12

Biology and Ecological Functioning of Coral Reefs in the Main Hawaiian Islands

Paul L. Jokiel

12.1 Introduction

12.1.1 Geographic Location

The eight main Hawaiian Islands (MHI) are the emergent volcanic islands of the Hawaiian Archipelago (Fig. 12.1). The Hawaiian Archipelago is located in the center of the north Pacific Ocean and consists of islands, atolls, submerged banks and shoals, trending northwest by southeast in the between latitudes 19° N and 29° N. The island chain extends approximately 2,400 km (1,500 miles) from the Island of Hawaii in the southeast to Kure Atoll in the northwest. Hawaii is among the most isolated island groups on the planet being located approximately 3,000 km (1,860 miles) from the nearest continent. These islands are the emergent portion of the undersea Hawaiian-Emperor seamount chain that was formed continuously over the past 70–75 million years as the Pacific tectonic plate moved north and northwest over a stationary magma "hot spot" (Clague and Dalrymple 1994) at a rate of from 5 to 10 cm/year. Molten lava breaking through the thin rigid crust slowly creates volcanic mountains that eventually reach the surface of the ocean and emerge as islands (Macdonald et al. 1983). As the islands move off the hot spot they undergo erosion and subsidence. Eventually they are worn down and gradually sink, forming low islands and atolls and ultimately submerged seamounts. The eight MHI at the southeastern end of the archipelago represent approximately 5 million years of that cycle. The island of Hawaii is the youngest island with the oldest rocks dating to only about 430,000 years ago. Its youngest volcano, Kilauea, is currently active, along with a newly forming submerged volcano named Loihi located to the southeast of the Island of Hawaii.

The Hawaiian Archipelago has traditionally been split into two artificially defined groups of islands: the Northwestern Hawaiian Islands (NWHI) and the Main Hawaiian Islands (MHI) for various political, administrative and biogeographic purposes. The MHI consist of populated, high volcanic islands with non-structural reef communities and fringing reefs, while the (NWHI) consist of uninhabited atolls and banks as discussed by Grigg et al. in Chapter 14. However, Jokiel and Rodgers (2007) observed that the ten NWHI and the eight MHI are not parts of two disjointed systems, but rather are inseparable components of a single highly isolated ecosystem. Most fish, corals and other marine species found in Hawaii occur on reefs throughout the archipelago. Green Sea Turtles are a single genetic population with individuals that migrate from forage areas in the MHI to nest in the NWHI (Balazs and Chaloupka 2004a, b). Sharks and other large fish are known to move freely throughout the archipelago and do not observe the artificial boundary created by humans (K. Holland and C. Meyer 2006, personal communication). During past decades, the endangered Hawaiian Monk Seal was largely restricted to the NWHI, but has not respected this arbitrary division and recently has begun to re-colonize the MHI (Baker and Johanos 2005).

B.M. Riegl and R.E. Dodge (eds.), *Coral Reefs of the USA*,

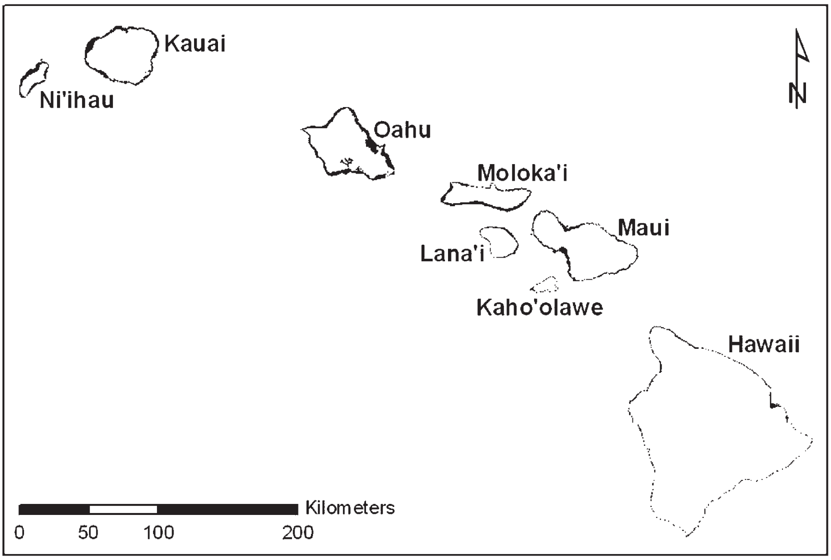

FIG. 12.1. Major features of the main Hawaiian Islands relevant to coral reef development include steep volcanic slopes running into very deep oceanic waters. The dark line in the figure represents the area between the high tide mark and the 30 m depth contour which generally exceeds the lower limit of reef coral development in Hawaii. Note more extensive fringing reefs on older islands or south facing shores, especially S. Molokai

12.1.2 Political and Social History

12.1.2.1 Background

Detailed accounts regarding the history of Hawaii are presented elsewhere (Daws 1968; Kuykendall and Day 1976), but are summarized here in relation to human impact on coral reefs. The Hawaiian Islands were initially settled by Polynesians. The earliest immigration appears to have been from the Marquesas as early as AD 500, followed by continued immigration from Tahiti after AD 1300. During 1778 Captain James Cook made the first western contact. Kamehameha I unified the Hawaiian Islands in battle and formally established the Kingdom of Hawaii in 1810. In 1819, Kamehameha II ascended to the throne and abolished the traditional kapu system of laws and regulations. In 1820, missionaries from New England arrived and converted some of the highest-ranking chiefs. Commoners followed the example of their leaders and converted to Protestant Christianity. Under the traditional system all land was held by the chiefs. Westerners pushed for private ownership of land. The ruling chiefs eventually allowed the land to be divided between the king, the chiefs, and the commoners. The Great mahele (land division) was signed into law in 1848 by King Kamehameha III. In 1874 Hawaii signed a treaty with the United States granting Americans exclusive trading rights. The 1876 Reciprocity Treaty between the Kingdom of Hawaii and the United States allowed for duty-free importation of Hawaiian grown cane sugar. Sugar cane and plantation agriculture expanded. Asian immigrants were brought in to work the plantations. The traditional Hawaiian staple crop (taro) was replaced by rice growing to satisfy an expanding local market for the latter. In 1887, a group of cabinet officials and advisors to King David Kalukaua used armed militia to force the king to accept what is now known as the Bayonet Constitution, which stripped the monarchy of much of its authority. When Kalakaua died in 1891, his sister Liliuokalani took the throne. The queen proposed a new constitution that would restore the monarchy's authority. A group of European and American Hawaiian citizens and residents responded in 1893 by forming a committee of safety to prevent the queen from abrogating the 1887 constitution. United States Minister Stevens, concerned about possible threats to American lives and property, summoned a company of US Marines and US sailors who came ashore on January 16, 1893. A provisional government was established under threat of force by a local militia group. Liliuokalani gave up her throne. The Republic of Hawaii was established July 4, 1894 under the presidency of Sanford Dole with the intent of annexation to the United States. A subsequent investigation established by President Cleveland concluded that the United States diplomatic and military representatives had abused their authority. The request for annexation of Hawaii was initially denied, but changes in the political situation eventually led to Hawaii becoming a United States territory in 1900. The attack on Pearl Harbor on 7 December 1941 by the Empire of Japan was a trigger for the United States' entry into World War II. Hawaii became a major staging area for the conquest of the Pacific during the war with a large buildup of troops. The Island of Kahoolawe was declared a target island for ships and aircraft to practice bombing before deploying into the Pacific, with massive impact on the island and its coral reefs (Jokiel et al. 1993b). The strategic role of Hawaii in the areas of military activity and transportation combined with its appeal as a tourist destination and an attractive place to live led to rapid increases in human population and rapid development following the war. Hawaii formally became the 50th state of the Union on August 21, 1959.

12.1.2.2 Historical Changes in the Condition and Management of Reefs

Political and social changes in Hawaii over the past centuries as noted above had a direct impact on natural resource management and the condition of Hawaii's reef resources (Jokiel PL, Rodgers KS, Walsh WJ, Polhemus D, personal communication 2007). After the initial colonization of Hawaii by Polynesians, the increase in human population and depletion of resources eventually led to the development of a carefully regulated and sustainable "ahupua'a" system. This system was based on an integration of watershed, streams and near shore resources and involved local control and use of adaptive management practices that were triggered by subtle changes in fisheries resources. Sophisticated social-spiritual controls on resource utilization were an important component of the system. After western contact, many rapid changes occurred. Introduction of livestock and plantation agriculture resulted in overgrazing and rapid erosion of watersheds (Roberts 2001). Breakdown of the "ahupua'a" system due to the initiation of private land ownership resulted in open access to reef resources with little or no control. New and more efficient fishing gear and methods were rapidly introduced. Advances in technology led to dredging and filling of reef areas. With increasing urbanization sewage outfalls were constructed. The present "western management system" gradually evolved and replaced much of the traditional Hawaiian system. Both systems target sustainable productivity of the reefs. However, major differences exist in the areas of management practices, management focus, knowledge base, dissemination of information, resource monitoring, legal authority, access rights, stewardship and enforcement (Jokiel PL, Rodgers KS, Walsh WJ, Polhemus D, personal communication 2007). Failures of the western system of marine resource management in maintaining productivity of inshore fisheries are leading to a re-evaluation of current practices in reference to the traditional system (Jokiel PL, Rodgers KS, Walsh WJ, Polhemus D, personal communication 2007). There has been a recent trend toward incorporation of major features of the traditional scheme using methods and terminology acceptable and appropriate to present day realities (e.g. community based management, marine protected areas, environmental education and outreach). The major strength of the present western system appears to be an ability to adapt to changing social, political, and economic conditions, and to the impacts of invasive species. The continued integration of several basic principles found in the traditional system may further strengthen the ability of contemporary mangers to insure sustainability in a manner that complements and supports the growing interest in ancient Hawaiian culture.

12.1.3 History of Biological Research

Prior to western contact, the traditional fisheries knowledge of the native Hawaiians may have surpassed that of modern marine biologists in some areas (Gosline and Brock 1960; Lowe 2004). Hawaiians in pre-historic times possessed an understanding of the life histories of fishes. Careful observations led to an intimate knowledge of the physical, biological, and ecological factors that influence fisheries. This knowledge was transmitted orally through the generations but was largely lost as western practices replaced the traditional Hawaiian system. The first contemporary scientific information on Hawaiian inshore marine biology in Hawaii began with the slow gathering of information and specimens obtained during infrequent expeditions into the region. Such accumulated data were periodically synthesized and published. For example, Vaughan (1907) compiled taxonomic and distributional information on Hawaiian scleractinian corals. In 1907 the College of Hawaii, which later became the University of Hawaii, was formed. From the beginning there was a strong interest in marine science and the history of coral reef studies in Hawaii. The first president, John Gilmore, recommended construction of a marine biology laboratory as part of the Department of Zoology as early as 1910. A temporary facility was in operation at Pier 6 in Honolulu Harbor by 1917 which moved to the Waikiki Aquarium in 1919. Charles Howard Edmondson came to Hawaii in 1920 under a joint appointment between the Bishop Museum and the University of Hawaii and served as Director of the marine laboratory at Waikiki which had been named the Cook Memorial Laboratory. Edmondson is regarded as the father of Hawaii marine biology. Over the years he published numerous scientific papers and reports and synthesized much information in the classic book “Reef and Shore Fauna of Hawaii” (Edmondson 1933). The major figure in the continued development of marine science was Robert W. Hiatt who expanded the UH Department of Zoology curriculum to include marine coursework in 1951. Notable faculty involved in the growth of the marine biology program at that time included Albert Testor, Vernon Brock and Albert (Hank) Banner. That same year Hiatt moved the marine laboratory at he Waikiki Aquarium to Coconut Island in Kaneohe Bay which was renamed the Hawaii Marine Laboratory (Hiatt 1955). The laboratory grew and later became the Hawaii Institute of Marine Biology (HIMB) in 1965 with construction of a major new building. In addition to HIMB, Hiatt founded the University of Hawaii Department of Oceanography in 1964, along with the Hawaii Institute of Geophysics and the Pacific Biomedical Research Center among other programs. These units have continued a substantial involvement in coral reef studies. The expansion in marine sciences and coral reef studies initiated by Hiatt has continued at an accelerating pace over the past 40 years (Karl 2004).

12.2 Regional Setting

12.2.1 Geography

Hawaii is truly an ocean state, being located in the middle of the North Pacific Ocean. Hawaii’s coral reef communities provide food and recreation to the people of Hawaii and are critically important to the State’s approximately $800 million/year marine tourism industry (Cesar and van Beukering 2004). Over 70% of the state’s 1.2 million people live on Oahu, and are mostly concentrated in Honolulu. In addition to the resident population, nearly seven million tourists visit Hawaii each year. Increasing population has put anthropogenic pressure on Hawaii’s coral reefs through various direct and indirect means.

12.2.2 Climate

The Hawaiian Islands are located at the northern edge of the tropics and experience a mild subtropical climate due to the persistent northeasterly trade winds. The average wind velocity varies between 10 and 20 knots with extended velocities of over 20 knots for periods of a week or more (Patzert et al. 1970). Length of day and temperature are relatively uniform throughout the year. Hawaii’s longest days are about 13.5 h and the shortest days about 11 h, which translates into small seasonal variations in incoming solar radiation and air temperature. The major features of Hawaii’s climate are: year round mild and equitable temperature, persistence of northeasterly trade winds, significant differences in rainfall within short distances due to orographic effects on the steep slopes of the high islands, and infrequent hurricanes or severe storms (Bach and Daniels 1973; Price 1983). Evaporation exceeds precipitation between 15° N and 36° N, but extremely high rainfall occurs over some areas of the high islands. Hawaii’s steep volcanic topography influences local weather and climate. The volcanic mountains block, deflect, and accelerate the flow of air through channels and passes and alter local conditions on the reefs.

When warm, moist air is forced over windward coasts and slopes, clouds are formed with high rainfall. After being stripped of its moisture the air descends into leeward areas that tend to be sunny and dry. Due to the seasonal lag in ocean temperature, Hawaii's warmest months are not June and July, but rather August and September. Likewise, the coolest months, are February and March rather than December and January. Seasonal variation in climate is related to storm tracks and the Pacific High which follow the seasonal shift of the sun, moving north in summer and south in winter. The Pacific High tends to be stronger and more persistent in summer than in winter. Therefore, in winter, the trade winds may be blocked for days or weeks by fronts or migratory cyclones from the northern latitudes and by "Kona" storms forming south of the islands. Therefore, the winter season in Hawaii has more frequent clouds and rainstorms, as well as southerly and westerly winds. Hawaii's heaviest rains occur during winter storms between October and April.

Flash floods are an important feature of the climate and are often highly localized, intense and of short duration. According to Ramage (1971), factors leading to heavy rains include a large-scale disturbance (e.g. weather front), plentiful moisture supply (e.g. warm humid warm air as found around Hawaii) and a surface discontinuity (e.g. steep slopes of a high island). The coastline in the main Hawaii Islands (MHI) fits all of these features with steep topographic relief, humid air and frequent exposures to frontal movements. Therefore the MHI are and their offshore reefs are extremely vulnerable. Flooding often occurs when convective cells are formed or enhanced by orographic effects, and become anchored against the high-vertical relief features of the MHI. Such floods can trigger mudflows and landslides which transport mud onto coral reefs directly or via stream flow. Jokiel (2006) estimated from 5 to 10 flash floods per year from available data. Such flood waters may contain up to 90% sediment by some estimates (Jones et al. 1971).

12.2.3 Biogeography

The Hawaiian marine fauna is depauperate with a large percentage of endemics. In general, those species that have reached Hawaii are derived from the Indo-west Pacific region and have a broad geographic distribution. Approximately 30% of invertebrates, corals and fish are endemic (Kay and Palumbi 1987; Jokiel 1987; Hourigan and Reese 1987). A striking feature of the Hawaiian reef-fish fauna is that the majority of the abundant and ubiquitous species are endemics (Gosline and Brock 1960). Genera containing multiple endemic species generally are derived from separate Indo-west Pacific species rather than radiating from a common ancestor. Thus, while the Hawaiian Archipelago is severely isolated from other reef areas, the geographic barriers between the different islands of the Hawaiian archipelago are insufficient to isolate marine populations long enough to allow speciation within most of the taxonomic groups. However, sub-populations can be detected at the genetic level in some cases. Thus the NWHI and the MHI comprise a single biogeographic region. Perhaps this generalization should include nearby Johnston Atoll which has a coral fauna very similar to Hawaii (Maragos and Jokiel 1986).

Factors contributing to the low number of species in Hawaii include a northerly subtropical location with lower temperatures and irradiance, remoteness, lack of favorable currents to transport larvae from the southwest Pacific, lack of reef stepping stones in the region since the Cretaceous, and possible defaunation during eustatic sea-level rise and fall. For example, there are approximately 40 species of stony corals in Hawaii (Maragos 1995), whereas the Philippines, Palau and Japan each have over 400 species of reef corals (Veron 1993). Over 7,000 marine species have been recorded from the Hawaiian Islands (Paulay 1997). There are approximately 450 species of inshore fishes on Hawaiian reefs (Gosline and Brock 1960; Randall 1996).

Currents as well as distance control dispersal. Jokiel and Cox (2003) used pumice as a geological tracer of oceanic dispersal patterns by comparing the elemental signatures of drift pumice collected from Christmas Island and Hawaii in relation to prevailing oceanic currents and pumice source areas. Both sites lie isolated in the middle of the Pacific Ocean, far from sources of volcanic pumice or potential colonizers of the reefs. Hawaii lies in the persistent westward-flowing North Equatorial Current. Christmas Island, in contrast, is influenced by the highly variable westward-flowing South Equatorial Current and the eastward-flowing

Equatorial Counter Current. Analyses of pumice collected from the two locations revealed that Christmas Island pumice and Hawaii pumice distributions are dissimilar. Pumice is very abundant at Christmas Island in the beach drift. Pumice from Christmas Island is derived from the western Pacific Ocean (Krakatau), southwestern Pacific Ocean (Tonga Trench), east Pacific Ocean (Mexico), South Atlantic Ridge and an unknown source. In contrast, pumice is rare in Hawaii. Pumice from Hawaii originates primarily from the South Sandwich Islands, Mexico (Isla San Benedicto) and Krakatau. The currents that control dispersal of pumice also control dispersal of larvae and rafted organisms. Christmas Island has a higher coral diversity (31 genera, 81 species) than Hawaii (17 genera, 50 species). Hawaii receives only small amounts of pumice drift from a limited area to the east and has a more restricted coral diversity, while Christmas receives massive amounts of pumice (and presumably larvae and rafted organisms) from the area of high coral diversity to the west.

Johnston Atoll lies 800 km southwest of the nearest reefs of Hawaii and appears to fall into the same faunal region as Hawaii (see also Chapters 17 by Lobel and Lobel, 15 and 16 by Maragos et al.). Only 33 species and 16 genera and subgenera of shallow water stony corals have been reported from the atoll, with most of them being the same species found in Hawaii (Maragos and Jokiel 1986). Despite low species diversity, coral coverage is high in most environments. The coral reefs of Johnston Atoll are dominated by several species of *Acropora* that occur rarely in Hawaii. Several reefs in the center of the Hawaiian archipelago appear to have been colonized by *Acropora valida*, *Acropora cytherea* and *Acropora humilis* larvae from Johnston Atoll (Grigg 1981; Grigg et al. 1981). It has been proposed that larvae are transported from Johnston Atoll to Hawaii by the Subtropical Countercurrent. Available evidence suggests that the larvae could reach Hawaii in 50 days under optimum current conditions. Barkley (1972) computed currents from long line and ship drift data in the region. These data suggested the existence of 60 cm s^{-1} northerly current that produced an eddy wake moving downstream of Johnston to the northwest (320° at 45 cm s^{-1}). This wake probably extended at least 600 km downstream of the atoll (Barkley 1972). Journey time for such eddies moving north into Hawaiian waters could be as little as 21 days if maximum speeds were sustained. The possibility of reciprocal exchange of larvae between Hawaii and Johnston is thus established. The similarity of the species lists of the two locations certainly supports this interpretation. Lack of common Hawaiian coral species such as *Montipora flabellata*, *Porites compressa* and *Tubastraea coccinea* at Johnston and the absence of common Johnston Atoll species, including all three hydrozoan corals (*Millepora, Distichopora* and *Stylaster*) in the Hawaiian Archipelago suggest that larvae of some species might not be able to bridge this gap. Kobayashi (2006) used computer simulation and high-resolution ocean current data to identify two potential larval transport corridors between Johnston Atoll and the Hawaiian Archipelago. One corridor connects Johnston Atoll with the middle portion of the Hawaiian Archipelago in the vicinity of French Frigate Shoals in the Northwestern Hawaiian Islands with the second connection to Kauai in the MHI.

A notable inhabitant of Hawaiian coral reefs is the Hawaiian monk seal (*Monachus schauinslandi*) which is an endemic endangered species. The major part of the population resides in the NWHI, but increasing numbers of seals are observed in the MHI. In other parts of the world similar species of tropical seals have been extirpated or greatly reduced in numbers. This last major population of monk seals is a valuable resource from the standpoint of biodiversity, conservation and the ecology in the Hawaiian Archipelago.

12.3 Natural Forces Influencing Reef Biology

The major natural factors influencing reef coral community structure and reef fish community structure in the Hawaiian Islands include currents, waves, substrate type, depth, island age, and rugosity (Friedlander et al. 2003; Jokiel et al. 2004). Some of these important parameters show correlations with each other. For example, water motion and light penetration are both negatively correlated with depth and positively correlated with each other.

12.3.1 Ocean Currents

The north Pacific gyre, centered at about 28° N latitude controls the general oceanographic conditions in the Hawaiian region. The dominant waves in Hawaii are generated by the prevailing Northeast trade winds which also drive surface currents to the west at speeds of from 15 to 30 cm s^{-1} (Flament et al. 1998). The resulting North Equatorial Current (NEC) flows past Hawaii and reaches an average westward speed of 17 cm s^{-1} to the south of with current speed gradually decreasing to the north along the island chain where the currents are strongly influenced by the islands. The NEC forks at the island of Hawaii with the northern branch becoming the North Hawaiian Ridge Current that intensifies as it moves along the eastern edge of the archipelago. West of the islands a clockwise circulation is evident with a centered at 19° N, merging to the south with the southern branch of the NEC.

Patterns of wind, currents and waves produce cooler surface temperatures in the channels and warmer surface temperatures in the lee of the larger islands. These variations in wind speed induce divergent and convergent surface currents, which in turn lift or depress the thermocline and form clockwise (anticyclonic) and counterclockwise (cyclonic) eddies in the lee of the major islands. The large counterclockwise average circulation is believed to result from the repeated occurrence of eddies spun off by the shear lines of the islands of Maui and Hawaii. Eddies can also be generated by intense currents such as the NEC impinging on the islands, much like swirls formed in a swift river downstream of a bridge abutment. The large clockwise circulation southwest of the Island of Hawaii appears to be caused by many such clockwise eddies that repeatedly form near South Point on the island of Hawaii. Geostrophic currents result from these variations of thermocline depth, in the form of intense counterclockwise eddies under northern shear lines, and (somewhat less intense) clockwise eddies under southern shear lines. The depth of the mixed layer in the lee of the island of Hawaii can vary from less than 20 m in the counterclockwise eddy, to more than 120 m in the clockwise eddy.

Localized currents resulting from tides and other oscillations are produced by the combination of diurnal, semidiurnal and fortnightly tidal components control sea level in the Hawaiian Islands (Flament et al. 1998). Mean tidal range for various stations in the MHI vary from 0.3 to 0.5 m with maximum diurnal change varying between 0.3 and 0.8 m. The small tidal range and steep nature of Hawaiian shorelines results in a very narrow intertidal zone and poorly developed intertidal fauna. Local bathymetry affects the ranges and phases of tides along the shore as the tidal waves wrap around the islands. Nearshore tidal currents are often stronger than caused by the large scale circulation and have an effect on local coral and fish communities. Semi-diurnal and diurnal tidal currents tend to move parallel to the shoreline. Localized accelerated currents on reefs often result from tidal currents flowing around points and headlands.

12.3.2 Waves

Wave damage is often cited as the single most important factor in determining the community structure and composition of exposed MHI reef communities (Dollar 1982; Dollar and Tribble 1993; Dollar and Grigg 2004; Jokiel et al. 2004). Response of Hawaiian coral community structure to periodic wave damage has been shown to fit Connell's (1978) 'intermediate disturbance hypothesis' (Grigg, 1983). Moderate coral cover and high diversity results from a continual cycle of intermediate intensity disturbances. High coral cover with low species diversity occurs in sheltered embayments and reefs in the wave shadow of other islands. Studies of coral communities on dated lava flows on the island of Hawaii suggest that it takes about 50 years for Hawaiian reefs to reach peak diversity following a catastrophic event (Grigg and Maragos 1974). A study of the impacts of storm waves of varying intensity on the west coast of the island of Hawaii has been conducted over a period of 30 years (Dollar 1982; Dollar and Tribble 1993; Dollar and Grigg 2004). Results indicate that shallow areas populated primarily by a wave-resistant pioneering species of cauliflower coral (*Pocillopora meandrina*) can recover completely within 20 years. However, deep reef slope zones populated by more delicate branching and plating species showed only the initial stages of recovery during the same period. Recovery does not always result in immediate replacement of the same dominant species in a particular zone. This cycle of repetitive impact and recovery is believed to be the major factor responsible for the present-day lack of reef accretion in exposed areas throughout the Hawaiian Islands. In wave sheltered areas Holocene reef accretion is on the order of 10–15 m thick. At wave exposed stations, Holocene accretion is represented by only a thin veneer of living corals resting on antecedent Pleistocene limestone foundations (Grigg 1998). The lack of coral reef accretion along open ocean coastlines may explain the absence of mature barrier reefs in the high Hawaiian Islands. However, extensive accretionary pre-Holocene reefs did form throughout the Hawaiian chain approximately 11,000 years ago. Rooney et al. (2004) proposed that storm wave intensity now is much greater compared to this earlier time and that the present wave regime is preventing formation of massive carbonate reef structures.

Reef corals can modify growth form within limits in order to adjust to a particular wave regime. For example, the Hawaiian coral *Montipora capitata* can assume encrusting, massive, plate-like or branching growth forms depending on the light and wave environment. In high wave energy environments robust species such as *Pocillopora meandrina* and *Porites lobata* dominate (Fig. 12.2). Delicate fast growing forms of species such as *Montipora capitata* or *Porites compressa* dominate in low wave environments. The normal biological processes of recruitment, growth, mortality and competition lead to the orderly development of a reef community adapted to the prevailing wave energy regime. However, an unusual storm wave event that occurs rarely (on the order of 10–50 years) can fragment the corals and totally alter the community composition within a matter of hours. Coral reef fish communities are influenced by reef coral development, so a relationship between wave exposure and fish community structure has been documented (Friedlander et al. 2003).

A hydrodynamic force-balance model was developed to calculate wave-induced forces on stony corals and predict the hydraulic conditions under which the skeletons of four dominant species of Hawaiian reef forming corals would fail and break (Storlazzi et al. 2005). The robust high-energy corals *Porites lobata* and *Pocillopora meandrina* are found in high wave energy environments. The more delicate branching corals such as *Porites compressa* and *Montipora capitata* are found in areas that are deeper or more sheltered from storm waves (Fig. 12.2). The model was tested against observed species distribution along the south shore of Molokai, Hawaii. Results suggest that wave-induced forces are the primary control on coral species distribution and that the transition from one species to another is very likely due to the corals' strength in relation to prevailing wave conditions. Overall, the model appears to accurately define coral species distribution in the Hawaiian Islands based solely on the region's general wave climate and the corals' strength and morphologies; these results further support the long-standing ideas that waves are the dominant control on coral species zonation.

Jokiel et al. (2004) surveyed sites throughout the MHI and showed that mean wave height had a positive relationship with species richness, an observation consistent with the intermediate disturbance hypothesis (Connell 1978). Mean wave direction (compass bearing) shows a negative relationship with coral cover and diversity (Jokiel et al. 2004) because major storm surf in Hawaii arrives along a gradient that roughly diminishes in a counter clockwise direction from the North (Table 12.1). The largest and most frequent storm surf arrives during the winter North Pacific Swell (bearing 315°) with the less frequent and less damaging storm waves during the summer from the South Swell (bearing 190°) to the less severe Trade Wind Swell (bearing 45°). Maximum wave height is the most prominent factor with a negative relationship with coral cover, diversity and species richness (Jokiel et al. 2004). Maximum wave height is a good index of destructive wave events that damage Hawaiian reefs. In general, a reef's optimum growth and coral cover exists between 10 and 20 m, reflecting the trade-off between reduced wave induced stress at depth with decreased light available for photosynthesis (Storlazzi et al. 2002).

Events classified as storm waves strike Hawaiian shores from various directions with a frequency of from 2 to 7 times each month (Jokiel 2006). These waves come from different directions and are generated by various sources (Table 12.1).

The NE Trade Winds predominate throughout the year in Hawaii, but reach maximum intensity between spring and fall. These winds can build substantial waves as they move across the

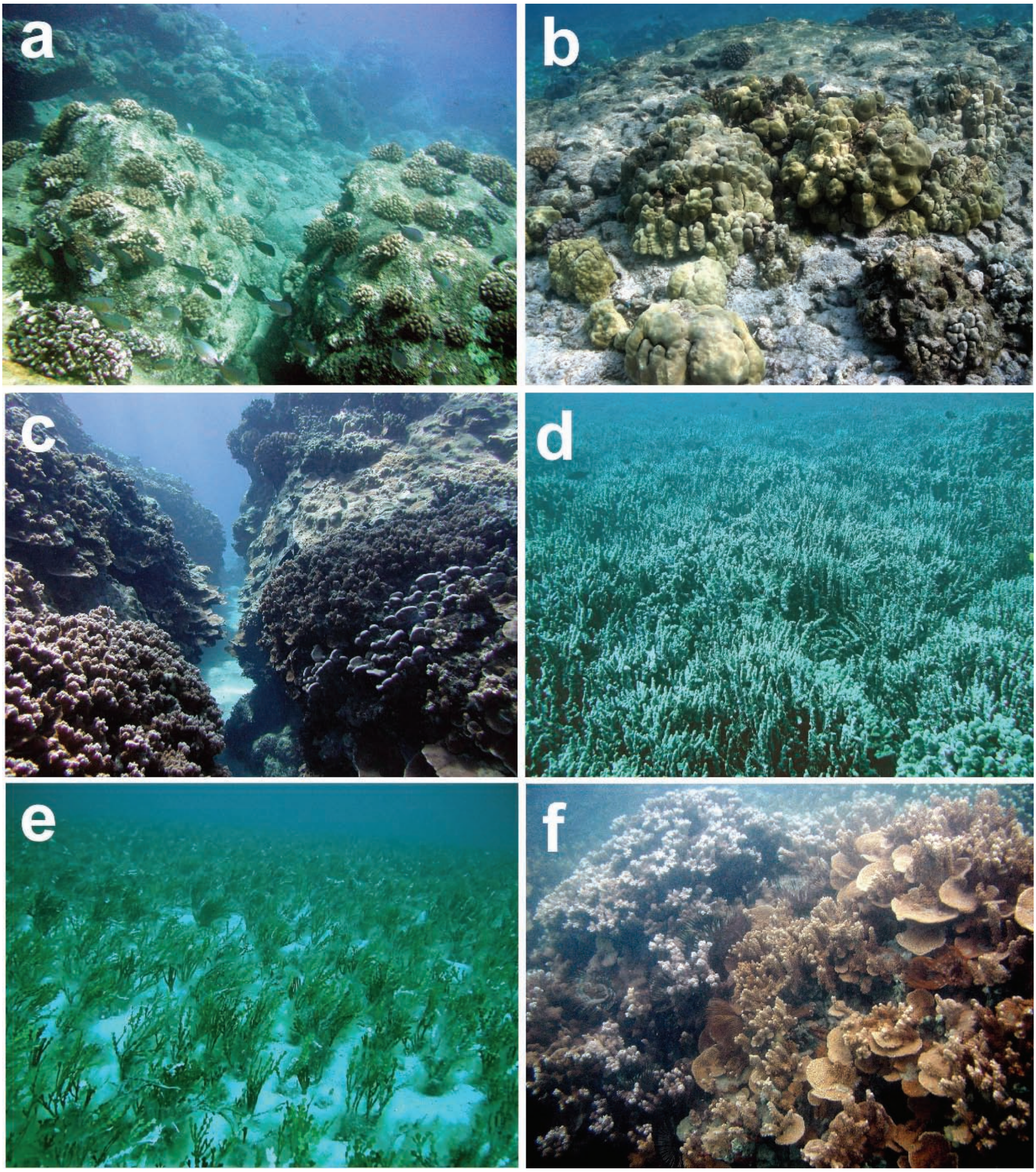

FIG. 12.2. (**a**) *Pocillopora meandrina* community, Kauai. (**b**) *Porites lobata* community, Hawaii. (**c**) Diverse community in shallow water with high complexity, Molokai. (**d**) *Porites compressa* community, Maui. (**e**) Algal community on deep shelf, South Molokai. (**f**) *Montipora capitata* community, Kaneohe Bay, Oahu

Pacific toward Hawaii. Trade Winds diminish during the night and gradually increase throughout the morning to maximum wind speeds in the afternoon. Increased wind speed results in an increase in the size of wind-driven waves. Offshore wind-generated wave heights of 0.4–1.1 m are typical with periods of only 5–8 s (Table 12.1). These offshore waves break and dissipate along the north and east shores of the MHI. The high islands are a barrier to the surface winds, which

TABLE 12.1. Waves influencing the main Hawaiian Islands (Summarized from Moberly 1974 and Pat Caldwell National Oceanographic Data Center, Honolulu, personal communication 2006).

	Typical			Extreme				
	Height		Period	Height		Period	Direction	
Wave type	(m)	(ft)	(s)	(m)	(ft)	(s)	Mean	Range
NE Trade wind waves	1.2–3.7	4–12	5–8	4.0–5.5[a]	13–18[a]	9–12	NE 45°	0–90°
North Pacific swell	2.4–4.6	8–15	10–17	4.9–7.6	16–25	18–25	NW 315°	282–45°
Southern swell	0.3–1.2	1–4	12–17	1.5–3.1	5–10	14–25	SSW 190°	236–147°
Kona storm waves	0.9–1.5	3–5	8–10	1.8–3.1	6–10	11–14	SW 210°	258–247°

[a] Fully developed seas

increase in velocity as they form a jet of high velocity wind and funnel through gaps between the islands. The NE Trades are forced between the MHI and produce considerable wave chop in the channels with sharp boundaries known as shear lines. During late November 2003 an extremely destructive NE wave event struck Hawaii, which produced wave heights well above the NE Trade Wind wave height that is normally encountered. The November 2003 storm is believed to be the cause of damage observed on a section of reef flat at Pilaa, Kauai (Jokiel and Brown 2004b). Coral cover in this area declined from 14% to 6% with extensive breakage of coral colonies into rubble. A similar decline as the result of this storm was observed on the NE facing shore at Sandy Beach, Oahu (S.J. Dollar, personal communication 2005).

North Pacific Swell is generated by Northern Hemisphere winter storms in the North Pacific (Table 12.1). Breaking waves inshore with faces over 15 m have occasionally been observed. Wave energy of this magnitude prevents coral reef development along the north shores of the islands.

Southern Swell is generated by Antarctic Southern Hemisphere winter storms and is generally encountered in summer and early autumn (Table 12.1). Waves generated in the southern Pacific take 6–8 days to reach Hawaii and lose much of their energy due to spreading before they arrive in the islands. Southern Swell rarely approaches the heights of North Pacific Swell seen on the northwest shores in winter. The largest southern waves on record (June 1955) had faces over 6 m breaking in shallow water.

Kona Storm Waves can occur throughout the year, but are most common from October through April. During this time, waves may be generated by southerly or southwesterly winds that precede the northerly winds of cold fronts. Typical wave heights are from 0.9 to 1.5 m with periods of 8–10 s. Under extreme conditions these waves can exceed 3 m in height. A 1980 Kona storm generated inshore plunging breakers of up to 6 m, reduced living coral cover at a site off the west coast of the Island of Hawaii from 46% to 10% (Dollar and Tribble 1993).

Hurricane Waves are infrequent and unpredictable events that can have profound effects on reefs. Limited historical information exists on the location, size of waves and amount of reef damage on Hawaiian reefs caused by Hurricane waves. Recorded hurricanes in Hawaii have followed trajectories that led to direct impact on the islands of Kauai and Oahu, with less impact on the other islands (Schroeder 1998). Most central Pacific hurricanes originate near Central America or southern Mexico. Many of these storms die out if they move northwestward over cooler water or encounter unfavorable atmospheric conditions. Of those that survive, most pass far to the south of Hawaii. Hurricane season begins in June and lasts through November in the Hawaiian Islands. Hurricane Iniki in 1992 produced waves powerful enough to break and abrade corals over much of south Kauai. Homes, appliances, furnishings, trees and other objects were carried into the surf and added to the mechanical damage to the reefs. Re-colonization and recovery of the reef corals over the past decade has been substantial, and most of the reefs have returned to their pre-hurricane condition. Waves generated by Hurricane Iniki had a small but measurable impact on reefs hundreds of kilometers to the east at Kona, Hawaii where coral cover decreased from 15% to 11% (Dollar and Tribble 1993). Hurricane Iniki also impacted coral reef communities in Mamala Bay, Oahu (Brock 1996). The greatest change attributable to the hurricane was the loss of topographical relief and shelter habitat for many fish and invertebrate species. This loss was caused by the movement of loose materials (rubble and sand) across the bottom with infilling of holes and depressions resulting in a less heterogeneous habitat. However, in other areas storm waves removed accumulated sediment and rejuvenated certain reef environments.

Tsunamis or seismic sea waves consist of a series of immense waves caused by violent movement of the sea floor during an earthquake, underwater landslide, or volcanic eruption. These waves are characterized by great speed (up to 950 km h^{-1}), substantial wave length (up to 190 km), long period between successive crests (varying from 5 min to a few hours, generally 10–60 min), and low height in the open sea. A tsunami event can last several hours and destroy everything in its path. The first tsunami recorded in Hawaii occurred in 1819, and since then 85 others have been observed, 15 of which resulted in significant damage along the coastline (Curtis 1998). Tsunamis have accounted for more lost lives than the total of all other local disasters. Damage to reefs resulting from past tsunamis has not been documented on Hawaiian coral reefs, but may have been considerable as evidenced by the level of destruction to property and human life.

The impact of waves on a given reef involves a complex interaction between wave direction, island topography, and bathymetry (Dollar and Tribble 1993; Storlazzi et al. 2002, 2005). The islands block waves and create a "wave shadow" that moderates the impact of waves on reefs in the lee of islands (Storlazzi et al. 2005). Islands such as Molokai with an elongate E–W morphology create a large wave shadow along the south coast that blocks wave energy from the North Pacific Swell although wave refraction does impact the reefs on the east and west ends of the south coast. Other islands to the south and east further protect the south coast of Molokai. In contrast, circular islands such as Kauai that do not fall into the wave shadow of other major islands are vulnerable to waves and wave refraction from all compass directions.

12.3.3 Solar Radiation

The growth of coral reefs is limited by light due to the dependence of reef corals and algae on photosynthesis (Wells 1957). Corals are plant–animal symbioses that require sunlight as a primary source of energy. Therefore, their lower depth distribution is set by light penetration. Light is attenuated by sea water, so eventually a depth is reached where photosynthesis cannot support reef building. The exceptional clarity of offshore oligotrophic waters off Hawaii allow sufficient light penetration for the development of coral communities of *Leptoseris* spp. to develop to depths as great as 150 m (Kahng and Maragos 2006). However, these corals exist as thin plates and are not major reef builders. In clear offshore Hawaiian waters not influenced by severe swell, impressive reef communities develop in deeper water. For example, the offshore ocean reefs off south Moloka'i have rich *Porites compressa* communities to depths of 30 m (100 ft). At greater depths, the substrate is unsuitable for corals as the reef gives way to a sand terrace dominated by the alga *Halimeda* (Fig. 12.2e). High turbidity inshore due to fine sediment dramatically reduces light penetration and consequently reduces coral reef development in many areas.

Sunlight is necessary for photosynthesis, but the short ultraviolet wavelengths of solar radiation are potentially lethal. Hawaiian reef corals thrive under levels of solar ultraviolet radiation that would kill or severely damage many forms of marine life (Jokiel 1980). Early work suggested that an undefined substance termed "S-320" had such characteristics and might act as a protective screen against UV radiation (Shibata 1969). Concentration of this material was shown to decrease in Hawaiian corals with increasing depth, presumably as a result of attenuating UV radiation (Maragos 1972). Growth of zooxanthellae in vitro is inhibited by solar UV (Lesser and Shick 1989), but zooxanthellae in vivo apparently are not affected (Jokiel and York 1982), unless a non-acclimatized coral is subjected to a sudden increase in UV irradiance (Scelfo 1984). The S-320 material in corals was subsequently identified by Dunlap and Chalker (1986) as a group of compounds known as mycosporine-like amino acids (MAAs). Effects of UV radiation can be subtle. For example, Kuffner (2001) found that larvae of the Hawaiian reef coral *Pocillopora damicornis* delay settling to the substrate when UV radiation levels are high.

12.3.4 Water Temperature

Temperature is a primary physical factor governing reef coral distribution (Wells 1957). The optimum growth temperature for Hawaiian reef coral is 27°C, although they can tolerate prolonged temperature of from 20°C to 29°C, and short exposure to temperatures of from 18°C to 31°C (Jokiel and Coles 1990). Surface water temperature shows a strong north-to-south gradient along the Hawaiian Archipelago, with lowest sea surface temperature in March, and highest in September. The seasonal range of sea surface temperatures near Hawaii is only about 3° with the average surface water temperature around O'ahu ranging from 24°C in winter to 27°C in summer. In the open ocean, the surface waters are mixed by the wind and have uniform properties. The depth of this warm mixed layer can vary from nearly 120 m in winter to less than 30 m in summer (Flament et al. 1998).

Field investigations on a reef impacted by thermal discharge from a power generation station (Jokiel and Coles 1974) and controlled experiments with Hawaiian corals (Jokiel and Coles 1977) demonstrated that loss of symbiotic zooxanthellae, or "bleaching" is one of the first visible signs of thermal stress. Bleaching in Hawaiian corals can be induced by short-term exposure (i.e. 1–2 days) at temperature elevations of from 3° to 4° above normal summer ambient or by long-term exposure (i.e. several weeks) at elevations of 1–2° above normal long term summer maxima (Jokiel and Coles 1990). Temperature and light interact synergistically; high light accelerates bleaching caused by elevated temperature (Jokiel and Coles 1990). Bleaching threshold is determined by level of solar irradiance, degree of heating over summer maximum and duration of exposure (Jokiel 2004). Critical threshold temperatures for coral bleaching vary geographically, but can be expressed universally as fixed increments of 1–2°C relative to the historical mean local summer maximum (Coles et al. 1976; Jokiel 2004). Temperature elevations above summer ambient, but still below the bleaching threshold, can impair growth and reproduction in the Hawaiian coral *Pocillopora damicornis* (Jokiel and Guinther 1978). Bleaching susceptibility is correlated with respiration rate. Any factor that increases respiration (such as high incident solar radiation) accelerates bleaching at higher temperatures.

Hawaiian surface waters have shown a trend of increasing temperature over the past several decades (Jokiel and Brown 2004a) that is consistent with observations in other coral reef areas of the world (Coles and Brown 2003). Jokiel and Coles (1990) observed a warming trend in Hawaiian waters and warned that Hawaiian corals were perilously close to their bleaching threshold during the summer months. The first documented regional coral bleaching in the main Hawaiian Islands occurred in Hawaii in late summer of 1996 (Jokiel and Brown 2004a). Bleaching was recorded at a number of locations, with the most severe impact observed on Oahu (Kaneohe Bay, Kailua Bay) and lesser bleaching reported on Maui and Hawaii. On Maui, weekly temperatures on reefs along the southwest coastline experienced temperature of 28.0–28.5°C in late August and early September, with peak temperatures approaching 29°C. Corals began to bleach at Olowalu, Maui in late August, but the extent and severity of bleaching was minor, with less than 10% of the corals being affected. Recovery occurred after several months. Documented bleaching events in Hawaii were all triggered by prolonged regional oceanic positive oceanic sea surface temperature anomalies greater than 1°C that developed offshore during the time of the annual summer temperature maximum. High summer solar energy input and low winds further elevated inshore water temperatures by 1–2°C in reef areas with restricted water circulation and in areas in the lee of the larger islands where mesoscale eddies retain water masses close to shore for prolonged periods of time. Major bleaching events were observed in the NWHI during the summer of 2002 (Aeby et al. 2003; Jokiel and Brown 2004a) and again in the summer of 2004 (Kenyon et al. 2004; Kenyon and Brainard 2006).

12.3.5 Depth

As noted above, vertical distribution of corals is controlled largely by light and water motion which both diminish with depth. Grigg (2006) used growth rate of the abundant Hawaiian reef building coral *Porites lobata* as a proxy to describe the relationship between reef development and depth. The lower limit for this species is 80–100 m, yet reef accretion ceases at approximately 50 m depth. Below this depth the rate of bio-erosion exceeds coral growth, causing coral colonies to fragment and break down into rubble.

12.3.6 Substrate Type

Substrate type is a major factor that defines Hawaiian habitats (Coyne et al. 2003). The reef building crustose coralline algae and reef corals generally require a hard substratum. Sand and mud substratum is unsuitable for coral settlement and growth. Corals can, however, develop in these areas through settlement on isolated outcrops of hard rock. Accretion of skeletal material over many generations of coral will produce large coral "mounds" or "ridges" surrounded by mud and/or sand. Sand and mud are transported onto and off the reef in response to currents and wave regime. Passage of sediment through coral communities can smother new coral settlements and encrusting corals, and can even bury large coral colonies, which are killed and sometimes uncovered later by subsequent erosion.

12.3.7 Land Impact

Terrigenous runoff carries fresh water, fine sediment and nutrients onto the reef. Fine sediments can reduce light penetration to the corals and can smother and kill colonies. Fine sediment prevents settlement of coral larvae. High nutrient levels carried off the watershed or seeping in with ground water stimulate growth of macroalgae that can choke out corals.

12.3.8 Salinity

Reef corals have been described as having very narrow salinity tolerance (Wells 1957), but corals and coral reefs are known to occur under natural conditions at salinities ranging from 25‰ to 42‰ (Coles and Jokiel 1992). Hawaiian corals can tolerate salinity of 15‰ for several days before they die (Coles and Jokiel 1992; Jokiel et al. 1993a). This represents a 50% dilution of seawater with fresh water. Steep bathymetry and exposure to high wave energy characterize most of the coastline of the Hawaiian Archipelago and the resulting flushing by waves and currents maintains salinity on reefs within the range of tolerance for reef corals. Salinity on ocean reefs in Hawaii is generally close to that of the open ocean which is on the order of 34–35‰. Low salinity can occur near stream mouths on reef flats, but the fresh water is rapidly mixed with seawater in most open coastal situations. Nevertheless, discharge of fresh water from rivers and streams limits the development of reefs at river mouths, forming breaks in otherwise continuous fringing reefs (Stoddart 1969). Suppression of reefs in these areas is due to input of nutrients and sediment as well as fresh water. Fresh water is much more buoyant than seawater, so it often forms a surface layer that does not impact corals in deeper water.

"Reef kills" caused by low salinity associated with flood events have occurred in Hawaii (Jokiel et al. 1993a). Such floods represent a major but episodic stress for corals in highly enclosed embayments such as Kaneohe Bay (Oahu), Hilo Bay (Island of Hawaii), Kahalui Bay (Maui), Pearl Harbor (Oahu) and Nawiliwili Bay (Kauai), where circulation is restricted and salinity can be reduced to levels lethal to corals. The best documented events occurred in Kaneohe Bay, Oahu which is a large (4 × 10 km) estuarine system with relatively unrestricted exchange of water with the open ocean. Consequently a rich coral reef complex has developed in the bay. Salinity in the bay is normally close to oceanic conditions of 34–35‰, but commonly surface waters drop to 29‰ during flood events. However, during extreme flood conditions, salinity can be reduced to the point of killing corals on the reefs. For example, rainfall exceeding 60 cm in 24 h on the Kaneohe Bay watershed during May 1965 produced a surface layer of low salinity water that killed corals and invertebrates to a depth of 1–2 m on reef flats throughout the inner portion of the bay (Banner 1968). Storm floods again occurred in late December 1987 and early January 1988 that reduced salinity in the surface waters of Kaneohe Bay to 15‰ and produced massive mortality of coral reef organisms in shallow water. Virtually all coral was killed to a depth of 1–2 m in the inshore regions of the Bay (Jokiel et al. 1993a).

12.3.9 Sedimentation

Hawaiian corals and coral reefs are sensitive to sediment loading (Maragos 1972; Banner 1974).

The detrimental effects of sediment on corals, their larvae and other reef organisms have been reviewed by Rogers (1990). Sedimentation buries or smothers coral, blocks light needed for photosynthesis and inhibits settlement of corals. Nutrients associated with the sediment can stimulate algal blooms and toxic materials contained in the sediments can be harmful to delicate marine life. Maragos (1972) reported a significant negative relationship between light extinction coefficient and growth for the Hawaiian coral *Montipora verrucosa* during the time when Kaneohe Bay was undergoing severe impact from sewage outfalls.

In Hawaii, factors such as wave exposure, water motion and localized topography influence sediment stress on coral reefs. Sediment deposits on the coral reefs of Hawaii are dynamic features that are continually being replenished by terrestrial runoff as well as by biogenic carbonate material from the reef. Roy (1970) estimated that more than 70% of the sediment in Kaneohe Bay, Oahu is internally derived from the breakdown of calcium carbonate materials. These deposits are, in turn, being altered and depleted by resuspension and removal of fine fractions during periods of strong surf and currents. On reef slopes there is a continual resuspension and movement of sediments into deeper water that is enhanced by waves and currents. For example, Bothner et al. (2006) deployed sediment traps on the south Molokai reefs and found that storms with high rainfall, floods, and exceptionally high waves resulted in sediment trap collection rates greater than 1,000 times higher than during non-storm periods, primarily because of sediment resuspension by waves. Floods recharged the reef flat with land-derived sediment, but had a low potential for burying coral on the fore reef when accompanied by high waves. The high trapping rate and low sediment cover indicate that coral surfaces on the fore reef are exposed primarily to transient resuspended sediment. Studies were undertaken on a shallow fringing reef flat on Molokai, Hawaii to determine the temporal and spatial dispersal patterns of terrigenous suspended sediment (Presto et al. 2006). Trade-wind conditions produced strong currents and resuspended moderate amounts of sediment on the reef flat on a daily basis, resulting in an overwhelming contribution to the total sediment flux. Sediment resuspension and transport was found to be controlled by state of tide and magnitude and direction of the trade winds relative to the orientation of the coastline. Locations where sediment moves offshore appear to be correlated with areas of low coral coverage on the fore reef.

The high wave energy regime of Hawaiian coastal reefs coupled with the existence of very deep ocean waters offshore of the reefs allows rapid removal of sediments from the reefs. The dynamic relationship between sediment input, deposition, resuspension and removal favors rapid regeneration of costal reefs once the terrigenous input has been reduced or eliminated. For example, a major program resulted in the removal of 20,000 goats from the island of Kahoolawe so that re-vegetation could occur and stabilize the soils that were rapidly being eroded into the sea. Following corrective action, Jokiel et al. (1993b) noted uncovering of old buried reefs with intact dead skeletons of delicate corals at many locations previously subjected to high sediment loading. Rapid recruitment of new coral colonies onto the recently uncovered reef surfaces was noted at all sites. The reefs appeared to be undergoing recovery as sediment input diminished and as waves and currents removed the existing deposits. Similar observations were made by Grigg (1985), who reported a recovery period of 5–10 years for sediment damaged reefs after the discharge from sugar plantations was halted on the island of Hawaii. Extensive mud flows from an illegal grading project covered the reef at Pilaa, Kauai. Measures were taken to stabilize the graded area and stop the chronic flow of mud. Subsequently, winter storms over a period of years mobilized and removed much of the mud from the damaged reef (Jokiel and Brown 2004b).

12.4 Zonation and Community Patterns

Gosline and Brock (1960) presented a zonation scheme in relation to distributions of Hawaiian fishes including offshore pelagic, littoral, reef sub-surge zone, reef surge zone and supra-surge zones. They concluded that zonation of reef fishes is controlled largely by wave regime and substrate type. The habitat and zone descriptions presented by Maragos (1998) are more detailed in three dimensional space and time. This approach is based on a number of interacting ecological factors and is consistent with the nomenclature of contemporary field ecologists working on Hawaiian coral reefs. The habitat and zone classification scheme of Coyne et al. (2003) for Hawaiian reefs is a simplified two-dimensional mapping approach necessitated by the limitations of producing maps from remote sensing images. The various classification approaches are of value in describing ecological features of Hawaii coral reefs and can be readily modified and adapted to meet the requirements of specific investigations. A very wide range of reef types occurs throughout the MHI (Fig. 12.3). A synthesis of information relevant to descriptions of habitats and zonation on Hawaiian coral reefs is as follows:

12.4.1 Physical Factors Controlling Community Composition

Major factors that control zonation and community patterns (Fig. 12.2) include reef type (morphology), wave exposure (Fig. 12.3f), depth, substrate type, sedimentation, island age, latitude and nutrient availability. Freshwater intrusion either through surface runoff or groundwater seepage can also influence community composition. Light penetration,

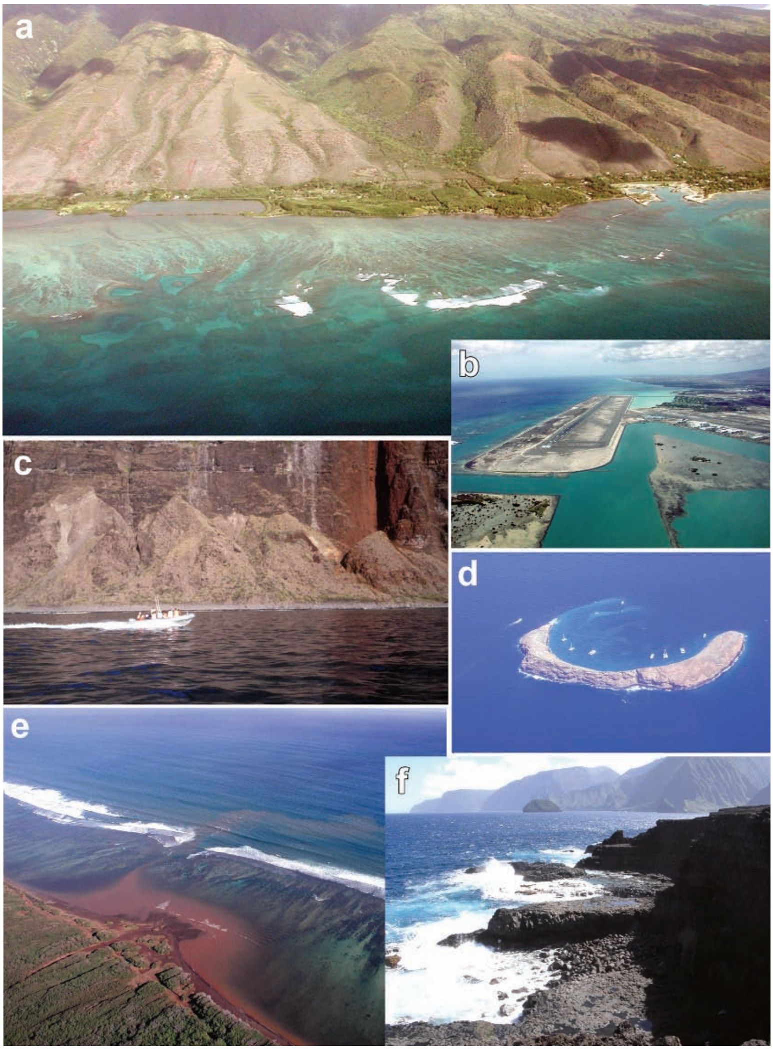

FIG. 12.3. (**a**) Fringing reef, South Molokai. (**b**) Highly modified reef, Honolulu, Oahu. (**c**) Vertical walls, Napali Coast, Kauai. (**d**) Molokini Island, Maui. (**e**) Sediment-impacted fringing reef, Lanai. (**f**) Wave-exposed coastline, North Molokai

wave energy and temperature diminish with depth and create environmental gradients leading to vertical zonation over a depth range (Friedlander et al. 2003).

12.4.2 Major Reef Types

As volcanic islands in the Hawaiian Archipelago form and move to the northeast with the Pacific Plate they gradually erode to sea level and eventually subside to form atolls, banks and eventually deep water seamounts. The formation of reefs around the perimeter of the main Hawaiian Islands follows the early phases of atoll formation in the general scheme first proposed by Charles Darwin in the nineteenth century (Darwin 1976). During the first stages of development, Hawaiian reefs are nothing more than a thin veneer of corals and crustose coralline algae overlaying the volcanic rock of a high island. As carbonate is accumulated the reefs grow outward to form wide fringing reefs. The next stage is the gradual submergence of the reef with rapid growth on the seaward margin. Rapid outward growth forms a barrier reef. As the island subsides, upward growth of the outer barrier reefs keeps pace with subsidence to form an atoll as the volcanic core sinks below the surface. Such atolls occur in the NWHI.

12.4.2.1 Apron Reefs

Apron reefs are the first phase of reef development and consist of a thin veneer of calcifying organisms overlaying the basalt substratum. A newly emergent Hawaiian island starts as a series of volcanic eruptions on the deep ocean floor. As the island builds into the photic zone, calcifying organisms such as corals and coralline algae can colonize the basalt and begin the process of reef building. Marine habitats on the young volcanic islands of Hawaii and Maui are characterized by steep unstable volcanic slopes, rocky shorelines and beaches consisting of basalt cobble. Reef coral communities form on these basalt surfaces as discontinuous "apron reefs" that consist of a thin veneer of corals and calcifying organisms. Sandy carbonate beaches are uncommon and where beaches occur, they consist largely of black volcanic sand. Lava flows reaching the sea create new basalt surfaces that are devoid of life. As the lava cools it is colonized by bacteria, algae, various invertebrates and eventually by corals. Development rate of the coral community on a fresh lava flow depends largely on exposure to sea and swells (Grigg and Maragos 1974). In wave-exposed areas, recovery time (in terms of number of species, percent cover and diversity) of coral communities is approximately 20 years. In sheltered embayments more than 50 years is required for complete recovery. Succession in exposed areas is continually interrupted by large wave events which keeps these communities in perpetual pioneer stages. In wave-sheltered areas the reefs become more fully developed and therefore require more time for recovery to their original condition after being covered by a lava flow. Coral coverage and diversity increase over time, but diversity shows a decline as climax is approached. The downturn is due to interspecific competition for space, with dominance by fast-growing species that can crowd out competitors.

12.4.2.2 Fringing Reefs

If conditions are favorable to growth of carbonate -secreting organisms the pioneer apron reefs will continue to accrete carbonate materials and eventually grow seaward and form true biogenic fringing reefs, provided that the shoreline is not undergoing submergence, slumping or is being impacted by extremely heavy wave action (Fig. 12.3f). The older islands of Maui, Molokai, Oahu and Kauai have areas of well developed fringing reefs that are lacking on the younger islands of Maui and Hawaii. The structure of a fringing reef is developed by accretion of the skeletons of calcifying organisms rather than taking the form of the underlying basalt. The outer slope of fringing reefs typically extends to a depth of 30–50 m.

12.4.2.3 Barrier Reefs

An ancient drowned barrier reef exists at Mana off northwest Kauai at a depth of about 30 m with a lagoon that is presently at a depth of 50 m. Kaneohe Bay, Oahu is a lagoon that is formed by a structural barrier reef on the seaward margin and is the largest sheltered body of water in the main Hawaiian Islands (Holthus 1986). The bay is about 13 km long and 4 km wide. This barrier reef is not a true biogenic barrier reef, but rather is a ridgeline formed along a drowned river valley that has developed a veneer of carbonates. Two major channels connect the lagoon to the open ocean. Patch reefs have developed within the lagoon and fringing reefs have formed along the landward side of the lagoon. The area is unique and atypical of Hawaii's coastline but is noteworthy because of the complex structural reef development, diversity of habitats and organisms, occurrence of patch reefs, presence of a well developed fringing reef along the landward margin, blue holes, and presence of a well-flushed lagoon. Further, this system has been studied extensively for the past 50 years by scientists working at the Hawaii Institute of Marine Biology at Coconut Island.

12.4.3 Zones

12.4.3.1 Supra-tidal

Anchialine ponds are salt water ponds located in the supra-tidal with no surface connection to the ocean. However, they have a subsurface connection to the sea through the porous volcanic rock as evidenced by the rising and falling of water level with changes in tide. There are more than 700 of these ponds in Hawaii with most of them occurring on young lava flows on the Island of Hawaii and Maui. These are unique Hawaiian ecosystems are inhabited by a number of exotic organisms including endemic species of small red shrimps (Brock and Bailey-Brock 1998; Santos 2006). Some of the shrimp species feed on algae and bacteria, while others are predators on the herbivorous shrimp.

Tide pools are depressions along rocky coastlines that flood at high tide and are intermittently continuous with the open ocean. They experience extreme fluctuations in temperature and salinity and typically are inhabited by hardy species capable of withstanding high solar radiation, temperature extremes, desiccation, periods of low salinity and episodes of high wave energy. A wide variety of algae, echinoderms, mollusks, barnacles, crustaceans and worms occur in this habitat. Fish fauna include blennies, gobies and juveniles of certain species (Gosline and Brock 1960) that use the area as a nursery grounds to avoid predators.

12.4.3.2 Intertidal

The area between the mean high water line and lowest spring tide level is defined as the intertidal. Typically, this zone is narrow due to the small tidal range in the main Hawaiian Islands. The intertidal along sheltered shorelines typically consists of sand and/or mud substratum. In open coastal situations wave action scours rocky coastlines and creates beaches. Sandy beaches are most common on the older islands where carbonate reefs have developed (Kauai, Niihau, and Oahu,) and less common on the younger islands (Hawaii and Maui). Surf run up caused by waves that may reach a height of several meters overshadows the importance of tidal range which is only the order of one meter.

Mangroves were introduced on the island of Molokai in 1902, primarily for the purpose of stabilizing coastal mud flats. Throughout the main Hawaiian Islands mangroves have become a conspicuous component of the intertidal and shallow subtidal in sheltered embayments or along shorelines with well developed fringing reefs or barrier reefs. Mangroves are considered to be valuable components of coral reef ecosystems in the tropics, but in Hawaii they are invasive and have negative ecological impacts (Allen 1998) such as reduction in habitat quality for endangered water birds and colonization of habitats to the detriment of native species (e.g. in anchialine pools).

12.4.3.3 Subtidal

Reef Flats

Reef flats are shallow (semi-exposed) areas between the shoreline intertidal zone and the reef crest of a fringing reef. This zone is protected from the high-energy waves commonly experienced on the fore reef and reef crest. Typical reef flat habitats have a substrate ranging from mud to sandy reef rubble with coral mounds or ridges depending on water motion, circulation and rate of terrigenous input of mud. Typical assemblages include coral communities on mounds or ridges of hard substratum, algal communities and occasionally sea grass in mud/sand areas. Blue holes are interesting features found on wide reef flats off south Molokai (Fig. 12.3a) and Kaneohe Bay Oahu.

Lagoons

Lagoons are shallow areas inshore of a fringing or barrier reef. Kaneohe Bay, Oahu is the best developed example in Hawaii. The lagoon lies between the shoreline intertidal zone and the back reef of a barrier reef. This zone is protected from the high-energy waves by the barrier reef. Typical habitats include mud and sand substrate due to lack of wave action. Seagrass may be present, along with algal communities, patch reefs, and rich coral communities.

Lagoon Patch Reefs

Small isolated reefs that rise from lagoon bottom and break the surface of the sea are often called patch reefs. These are unique features in the MHI that are restricted largely to Kaneohe Bay, Oahu.

Back Reef

This is the area between the seaward edge of a lagoon floor and the landward edge of a reef crest. This zone is present only when a reef crest and lagoon exist. Typical habitats include sand, reef rubble, seagrass beds, and algal communities.

12.4.4 Seaward Ocean Reef Zones

12.4.4.1 Reef Crest

The term refers to the flattened, emergent (especially during low tides) or nearly emergent segment of a reef. This zone lies between the back reef and fore reef zones. Breaking waves will often be visible in aerial images at the seaward edge of this zone. The major feature is an algal ridge that breaks the surface and is built by crustose coralline algae and other organisms. Small channels, depressions, areas of sand and cobble, areas with wave-resistant corals and flat areas with attached macro algae are typically present.

12.4.4.2 Fore Reef

This is the area from the seaward edge of the reef crest that slopes into deeper water down to the bank/shelf platform in typical situations. The term applies to reefs without an emergent reef crest but still having a seaward-facing slope that is significantly greater than the slope of the bank/shelf.

12.4.4.3 Bank or Shelf

This refers to a deep water area extending offshore from the seaward edge of the fore reef to the beginning of an escarpment where the insular shelf drops off into deep, oceanic water. Such flattened platforms between the fore reef and deep open ocean waters are common in Hawaii. Typical Habitats in these areas (Fig. 12.2e) include sand deposits, algal beds (*Halimeda* spp., *Padina* spp., sea grass, etc.), colonized and uncolonized pavement, and sand channels.

12.4.4.4 Shelf Escarpment

In this zone the depth increases rapidly into deep, oceanic water. The zone begins at approximately 20–30 m depth and extends into much deeper water.

12.4.5 Other Zones

12.4.5.1 Vertical Walls

In many locations throughout Hawaii vertical walls of basalt remain (Fig. 12.3c) where sections of islands have fallen away in slumps and prodigious submarine avalanches (Moore et al. 1989). These coastlines are characterized by near-vertical slope from shore to shelf or shelf escarpment. Such areas are typically narrow and may not be distinguishable in remote sensing imagery, but are important habitats along the coastlines of Hawaii. The resulting steep cliffs rise above sea level and can extend vertically to great depths. These stretches of coastline typically contain sea caves where waves rapidly erode areas of softer lava rock or where lava tubes occur. Such shorelines often have wave cut benches with tide pools. A typical intertidal develops on the upper rock face grading into a heavily wave impacted subtidal that typically has low coral coverage of wave resistant *Pocillopora meandrina* (Fig. 12.2a). Deeper on the face encrusting *Porites* spp. (Fig. 12.2b) become more abundant with *Montipora* spp. (Fig. 12.2f) increasing in abundance in deeper water as wave action is less and light becomes limiting.

12.4.5.2 Naturally Formed Channels

These are a common feature of coral reefs. Such channels often are drowned river valleys. Channels can cut across several other zones. On fringing reefs breaking waves on the reef crest transport water onto the reef flat. This water eventually drains off the reef through channels (Fig. 12.3c).

Channels are characterized by strong out-flowing currents, especially during periods of high waves and at falling tide. The typical habitat in the bottoms of the channels is unconsolidated cobble, sand or mud depending on current speed and wave action. Channel sides typically are colonized by corals and crustose coralline algae. Fish often are abundant due to the vertical relief of the walls and the strong currents which carry algae, small organisms and detritus that serves as food for the fishes.

12.4.5.3 Pinnacles, Stacks and Offshore Islets

Such features occur throughout the MHI and possess a surprisingly rich and diverse marine fauna. For example, the islet of Moku Manu off Mokapu Peninsula (east Oahu) has an extensive system of undersea caves with extremely high abundance and diversity of sponges and associated organisms. Numerous habitats such as spur and groove, vertical wall, boulder and coral communities are represented in a small area. The sea stack called Mokapu which is located off Kalupapa, Molokai has a very rich benthic fouling community along with diverse associated organisms such as nudibranchs and starfish that are seldom seen in other locations. The sheltered side of this sea stack has been colonized by the soft coral *Sinularia,* which is uncommon in Hawaii. Antipatharians normally found in deeper water occur at 10 m depth. Another well known example is Molokini, Maui (Fig. 12.3d). The crescent-shaped islet represents the emergent one third of the rim of a small tuff cone about 400 m in diameter. The submerged crater area of the cinder cone forms a "lagoon" and has extremely high coral coverage and a rich reef fish assemblage. Maximum lagoon depth is 30 m with the surrounding waters is being approximately 150 m deep. Rich coral reefs in the crater support a diverse and abundant fish fauna. Coral coverage in this area can reach over 70% of available hard substratum. Boulder, sand and coral habitats are present. The south face of the crater is a nearly vertical wall that extends down to over 100 m (300 ft) depth and is subjected to seasonal south swells. The area is a marine life conservation district and attracts a large number of visitors.

12.4.5.4 Modified Shorelines

This zone is the result of human impact in which natural geomorphology is disrupted or altered by excavation, dredging, filling or construction of sea walls (Fig. 12.3c). Such zones are commonly encountered throughout Hawaii due to land fills, construction of harbors, sea walls and modification of beached for recreational. Sand and mud habitats are generally present along the bottom of dredged areas. Vertical dredged faces or boulder rip-rap are common habitats along the margins. These often become coral habitats such as has occurred at Honokahau Harbor on the Island of Hawaii (Maragos 1991) and Maalaea Harbor on Maui (Jokiel and Brown 1998).

12.4.6 Habitat Mapping

Rohmann et al. (2005) estimated a coral reef habitat area of 1,231 km^2 within 10 fathom (18 m) depth curve for the MHI. Within this area a hierarchical classification scheme was created by Coyne et al. (2003) to define and delineate reef habitats in the MHI. The classification scheme was designed to be as consistent as possible with NOS's coral reef mapping in the Florida Keys and Caribbean as well as with existing classification schemes for the Pacific. The minimum mapping unit (MMU) was set at 1 acre for visual photo-interpretation based on time and resource constraints. The hierarchical scheme allows users to expand or collapse the thematic detail to suit their needs. Habitat polygons smaller than the MMU can be delineated or habitat polygons already delineated using this scheme can be further attributed with other information such as dominant species of coral. The classification scheme defines the benthic communities on the basis of two attributes: large geographic "zones" which are composed of smaller "habitats". Zone refers only to benthic community location and habitat refers only to substrate and/or cover type. Eleven mutually exclusive zones were identified from land to open water corresponding to typical insular shelf and coral reef geomorphology. These zones include: land, vertical wall, shoreline intertidal, lagoon, reef flat, back reef, reef crest, fore reef, bank/shelf, bank/shelf escarpment, channel, and dredged. Zone refers only to each benthic community's location and does not address substrate or cover types. For example, the lagoon zone may include patch reefs, sand, and seagrass beds. Twenty-seven distinct and non-overlapping habitat types were identified that could be mapped by visual interpretation of remotely collected imagery. Habitat refers only to substrate and/or cover type and does not address location or depth. Habitats are defined in a collapsible hierarchy ranging from four broad classes (unconsolidated sediment, submerged vegetation, coral reef and hardbottom, and other), to more detailed categories (e.g. emergent vegetation, seagrass, algae, individual patch reefs, uncolonized volcanic rock), to patchiness of some specific features (e.g. 50–90% cover of macroalgae).

Approximately 60–70% of the total reef area of the MHI was mapped (total = 813 km^2), being limited by factors such as high turbidity, cloud cover or lack of imagery. Approximately 27% of the mapped area was classified as "soft" bottom (21% sand, 6% mud). Macraoalgae communities account for 19% of the total area mapped with 15% falling into the 10–50% macroalgae category and 4% in the 50–90% macroalgae category with only a fraction of a percent in the greater than 90% coverage category. The remaining hard bottom in various categories accounts for most of the remaining area (50% total). Hard bottom areas with less than 10% coral cover classified as "uncolonized" and comprise a total of 29% of the mapped area with 13% as uncolonized pavement, 12% as volcanic rock/boulder and 4% as uncolonized pavement with channels. Areas with greater than 10% coral cover were classified as "colonized" and account for 21% of the total distributed over 5 subcategories. On a broad scale for the entire MHI this translates roughly into 27% soft bottom, 19% algal communities, 29% uncolonized (less than 10% coral), 21% colonized and the remaining 14% in various other categories such as emergent vegetation, fishponds, man-made structures, etc. Average reef coral coverage for 152 reef stations measured on hardbottom substrate throughout the MHI was 21%, with six species accounting for most of the coverage (Jokiel et al. 2004a). The six dominant species were: *Porites lobata* (6%), *Porites compressa* (5%), *Montipora capitata* (4%), *Montipora patula* (3%), *Pocillopora meandrina* (2%) and *Montipora flabellata*.

12.5 Human Impact on Local Coral Reefs and the Present Status of Reef Health

In general, Hawaii's coral reefs are in better condition than many other reefs around the world. Coral ecosystems in the MHI are in fair to excellent condition, but are threatened by continued population growth, over fishing, runoff, and development (Friedlander et al. 2004, 2005). There is clear evidence of overexploitation of many food fishes and invertebrates. Introduced aquatic alien species have an impact on the structure and function of Hawaii's reefs and may out-compete endemic species. Human activity has already taken a toll on the reefs of the populated high islands. Jokiel et al. (2004) showed that human population within 5 km of a reef had a negative relationship in Hawaii with coral cover, diversity and species richness, suggesting that anthropomorphic stressors are important contemporary forces shaping Hawaii coral reef community structure along with natural factors. Also there was a significant relationship between reef condition and degree of management protection (Friedlander et al. 2003; Jokiel et al. 2004).

The unpopulated islands and reefs of the NWHI have fared better than the MHI. For example, results of a recent analysis of "reef health and reef value" indicate that the "worst island" of the NWHI ranks with the "best island" of the MHI (Jokiel and Rodgers 2007). The quantitative numerical ranking devised in this study is based on extensive data on fish, corals and endangered species. The result mirrors the personal experience of marine biologists and others who visit the area and note how different the NWHI islands appear to be compared to the MHI in terms of biological abundance and diversity on the shallow coral reefs

12.5.1 Land Use and Pollution

Areas of reef decline appear to be concentrated on islands with high human population or in areas suffering from extensive land runoff and sedimentation (Jokiel et al. 2004). Reefs receiving high terrigenous runoff contain sediment deposits with high organic content. Spatial analysis shows an inverse relationship between percent organics and coral species richness and diversity (Jokiel et al. 2004), suggesting that organic addition is a negative factor on Hawaiian coral reefs. Improper land use increases sedimentation and freshwater runoff. Major anthropogenic impacts such as increased sedimentation and nutrification dominate Hawaiian reef environments where waves are not a major controlling factor (Dollar and Grigg 2004). These environments are typically bays and lagoons that do not receive sufficient wave energy to flush fine sediments from the system. Thus we observe a paradox that areas vulnerable to storm waves are less vulnerable to storm floods and areas impacted by storm floods are less vulnerable to storm waves. Large-scale sugar cane and pineapple agriculture, which periodically exposes land to erosion, is being phased out throughout Hawaii and may result in a decrease in sediment delivery to the ocean. However, many low-lying coastal areas that were once wetlands and flood plains have been altered and continued development of these areas is underway. These low-lying areas once served as settling basins and filters, removing sediments and nutrients from runoff before it entered the ocean. Development increases the amount of impervious surface and causes increased runoff which is generally diverted to storm drain systems. The drains transport sediment, trash, and chemical pollutants directly into coastal waters. As coastal areas are developed, the floodplains are filled, storm drains are constructed, and streams are “channelized”, resulting in more sediment being delivered to the reefs. More coastal construction is planned in order to accommodate new large cruise ships, container ships, and an inter-island ferry. Harbor improvements involve dredging which can influence adjacent reefs.

12.5.1.1 Anthropogenic Increases in Sedimentation

Historically the major cause of erosion, runoff and accelerated sedimentation on Hawaiian coral reefs has been overgrazing on watersheds. Roberts (2001) has reviewed the importance of this process on the reefs of south Molokai. Serious overgrazing by feral ungulates (pigs, goats, deer) continues to cause severe damage to watersheds on Molokai, Lanai, west Maui and the north coast of Kauai. A serious overgrazing problem over the past two centuries led to massive erosion on the island of Kahoolawe. The Kahoolawe situation was corrected with the complete eradication of over 20,000 goats in 1990 (Jokiel et al. 1993b). Elimination of the goats and efforts to reestablish vegetation on the island appear to be having a positive effect on the reefs. Currently sediment deposits are being winnowed off the reefs by wave action faster than new sediments are being deposited.

Muddy runoff pollution of coral reefs from development sites is a frequent occurrence in Hawaii. In 1996, rivers of mud filled Maalaea harbor on Maui, causing hundreds of thousands of dollars in damage. In 2000, a torrent of mud flowed off acres of land graded for a golf course just north of Kealakekua Bay on the island of Hawaii. Similar incidents took place off Lanai in 2002.

12.5.1.2 Sewage

Starting in the early 1960s, raw sewage discharged into the south basin of Kaneohe Bay, Oahu had a dramatic effect on the reefs (Maragos 1972; Banner 1974; Smith et al. 1981; Hunter and Evans 1993). High nutrient levels led to blooms of phytoplankton which reduced water transparency and blocked light to the photosynthetic benthos. Massive mats of the “green bubble algae” overgrew and choked out living corals. The benthic community became dominated by macro-algae and filter feeding invertebrates. Sediments became anoxic and seaweed washed ashore to form large rotting berms of organic matter. Removal of sewage outfalls in Kaneohe Bay in 1979 led to dramatic decrease in nutrient levels, turbidity and phytoplankton abundance (Smith et al. 1981) and a rapid recovery of reef coral populations (Maragos et al. 1985). By 1983 coral coverage had more than doubled from 12% to 26% (Hunter and Evans 1993). However, initial planning in the early 1960s should have placed outfalls in deep water outside the bay, avoiding the impact and cost to relocate them in the late 1970s.

A major reef kill occurred in Kaneohe Bay in May 1965 due to heavy rains (Banner 1968). However, conditions of heavy sewage pollution prevented recovery of the reefs until after sewage abatement in 1979. The same coral reefs were subjected to a similar reef kill in late 1987, but showed substantial recovery within 5 years (Jokiel et al. 1993a). It appears that coral reefs can recover quickly from major natural disturbances, but not under polluted conditions.

A recurring problem in Hawaii occurs when storm floods overwhelm wastewater treatment facilities. For example, a recent storm flood event in early January 2004 caused sewage spills at 14 locations on Oahu and forced the closing of beaches off Honolulu, Kailua and Waimanalo (Hoover 2004). Another storm flood in early February 2004 again resulted in wastewater spills and beach closures (Honolulu Advertiser 2004).

12.5.1.3 Dredging, Filling and Other Shoreline Construction.

Much of Hawaii's shoreline has been modified by human activity. Notable examples include Kaneohe Bay, Oahu, Hawaii. Major dredging activities in the late 1930s and early 1940s removed reefs and patch reefs to create sea plane runways and cut a deep ship channel (Devaney et al. 1982). The 1972 Reef Runway Project at Honolulu International Airport (Fig. 12.3b) involved the dredging and fill of some 11 million cubic meters of coral reef material, impacting over 480 ha of coral reef (Chapman 1979).

12.5.2 Fisheries

Management of the biological resources of Hawaiian coral reefs is primarily the responsibility of the State of Hawaii Division of Aquatic Resources (DAR), but with many overlapping areas of responsibilities with other agencies. DAR utilizes several management tools including full or partial closure of a reef area as a marine protected area (MPA), rotational and seasonal closures, restrictions on fishing gear or methods, size and bag limits, and rules preventing the take of certain species.

Even though it is likely that a much smaller proportion of the population presently fishes relative to ancient times, marine resources in Hawaii have steadily declined over at least the last century (Maly and Maly 2004; Shomura 1987). Comparison of fish abundances in the Main Hawaiian Islands with those of the relatively unexploited Northwestern Hawaiian Islands also points to major fishery declines in the populated islands (Friedlander and DeMartini 2002). Early in the century Jordan and Evermann (1902) noted that the fisheries of Honolulu were declining rapidly due to localized overfishing. In 1927 it was reported that the fish fauna of Hawaiian reefs was much less abundant than several decades earlier and many common species had become rare (Jordan et al. 1927). Declining marine resources were acknowledged again by resource managers in the 1950s when they reported that desirable food and game fishes were on a "declining trend and have deteriorated to such an extent that the need for sound conservation measures is urgent" (Division of Fish and Game 1956). Fishermen and other ocean users are well aware of declining reef resources. Surveys of both commercial and noncommercial fishers (Harman and Katekaru 1988; Division of Aquatic Resources 1998) have documented this perception. In the 1998 survey 57% of respondents felt inshore fishing was now poor to terrible. Over fishing is most often cited as the prime cause of resource depletion (Division of Aquatic Resources 1998). Increased fishing pressure is due to increased human population, introduction of new fishing technology and loss of traditional conservation practices (Lowe 2004; Birkeland and Friedlander 2002).

Perhaps the major factor behind the historical decline has been improved fishing techniques (gill nets, skin diving and scuba equipment, geographic positioning systems, power boats, sonar fish finders). The introduction of inexpensive monofilament gill nets enables further exploitation of fish stocks that are already depleted and stocks in deeper water that had previously escaped overharvesting (Clark and Gulko 1999).

Recreational and subsistence fishers in Hawaii are not licensed and have no reporting requirements, so data on their catch are lacking. The possibility of under-reporting by the commercial fishermen further increases the uncertainty of catch statistics for the state. The recreational and subsistence catch use a wider range of fishing techniques and targets a wider range of species than the commercial fishermen and is probably equal to the commercial fisheries catch (Everson and Friedlander 2004). The commercial catch underwent a 70% decline between 1950 and 2002 (Zeller et al. 2005).

It is against the law in Hawaii to take or have stony coral and "live rock" (marine substrate with live attached organisms). This law is being enforced as evidenced by numerous convictions for violations. However, the collecting of aquarium fish and certain invertebrates is allowed. A relatively small number of species dominates the aquarium trade catch with only ten species constituting over 70% of the total (Walsh et al. 2004). The most commonly caught fish species include surgeonfishes, butterflyfishes, and wrasses. The yellow tang (*Zebrasoma flavescens*) accounts for nearly 40% of the total catch. Feather duster worms, hermit crabs, and shrimp are the main targets among the invertebrates. The commercial aquarium fishery in Hawaii has grown into one of the state's major inshore fisheries, with landings of over 708,000 specimens with a reported value of over $1 million (Walsh et al. 2004). Cesar et al. (2002) estimated industry gross sales at over $3 million. There is a general belief that aquarium fishery catch is underreported throughout the state. Such collecting activities in Hawaii can deplete targeted species (Tissot and Hallacher 2003). In response to the growing problem, a network of fish replenishment areas was established on the Kona coast on the island of Hawaii in 2000. Within 4 years there were increases in the abundance of several targeted species, and the overall value of the fishery reached an all-time high (Walsh et al. 2004).

12.5.3 Alien Species

Increasing human population and resulting human activity have led to both accidental and intentional species introductions. Although most of these don't survive, a few persistent species have become a source of serious ecological and economic impacts to the state. In the MHI, 343 alien marine species have been documented and inventoried (Eldredge and Carlton 2002). Invertebrate species dominate with 287 species, followed by algae (24), fishes (20), and flowering plants (12). The mechanisms of introduction and the number of estimated introductions into Hawaii are as follows: Hull fouling (212), solid ballast (21), ballast water (18), intentional release for fisheries (18), parasites associated with alien introduced species (8), organisms associated with commercial oyster shipments (7) and aquarium release (3). A more comprehensive summary of alien species in Hawaii can be found in Godwin et al. (2006). None of these species are viewed as desirable by the public or by marine managers. For example, the blue-lined snapper or Ta'ape, (*Lutjanus kasmira*) was introduced from the Marquesas in 1958 and although only 3,200 Ta'ape were released on the island of Oahu, they have increased their range to include the entire Hawaiian archipelago. The fish has become locally abundant but is not seen as a desirable food fish and might be displacing locally more desirable fish. Another example is the soft coral *Carijoa riisei*. This species was originally observed in Pearl Harbor and is thought to have arrived through ship hull fouling or in ballast water. In its native Caribbean, it is found in shallow waters as part of the fouling community on pier pilings. Initially, it was not considered a threat since it was thought to be restricted to such underutilized low-light habitats. *C. riisei* has since expanded its range to all islands in the MHI chain. Results from a 2001 found *C. riisei* had spread into waters up to 110 m deep and is competing with the native black corals. They both feed and compete for the same zooplankton and are competing for space. *C. riisei* can grow up to 12 times faster than the valuable black coral. This species blankets everything in its path and drastically reduces the biodiversity of the area. Grigg (2003) has reported that this species has completely decimated black coral beds in areas in the deep trench (75–110 m) between West Maui and Lanai.

12.5.4 Disease

All organisms are subject to disease, and coral reef organisms are no exception. Interest in the diseases of corals has grown tremendously due to serious outbreaks of coral disease in many parts of the world (Richardson 1998). Environmental stress renders corals more prone to disease, as is the case with other organisms. Reef corals in the main Hawaiian Islands have not experienced the massive epidemic disease outbreaks reported from other areas. Baseline surveys show low prevalence of disease (Hunter 1999; Work and Rameyer 2001).

Disease is a major cause of concern for population of the endangered Hawaiian green sea turtle. Turtles are being affected by fibropapillomatosis, which causes large external and internal tumors and occurs in 40–60% of observed Hawaiian turtles (Balazs and Pooley 1991). This may pose a significant threat to the long-term survival of the species.

An alpha-herpes virus appears to be the cause (Lu et al. 2004).

12.5.5 Crown-of-thorns Starfish

There has been a long standing suspicion that outbreaks of crown-of-thorns starfish, *Acanthaster planci,* are related to human activity (Birkeland and Lucas 1990). Such outbreaks have not been a major problem in Hawaii. The only documented outbreak occurred during 1969–1970, a large aggregation estimated to consist of 20,000 *A. planci* was observed off south Moloka'i (Branham et al. 1971). The State of Hawaii Department of Fish and Game undertook extensive surveys and eradication efforts after discovery of the infestation (Onizuka 1979). Divers killed a total of approximately 26,000 starfish between 1970 and 1975 by injecting them with ammonium hydroxide. Additional surveys were conducted throughout the State of Hawaii, but no other infestations were detected at that time, nor have any been found since.

12.5.6 Landmark Case Study – Illegal Grading and Coral Reef Damage

A landmark case in Hawaiian coral reef protection occurred as the result of damage to a pristine coral reef at Pilaa in a secluded area on the northeast coast of Kauai. Jimmy Pflueger, a prominent figure in Hawaii, conducted grading without permits on his 378 acre property which included extensive massive grading of a coastal plateau, building a road just above the beach and creating a 40-ft cliffside cut. The grading work did not include measures to control storm water in case of heavy rain. During a rainstorm on November 26, 2001, tons of graded mud slid from the hillside onto the beach, engulfing a waterfront private home and spread across the white sand beach and onto the reefs. In continuing rains, mud ran repeatedly into the sea. Studies showed significant damage to the reef which included extensive coral mortality, high turbidity, high percentages of mud in reef sands, anoxic substratum and formation of algal mats over the reef (Jokiel et al. 2002; Jokiel and Brown 2004b).

Legal action against Pflueger was initiated by US Department of Justice; the Environmental Protection Agency; Hawaii Department of Land and Natural Resources, State Department of Health; Kauai County; and Earthjustice, representing the Limu Coalition and Kilauea Neighborhood Association. Pflueger was sentenced to a $500,000 fine after pleading guilty to ten felony water pollution counts and a county fine of $310,000 for coastal zone violations. He also agreed to pay nearly $8 million to settle claims under the federal Clean Water Act. The settlement is the largest storm-water settlement in the country for violations at a single site by a single landowner according to Wayne Nastri, regional administrator for the U.S. Environmental Protection Agency, which enforces the Clean Water Act (Leone 2006). A lawsuit against Pflueger by neighbors whose property was damaged by the landslide is still pending.

The response at all levels of government as well as by community groups in defense of the reef was noteworthy. However, a major precedent in the protection of Hawaiian reefs was set the State of Hawaii DLNR when they determined that the reef had been damaged in the amount of $4 million and ordered payment together with administrative costs to the State of Hawaii special land and development fund. The ruling was subsequently appealed and upheld in the Hawaii State Circuit Court. This action marks the first time that the State of Hawaii has taken action against a developer responsible for damaging reef resources. Further, the ruling established the dollar value of coral reefs in Hawaii and a mechanism to recover the dollar value of the lost resources.

12.5.7 Reef Restoration and Mitigation

Numerous mitigation and restoration projects have been conducted in Hawaii as discussed in detail by Jokiel et al. (2006). Reef restoration efforts using transplanted corals have failed along exposed coastlines due to destructive storm waves and other factors. However, there have been transplant successes in sheltered embayments. One of the major conclusions of the Jokiel et al. (2006) review is that the cost of reef repair and coral transplantation is generally high but effectiveness is usually very low. Protection and conservation, rather than restoration of damaged reefs, is the preferred priority.

Nevertheless, there have been a number of successful mitigation efforts in Hawaii. Mitigation of sewage pollution in Kaneohe Bay as discussed in

Section 12.5.1.2 is one example. The efforts taken at Kahoolawe discussed in Section 12.5.1.1 is another. An extensive area of reef off Kahe Point, Oahu, was damaged by thermal effluent from a power generation station (Jokiel and Coles 1974). When generating capacity of the plant was increased from 270 to 360 MW, the area of dead and damaged corals increased from 0.38 to 0.71 ha. The requirement for plant expansion and further increases in discharge led to installation of a new outfall pipe in 1976 in deeper offshore waters. This pipe is over 100 m in length, is protected from wave action by heavy rock riprap, and now carries heated effluent offshore and away from the reef. Colonization of the damaged area and the riprap was dramatic, with coral colonization rates among the highest reported in the literature (Coles 1984). Discharge of silt-laden water and crushed cane (bagasse) from sugar mills along Hawaii's Hamakua coastline for many decades caused extensive damage to coral reefs (US Environmental Protection Agency 1971). Termination of discharges led to a rapid clearing of the sediment and bagasse waste by wave action and subsequent regeneration of coral reefs in the former discharge zones (Grigg 1985).

Acknowledgement This work partially supported by USGS cooperative agreement 04WRAG001 and EPA Star Grant R832224-010.

References

Aeby GS, Kenyon JC, Maragos JE, Potts DC (2003) First record of mass coral bleaching in the Northwestern Hawaiian Islands. Coral Reefs 22:256

Allen JA (1998) Mangroves as alien species: the case of Hawaii. Glob Ecol Biogeogr Lett 7:61–71

Bach W, Daniels AP (1973) Climate, pp 53–62. In: Armstrong RW (ed) Atlas of Hawaii. University of Hawaii Press, Honolulu., HI, 222 pp

Banner AH (1968) A fresh water "kill" on the coral reefs of Hawaii. Hawaii Inst Mar Biol Tech Rep 15:1–29

Banner AH (1974) Kaneohe Bay, Hawaii: urban pollution and a coral reef ecosystem. Proc 2nd Int Coral Reef Symp 2:685–702

Baker JD, Johanos TC (2005) Distribution and abundance of Hawaiian Monk Seals in the main Hawaiian Islands. Values are from 2001 survey reported in (http://www.mmc.gov/reports/workshop/pdf/baker.pdf)

Balazs GH, Chaloupka M (2004a) Thirty-year recovery trend in the once depleted Hawaiian green sea turtle stock. Biol Cons 117:491–498

Balazs GH, Chaloupka M (2004b) Spatial and temporal variability in somatic growth of green sea turtles (*Chelonia mydas*) resident in the Hawaiian Archipelago. Mar Biol 145:1043–1059

Balazs GH, Pooley SG (eds) (1991) Research plan for marine turtle fibropapilloma. NOAA Technical Memorandum NMFSSWFSC-156,113 pp

Barkley RA (1972) Johnston Atoll 's wake. J Mar Res 30:201–216

Birkeland C, Friedlander AM (2002) The importance of refuges for reef fish replenishment in Hawaii. The Hawaii Audubon Society, 19 pp

Birkeland C, Lucas J (1990) *Acanthaster planci*: major management problem of coral reefs. CRC, Boca Raton, FL, 272 pp

Bothner MH, Reynolds RL, Casso MA, Storlazzi CD, Field ME (2006) Quantity, composition, and source of sediment collected in sediment traps along the fringing coral reef off Molokai, Hawaii. Mar Pollut Bull 52:1034–1047

Branham JM, Reed SA, Bailey JH, Caperon J (1971) Coral-eating sea stars *Acanthaster planci* in Hawai'i. Science 172:1155–1157

Brock RE (1996) A study of the impact of hurricane Iniki on coral communities at selected sites in Mamala Bay, Oahu, Hawaii. Project report PR-96–09. University of Hawaii Water Resources Research Center, Honolulu, HI

Brock RE, Bailey-Brock JH (1998) An unique anchialine pool in the Hawaiian Islands. Int Rev Hydrobiol 83:65–75

Cesar H, van Beukering P (2004) Economic valuation of the coral reefs of Hawaii. Pac Sci 58:231–242

Cesar H, van Beukering P, Pintz S, Dierking S (2002) Economic valuation of the coral reefs of Hawaii. Final report. Hawaii Coral Reef Initiative Research Program, 117 pp

Chapman GA (1979) Honolulu International Airport reef runway post-construction environmental impact report, Vol. 2. Technical report to the Department of Transportation, Air Transportation Facilities Division, State of Hawaii by Parsons Hawaii, 137 pp

Clague DA, Dalrymple GB (1994) Tectonics, geochronology and origin of the Hawaiian Emperor Volcanic Chain, pp 5–40. In: Kay EA (ed) A Natural History of the Hawaiian Islands. University of Hawai'i Press, 274 pp

Clark AM, Gulko DA (1999) Hawaii's state of the reef report, 1998. State of Hawaii Department of Land and Natural Resources, Honolulu, HI, 41 pp

Coles SL (1984) Colonization of Hawaiian reef corals on new and denuded substrata in the vicinity of a Hawaiian power station. Coral Reefs 3:123–130

Coles SL, Brown BE (2003) Coral bleaching -capacity for acclimatization and adaptation. Adv Mar Biol 46:183–223

Coles SL, Jokiel PL (1992) Effects of salinity on coral reefs. In: Connell DW, Hawker DW (eds) Pollution in tropical aquatic systems. CRC, London pp 170–191

Coles SL, Jokiel PL, Lewis CR (1976) Thermal tolerance in tropical versus subtropical Pacific reef corals. Pac Sci 30:156–166

Connell JH (1978) Diversity in tropical rainforests and coral reefs. Science 199:1302–1310

Coyne MS, Battista TA, Anderson M, Waddell J, Smith W, Jokiel P, Kendell MS, Monaco ME (2003) NOAA Technical Memorandum NOS NCCOS CCMA 152 (On-line). Benthic habitats of the Main Hawaiian Islands. National Oceanic and Atmospheric Administration, Silver Spring, MD, 48 pp and CD-ROM

Curtis G (1998) Tsunamis. In: Juvik S, Juvick JO (eds) Atlas of Hawai'i, 3rd edition. University of Hawaii Press, Honolulu, HI, pp 76–78

Darwin C (1976) The structure and distribution of coral reefs. (Reprinted from Geological observations on coral reefs, volcanic islands, and on South America published by Smith, Elder and Co., London 1851.) University of California Press, Berkeley, CA, 214 pp

Daws G (1968) Shoal of time; history of the Hawaiian Islands. University of Hawaii Press, Honolulu, HI, 494 pp

Devaney D, Kelly MM, Lee PJ, Motteler LS (1982) Kane'ohe a history of change. The Bell Press, Honolulu, HI

Division of Aquatic Resources (1998) Fishing survey summary report. Division of Aquatic Resources, State of Hawai‘i, 9 pp

Division of Fish and Game (1956) Annual report of the Board of Agriculture and Forestry, Territory of Hawaii. FY July 1, 1955; June 30, 1956

Dollar S (1982) Wave stress and coral reef community structure in Hawaii. Coral Reefs 1:71–81

Dollar SJ, Grigg RW (2004) Anthropogenic and natural stresses on selected coral reefs in Hawaii: a multidecade synthesis of impact and recovery. Pac Sci 58:281–304

Dollar SJ, Tribble GW (1993) Recurrent storm disturbance and recovery: a long-term study of coral communities in Hawaii. Coral Reefs 12:223–233

Dunlap WC, Chalker BE (1986) Identification and quantification of near-UV absorbing compounds (S-320) in a hermatypic scleractinian. Coral Reefs 5:155–159

Edmondson CH (1933) Reef and shore fauna of Hawaii. Bernice P. Bishop Museum Special Publication 22. Honolulu, HI, 295 pp

Eldredge LG, Carlton JT (2002) Hawai‘i marine bioinvasions: a preliminary assessment. Pac Sci 56:211–212

Everson A, Friedlander AM (2004) Catch, effort, and yields for coral reef fisheries in Kaneohe Bay, Oahu and Hanalei Bay, Kauai : comparisons between a large urban and a small rural embayment. In: Friedlander AM (ed) Status of Hawaii's coastal fisheries in the new millennium. Proceedings of a symposium sponsored by the American Fisheries Society, Hawaii Chapter, Honolulu, HI, pp 110–131

Flament P, Kennan S, Lumpkin R, Sawyer M, Stroup E (1998) The Ocean. In: Juvik S, Juvick JO (eds) Atlas of Hawai'i, 3rd edition. University of Hawaii Press, Honolulu, HI, pp 82–86

Friedlander A, Aeby G, Brainard R, Brown E, Clark A, Coles S, Demartini E, Dollar S, Godwin S, Hunter C, Jokiel P, Kenyon J, Kosaki R, Maragos J, Vroom P, Walsh W, Williams I, Wiltse W (2004) Status of coral reefs in the Hawaiian Archipelago. In: Wilkinson C (ed) Coral reefs of the world, Vol. 2, Australian Institute of Marine Science, Townsville, pp 411–430

Friedlander A, Aeby G, Brown E, Clark A, Coles S, Dollar S, Gulko D, Hunter C, Jokiel P, Smith J, Walsh W, Williams I, Wiltse W (2005) The status of the coral reef ecosystems of the Main Hawaiian Islands. In: Waddell JE (ed) The status of the coral reef ecosystems of the United States and Pacific Freely Associated States. National Oceanic and Atmospheric Agency, Silver Spring, MD, pp 222–269

Friedlander AM, DeMartini EE (2002) Contrasts in density, size, and biomass of reef fishes between the northwestern and the main Hawaiian Islands : the effects of fishing down apex predators. Mar Ecol Prog Ser 230:253–264

Friedlander AM, Brown EK, Jokiel PL, Smith WR, Rodgers KS (2003) Effects of habitat, wave exposure, and marine protected area status on coral reef fish assemblages in the Hawaiian archipelago. Coral Reefs 22:291–305

Godwin S, Rodgers KS, Jokiel PL (2006) Reducing potential impact of invasive marine species in the northwestern Hawaiian Islands marine national monument. Report submitted to northwest Hawaiian Islands Marine National Monument Administration, Honolulu, HI, August 2006, 66 pp http://cramp.wcc.hawaii.edu/

Gosline WA, Brock VE (1960) Handbook of Hawaiian fishes Honolulu,. University of Hawaii Press, Honolulu, HI, 372 pp

Grigg RW (1981) *Acropora* in Hawaii Part 2. Zoogeography. Pac Sci 35:15–24

Grigg RW (1983) Community structure, succession and development of coral reefs in Hawai‘i. Mar Ecol Progr Ser 11:1–14

Grigg RW (1985) Hamakua coast sugar mills revisited: an environmental impact analysis in 1983. University of Hawaii, Sea Grant Pub. No. UNIHI-SEAGRANT-TR-85–02, Honolulu, HI, 81 pp

Grigg RW (1998) Holocene coral reef accretion in Hawaii: a function of wave exposure and sea level history. Coral Reefs 17:263–272

Grigg RW (2003) Invasion of a deep black coral bed by *Carijoa riisei* off Maui, Hawai'i. Coral Reefs 22:121–122

Grigg RW (2006) Depth limit for reef building corals in the Au'au Channel, S.E. Hawaii. Coral Reefs 25:77–84

Grigg RW, Maragos JE (1974) Recolonization of hermatypic corals on submerged lava flows in Hawaii. Ecology 55:387–395

Grigg RW, Wells J, Wallace C (1981) *Acropora* in Hawaii. Part 1. History of the scientific record, systematics and ecology. Pac Sci 35:1–13

Harman RF, Katekaru AZ (1988) 1987 Hawai'i commercial fishing survey. Division of Aquatic Resources, State of Hawai'i, 71 pp

Hiatt RW (1955) The Hawaii marine laboratory. AIBS Bull 5(1):26–27

Holthus P (1986) Coral reef communities of Kaneohe Bay, Hawaii: an overview. In: Jokiel PL, Richmond RH, Rogers RA (eds) Coral reef population biology. Hawaii Inst Mar Biol Tech Rep 37:19–34

Honolulu Advertiser (2004) City dealing with wastewater, sewage spills. Honolulu Advertiser 9 Feb 2004 edition

Hoover W (2004) Oahu beaches, streams spoiled by sewage spills. Honolulu Advertiser 4 Jan 2004 edition

Hourigan TF, Reese RS (1987) Mid-ocean isolation and the evolution of Hawaiian reef fishes. Trends Ecol Evol 2:187–191

Hunter CL (1999) First record of coral disease and tumors on Hawaiian reefs. In: Maragos JE, Gober-Dunsmore R (eds) Proceedings of the Hawaii coral reef monitoring workshop, June 7–9, 1998, pp 73–98

Hunter CL, Evans CW (1993) Reefs of Kaneohe Bay, Hawai'i: two centuries of western influence and two decades of data. pp 339–345. In: Ginsburg RN (ed) Global aspects of coral reefs. University of Miami, Rosenstiel School of Marine and Atmospheric Science, pp 339–345

Jokiel PL (1980) Solar ultraviolet radiation and coral reef epifauna. Science 207:1069–1071

Jokiel PL (1987) Ecology, biogeography and evolution of corals in Hawaii. Trends Ecol Evol 2:179–182

Jokiel PL (2004) Temperature stress and coral bleaching. In: Rosenberg E, Loya Y (eds) Coral health and disease. Springer, Heidelberg, pp 401–425

Jokiel PL (2006) Impact of storm waves and storm floods on Hawaiian reefs. Proc 10th Int Coral Reef Sym:390–398

Jokiel PL, Brown EK (1998) Coral baseline survey of Ma'laea Harbor for light draft vessels, Island of Maui. Final report for DACW83–96-P-0216. US Army Engineer District, Environmental Resources Branch, Fort Shafter, HI, 44 pp

Jokiel PL, Brown EK (2004a) Global warming, regional trends and inshore environmental conditions influence coral bleaching in Hawaii. Global Change Biol 10:1627–1641

Jokiel PL, Brown EK (2004b) Reef coral communities at Pila'a reef. Results of the 2004 survey Hawaii coral reef assessment and monitoring program report, May 20. Kaneohe, HI, 23 pp

Jokiel PL, Coles SL (1974) Effects of heated effluent on hermatypic corals at Kahe Point, Oahu. Pac Sci 28:1–18

Jokiel PL, Coles SL (1977) Effects of temperature on the mortality and growth of Hawaiian reef corals. Mar Biol 43:201–208

Jokiel PL, Coles SL (1990) Response of Hawaiian and other Indo-Pacific reef corals to elevated temperatures associated with global warming. Coral Reefs 8:155–162

Jokiel PL, Cox EF (2003) Drift pumice at Christmas Island and Hawaii: evidence of oceanic dispersal patterns. Mar Geol 202:121–133

Jokiel PL, Guinther EB (1978) Effects of temperature on reproduction in the hermatypic coral *Pocillopora damicornis*. Bull Mar Sci 28:786–789

Jokiel PL, Rodgers KS (2007) Ranking coral ecosystem "health" and "value" for the islands of the Hawaiian Archipelago. Pac Conserv Biol 13:60–68

Jokiel PL, York RH (1982) Solar ultraviolet photobiology of the reef coral *Pocillopora damicornis* and symbiotic zooxanthellae. Bull Mar Sci 32:301–315

Jokiel PL, Hunter CL, Taguchi S, Watarai L (1993a) Ecological impact of a fresh water "reef kill" in Kaneohe Bay, Oahu, Hawaii. Coral Reefs 12:177–184

Jokiel PL, Cox EF, Crosby MP (1993b) An evaluation of the nearshore coral reef resources of Kahoolawe, Hawaii. Final report for co-operative agreement NA27OM0327. Hawaii Institute of Marine Biology, Kaneohe, HI 185 pp

Jokiel PL, Hill E, Farrell F, Eric K, Rodgers K (2002) Reef coral communities at Pila'a reef in relation to environmental factors. Hawaii coral reef assessment and monitoring program report, December 12. Kaneohe, HI, 100 pp

Jokiel PL, Brown EK, Friedlander A, Rodgers SK, Smith WR (2004) Hawaii coral reef assessment and monitoring program: spatial patterns and temporal dynamics in reef coral communities. Pac Sci 58:145–158

Jokiel PL, Kolinski, SP,Naughton J, Maragos JE (2006) Review of coral reef restoration and mitigation in Hawaii and the US- affiliated Pacific Islands. In: Precht WF (ed) Coral reef restoration handbook – the rehabilitation of an ecosystem under siege. CRC, Boca Raton, FL, pp 271–290

Jones BL, Nakahara RH, Chinn SSW (1971) Reconnaissance study of sediment transported by streams, Island of Oahu. Circular C33, US Geological Survey, Honolulu, HI 45 pp

Jordan DS, Evermann BW (1902) Preliminary report on an investigation of the fishes and fisheries of the Hawaiian Islands. In: Report of the Commissioner for the year ending June 30, 1901. U.S. Commission of Fish and Fisheries, Government Printing Office, Washington, DC, pp 353–380

Jordan DS, Evermann BW, Tanaka S (1927) Notes on new or rare fishes from Hawai'i. Calif Acad Sci Proc 4:649–680

Kahng SE, Maragos JE (2006) The deepest zooxanthellate scleractinian corals in the world? Coral Reefs 25:254

Karl DM (2004) UH and the sea. SOEST report 04–01. University of Hawaii School of Ocean and Earth Science and Technology, Honolulu, HI, 104 pp

Kay EA, Palumbi SR (1987) Endemism and evolution in Hawaiian marine invertebrates. Trends Ecol Evol 2:183–186

Kenyon JC, Aeby GS, Brainard RE, Chojnacki JD, Dunlap MD, Wilkinson CB (2004) Mass coral bleaching on high-latitude reefs in the Hawaiian Archipelago. Proc 10th Int Coral Reef Sym, Okinawa:631–643

Kenyon JC, RE Brainard (2006) Second recorded episode of mass coral bleaching in the Northwestern Hawaiian Islands. Atoll Res Bull 543:505–523

Kobayashi DR (2006) Colonization of the Hawaiian Archipelago via Johnston Atoll : a characterization of oceanographic transport corridors. Coral Reefs 25:407–417

Kuffner I (2001) Effects of ultraviolet (UV) radiation on larval settlement of the reef coral *Pocillopora damicornis*. Mar Ecol Progr Ser 217:251–261

Kuykendall RS, Day AG (1976) Hawaii: a history, from Polynesian kingdom to American state. Prentice-Hall, Englewood Cliffs, NJ, 331 pp

Leone D (2006) Pflueger is fined more than $7.8M. Honolulu Star Bull 11(79) March 20, 2006

Lesser MP, Shick JM (1989) Effects of irradiance and ultraviolet radiation on photoadaptation in the zooxanthellae of *Aiptasia pallida*: primary production, photoinhibition, and enzymatic defenses against oxygen toxicity. Mar Biol 102:243–255

Lowe MK (2004) The status of inshore fisheries ecosystems in the Main Hawaiian Islands at the dawn of the millennium: cultural impacts, fisheries trends and management challenges. In: Friedlander AM (ed) Status of Hawai'i's coastal fisheries in the new millennium. Hawai'i Audubon Society, Second Printing, Honolulu, HI, pp 12–107

Lu Y, Wang Y, Yu Q, Aguirre AA, Balazs GH, Nerurkar VR, Yanagihara R (2004) Detection of herpes viral sequences in tissues of green turtles with fibropapilloma by polymerase chain reaction. Arch Virol 45:1885–1893

Macdonald GA, Abbott AT, Peterson FL (1983) Volcanoes in the sea. University of Hawaii Press, Honolulu, HI, 517 pp

Maragos J (1991) Two decades of coral monitoring surveys following construction of Honokohau Harbor, Hawaii. In: Studies of water quality, ecology, and mixing processes at Honokohau and Kawaihae Harbors on the Island of Hawaii. Oceanic Institute, Makapu Point, Waimanalo, HI, 28 pp

Maragos JE (1972) A study of the ecology of Hawaiian reef corals. Ph.D. dissertation, University of Hawaii, 290 pp

Maragos JE (1995) Revised checklist of extant shallow-water stony coral species from Hawaii (Cnideria: Anthozoa: Scleractinia). Occ Pap Bishop Mus 42:54

Maragos JE (1998) Marine Ecosystems. In: Juvik S, Juvick JO (eds) Atlas of Hawai'i, 3rd edition. University of Hawaii Press, Honolulu, HI, pp 111–120

Maragos JE, Jokiel PL (1986) Reef corals of Johnston Atoll : one of the world's most isolated reefs. Coral Reefs 4:141–150

Maragos JE, Evans C, Holthus P (1985) Reef corals in Kaneohe Bay six years before and after termination of sewage discharges. Proc 5th Int Coral Reef Symp 4:189–194

Maly K, Maly O (2004) Ka Hana Lawai'a a me n? Ko'a o n? kai 'Ewalu. A history of fishing practices and marine fisheries of the Hawaiian Islands. Prepared for the nature conservancy by Kumu Pono Associates LLC, Hilo, HI, 506 pp

Moberly RM (1974) Types and sources of Hawaiian waves, p 48. In: Atlas of Hawaii. University of Hawaii Press, Honolulu, HI, 222 pp

Moore JG, Clague DA, Holcomb RT, Lipman PW, Normark WR, Torresan ME (1989) Prodigious submarine landslides on the Hawaiian ridge. J Geophys Res 94:17465–17484

Onizuka E (1979) Studies on the effects of crown-of-thorns starfish on marine game fish habitat. Final report of project F-17-R-2. State of Hawai'i Department of Fish and Game, Honolulu, HI, 25 pp

Patzert WC, Wyrtki K, Santamore HJ (1970) Current measurements in the central North Pacific Ocean. Hawaii Inst Geophys HIG-70- 31:1–26

Paulay G (1997) Diversity and distribution of reef organisms. In: Birkeland C (ed) Life and death of coral reefs. Chapman & Hall, New York pp 298–353

Presto MK, Ogston AS, Storlazzi CD, Field ME (2006) Temporal and spatial variability in the flow and dispersal of suspended-sediment on a fringing reef flat, Molokai, Hawaii. Est Coast Shelf Sci 67:67–81

Price S (1983) Climate. In Armstrong RW (ed) Atlas of Hawaii, 2nd edition. University of Hawaii Press, Honolulu, HI, 238 pp

Ramage CS (1971) Monsoon meteorology. Academic, pp 112–116

Randall JE (1996) Shore fishes of Hawaii. Natural World Press, Vida, OR, 216 pp

Richardson LL (1998) Coral diseases: what is really known? Trends Ecol Evol 13:438–443

Roberts L (2001) Historical land use, coastal change and sedimentation on South Molokai reefs. In: Saxena N (ed) Recent advances in marine science and technology, 2000. PACON International, Honolulu, HI, pp 167–176

Rogers CS (1990) Responses of coral reefs and reef organisms to sedimentation. Mar Ecol Prog Ser 62:185–202

Rohmann SO, Hayes JJ, Newhall RC, Monaco ME, Grigg RW (2005) The area of potential shallow-water tropical and subtropical coral ecosystems in the United States. Coral Reefs 24(3):370–383

Rooney J, Fletcher C, Grossman E, Engels, Field M (2004) El Nino influence on Holocene Reef Accretion in Hawaii. Pac Sci 58:305–324

Roy KJ (1970) Changes in bathymetric configuration, Kaneohe Bay, Oahu. 1882–1969. Hawaii Institute of Geophysics report 13 70–15. University of Hawaii, 226 pp

Santos SR (2006) Patterns of genetic connectivity among anchialine habitats: a case study of the endemic Hawaiian shrimp *Halocaridina rubra* on the island of Hawaii. Molec Ecol 15:2699–2718

Scelfo G (1984) Relationship between solar radiation and pigmentation of the coral *Montiproa verrucosa* and its zooxanthellae. In: Jokiel PL et al. (eds) Coral reef population biology. Hawaii Institute of Marine Biology Technical Report 37, pp 440–451

Schroeder TA (1998) Hurricanes. In: Juvik S Juvick JO (eds) Atlas of Hawai'i, 3rd edition, University of Hawaii Press, Honolulu, HI, pp 74–75

Shomura RS (1987) Hawai'i's marine fisheries resources: yesterday (1900) and today (1986). Southwest fisheries administrative report H-87–21, 15 pp

Shibata K (1969) Pigments and a UV-absorbing substance in corals and a blue-green alga living in the Great Barrier Reef. Plant Cell Physiol 10:325–335

Smith SV, Kimmerer WJ, Laws EA, Brock RE, Walsh TW (1981) Kaneohe Bay Sewage Diversion Experiment: perspectives on ecosystem response to nutritional perturbation. Pac Sci 34:279–402

Stoddart DF (1969) Ecology and morphology of recent coral reefs. Biol Rev 44:433–498

Storlazzi CD, Field ME, Dykes JD, Jokiel PL, Brown E (2002) Wave control on reef morphology and coral distribution: Molokai, Hawaii. Proc 4th Int Symp Waves, pp.784–793

Storlazzi CD, Field ME, Jokiel PL, Rodgers SK, Brown E, Dykes JD (2005) A model for wave control on coral breakage and species distribution: southern Molokai, Hawaii. Coral Reefs 24:43–55

Tissot BN, Hallacher LE (2003) Effects of aquarium collectors on coral reef fishes in Kona, Hawaii. Conserv Biol 17:1759–1768

US Environmental Protection Agency (1971) The Hawaii sugar industry waste study. US Environmental Protection Agency, Region IX, San Francisco, CA, US Government Printing Office Publication, Washington, DC, pp 81–150

Vaughan TW (1907) Recent Madreporaria of the Hawaiian Islands and Laysan. Bull US Natl Mus 59:1–427

Veron JEN (1993) A biogeographic database of hermatypic corals. Species of the central Indo-Pacific, genera of the world. Aust Inst Mar Sci Monogr Ser 10:1–433

Walsh WJ, Cotton SP, Dierking J, Williams ID (2004) The commercial marine aquarium fishery in Hawaii 1976–2003. In: Friedlander AM (ed) Status of Hawaii's coastal fisheries in the new millennium. Proceedings of a symposium sponsored by the American Fisheries Society, Hawaii Chapter, Honolulu, HI, pp 132–159

Wells J (1957) Corals. Geol Soc Am Mem 67:1087–1104

Work T, Rameyer R (2001) Evaluating coral health in Hawaii. US Geological Survey, National Wildlife Health Center, Hawaii Field Station, 42 pp

Zeller D, Booth S, Pauly D (2005) Reconstruction of coral reef- and bottom-fisheries catches for US flag island areas in the Western Pacific, 1950 to 2002. Report to the Western Pacific Regional Fisheries Management Council, August 2005