than 60% with crustose calcareous algae second in prominence. As of 2007, live coral cover was about 30% and crustose calcareous algae were more abundant. Since the late 1970's, the reefs have experienced many disturbances including crown-of-thorns sea star outbreaks (1978), hurricanes (1986, 1990, 1991, 2004, 2005), and mass coral bleachings (1994, 2002, and 2003). It unclear if this change in benthic structure is or is not due to a culmination of long-term pressures exerted by these stressor events, if the present partitioning is part of a long-term cycle, a combination of the two, or some other forcings.

2. Geographic Range Shifts

As climate change impacts the oceans, especially via changes in SST, the geographic distribution of fish species is already shifting or is expected to shift. Upper temperature ranges and rates of thermal acclimation by fish species determine how species will react to changes in ocean temperatures. Sudden changes in temperature, either increases or decreases, can have a severe impact on fish populations, especially if for some reason the population is unable to find a new, suitable habitat with the necessary temperature range. Range shifts as a result of climate change have already been observed for temperate and subtropical fish species such as damselfish in rocky reef environments and the same is expected to occur for coral reef fish species. Poleward migration of tropical coral reef fish into temperate waters off the coast of southeast Australia is effectively blocked by winter water temperatures that are below survival thresholds, but future winter temperate water temperatures are expected to increase enough to allow for a shift in range of these species.

We can use our understanding of butterfly fish species to investigate the possible impacts of tropical seawater temperature changes on coral reef species (Figure 3-4). Note that these example species are from the same family. The likelihood of a species either extending or contracting its geographical range depends on many factors including its thermal tolerance, ability to acclimate, how other parts of the ecosystem it interacts with react to the temperature changes, alterations in current patterns and reef distribution, etc. Of particular note for island situations like Hawaiʻi, which is geographically isolated and has high levels of endemic coral reef fish species, is the species *C. trichrous* (see Figure 3-4 d). This species is indicative of a small geographic range reef species that is near the temperature limit (e.g., relatively high latitude) of coral reef development. It is likely that these types of species will incur further range limitation with increasing water temperatures which, at worst case, ultimately results in the extinction of species.

C. Ocean circulation, Extreme Weather, and Sea-Level Rise

1. Ocean Circulation

Climate change is expected to impact ocean circulation, upwelling, downwelling, and currents around the world with both the changes and the magnitude of these physical processes varying from region to region. Additionally, thermal stratification of the ocean's surface layer, which will reduce surface water mixing and upwelling, will likely increase. This increased stratification will reduce the flux of nutrients via upwelling that feeds the phytoplankton and zooplankton that form the base of the marine food web. Changes in productivity and thus the food base for larval reef fish will impact their growth

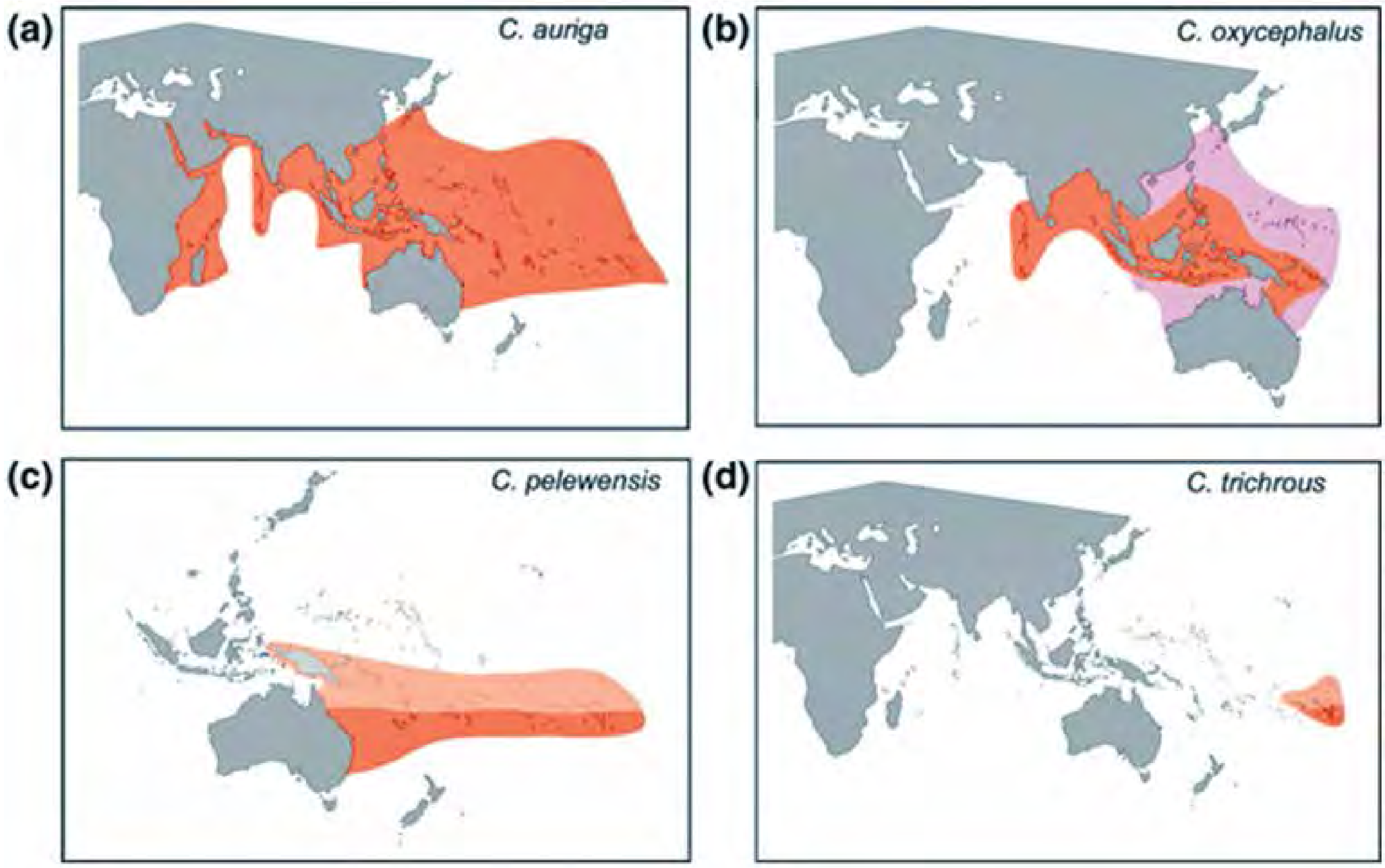

Figure 3-4. Examples of potential range shifts that could occur among four species of butterfly fish in the genus Chaetodon [(a) C. auriga; (b) C. oxycephalus; (c) C. pelewensis; (d) C. trichrous] as sea temperatures increase. Orange shading represents existing range, purple represents possible range expansion and faded orange represents possible range contraction. (a) Existing geographical range spanning the latitudinal extent of coral reef development – range shift unlikely to occur. (b) Existing geographical range centered near the equator and not extending to the latitudinal extent of coral reef development – range expansion possible. (c) Existing geographical range centered near mid-latitudes, often reaching the latitudinal extent of coral reef development – range contraction likely. (d) Existing small range near the latitudinal extent of coral reef development – range contraction leading to serious reduction in area is possible. Species selected for illustrative purposes only. Reprinted from Fish and Fisheries, 9, Munday, P.L., Jones, G.P., Pratchett, M.S., and A.J. Williams, Climate change and the future for coral reef fishes, 261-285, 2008, with permission from Blackwell Publishing Ltd.

and survival. The changes in heat content and its distribution of the atmosphere and surface ocean layer will also impact the average prevailing winds at the ocean surface by changing one or both in their direction or magnitude. Major surface ocean currents may intensify further as the stability of the surface water layer increases due to thermal stratification, thus reducing friction to the current. Changes in current patterns will impact the dispersal patterns of larval reef fish.

2. Extreme Weather

Climate change will undoubtedly alter global ocean circulation, upwelling and downwelling, and general atmospheric circulation along with the frequency and intensity of large scale weather patterns (e.g., El Niño) and storms (e.g., hurricanes and cyclones). Figure 3-5 depicts how storminess is projected to change in the tropical and subtropical Pacific. Tropical storms can cause a short-term reduction in the abundance of reef fish by altering, reducing, and destroying their habitat and food sources. The reef fish populations can recover, although this process may take years to occur. Generally speaking, the stronger the storm the worse the impacts for the reef community; furthermore, storms will tend to amplify reef community problems that result from pre-existing disturbances.

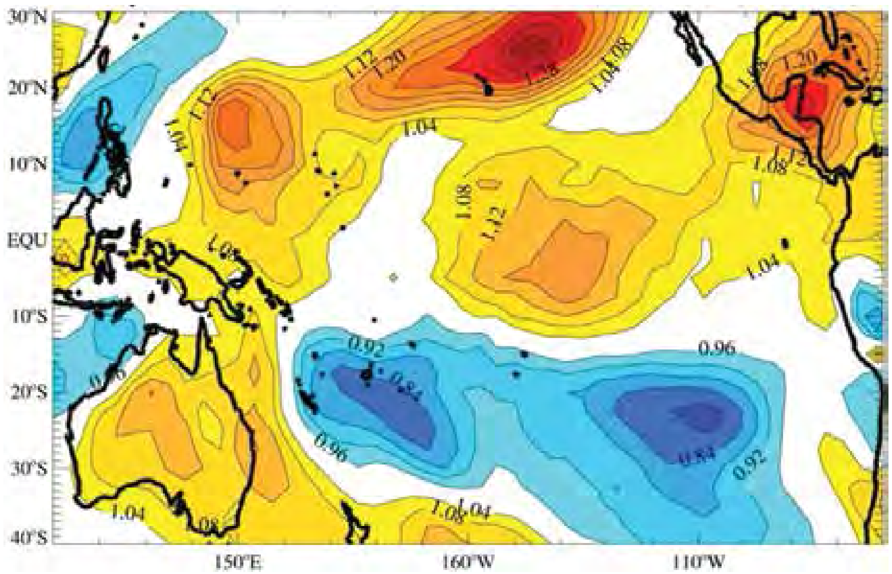

Figure 3-5. Projected sea level pressure (SLP) ratios during winter months for the period between 2070-2100. SLP ratios >1 indicate more storminess in the future. Reprinted from Shea, E.L., Dolcemascolo, G., Anderson, C.L., Barnston, A., Guard, C.P., Hamnett, M.P., Kubota, S.T., Lewis, N., Loschnigg, J., and G. Meehl. Preparing for a changing climate. The potential consequences of climate variability and change. A report of the Pacific Islands Regional Assessment Group. East-West Center. 102pp.

3. Sea-Level Rise

Sea level is rising presently due to two major factors: (1) thermal expansion of the oceans due to the atmospheric warming, and (2) melting of glacial ice that is on land. Melting of ocean icebergs does not cause a change in sea level as these icebergs have already displaced the volume of seawater that is commensurate with their mass. However, even with worst case scenarios of warming and subsequent sea-level rise from melt water and thermal expansion, it is unlikely that changes in sea level during the next fifty to one hundred years will negatively directly impact coral reef fish species. Many coral reef fish species tend to have depth ranges greater than even extreme projected sea level changes and in addition many of the fishes are subjected to sea level fluctuation, via tides, that are greater than the changes projected for the next fifty to one hundred years. Sea-level rise will have a much greater impact indirectly on coral reef fish species if it impacts the reef structure itself (e.g., through increased turbidity) since these fish depend on the reef for their habitat (see Figure 1-10).

D. Ocean Acidification

Little research has been conducted on the effects of decreasing pH on reef fish species. The uptake of anthropogenic carbon dioxide since 1750 has reduced the pH of the ocean by 0.1. Depending on the IPCC model results used, atmospheric CO_2 levels are projected to reach concentrations roughly between 500 to 1000 ppm by the year 2100, which would correspond in a reduction of average global surface ocean pH up to ~ 0.4 pH units. This translates into an increase in H^+ ions of up to 150%. At these reduced pH levels, the surface ocean will be more acidic than at any time during the past 400,000 years. At an atmospheric CO_2 concentration of approximately 600 ppm, areas of the global ocean surface water are projected to become undersaturated with respect to aragonite. Laboratory experiments have demonstrated the impacts of the projected level of CO_2 on surface seawater pH on carbonate mineral compositions such as pteropod shells (Figure 3-6), coralline algae, and corals. Given the lack of information on acidification effects on tropical fish, we can use impacts on freshwater fish as a proxy. The acidification of lakes has negatively impacted the reproductive success, growth rate, and ultimately survival of freshwater fish species. Coral reef fish species have evolved in a less dynamic pH environment compared to freshwater fish and so may be more sensitive to pH changes resultant from climate change compared to freshwater fish.

Acidification of surface waters can also increase the acidity of fish tissue. The internal pH in fish is controlled by ion exchange and fish have the ability to regulate small changes in internal pH. This internal tissue pH regulation though comes at a metabolic cost adding to the already elevated metabolic demands imposed by elevated water temperatures. Additionally, with increased acidification comes the accompanying reduction in the concentration of carbonate ion. Decrease in carbonate ion concentration can impact invertebrate larvae skeletal or otolith development during embryonic or larval stages. Carbonate ion concentrations commensurate with the projected

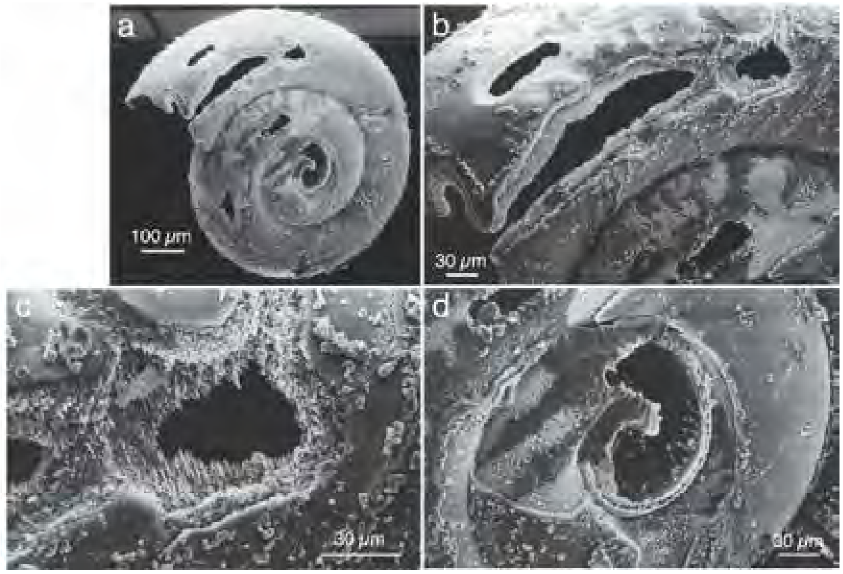

Figure 3-6. Pteropod shell dissolution when reared at 3 °C and 1100 μatm. Reprinted from Biogeosciences, 8, Lischka, S., Büdenbender, J., Boxhammer, T. and U. Riebesell, Impact of ocean acidification and elevated temperatures on early juveniles of the polar shelled pteropod Limacina helicina: mortality, shell degradation, and shell growth, 919-932, 2011, with permission from Copernicus Publications.

lower surface water pH for the year 2100 have been shown in experiments to reduce skeletal larvae calcification rates. Alteration or disruption of skeletal or otolith development by acidification could negatively impact larvae, for example, by reducing swimming and feeding efficiencies. In one recent study, juvenile clownfish reared under IPCC projected elevated CO_2 conditions for the years of 2050 and 2100 displayed an absence of avoidance behavior in response to exposure to reef noise that is normally used as an auditory proxy for reef predators. In the same study, juveniles reared under present CO_2 conditions, as expected, significantly avoided the reef noise. So acidification can possibly impact the early survivability of juvenile reef fish like the clownfish.

E. Possible Adaptations to Climate Change

The ability of reef fish species to adapt to climate change is determined by how reactive these species are to climate change impacts. Geographic range, temperature tolerances, generation times, and how well species are able to pass beneficial genetic characteristics between geographically distinct populations are examples of species-specific traits that factor into how well species will cope with climate change impacts. Species with large temperature survival ranges coupled with large geographic ranges have potentially the best ability to adapt and adjust to increases in temperature. Many tropical coral reef fish exhibit geographic ranges that span 2 to 3 °C and therefore may be able to acclimate to increases in surface ocean temperature caused by future climate change. The ability to pass on genetic information (i.e., genetic connectivity) is also critical because populations that have traits allowing them to adapt better to climate change can pass them on to other geographically distinct populations. Isolated populations, such as those in Hawaiʻi or the central Pacific, will likely have more difficulty acclimating or adapting because they will not benefit from the transfer of genes. The ability to incorporate traits of other populations is also dependent on generation time, which varies depending on the coral reef species. Some gobi species have generation times on the order of a year. Short generation times like this allow for many gene selection opportunities in the near future. Other species that are late maturing, such as snappers, and thus have long generation times, will not benefit as much from genetic adaptions.

F. Management Implications

Management strategies for mitigating the short and long-term effects of climate change on coral reef fisheries should first target impacts from other sources, mainly anthropogenic. Examples of these sources of negative impacts include overfishing and runoff of sediment, waste, and nutrients from terrestrial sources that can negatively impact both the coral reef and the reef fisheries. These types of negative impacts serve to weaken and/or retard the reef and reef fishery from dealing with, and recovering from, other negative forcings.

Currently, Marine Protected Areas (MPAs) are used in an attempt to protect reefs and their associated fisheries. However, the biological, chemical, and

physical conditions necessary for healthy reefs and associated fisheries are not necessarily located within presently defined MPA geographical boundaries. With climate change, the geographical location of these environmental conditions necessary may shift so that some or all important components (e.g., larval dispersal, breeding grounds, water temperature, etc.) of the coupled reef and reef fishery system are outside, or partially outside, of MPAs and thus are not protected. By monitoring and identifying shifts in geographical location of the environmental conditions necessary to support healthy reefs and reef fisheries, management can be proactive and anticipate how protected area boundaries can be shifted to accommodate the needs, as best possible, of the reef and reef fisheries.
How to manage reef fishery harvest under the impacts of future climate change is an important area to consider. We have seen how the recruitment of various reef fishery species will change with climate change. Reef fisheries are important contributors to subsistence fishing efforts of coastal communities. These communities are projected in many coastal areas to continue to grow in population during the next few decades placing the reef fishery resource under greater pressure. The combined fishing pressure coupled with the effect of climate change could result in a collapse in the reef-related fisheries. Imposing more control on harvest levels could build in some margin for minimizing fishing pressures on populations that are depleted from the combination of heavy fishing and low recruitment. The island of Bermuda's control policies of their reef fishery is an excellent example of how simply a reduction in the fishery by minimizing the fishing fleet and the setting up and enforcement of protected areas on the Bermuda platform have led to larger sustainable fish stocks. It is clear that climate change possibilities and their impacts on reef fishery populations need to be incorporated into any coral reef fishery management plan if the results are to be sustainable in the face of climate change and coastal population impacts.

G. Summary

As an example of present knowledge and given the variety of effects that climate change can have on fish species, Table 3-3 summarizes some examples of predicted shifts in fish species based on their present-day geographic regions. It is clear that climate change is going to impact fisheries worldwide and understanding how future climate change impacts the recruitment and populations of fishes is crucial to implementing management protocols that will minimize the negative impacts of climate change.

Table 3-3. Predicted changes in various fish populations associated with warmed habitats based on geographic regions. Reprinted and altered from Reviews of Fish Biology and Fisheries, 14, Roessig, J., Woodley, C.M., Cech, Jr., J.J., and L.J. Hansen, Effects of global climate change on marine and estuarine fishes and fisheries, 251-275, 2004, with permission from Springer.

Region	Species	Prediction
Polar	North Sea Cod, haddock, herring, and sardines	Possible shift in spawning times; alteration of bioenergetics; changes in transport of larvae
	Barents Sea cod and haddock	Changes in early life stages growth rates and recruitment levels
	Cod, haddock, plaice	Recruitment decreases off West Greenland with increasing temperature; changes in growth rates
Temperate	Pacific salmon	Distribution shifts northward; changes in size; decreased population
	Sockeye salmon	Distribution shifts towards the sub-Arctic
	Skipjack tuna (warm temperate)	Spatial shifts with temperature
	Atlantic Salmon	Distribution and survival changes
Tropical	Atlantic tropical reef species; pogies, snappers, sea bass, and skipjack tuna	Species shift into new areas and change in abundance
	Pacific reef species	Decrease in corallivore and coral nester abundance; increases in invertebrate feeders

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IV. Tuna Fisheries

A. Introduction

The Western and Central Pacific Ocean is home to the largest tuna fishery in the world with an estimated 55% of the world's total tuna catch (Figure 4-1). Many tropical Western and Central Pacific coastal communities interact in some capacity with near shore or pelagic tuna fisheries that are prominent in the region. Subsistence or commercial fishing, jobs related to tuna canning and loining plants, spin-off businesses, and social and environmental impacts are all ways that the fisheries influence Pacific island residents. Pacific-related tuna species are not evenly distributed geographically and vary across ecological zones based on their biological needs. The larger tropical pelagic fisheries that sustain canning practices are found concentrated in equatorial waters. There are several different techniques and types of equipment used in tuna fishing including purse-seining, long-lining, and pole-and-line (Figure 4-2). Purse-seining is responsible for most of the skipjack and yellowfin catch (Figure 4-3). The long-lining effort for tropical bigeye and yellowfin tuna is more dispersed as the species has a wider geographical and ecological range (Figure 4-4).

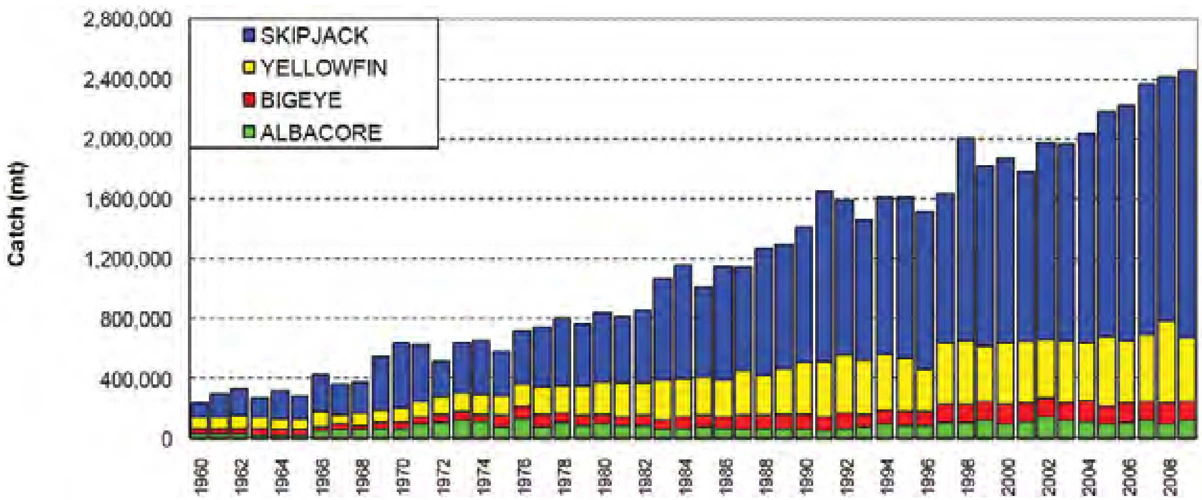

Figure 4-1. Yearly (from 1960 to 2009) commercial catch (subsistence catch not taken into account) in metric tonnes (mt) of skipjack, yellowfin, bigeye, and albacore tuna in the Western and Central Pacific. The subsistence catch is minor compared to the commercial catch. Reprinted from Tuna Fishery Yearbook 2009. Western and Central Pacific Fisheries Commission. Pohnpei, Federated States of Micronesia. 120pp.

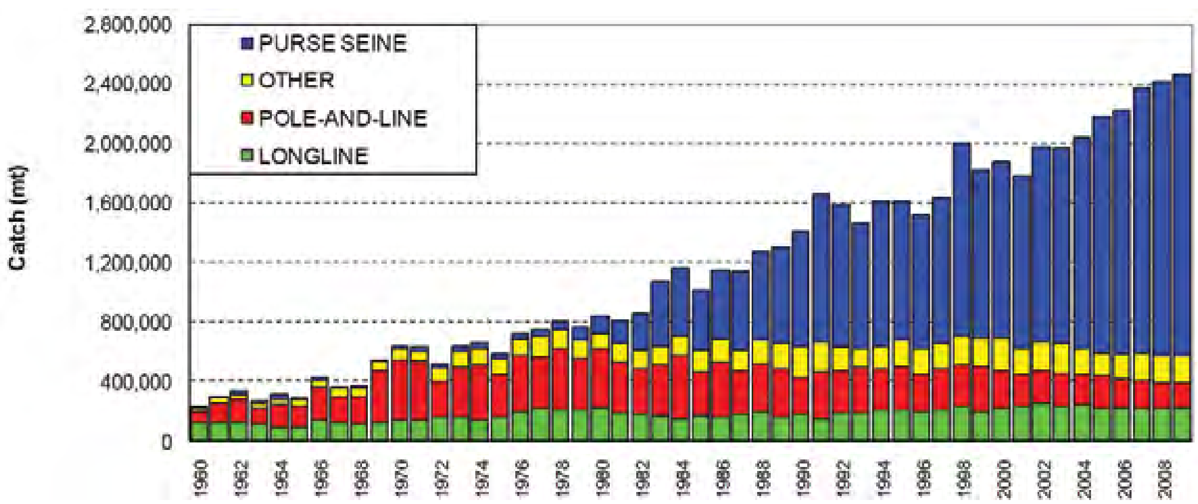

Figure 4-2. Western and Central Pacific tuna catch in metric tonnes (mt) per fishing equipment type and technique from 1960 to 2009. Reprinted from Tuna Fishery Yearbook 2009. Western and Central Pacific Fisheries Commission. Pohnpei, Federated States of Micronesia. 120pp.

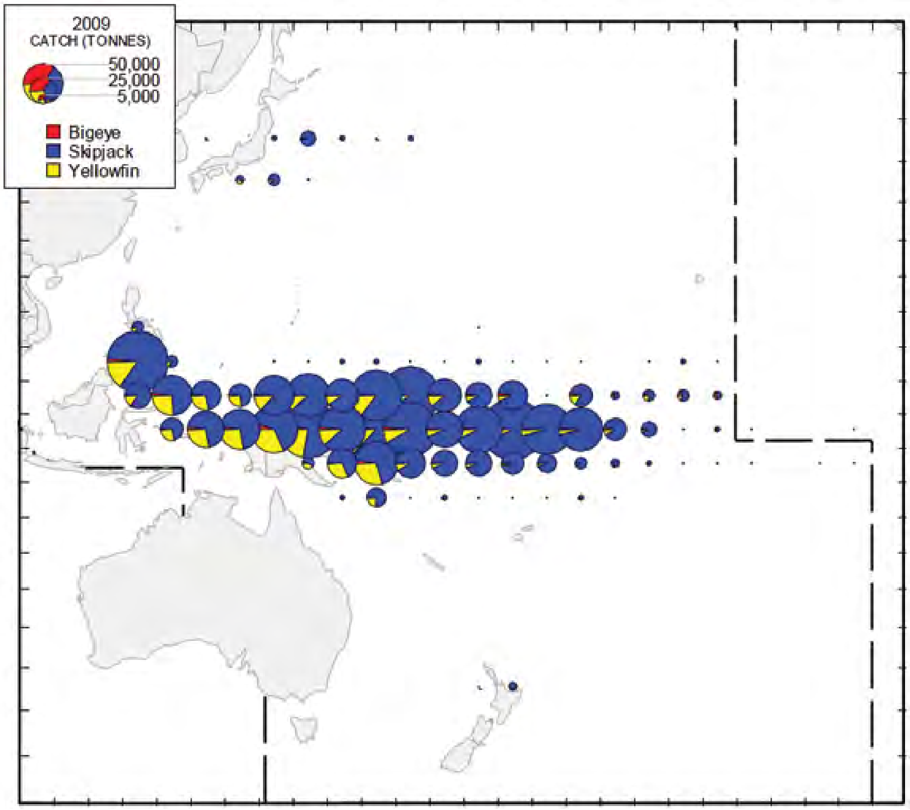

Figure 4-3. 2009 Purse-seine tuna catch in metric tonnes (mt) in the Western and Central Pacific Ocean. Note that the catch is concentrated around the equatorial Pacific and that skipjack (blue) is the largest portion of the catch followed by yellowfin (yellow). Reprinted from Tuna Fishery Yearbook 2009. Western and Central Pacific Fisheries Commission. Pohnpei, Federated States of Micronesia. 120pp.

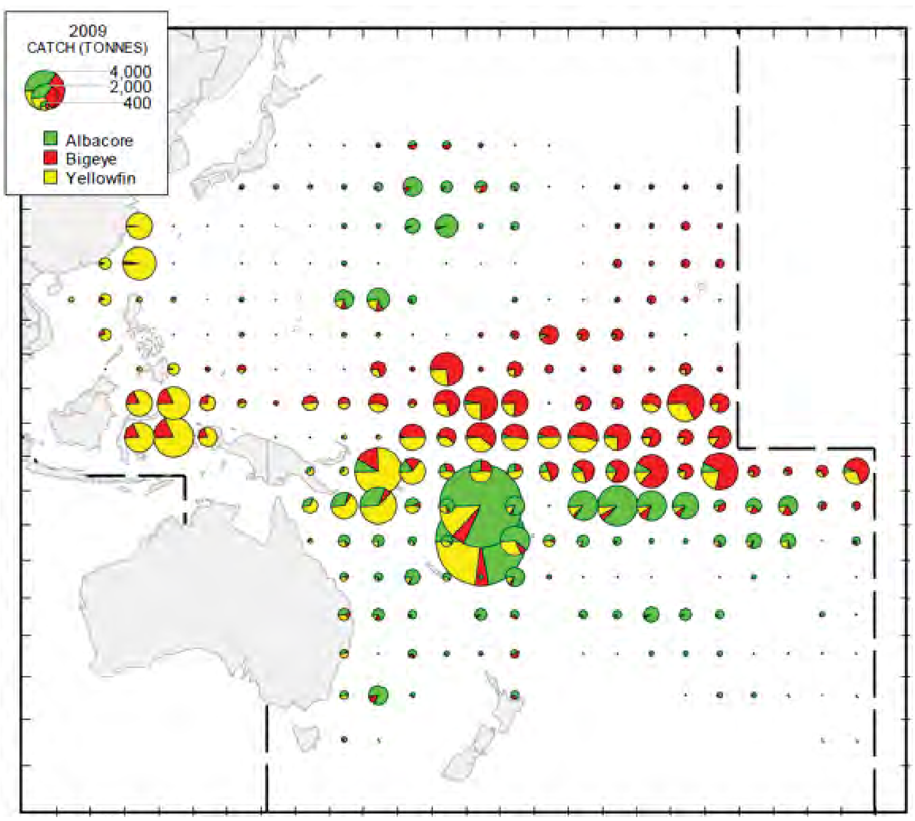

Figure 4-4. 2009 long-line tuna catch in metric tonnes (mt) in the Western and Central Pacific Ocean. Note that the catch area is more dispersed compared to the purse-seine, although the largest catch is still concentrated around the equator. Note also that the catch amount is much less than that from purse-seining. There is geographic variation in the species type and amount caught via long-lining with albacore (green) south of the equator, bigeye (red) north of the equator, and yellowfin (yellow) predominant in the western Pacific. Finally, note that the tonnage caught by long-lining is well below the tonnage caught from purse-seining. Reprinted from Tuna Fishery Yearbook 2009. Western and Central Pacific Fisheries Commission. Pohnpei, Federated States of Micronesia. 120pp.

Tropical tuna are a short-lived, fast swimming top predator species. Their high metabolism necessitates readily available access to abundant food sources. In some circumstances, they can require a daily food intake of up to 15% of their body weight. Their migratory patterns closely match ocean processes that create the union of habitat needs (e.g., water temperature and dissolved oxygen concentrations) and adequate food supply. Climate in large part determines the short-term, seasonal, and multiyear variability in the patterns of water temperature, dissolved oxygen concentrations, and productivity that determine the geographical location of optimal tuna habitats. Changes in Pacific tropical and subtropical climate, especially with regards to the ENSO, have been shown to impact the location and stock sizes of Pacific tuna fisheries. What is ENSO and why does it impact tropical tuna fisheries?

B. ENSO and Temperature

ENSO is an interannual climate pattern that occurs across the tropical Pacific approximately every 3 to 7 years and is characterized by coupled variations in the surface water temperatures of the equatorial Pacific and air surface pressure in the tropical Western Pacific. There are two end member phases or patterns to the ENSO – El Niño and La Niña. During an El Niño phase, there is high air surface pressure in the Western Pacific and the warm, stratified, low nutrient and chlorophyll western Pacific pool of water (termed the Western Pacific Warm Pool or WPWP) extends eastward into the central and eastern Pacific. During a La Niña, the pool of warm water in the Western Pacific contracts. Figure 4-5 shows the SST for the equatorial Pacific for El Niño, normal, and La Niña periods.

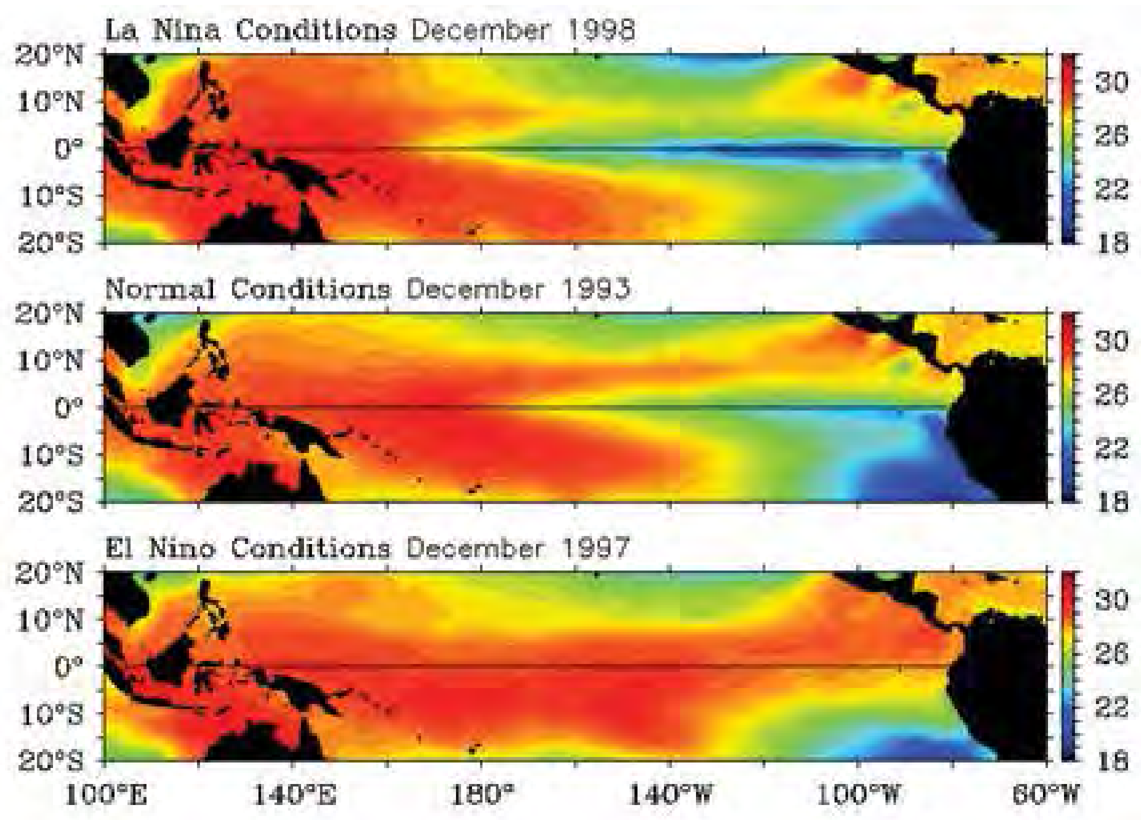

Figure 4-5. SST (in °C) for La Niña (top), normal (middle), and El Niño (bottom) periods. During La Niña, the pool of warm western equatorial Pacific water contracts westward while the cooler eastern equatorial Pacific water pool expands westward. During El Niño, the pool of warm western equatorial Pacific water expands eastward and the cooler eastern equatorial Pacific water pool contracts. Retrieved 6 June 2011 from http://www.pmel.noaa.gov/tao/elnino/la-nina.html. (Dai McClurg, TAO Project. PMEL/NOAA).

Some very dramatic physical–biological linkages in the equatorial region are observed in response to ENSO forcing. In the eastern equatorial region, weak easterlies and eastward transport of warm water during El Niño events result in enhanced vertical stratification of the water column. This stratification leads to decreased upwelling along the coast of Peru and adjacent coastal environments north and south and thus decreased nutrient availability in the surface waters reducing primary productivity. During La Niña, the reverse pattern is observed with intensified easterly winds leading to an increase in upwelling resulting in increases in nutrients and plankton productivity in surface waters. In contrast, the western warm pool exhibits ENSO changes in the opposite phase with weaker stratification and increased productivity due to western wind bursts and a shoaling thermocline during an El Niño event.

Climate Change and Tropical-Subtropical Tuna Fisheries

It is uncertain how future climate change will impact the severity, duration, and periodicity of the overall ENSO cycle. As climate change is expected to warm the surface waters of the tropical and subtropical Pacific, we might expect more El Niño-like conditions relative to present day. What is certain though is that climate variability already, via the ENSO, impacts the abundance, concentration, location, and accessibility of tuna stocks. By influencing the location of the nutrient-poor WPWP and the adjacent colder nutrient-rich body of surface water generally found in the central equatorial Pacific, the ENSO alters the habitat conditions in the subtropical and tropical Pacific. The WPWP is the Western Equatorial Pacific area of warm surface water that exceeds 28 °C and supports the species (e.g., skipjack) that are primarily caught via the purse-seining method. It is the relative geographic position of these two general surface water entities, the WPWP and adjacent colder nutrient-rich body, which determines the habitats for the tuna species.

Generally speaking, skipjack tuna are ubiquitous throughout the equatorial Pacific, but catches are usually greatest in the Western Pacific with the warmest waters (Figure 4-3). During an El Niño phase, the recruitment of the predominantly tropical tuna species skipjack increases in the Western and Central Pacific along with a general eastward shift in their population; the opposite occurs during a La Niña event or phase (Figure 4-6). Additionally, we can see that the distribution of the purse-seine catch of skipjack also follows these trends (Figure 4-7). So all things being equal, El Niño conditions increase skipjack populations as stock assessments have confirmed. The recruitment of the subtropical species albacore decreases during El Niño phases, but increases during La Niña phases. Table 4-1 summarizes how ENSO impacts the WPWP placement and thus distribution of tuna species.

Table 4-1. ENSO impacts on the Western Pacific Warm Pool (WPWP) and purse-seining efforts of major tuna fisheries in the Western and Central Pacific.

Phase	WPWP placement	Focus of purse-seining efforts	Species Abundance
El Niño	Moves east	Central Pacific (e.g., Kiribati & Samoa)	Skipjack
La Niña	Moves west	Western Pacific (e.g., Solomon & Marshall Islands)	Albacore

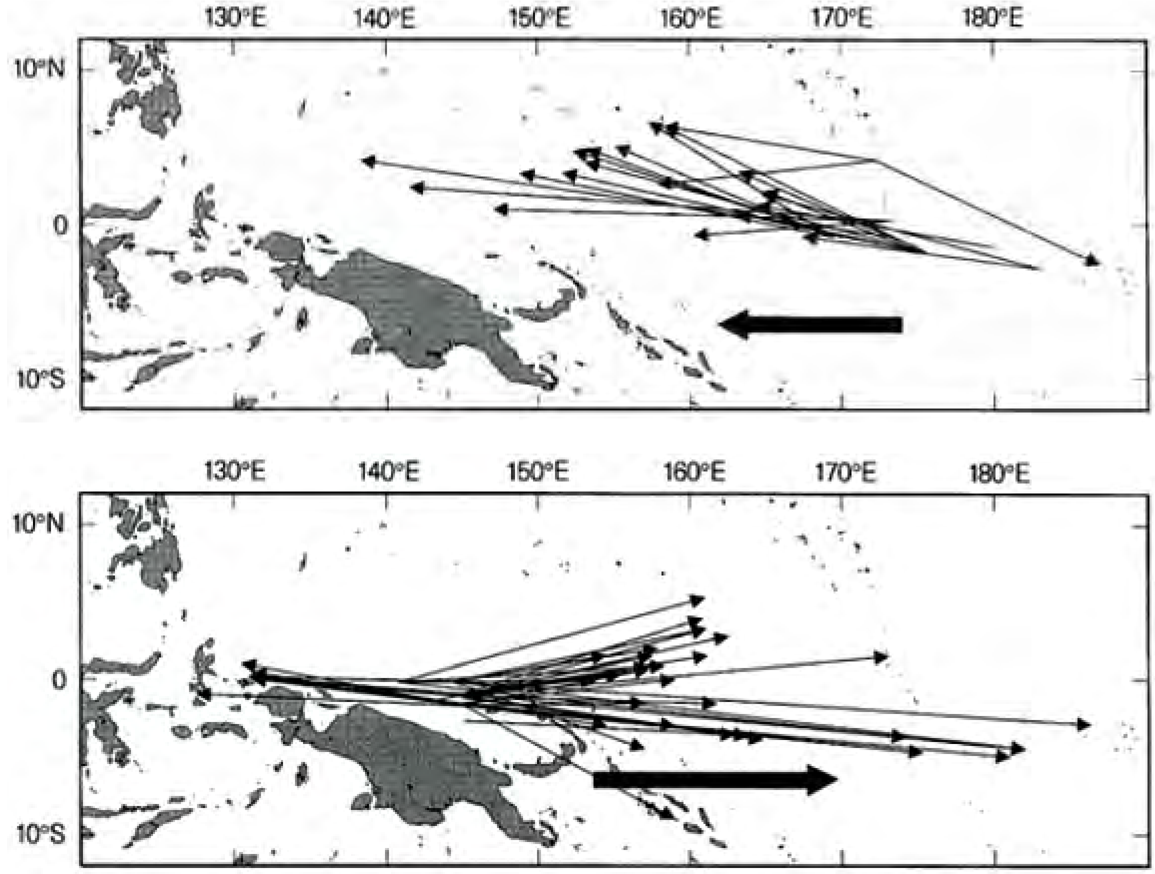

Figure 4-6. Movement of tagged skipjack tuna in the Central and Western Pacific with changes in the ENSO cycle during 1991 and 1992. (Top) La Niña, (Bottom) El Niño. Smaller arrows are individual tagged fish. The single large thick arrow in each plot is the general magnitude and displacement of the tagged tuna. Note how during a La Niña, skipjack tuna move westward with the WPWP westward movement and during an El Niño, skipjack tuna move eastward with the WPWP eastward movement. Reprinted from Nature, 389 (6), Lehodey, P., Bertignac, M., Hampton, J., Lewis, A., and J. Picaut, 715-718, 1997, with permission from Nature Publishing Group Ltd.

The impact of climate change on marine primary production has been estimated for a future doubling of atmospheric CO_2 values. Generally speaking for a CO_2 doubling, primary production is predicted to increase in the high latitudes and decrease in low latitudes. This future primary productivity decrease in the low latitudes is generally due to more sluggish ocean circulation, less upwelling of nutrient-rich water, and a warmer ocean surface layer leading to increased stratification in the upper ocean. So increases in atmospheric CO_2 result in reduction of tropical primary production by alteration of ocean circulation. How might this impact tuna? Tuna are top-level predators and thus are dependent on the base of the food chain to ultimately supply food. When these tropical ocean primary productivity changes were coupled with a skipjack tuna-specific predator-prey model, model calculations showed that future climate change could result in large scale alterations in the tropical skipjack habitat with an eastward expansion of the skipjack habitat. So, the warming of the tropical Pacific by doubling of CO_2 may have similar impacts on skipjack tuna fisheries that have been observed already with El Niño events. For species like bigeye and yellowfin though, the warming will reduce abundance by reducing primary productivity in the central and eastern Pacific due to reduced upwelling (i.e., less nutrients) and increased surface water stratification.

C. Sea Level and Ocean Acidification Impacts

Little is understood about the potential longer-term impacts, compared to those of future temperature changes, of sea-level rise and ocean acidification on tropical tuna fisheries. At this point, sea level changes may, along with temperature changes, impact current patterns, which could then play a role in the distribution of tuna populations. However, the timing and magnitude of significant future sea level change are not well known and so it is difficult to even model how these changes could impact tuna populations. Ocean acidification impacts on tuna are likely both indirect and direct. One example of a possible indirect impact is via ocean acidification influence on primary producers (e.g., carbonate skeletal organisms such as coccolithophores), which form, in part, the basis of the food chain for tuna. As with other fish species, such as coral reef fish species, ocean acidification could directly impact tuna populations via tuna larvae mortality. As of the writing of this case study, experiments are underway to investigate how changes in pH impact tuna larvae. The results of studying the influence of pH on tuna larvae will then be integrated into a physical-biological yellowfin tuna model to project how future climate change scenarios will impact the yellowfin population.

D. Management Implications

Natural climate variability has resulted in demonstrated impacts on the abundance and distribution of tuna stocks. Operators of modern tuna fleets are using sophisticated technology and available information on how climate change impacts tuna to better guide their fishing efforts. All the while, there is continued effort by scientists to provide even better predictability of tuna stock location and population trends. All major tuna stocks migrate across Exclusive Economic Zones (EEZ) and high sea boundaries. On the high seas, these stocks are vulnerable to fishing pressures from many competing nation fishing fleets. Some of the nations are not members of fishing agreements whose goal is to sustain the stocks over the long-term. Commercial fishing for skipjack, yellowfin, and bigeye tuna has developed rapidly in the tropical Western and Central Pacific since the mid-1980s. Most of this development has not been by those island nations near these fishing grounds, but rather what are termed distant water fishing nations (DWFN). These foreign fleets use more modern techniques such as purse-seigning, which is very efficient (e.g., see Figure 4-3). Many Western and Central Pacific island nations provide access to their EEZ to DWFN in exchange for payment that can be in the form of access fees, foreign aid, jobs, fishing infrastructure (e.g., canning), etc. It is

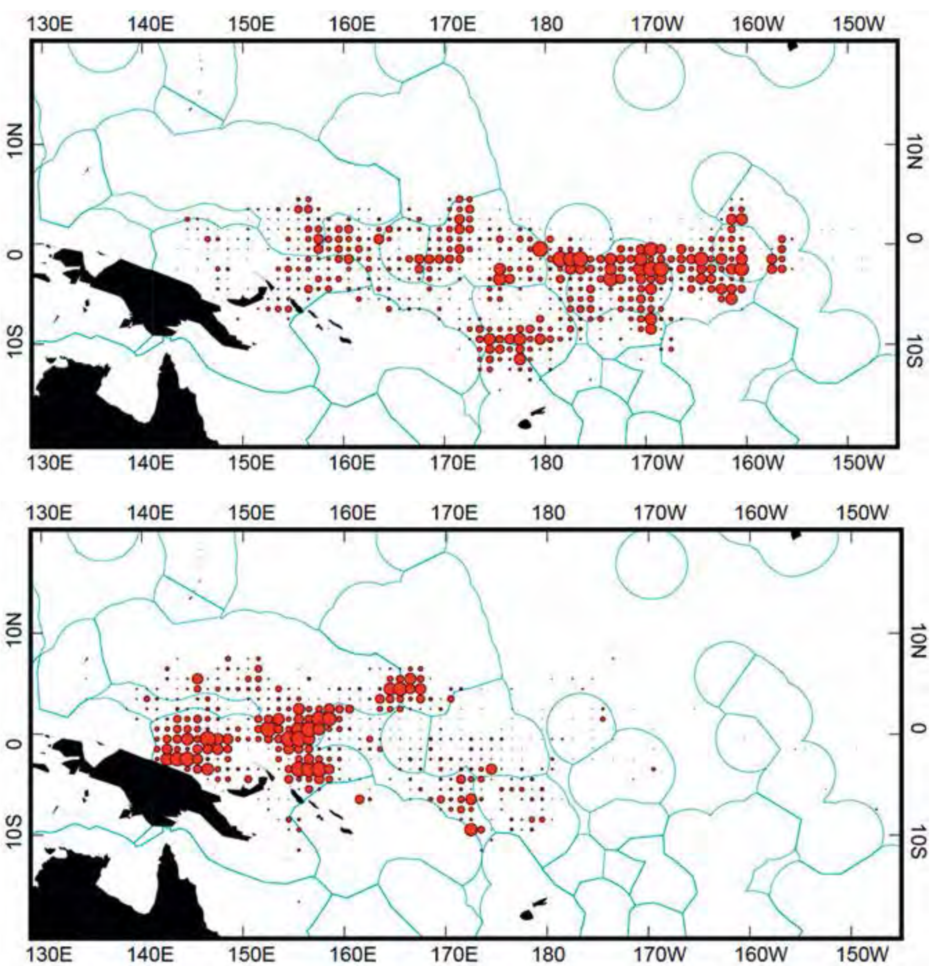

Figure 4-7. Distribution of purse-seine catch of skipjack tuna catch by United States tuna fleet during the (top) 1994 El Niño; and the (bottom) 1995 La Niña. Notice the relative shift eastward of the catch during El Niño and westward during La Niña. Source: Secretariat of the Pacific Community as presented in Asian Development Bank (ADB), 2003. On or Beyond the Horizon: a discussion paper on options for improving economic outcomes from the Western and Central Pacific Tuna Fishery, ADB TA 6128-REG 226, Technical Assistance for Alternative Negotiating Arrangements to Increase Fisheries Revenues in the Pacific, Asian Development Bank, Manila.

important to note that no entity owns the tuna fishery resource.

Although anyone is free to harvest on the high seas, the tropical Western and Central Pacific island nations, via their EEZs, effectively control much of the most productive tuna fishing grounds in the Western and Central Pacific. However, as we have already seen, climate variability (Figure 4-6), and thus likely future climate change, results in geographically shifting tuna stocks (Figure 4-7). Generally speaking, those nations located close to the equator and west of the dateline have far better access to tuna stocks during "normal" times relative to those nations farther north or south of the equator or more east. However, during El Niño years, those nations located farther east or west are positioned to benefit. This difference in access to the tuna stocks results in a significantly different outlook regarding the tuna as a sustainable resource and thus advocacy for different tuna resource policies, which potentially threaten the long-term sustainability of the tuna resource.

The current catch levels and resultant impact on the stocks of bigeye and yellowfin tuna appear to be unsustainable while the skipjack tuna fishery appears more robust with room for argument regarding the current levels of catch and sustainability. The tuna fishery in the Western and Central Pacific Ocean is diverse. From small-scale to coastal subsistence efforts to large-scale, industrial purse-seine, pole-and-line, and longline operations in the EEZ of Pacific tropical and subtropical nations or on the high seas, climate change will likely have differing degrees of impact on the distribution and viability of the major tuna species.

E. Summary

It is clear from previous experience (e.g., during past El Niño and La Niña phases) that climate change can impact tuna fisheries distribution. Coupled climate change and tuna models also suggest that future climate change will impact tuna populations by altering the distribution of their habitat. Ongoing research (e.g., pH impacts on tuna larvae) integrated into coupled tuna population dynamics and ocean models will help elucidate further how future climate change may impact tuna distribution and population. The tuna industry is a large economic engine for many Western and Central Pacific island nations and its long-term sustainability is crucial for both these economies and also the food subsistence and cultural aspects the tuna provide coastal communities. The better refined both climate and fishery models become on the impacts of climate change, the better information and ultimately decisions can be made to best manage the resource to minimize the negative impacts of climate change and fishing pressures.

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V. Management Implications and Conclusions

Local, coastal, and regional fisheries play an important role in Pacific Island communities. The local and regional fisheries serve as economic and dietary resources and embody cultural significance to local populations and endemic peoples of these island communities. Furthermore, the fishery environments (e.g., nearshore region, coral reefs, embayments, etc.) also serve as locations of recreation and leisure for the local population and attract tourism. Climate change and accompanying sea level and temperature rise and ocean acidification will impact pelagic Pacific Ocean fisheries as well as nearshore coral reefs and associated reef fisheries. The latest IPCC report states that for the next few centuries continued warming of the climate system is unequivocal, even if emissions of greenhouse gases are stabilized in the near future, and that global sea level will continue to rise. Furthermore, as atmospheric CO_2 concentrations continue to increase due to anthropogenic emissions (e.g., from deforestation, fossil fuel burning, agriculture, cement production), the surface layer of the ocean will continue to absorb CO_2 from the atmosphere and become more acidic. The scope and effects of climate change impact not just one or two species here and there, but rather entire ecosystems. As a further exacerbation to the future impacts of climate change on fisheries, other human-related negative impacts (e.g., coastal runoff and fishing pressures that will also be magnified by future population growth) have in some cases already tipped affected fisheries into unsustainability. Taking all this into account suggests that ecosystem-based management approaches that are flexible and acknowledge how ecosystems and habitats shift with climate change in conjunction with the minimization of other human-induced negative impacts on fisheries are necessary actions to obtain favorable, sustainable outcomes. Although a daunting challenge, fortunately the history and cultures of Pacific island communities are replete with holistic and time-proven approaches to resource management that give them the best opportunity at long-term fishery sustainability should, in the interim, the myriad of non-climate anthropogenic-related pressures be minimized.

1. Population, Coastal Runoff and Fishing Pressures

Various estimates place roughly one-fourth to one-third of the world's coral reefs as either highly degraded or destroyed. Many reef, coastal, and pelagic fish stocks are being fished unsustainably. Along with these issues, many Western and Central Pacific island nations and Hawai‘i have populations that are growing in parallel to the overall increase in global and coastal area populations. Presently, many of these coastal and island populations already place significant pressure on their coastal fishery resources via the associated terrestrial sediment and pollution runoff and fishing (both subsistence and commercial) practices. For example, if American Samoa's present population growth rate of 2.3% per year remains constant, then the population will double within 30 years. Coastal and conterminous watershed population growth drives terrestrial sediment and pollution runoff and subsequent water quality deterioration via the following land-based activities: soil erosion and fertilizer loss from increases in agriculture; vegetation removal; coastal land urbanization; discharge of untreated sewage; and industrial pollution. With population growth, human-associated runoff and pollution pressures on coastal fishery resources (not including the impacts of climate change) will only increase.

Population also drives fishing pressures on coastal resources for subsistence and commercial needs. The populations and cultures from Western and Central

Pacific island nations and Hawai'i have, in the past, employed sustainable fishing practices to harvest and also manage and protect the resource for the benefit of future generations. In a study of pre-historic and modern subsistence harvest of American Samoa coral reef resources, researchers found that outer islands are presently harvesting the same overall composition seafood as found in nearby archeological excavations that date back 1000 to 3000 years. This implies that the fishing practices employed by these cultures in these areas have allowed for the sustainable use of the fishery resource. Employing similarly minded efforts through best management practices, along with the reduction in coastal anthropogenic stressors, offers the best opportunity to manage sustainable fishery resources. We now outline some short- and long-term measures to aid in the sustainable management of fisheries based on the findings of this case study.

2. Short-term measures (< 25 years)

We define short-term measures as those which within the next approximately 25 years will mitigate the potentially synergistic impacts of climate change and population driven pressures on fishery resources of Hawai'i and the Western and Central Pacific island nations. Large scale negative impacts of SST, sea-level rise, and ocean acidification are likely relatively unimportant over this short time frame, although the policies and measures to address the long-term climate change implications need to be put in place during this interval of time. While the large-scale negative effects of climate change are probably outside the 25-year window, the impacts of shorter-term climate variability such as El Niño and La Niña events on the fishery resource need to be understood so that management practices can take them into account.

It is likely that the greatest positive impact we can have over this time frame is the control, reduction, and minimization of anthropogenic-generated coastal resource degradation. To do so requires measures such as the following:

- Educate the public as to how actions on land impact the nearshore marine environment.
- Develop better land use planning practices to ensure that the negative impacts of development driven by population increase are minimized.
- Actively safeguard habitat and the well-being of fishery resources with education programs and enforcement.
- Develop and improve waste treatment facilities and protect the coastal environments, like mangrove ecosystems, that provide natural filtration for land to coastal input of pollutants and sediments.
- Within the context of management practices (e.g., MPAs), scientifically monitor using a time series approach employing instrumentation in the watershed and coastal area and synoptic physical and biogeochemical studies of the ecological well-being of resource habitats, fishery population numbers, catch-levels, etc. This will enable management practices to be shared, altered, etc. as necessary and be as effective as possible with the sustainability of resources in mind.
- Along with these suggested measures, in parallel implement them with the spirit, nature, and practices of island nations with respect to resource management practices that have been proven successful in the sustainable management of fisheries over the past centuries and millennia.

3. Long-term measures (25+ years)

Climate change effects on fisheries via increased SST, sea level, and ocean acidification will become more pronounced over this time frame. As the time frame increases, so does the degree of uncertainty of the magnitude (but not the direction) of resultant environmental change. Sustainability of fisheries during this interval will in large part depend on the success of measures and actions taken during the short-term (< 25 years), so that fishery resources are as healthy and resilient as possible to best withstand the negative impacts of climate change. Suggested measures include:

- Strategic resource management plans that incorporate the possible impacts of climate change on the ecosystem and mitigation plans for their implementation.
- Continuation of resource management practices that best promote sustainability.
- Continued scientific study and monitoring of the impacts of these management practices along with those of climate change on the resources.
- Continued minimization of stress via pollution, runoff, and overfishing.
- Evaluation and refinement of local, regional, and

global policies implemented decades previously with regards to curbing anthropogenic emissions of greenhouse gases that help drive long-term changes in SST, sea-level, and ocean acidification.

It is evident that without short-term mitigation of destructive anthropogenic practices (i.e., pollution and sedimentation of nearshore environments and overfishing) fishery resources essential to the tropical island communities in the Western and Central Pacific and Hawai'i, if not already, will soon be severely degraded. Subsequently, the remaining relatively small fishery populations will be less resilient to withstanding future unfavorable changes in environmental conditions resulting from climate change. Continued scientific study and observation of the links between fisheries, climate and climate change, human use, and management practices are necessary to ensure that resource management is able to adapt to successfully sustain the fishery resources. Finally, with respect to the impact of long-term climate change on fishery sustainability, stabilization and decrease in the emissions of greenhouse gases such as carbon dioxide are necessary to slow down and reverse the buildup of atmospheric greenhouse gas concentrations.

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Tables

Figures

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2-13. Mean hard coral and algal cover on reefs (top) 6 meters and shallower, and (bottom) deeper than 6 meters for Fiji from 2002 to 2006. Note how in the deeper reef algal cover increases when coral cover decreases after the 2000 and 2002 bleaching events indicating algal colonization of dead coral.

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2-15. SST time series for a colony of staghorn coral during bleaching events from 2004 to 2007. The black line with diamonds is the percentage of partly bleached staghorn coral in the colony. The black line without symbols is the satellite measured SST in ^{o}C. The red dashed line is the projected summertime maximum temperature by NOAA's Coral Reef Watch, which is an effort to utilize remote sensing and in situ tools for real-time and long-term monitoring of coral reef ecosystems.

2-16. Aragonite saturation state for the years (top) 2000 to 2009 with pCO_2 = 375 ppmv, and (bottom) 2050 to 2059 with pCO_2 = 492 ppmv. Note how that for most of the western tropical Pacific and Hawai'i that saturation states go from > 4 (Optimal) to values between 3 to 3.5 (Marginal), which provides additional stress to corals.

2-17. Champagne Reefs Papua New Guinea.

3-1. Coral reef production versus sustainable coral reef fisheries production. Islands above and to the left of the solid black line are unsustainable at their current rate of coral reef fishery production. Island reef fisheries status is represented by four symbols. Green squares = underexploited. Orange circles = fully exploited. Red triangles = overexploited. Black diamonds = collapsed.

3-2. Red Tailed Wrasse.

3-3. Conceptual diagram of changes in coral cover, fish communities, species richness, and macroalgae cover in response to a major bleaching event.

3-4. Examples of potential range shifts that could occur among four species of butterfly fish from the family *Chaetodon* [(a) *C. auriga*; (b) *C. oxycephalus*; (c) *C. pelewensis*; (d) *C. trichrous*] as sea temperatures increase. Orange shading represents existing range, purple represents possible range expansion and faded orange represents possible range contraction. (a) Existing geographical range spanning the latitudinal extent of coral reef development – range shift unlikely to occur. (b) Existing geographical range centered near the equator and not extending to the latitudinal extent of coral reef development – range expansion possible. (c) Existing geographical range centered near mid-latitudes, often reaching the latitudinal extent of coral reef development – range contraction likely. (d) Existing small range near the latitudinal extent of coral reef development – range contraction leading to serious reduction in area is possible. Species selected for illustrative purposes only.

3-5. Projected Storminess during the late 21st century.

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4-1. Yearly (from 1960 to 2009) commercial catch (subsistence catch not taken into account) in metric tonnes (mt) of skipjack, yellowfin, bigeye, and albacore tuna in the Western and Central Pacific. The subsistence catch is minor compared to the commercial catch. Plot from the Western and Central Pacific Fisheries Commission.

4-2. Western and Central Pacific catch in metric tonnes (mt) per fishing equipment type and technique from 1960 to 2009.

4-3. 2009 purse-seine tuna catch in metric tonnes (mt) in the Western and Central Pacific Ocean. Note that the catch is concentrated around the equatorial Pacific.

4-4. 2009 long-line tuna catch in metric tonnes (mt) in the Western and Central Pacific Ocean. Note that the catch area is more dispersed compared to the purse-seine, although the largest catch is still concentrated around the equator. Note also that the catch amount is much less than that from purse-seining. Finally, there is geographic variation in the species type and amount caught via long-lining with albacore (green) south of the equator, bigeye (red) north of the equator, and yellowfin (yellow) predominant to the west.

4-5. SST for La Niña (top), normal (middle), and El Niño (bottom) periods. During La Niña, the pool of warm western equatorial Pacific water contracts westward while the cooler eastern equatorial Pacific water pool expands westward. During El Niño, the pool of warm western equatorial Pacific water expands eastward and the cooler eastern equatorial Pacific water pool contracts. Plot from the Tropical Atmosphere Ocean Project Office, Pacific Marine Environmental Lab, National Oceanographic Atmospheric Administration.

4-6. Movement of tagged skipjack tuna in the central and western Pacific with changes in the ENSO cycle during 1991 and 1992. (Top) La Niña (Bottom) El Niño. Smaller arrows are individual tagged fish. The single large thick arrow in each plot is the general magnitude and displacement of the tagged tuna. Note how during La Niña skipjack tuna move westward with the WPWP westward movement and during El Niño skipjack tuna move eastward with the WPWP eastward movement.

4-7. Distribution of purse-seine catch of skipjack tuna catch by United States tuna fleet during the (top) 1994 El Niño; and the (bottom) 1995 La Niña. Notice the relative shift eastward of the catch during El Niño and westward during La Niña. Source: Secretariat of the Pacific Community as presented in Asian Development Bank (ADB), 2003. On or Beyond the Horizon: a discussion paper on options for improving economic outcomes from the Western and Central Pacific Tuna Fishery, ADB TA 6128-REG 226, Technical Assistance for Alternative Negotiating Arrangements to Increase Fisheries Revenues in the Pacific, Asian Development Bank, Manila.



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