Impact of storm waves and storm floods on Hawaiian reefs.

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Abstract. Major storms are infrequent events of high intensity and short duration that can exert a profound influence the structure of Hawaiian reefs. Extreme wave energy directly damages corals and retards coral community development. A paradox is that storm surf also represents a positive factor that maintains vitality of many communities through the mobilization and removal of terrigenous, calcareous and organic sediments that otherwise will smother a reef system. Flood events erode watersheds and deposit sediments on the reefs that can kill corals and block recruitment of new coral colonies. Fresh water delivered by storms also can lower local salinity to levels that are lethal to corals and other reef organisms. Nutrients and pollutants associated with fresh water runoff are transported onto coral reefs during such storms. The impact of these events is poorly understood for several reasons. These events are very transient in nature and seldom are observed directly on reefs due to difficulties in making observations during conditions of extreme wave motion or turbidity. The duration of most coral reef investigations is too short to allow evaluation of the major storm events that occur with a frequency of decades to hundreds of years. The pattern of impact for a major storm is highly complex, and influenced by local bathymetry, shoreline topography and directionality of the storm event. Nevertheless, sufficient data are available to provide a general spatial and temporal description of the relative importance of major storm waves and storm floods on reefs throughout the main Hawaiian Islands. The relative impact of wave damage, damage due to terrigenous sediment runoff and damage due to factors associated with fresh water are described for the major Hawaiian coral reef habitats.

Key words: storms, floods, waves, coral reef.

Introduction

Disturbance of coral reefs by storm waves and floods are integral natural features of coral reef systems and serve to maintain high diversity by intermittent removal of dominant species (Connell 1978, Grigg and Maragos 1974, Dollar 1982, Jokiel et al. 2004a). Human activity plays an increasingly important detrimental role in amplifying the negative impact of these events. Improper land use increases sedimentation and freshwater runoff. In the future, climate change due to anthropogenic production of greenhouse gasses may exacerbate the problem through an increase storm activity and changes in precipitation patterns (e.g. Groisman et al. 1999).

Assessing the impact of storms and storm floods on Hawaiian reefs is a challenge. Major storm waves and floods that occur with an expected frequency of from 50 to 100 years may not occur during the lifetime of an observer. Storms are intense and of short duration and create local crises that often prevent any possibility of taking measurements or sampling until after the storm has passed. Roads are closed and communication and power are disrupted when lines are downed by a storm. Floods and storm waves create life-threatening situations on the reefs as well as land. Turbidity on the reef often prevents any observations until weeks after the event.

The interaction between storm waves and flood events may be strong in some cases or non-existent in other situations. The amplitude, frequency, and directionality of determine which reefs will be impacted. Previous history of wave action and storm discharge shapes the structure of reef communities and determines their susceptibility to extreme events. Distinguishing between natural events and the extent of damage attributable to anthropogenic factors is a major task. The relative importance of these events on a broad spatial and temporal scale across various environments in Hawaii deserves further attention and is the subject of this paper.

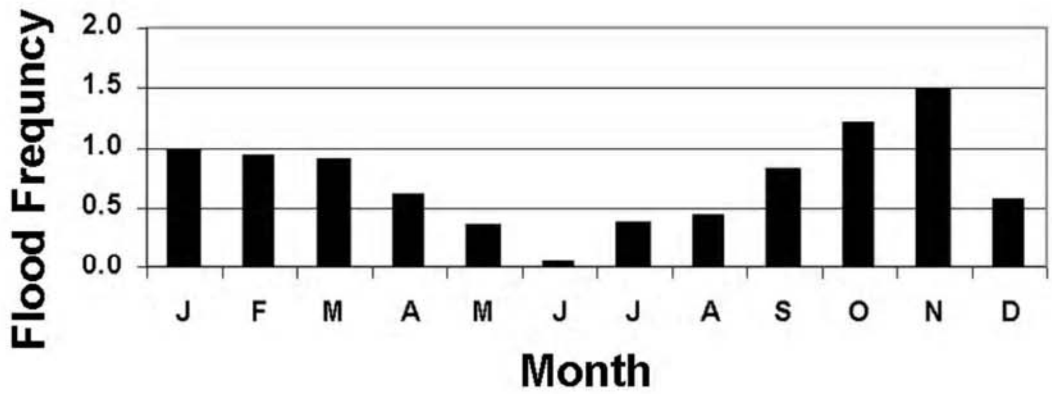

Fig. 1. Monthly frequency of flash flood events in Hawaii for period 1960-2002 inclusive. Data provided by the Honolulu Forecast Office of the US Weather Service.

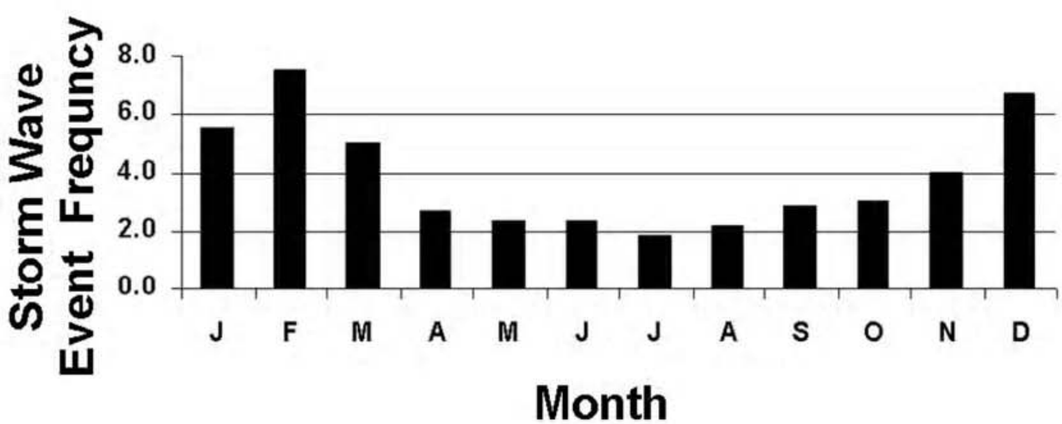

Fig. 2. Monthly frequency of storm wave events for time period 1996-2002 inclusive for all shores of Hawaii. Data provided by the Honolulu Forecast Office of the US Weather Service.

Storm Floods.

Rainfall intensity and duration are obviously the primary cause of floods, but the outcome is modified by other factors that include topography, soil conditions, and ground cover. Soils can absorb several inches of rainfall before becoming saturated - after which time runoff will occur. Floods can be of short duration or can be prolonged events that may last several days, or even weeks. Hurricanes can directly cause flood conditions as "storm surge" A tsunami causes flooding through run-up of waves.

Flash floods are intense and of short duration. Such floods are common events in Hawaii (Fig. 1). Flash floods often trigger mudflows and landslides which can flood onto coral reefs directly or via stream flow. Stream gauge records throughout the state of Hawaii show frequent flood events of short duration. Schroeder (1977, 1978) reports an average rate of five per year. More recent data summaries (Fig. 1) yield a higher estimate (Honolulu Forecast Office of the US Weather Service). Most frequent time of occurrence is October to April. 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. Kodama and Businger (1998) note that four types of synoptic events are responsible for most Hawaiian storm floods: a) cold fronts, b) Kona Lows, c) tropical upper tropospheric troughs, and d) tropical storms. The humid air at the marine boundary in Hawaii usually contains enough water vapor to produce heavy rains at any time. Heavy rainfall events normally are associated with upper-level forcing and increase in mid-level atmospheric moisture. The presence of moisture in the mid-troposphere is an indication of large-scale ascending air masses associated with synoptic circulation. Watershed topography contributes to the flash flood phenomenon. The main Hawaiian Islands are characterized by small steep watersheds. Peak stream flow typically occurs less than one hour after peak rainfall, followed by a rapid drop in flow. The short duration of these pulse flood events creates difficulties in documenting the volume and content of the discharge onto a reef.

Effect of floods on Hawaiian coral reefs.

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 salinity ranging from 25 o/oo to 42 o/oo (Coles and Jokiel 1992). "Reef kills" caused by low salinity associated with flood events have been reported throughout the world (Coles and Jokiel 1992) as well as from Hawaii (Jokiel et al. 1993). Steep bathymetry and exposure to high wave energy characterize the coastline of the Hawaiian Archipelago. Rapid flushing by waves and currents maintains salinity on reefs within the range of tolerance for reef corals. An exception occurs in major estuaries such as Hilo Bay (Island of Hawaii), Kahalui Bay (Maui), Pearl Harbor (Oahu) and Nawiliwili Bay (Kauai), where circulation is restricted and salinity frequently is reduced to levels lethal to corals. On a smaller scale the discharge of fresh water from rivers and streams limits the survival of corals 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.

Kaneohe Bay, Oahu is a large (4 km x 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 o/oo to 35 o/oo, but commonly surface waters drop to 29 o/oo during flood events. However, during extreme flood conditions, salinity can be reduced to the point of killing corals on the reefs. Rainfall exceeding 60 cm in 24 hours 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 m to 2 m on reef flats throughout the inner portion of the bay. Storm floods again occurred in late December 1987 and early January 1988 that reduced salinity in the surface waters of Kaneohe Bay to 15 o/oo 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. 1993). Such natural catastrophic disturbances are infrequent in the bay, with a recurrence of from 20-50 years. Conditions of heavy sewage pollution at that time prevented recovery of the reefs after 1965 until after sewage abatement in 1979. Corals reefs in Kaneohe Bay showed recovery from the 1987-88 kill within 5-10 years. It appears that coral reefs can recover quickly from natural disturbances, but not under polluted conditions.

Storm Waves.

Wave energy is clearly one of the major physical factors controlling the biological structure of Hawaii reef communities. Jokiel et al. (2004) surveyed sites throughout the MHI and showed that mean wave height had a positive relationship with species richness. This observation supports the intermediate disturbance hypothesis (Connell 1978). Waves in Hawaii, however, can reach destructive levels that will damage corals and restrict species distribution patterns (Dollar 1982, Storlazzi et al. 2002). 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 (Moberly and Chamberlain 1964). The largest and most frequent storm surf arrives during the winter North Pacific Swell (bearing 315^o) with the less frequent and less damaging storm waves during the summer from the South Swell (bearing 190^o) to the less severe Trade Wind Swell (bearing 45^o). 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 m and 20 m, reflecting the trade-off between reduced wave induced stress at depth with decreased light available for photosynthesis (Storlazzi et al. 2002).

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. The model was tested against observed species distribution along the south shore of Molokai, Hawaii. Results from the modeling 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' strengths and wave conditions typically observed in their habitat over the course of a few decades. 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.

Extreme wave events can break and abrade reefs corals along most of the Hawaii coastline. Events classified as storm waves strike Hawaiian shores from various directions with a frequency of from 2 to 7 times each month (Fig. 2). These waves come from different directions and are generated by various sources (Table 1).

Northeast (NE) Trade Wind Waves

The NE Trade Winds predominate throughout the year in Hawaii, but reach maximum intensity between spring and fall. These winds can to produce substantial waves as they move across the 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 1.2 to 3.7 feet are typical with periods of only 5 to 8 seconds (Table 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 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 event has been summarized by the National Honolulu Weather Forecast Office at (http://www.prh.noaa.gov/hnl/pages/watchwarn.php):

> "During the latter part of November, several unique weather systems in the north and northeast Pacific combined to produce a long lasting destructive surf event along northeast facing shores of the Hawaiian Islands. Surf heights of 4.6 m to 7.6 m, with some sets up to 12.2 m were reported beginning on the 20th and peaking on the 21st before slowly diminishing. Although surf events of this magnitude occur several times a year in Hawaii, they generally come from major storms far to the northwest of Hawaii and thus impact northwest facing shores. Over the eons, coastlines on these sides of the islands have been "shaped" to be able to handle such high surf with minimal impact. High surf of this magnitude from other directions is exceedingly rare, and thus when it occurs, can cause significant damage."

Table 1 Waves influencing the main Hawaiian Islands (summarized from Moberly 1987 and Pat Caldwell National Oceanographic Data Center Honolulu, pers. com. Jan 15, 2000).

	Typical			Extreme			Direction	
	Height		Period	Height		Period		
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*	13 - 18*	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°

*fully developed seas.

Table 2. Summary of hurricane classification and occurrence in the region of the Hawaiian Islands.

Category (Saffir-Simpson Scale			Storm Surge Height		Potential Damage to Property and Reefs	Recent Examples in Hawaii Region
No.	mph	km h^{-1}	ft	m		
1	74 - 95	119 - 153	4 - 5	1.2 - 1.5	Minimal	Iwa (148 km h^{-1}) Nov. 1982*
2	96 - 110	155 - 177	6 - 8	1.8 - 2.4	Moderate	none
3	111 - 130	178 - 209	9 - 12	2.7 - 3.7	Extensive	Uleki (206 km h^{-1}) Sept 1992
4	131 - 155	211 - 250	13 - 18	4.0 - 5.5	Extreme	Iniki (233 km h^{-1}) Sept. 1992*
5	>155	>250	>18	>5.5	Catastrophic	Emilia and Gilma (259 km h^{-1}) July 1994

* Hurricanes that caused extensive property damage in the Hawaiian Islands.

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 2004). 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 (SJ Dollar pers com).

North Pacific Swell.

North Pacific Swell is generated by Northern Hemisphere winter storms in the North Pacific. Typical wave heights offshore range from 2.4 m to 4.6 m with periods of from 10-17 seconds (Table 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

Southern Swell is generated by Antarctic Southern Hemisphere winter storms. South swell is generally encountered in summer and early autumn. Typical wave height ranges from 0.3 m to 1.2 m with periods of 12 to 17 seconds (Table 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 reach 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

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 m to 1.5 m with periods of 8 to 10 seconds. 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

Hurricane Waves are infrequent and unpredictable events that can have profound effects on reefs. Hurricanes are powerful storms that form over tropical waters whose effects include damaging surf and storm surge along coastlines, destructive winds, waterspouts, tornadoes, heavy rain and flooding. Limited historical information exists on the location, size of waves and amount of reef damage on Hawaiian reefs caused by Hurricane waves (Dollar, 1982; Dollar and Tribble 1993). 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.

Hurricanes are classified as storms with sustained winds of 119 km h^{-1} or higher while tropical storms are classified as storms with sustained winds of 63 to 118 km h^{-1}. Hurricanes are divided into five categories according to wind speed (Table 2). Most central Pacific hurricanes originate near Central America or southern Mexico. Many of these storms die 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. Frequency of occurrence of tropical cyclones in the Central Pacific is quite variable. In 1978, for example, there were 13 tropical cyclones with three of them classified as hurricanes. The following year there were none.

The long-term record on frequency of hurricane impacts on Hawaiian reefs is obscure. Before 1950 damaging windstorms that struck Hawaii were not called hurricanes. Newspaper stories and government records, however, demonstrate that such storms have struck all islands in Hawaii since the beginning of recorded history. The advent of meteorological satellites has revealed that hurricanes are a far more frequent in the central Pacific than previously suspected. Since 1950 five hurricanes have caused serious damage in Hawaii. Hurricane Nina in 1957 produced record winds in Honolulu. Hurricane Dot (August 1959) caused 6 million dollars of property damage on Kauai. Hurricane Iwa, in November of 1982 caused over 250 million dollars in damages on Kauai and Oahu. On south Molokai, waves damaged the docks and reefs at Kaunakakai. Hurricane Estelle produced very high surf on Hawaii and Maui and floods on Oahu in 1986. Hurricane Iniki caused extensive damage to property and reefs on Kauai and Leeward Oahu in 1992. Hurricane Iniki was by far the most destructive storm to strike Hawaii in recorded history, with widespread wind and water damage exceeding 2.2 billion dollars. Most of the damage occurred on Kauai and Oahu with storm surf striking the S and SE reefs of the other islands. In recent years, numerous hurricanes were detected that could have caused serious damage if they had passed closer to Hawaii. Hurricane Fernanda in 1993 and Hurricane Emilia in 1994 were the strongest on record to pass through the central Pacific.

Hurricanes that pass far offshore may cause extensive damage to reefs, but with little official notice due to lack of major property damage. For example, Hurricane Nina (November 1957) brought surf of 11 m to Kauai's southern coast. Waves from Hurricane Fico (July 1978) damaged homes and roads on the Big Island's Kau coast even though the storm itself was more than 400 miles to the southeast.

Both storm surge and floods are associated with hurricanes. Storm surge impact breaks corals and erodes reefs and shorelines. Rain associated with the hurricane causes flood events on a large scale that bring fresh water and mud to the reef. Hawaii's topography focuses the rains on mountain slopes, causing landslides and severe erosion. Strong winds create debris on land that often is carried onto the reefs.

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 km to the east at Kona, Hawaii where coral cover decreased from 15% to 11% (Dollar and Tribble 1993).

Tsunami Waves

A related type of rare destructive wave that is not included in the term storm surf is the tsunami. A tsunami or seismic sea wave is a series of immense waves caused by violent movement of the sea floor during an earthquake, underwater landslide, or volcanic eruption. It is known that the tsunami waves were focused on certain shorelines, and that directionality important. These waves are characterized by great speed (up to 950 km h^{-1}), long wave length (up to 190 km), long period between successive crests (varying from 5 minutes to a few hours, generally 10 to 60 minutes), and low height in the open sea. Often the first wave of a tsunami may not be the largest. Initially a tsunami causes the water near the shore to recede, exposing the ocean floor. In coastal areas the height of a tsunami can be as great as 9 m or more (30 m in extreme cases), and they can move inland several hundred meters. Tsunamis are turbulent, powerful, rubble filled, and deadly. Tsunamis are powerful enough to move house-sized boulders weighing many tons. Unlike surfing waves, which quickly wash up and down the shore, the crest of the next tsunami wave is out on the horizon, which allows its waves to keep coming and coming far inland with tremendous power. A tsunami event can last several hours and destroy everything in its path. In Hawaii, tsunamis have accounted for more lost lives than the total of all other local disasters. Information on tsunamis and on the impact of past tsunamis on Hawaii coastal communities has been gathered by the Pacific Tsunami Museum Archive (http://planet-hawaii.com/tsunami/) and the National Geophysical Data Center (http://www.geophys.washington.edu/tsunami/). Damage to reefs resulting from past tsunamis has not documented on Hawaiian coral reefs, but must have been considerable as evidenced by the destruction along the shoreline.

The tsunami of 1946 was generated by a magnitude 7.1 earthquake in the Aleutian Islands. This tsunami struck the Big Island of Hawaii on April 1st. The tsunami flooded the downtown area of Hilo killing 159 people and causing more than $26 million in damages. On November 4, 1952 a tsunami was generated by a magnitude 8.2 earthquake on the Kamchatka Peninsula in the USSR. In Hawaii, property damage from these waves was estimated at $800,000-$1,000,000 (1952 US dollars); no lives were lost. The waves beached boats, caused houses to collide, destroyed piers, scoured beaches, and moved road pavement. On March 9, 1957 a tsunami was generated by a magnitude 8.3 earthquake in the Aleutian Islands. It generated a 8 m tsunami that did great damage on Adak Island, especially to the fuel and oil docks. The Hawaiian Islands incurred about $5,000,000 of damage in 1957 US dollars. The highest wave in Hawaii was 3.6 m (12 feet). The tsunami of May 23, 1960 was generated by a magnitude 8.3 earthquake in Chile. The 11-m tsunami struck Hilo, Hawaii causing severe damage. Sixty-one deaths were recorded with $23 million in damage. In the area of maximum destruction, only buildings of reinforced concrete or structural steel remained standing - and even these were generally gutted. Frame buildings were either crushed or carried away by the flooding. On November 29, 1975, an earthquake occurred off the coast of the Island of Hawaii. When the quake-generated tsunami struck, 32 campers were at Halape Beach Park. The sound of falling rocks from a nearby cliff, along with earth movement caused the campers to flee toward the ocean. They were then forced back to the cliff by rising ocean waters. The first wave was 1.5 m high with a second wave that was 8 m high. Two campers died and 19 others suffered injuries.

Wave shadows, bathymetry and island topography

The impact of waves on a given reef involves a complex interaction between wave direction, island topography, and bathymetry (e.g. 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). Wave refraction occurs around islands. 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.

Ecological context

Storm waves

Variation in wave energy and storm control Hawaiian coral community structure in both time and space (Grigg and Maragos 1974, Dollar 1982, Dollar and Tribble 1993, Jokiel et al. 2004a). Reef corals of a given species can modify growth form within limits in order to adjust to a given wave regime. For example, the coral *Montipora captiata* 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. In low wave environments fast growing delicate growth forms of species such as *Montipora capitata* or *Porites compressa* dominate. The biological processes of recruitment, growth, and competition lead to the orderly development of a reef community adapted to the prevailing wave energy regime. Certain types of communities develop in high wave environments, other communities develop in low wave environments. However, it is the unusual storm wave event that occurs rarely (on the order of 10 to 50 years) that can fragment the corals and totally alter 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).

Anthropogenic factors in relation to storm floods and storm waves.

In general, anthropogenic impacts such as increased sedimentation and nutrification dominate in environments where wave forces 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. Jokiel et al. (2004) recently 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.

Muddy runoff pollution from development sites seems to be a perennial event 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 Big Island. In 2001, illegal grubbing at Pilaa on Kauai led to huge quantities of mud flowing onto the beach and smothering the reef. Pilaa had one of the most pristine reefs and clearest ocean waters on the island. Similar incidents took place off Lanai in 2002. Studies on the reefs off Pilaa, Kauai (Jokiel et al. 2002, Jokiel and Brown 2004) highlight an important paradox. Storm waves that we normally associate with reef damage are also an agent of reef renewal. Major storm surf off Pilaa during the 2002-2003 and the 2003-2004 winter seasons were responsible for flushing the terrigenous mud that had impacted the shallow reef flat system, which is showing the first signs of regeneration.

A major cause of erosion, runoff and accelerated sedimentation on reefs is overgrazing on watersheds of the MHI. Roberts (2001) has reviewed the importance of this process on the reefs of south Molokai. Serious overgrazing by feral ungulates (pigs, goats, deer) is presently causing 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. This situation has been corrected with the complete eradication of over 20,000 goats in 1990 (Jokiel et al. 1993). Elimination of the goats and revegetation efforts 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.

Accelerated sediment discharge onto reefs as a result of anthropogenic activity is the most visible evidence of human activity, but other materials such as nutrients and toxic materials are carried onto the reefs as well. Normally this process is not apparent, but can become graphically obvious 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).

In sum, it is apparent that further studies of storm floods and storm surf are critical to understanding the natural and anthropogenic processes that impact the reefs of Hawaii. The major conclusion is that these are not static communities growing in a benign environment. Rather, they are dynamic systems that have adapted to severe environmental disturbance from natural processes of storm waves and storm floods. The impact of increasing anthropomorphic environmental burden in addition to an already stressful natural disturbance regime is a cause of concern for Hawaiian coral reefs.

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