Climate Change and Pacific Islands: Indicators and Impacts

Case Studies from the 2012
Pacific Islands Regional Climate Assessment (PIRCA)

Edited by:

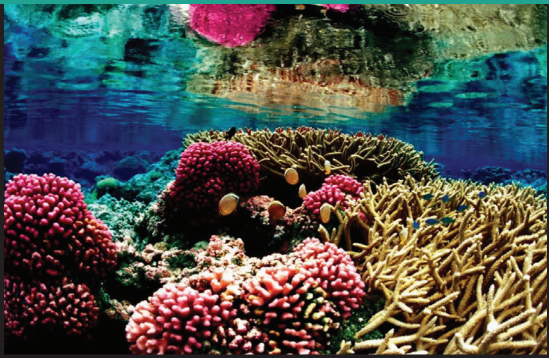
Victoria W. Keener

John J. Marra

Melissa L. Finucane

Deanna Spooner

Margaret H. Smith



These case studies have been adapted from the full-length report, which can be accessed at www.EastWestCenter.org/PIRCA.

© 2012 Pacific Islands Regional Climate Assessment (PIRCA)

ISLANDPRESS

FOCUS ON ADAPTATION

Case Study 1

Managing vulnerable water resources in atoll nations

Stephen Anthony (USGS PIWSC)

Water supplies on small, low-lying atoll islands are extremely vulnerable to droughts and to saltwater inundation caused by high tides. Water for drinking and other uses comes from two sources: rainwater catchments and shallow wells that draw from a layer or "lens" of freshwater that is underlain by brackish water or saltwater. Groundwater in the part of the lens that is near the ground surface in the central depression of the island is also important for taro cultivation. On some atoll islands, the freshwater lens is thin and highly vulnerable to contamination from the saltwater below, especially if too much freshwater is drawn from the lens.

The El Niño event of 1997–1998 caused severe droughts and water shortages on many of the Pacific Islands. Between January and April 1998, Majuro Atoll in the Marshall Islands received only 8% of the normal rainfall for the period (Presley, 2005). By April 1998, the Majuro Water and Sewer Company (MWSC), which relies primarily on rainwater catchment and to a less extent on groundwater, was only able to provide water to the island's 27,000 residents and businesses for about 10 hours every two weeks. Health officials reported more than 1,000 cases of dehydration, drought-related skin disease, and respiratory infections ("Marshall Islands drought assistance continues," 1998).

Because of human health concerns, large reverse-osmosis water-purification systems, capable of producing 473,174 liters (125,000 gallons) of freshwater per day from treated seawater, were brought to Majuro to help alleviate the water shortage. Concurrently, groundwater withdrawals from the freshwater lens in the Laura area of the atoll were increased from 378,541 liters (100,000 gallons) to a maximum of 1,082,627 liters (286,000 gallons) per day (Presley, 2005). During the drought, public concern arose about these increased groundwater withdrawals because of the potential impact of saltwater intrusion on taro, breadfruit, and banana crops. The US Geological Survey, in cooperation with the Republic of the Marshall Islands government and the Federal Emergency Management Agency, installed monitoring wells to determine the condition of the freshwater lens during the drought. Results indicated that saltwater intrusion had not affected crops despite the increase in groundwater withdrawals. The study demonstrated the importance of maintaining a groundwater monitoring program to (1) evaluate the status of the freshwater lens, (2) indicate a sustainable pumping rate that will protect the resource from saltwater intrusion, and (3) help local organizations such as the MWSC address public concerns (Presley, 2005).

This case study demonstrates the vulnerability of freshwater resources on atoll islands. Data from monitoring are needed to manage rainwater and groundwater resources conjunctively and increase the adaptive capacity of low islands to meet the challenges posed by climate variability and change. With no monitoring plan in place or funding to upgrade the groundwater pumps in Laura, the existing on-island adaptive capacity to respond to the drought was low, despite warnings received in advance.

Integrated management of rainwater and groundwater resources is critical for water security, especially on the less-developed atoll islands in the Republic of the Marshall Islands and Federated States of Micronesia (Hamlin & Takasaki, 1996). One way to help alleviate chronic water-supply shortages during droughts would be to develop groundwater resources for non-potable uses where feasible so that rainwater can be saved for drinking and cooking.

Although groundwater from shallow wells can be used to mitigate water shortages during droughts, rainwater catchment systems are the only source of freshwater when storm waves and uncommonly extreme high tides known as "king tides" inundate low-lying atoll islands, turning all the groundwater brackish. In December 2007 and again in 2008, several atoll islands in the Federated States of

Micronesia were flooded by a series of high-sea/surf events. These saltwater floods had a significant impact on taro crops that are commonly cultivated in a depression near the center of the island. In December 2007, on the outer islands of Chuuk State, where 13,000 people or one-fourth of the state population resides, an estimated 90% of all taro crops were destroyed by saltwater inundation (Hezel, 2009).

Taro crops destroyed by saltwater inundation at Lukunoch Atoll, Chuuk State, Federated States of Micronesia. Giant swamp taro (*Cyrtosperma*) is a staple crop in Micronesia that requires a two- to three-year growing period from initial planting to harvest. It may take two years of normal rainfall to flush brackish water out of a taro patch, so there will be a five-year gap before the next harvest, assuming no more saltwater inundation takes place (Hezel, 2009). (Courtesy of John Quidachay, USDA Forest Service.)

FOCUS ON ADAPTATION

Case Study 2

Using climate forecasts to save money and protect human health

Victoria W. Keener (East-West Center, Pacific RISA)

When we leave the house in the morning, we often check the local weather forecast and make some quick decisions: *Should I bring an umbrella? How about a sweater?* By assessing the risks and taking action, we are effectively mitigating our vulnerability to weather-related impacts. While most people do not think twice about weighing uncertain weather information and taking action based on their best estimate of risk, it has proven much more difficult for community members, policymakers, and natural resource managers to integrate climate forecasts into their decision-making processes. By definition, climate risks have longer-term consequences, which make them easier to ignore in the short term. Yet a landfill on the island of O'ahu in Hawai'i demonstrated that climate information can be used to make management decisions that save time, money, jobs, and the health of our communities and natural environment.

Each year, the Weather Forecast Office (WFO) in Honolulu uses national El Niño and La Niña outlooks from NOAA to create island-level forecasts for Hawai'i. In conjunction with the Pacific ENSO Applications Climate (PEAC) Center, the WFO uses television, radio, and print and electronic newsletters to inform policymakers, managers, and communities about the potential seasonal impacts of an El Niño or La Niña event. In October 2010, the Honolulu WFO gave its winter wet-season (October to April) briefing, indicating that due to a moderate-to-strong La Niña (Figure 2-1) developing in the Pacific, O'ahu could expect above-average winter rainfall.

The vice-president of an O'ahu commercial landfill, PVT Land Company in Nanakuli, used this information, and his company immediately took steps to mitigate the climate risks. The company's

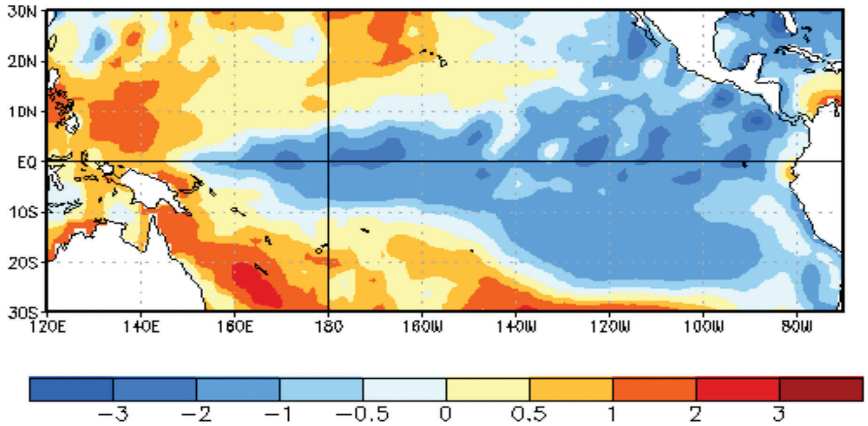


Figure 2-1 The NOAA Climate Prediction Center (CPC) released a seasonal ENSO outlook indicating La Niña conditions, or colder-than-average sea-surface temperatures in the equatorial Pacific Ocean. Here, in December 2010, the plume of cold (blue) water is visibly extending westward along the equator. (Courtesy of NOAA CPC, "December 2011 Sea-surface Temperatures.")

managers decided to move quickly to upgrade infrastructure that would divert and hold large amounts of stormwater. By the end of November 2010, PVT had finished upgrading its storm drainage system and retention ponds.

The dry Nanakuli area usually receives a total of 254 to 356 mm (10 to 14 inches) of rain annually, but on January 13, 2011, the area received about 356 mm (10 inches) in a single storm. Other local landfills were not prepared to handle the intense rainfall and ended up closing down. They also released hazardous untreated water and waste onto local beaches. But due to their good use of climate forecasts, PVT Land Company was open for business the next day.

By remaining open, PVT estimates that they saved about $1 million in gross sales, potential damage to infrastructure, and lost salaries. This estimate does not include the additional financial impacts from the construction and trucking jobs across the island that would have had to slow down or stop had they not been able to properly dispose of their on-site debris, or the savings from avoiding potential litigation had the stormwater system failed.

This case demonstrates the actual and potential savings associated with taking an active role in making planning and management decisions based on the best available climate information, as well as the type of successful adaptations that can be accomplished when adaptive capacity in a region and institution is very high. It is often difficult to quantify long-term negative consequences that are associated with failing to act on or make a decision earlier in time; however, the PVT case provides an excellent shorter-term example with quantifiable benefits for policymakers, scientists, communities, and businesses who are willing to work together to make and act upon climate forecast–based decisions. The PVT landfill continues to use seasonal climate forecasts to guide their mid-range

Case Study 2 Photo 1 The PVT Land Company (left) is O'ahu's only landfill for construction-site waste and receives over 200 truckloads of construction debris per day. If it was unable to receive waste, construction and trucking jobs on O'ahu would have to slow or cease. In making a fast decision using a seasonal climate forecast, PVT upgraded their stormwater drainage system and retention pond (right) to be able to accommodate increased volumes of stormwater. (Courtesy of Dr. Victoria Keener [left]; courtesy of Bill Lyon, TerraPac, LLC [right].)

planning process and is interested to learn about what longer-term local climate projections can assist them in their goals of continuing a safe and efficient business.

For more information on the PEAC Center or to receive their free regional ENSO forecast newsletter, please visit: *http://www.prh.noaa.gov/peac/*

FOCUS ON ADAPTATION

Case Study 3

Climate change likely to intensify freshwater disputes in Hawai'i

Jonathan L. Scheuer (Consultant)

While the high islands of Hawai'i are wetter than much of the western United States, Hawai'i has a similar regional history of intense legal fights over water. Ongoing conflicts not only illustrate how sectors and players compete but also show how changes in the abundance and distribution of water caused by climate change may intensify these prolonged battles.

Contemporary conflicts over water allocation in Hawai'i have their origins in the mid-1800s, when King Kamehameha III created private property in land but continued to hold water as a public trust, setting the stage for conflict between emerging water-intensive agribusiness and traditional users. Today's battles take place under a legal framework that includes judicial precedent (including decisions made during the Hawaiian Kingdom) (Hawai'i Revised Statutes [HRS] 1-1); state constitutional provisions that reiterate the public trust in water and Native Hawaiian rights (Haw. Const. art. XI, § 1 & 7, art. XII §1-4 & 7); and the state's Water Code (HRS 174C). The State Commission on Water Resource Management attempts to balance public trust uses of water (including traditional and customary Hawaiian practices, the procreation of fish and wildlife, and the maintenance of ecological balance and scenic beauty) against a goal of maximizing beneficial uses (including agricultural, commercial, and industrial consumption).

The largest ongoing fight has been on the island of O'ahu, where the Waiāhole Ditch system was developed in 1913–1916 to deliver water from the wet, windward Ko'olau Mountains to the dry, southern leeward plain for sugar cultivation. While originally designed to capture stream water, the construction of the delivery tunnels pierced large volcanic dike compartments (Figure 2-1), releasing stored groundwater and over time changing the underlying hydrology of windward streams (Takasaki & Mink, 1985). Beyond the immediate impact on ecosystems, this significantly disrupted nutrient flow into Kāne'ohe Bay, the largest estuarine system of the Pacific Islands (in re Water Use Permit Applications, 94 Haw. 97 P.3d 409 (2000)).

The current battle ignited in 1995 with the closure of the plantation using this water. Before the State Commission on Water Resource Management and later the Hawai'i Supreme Court, leeward interests (including groups in the agricultural, development, military, and tourism sectors) sought to maintain ditch flows, while conservationists, Native Hawaiians, and small riparian farmers sought to restore windward streams. The current allocation restores approximately one-half of the water to the streams of origin. The years of litigation have cost millions of dollars, and today, the case is on its third appeal to the Hawai'i Supreme Court.

The Hawai'i Supreme Court's decisions have affirmed a public trust in water and demand adherence to the precautionary principle in managing the trust. Decisions up to now, however, have not taken into account the decline in rainfall and base flow observed over the past 60 years (Oki, 2004) or effects from other threats to forested recharge areas.

An ongoing battle on Maui is even more intense than the Waiāhole fight because of concerns about groundwater available for the island's human population. Small riparian farmers and conservationists have sought regulation of groundwater withdrawals and restoration of streamflows from historic plantation diversions that were designed to capture 100% of base flows (Figure 3-1). This battle has pitted developers, agribusiness interests, and the county against small farmers, Native Hawaiians, and conservationists. It has been before the State Commission on Water Resource Management and is currently on appeal to the Hawai'i Supreme Court (Commission on Water Resource Management, 2010).

Figure 3-1 In Maui's 'Iao Valley, conservationists and small farmers would like to restore historic streamflows away from plantation-era diversions that capture all base flow. Proponents of restoring historic flow levels would like to use the water for traditional cultural and agricultural practices and for restoring the habitat of native species. (Courtesy of Jonathan L. Scheuer.)

As on O'ahu, rainfall and base flow on Maui show a statistically significant long-term decline. Recent data (Giambelluca et al., 2011) suggest that this trend could continue, with profound consequences for the island's water resources.

On the leeward side of Hawai'i Island, an emerging dispute over the allocation of water focuses on the effects of water use on groundwater-dependent ecosystems. Water demand is being driven by significant resort, commercial, and residential development. According to the 2010 US Census, population in the North Kona and South Kohala areas increased more than 30% in the past decade. With few streams on this part of the island, water needs must be met by groundwater. The underlying hydrology is poorly understood, however, and the state's calculation of sustainable yields depends on a simple mathematical model (Oki & Meyer, 2001). Water-planning documents that estimate consumption show demand likely to exceed the sustainable yield in most growth scenarios (Hawai'i County, 2010).

Important coastal resources with dual ecological and cultural significance depend on groundwater. These include anchialine pools (Figure 3-2), coral reefs, and Native Hawaiian fishponds. They may be significantly affected by increased groundwater withdrawals (Oki, 1999). Current work to model these systems and integrate new recharge and rainfall data may lower estimates of what withdrawal levels will be sustainable.

Figure 3-2 Anchialine pools, such as the Kuki'o Pools on Hawai'i Island, are unique environments found only in the coastal tropics and sub-tropics. The pools have no surface connection to the ocean yet can range from fresh to brackish. Anchialine pools are critical habitat for several rare and endemic species, such as *opae'ula* red shrimp, snails, and insects. (©2010 Rosa Sey, "One of the Kuki'o anchialine ponds," used under a Creative Commons Attribution-NonCommercial-NoDerivs license.)

In these and other emerging situations, changing climate may well intensify water disputes that already tend to be the most difficult, unresolved public policy issues in the islands. While some policy tools (such as the Public Trust and the Precautionary Principle) may help resolve these conflicts, it is likely that disputes will multiply and intensify as demand for water increases, possibly in the face of diminishing supply.

FOCUS ON IMPACTS

Case Study 4

A combination of processes creates extreme water levels and contributes to flooding and erosion

William V. Sweet (NOAA COOPS)

Episodic extreme water level events pose a serious risk to Pacific Island regions. Higher-than-normal sea levels, for example, allow more wave energy to pass over reef systems. Combined with high waves, this increases the possibility of inundation of low-lying coastal areas and low islands (e.g., atolls) and contributes to coastal erosion. This, in turn, can lead to saltwater intrusion, which damages freshwater sources and agricultural crops; damage to roads, houses, and other infrastructure; and destruction of critical habitat such as nesting sites for seabirds and turtles. Understanding and identifying the processes that cause such extreme events is essential to understanding impacts and informing disaster risk reduction as well as climate adaptation planning in a world where sea level is rising in response to a changing climate.

In December 2008, the Solomon Islands, Republic of the Marshall Islands (RMI), Federated States of Micronesia (FSM), and other low-lying islands in the Western North Pacific sub-region (Figure 4-1) experienced damage from ocean flooding due to a convergence of climate and weather factors:

- **High waves.** Low-pressure weather systems far to the north (near Wake Island) generated swells that were large, but not particularly extreme, ranging between 3 and 10 feet. These waves caused damage because they coincided with higher-than-normal sea levels.

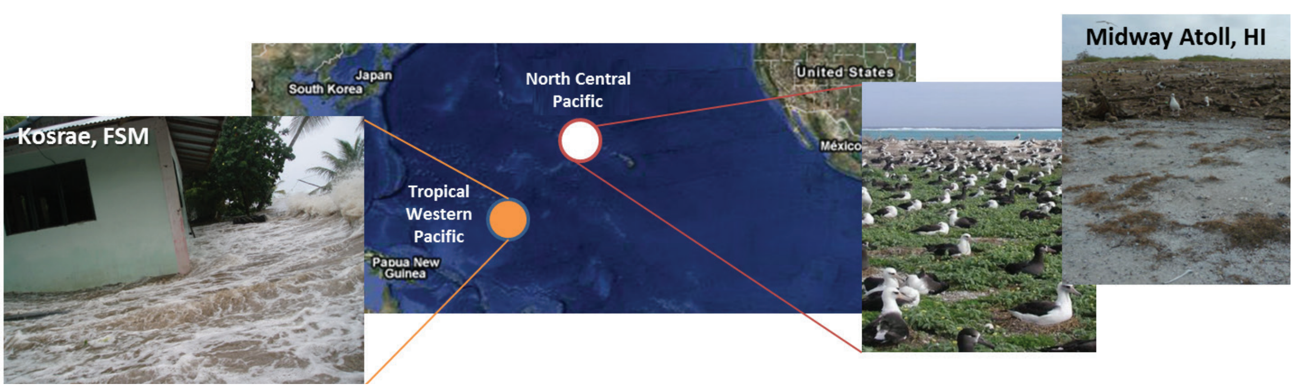


Figure 4-1 Locations of coastal inundation as measured by NOAA tide gauges: the Marshall Islands (orange) in December 2008, and Midway Atoll (white) in winter 2011. (Courtesy of US Fish and Wildlife Service, except for Kosrae image, which is courtesy of Kosrae Island Resource Management Agency staff.)

- **Seasonal high tides.** In early to mid-December 2008, the tides were building to their spring stage, an increased tide range during full and new moons. Though the first large storm hit a week prior to the spring peak (Figure 4-2a), tide levels were still relatively high due to the twice-annual strengthening of local spring tides during November–February (and again May–August).
- **The influence of La Niña.** In the central and western Pacific, the northeast trade winds generally increase during the second half of the year, bringing higher sea levels. This pattern is exacerbated during a La Niña period. In December 2008, weak La Niña–like conditions existed, producing higher-than-normal sea levels (Figure 4-2b).
- **Long-term sea-level rise.** Since the 1990s, sea levels have risen about 7.87 inches (20 cm) in the Western North Pacific sub-region (Fig. 4-2b). This sea-level rise, the largest of any region in the world, is the result of a long-term increase in Pacific trade winds (Merrifield & Maltrud, 2011), similar to the effect of La Niña conditions but over a longer time frame.

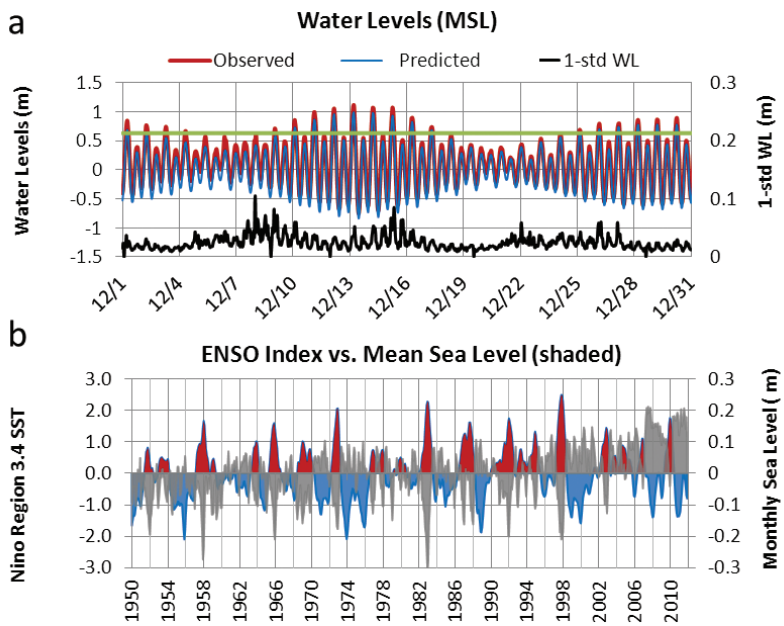


Figure 4-2 In mid-December 2008, the Marshall Islands experienced high seasonal spring (king) tides causing water levels to rise above the Mean Higher High Water (MHHW, green) level. Around this time (a) multi-day periods with enhanced wave activity and related swash motions at the shoreline occurred ~ Dec 8 and 15 seen as high variability within each hourly water-level measurement (1-std WL, Sweet et al., 2011). In (b), the ENSO Niño Region 3.4 anomaly (red/blue) shows elevated sea levels during cool phase/La Niña (blue) or warm phase/El Niño (red), which have steadily increased since about 1990. 0.1 m = 0.33 ft. (Data from NOAA Tide Station at Kwajalein, Marshall Islands.)

The result was widespread damage on numerous low-lying islands. Immediate impacts included eroded beaches, damaged roads, and flooding of houses. A state of emergency was declared on Majuro, capital of the Republic of the Marshall Islands, with damage topping $1.5 million (Wannier, 2011). In the Federated States of Micronesia, seawater contaminated aquifers, wells, wetlands, and farms, damaging or destroying nearly half of the nation's cropland (Fletcher & Richmond, 2010). Here, as well, a state of emergency was declared, sparked primarily by concerns about immediate and long-term food shortages. The coastlines on several islands were littered with debris, raising fears of a health crisis, particularly when local cemeteries were flooded.

In the winter months of 2011, a combination of high sea levels and large waves struck Midway Atoll on two different occasions. Midway and the other Northwestern Hawaiian Islands (NWHI; Figure 4-3) provide nesting sites for 95% to 99% (Arata et al., 2009) of the 1.3 million Laysan albatross (*Phoebastria immutabilis*) in the world and 95% of the world population of 132,000 black-footed albatross (*Phoebastria nigripes*). In January 2011, a powerful storm hit Midway Island, killing thousands of unhatched eggs and newly hatched chicks. The storm caused a drop in pressure that raised the sea level by more than 0.98 feet (0.3 m). At the same time, strong winds and waves battered the island. An even more severe storm hit Laysan Island in February, with large waves and winds of more than 74 miles per hour. This storm destroyed more than 40,000 Laysan albatross nests and 9,000 black-footed albatross nests (Flint et al., 2011). These birds tend to return to the same nest sites every breeding season, even after their nests are destroyed. However, as sea level rises, flooding events will become more frequent in albatross nesting zones, and breeding populations within the NWHI will drastically decline.

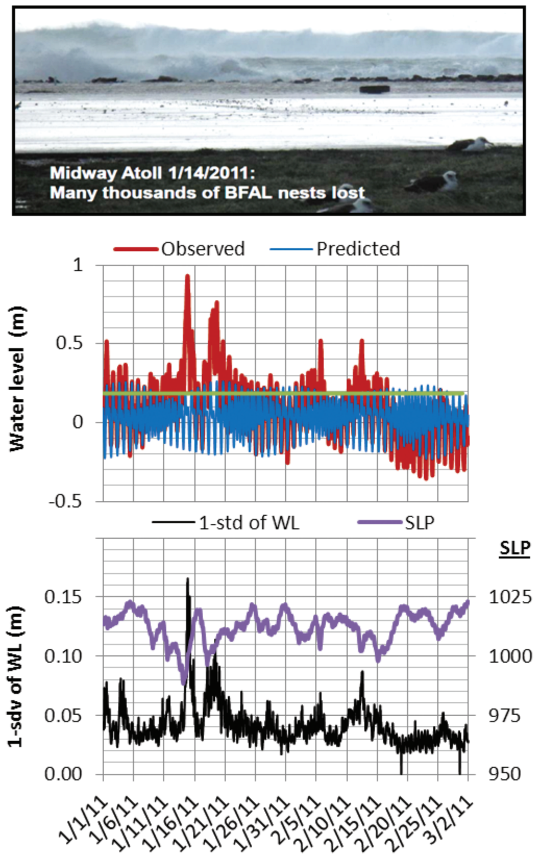


Figure 4-3 Photo (top panel) shows the impact of waves on the Midway Islands during a winter storm. Multiple extreme sea levels exceeded the level of Mean High High Water (MHHW, green line) by about 0.75 m in January 2011 and 0.3 m in February (red). Some storms overlapped with high spring tides (blue). As the storms passed overhead, sea-level pressure (SLP, purple) dropped and wave activity increased (black, 1-stdev of hourly WL as a proxy) causing a significant wave setup in water levels (red). BFAL = Black Footed Albatross. 1 m = 0.33 ft. (Courtesy of US Fish and Wildlife Service. Data from NOAA Tide Station at Midway Island.)

So-called mesoscale eddies are another phenomenon that has been observed to contribute to increased flooding and erosion (Firing & Merrifield, 2004). Unique to the Hawaiian Islands for the most part, these features are capable of producing a prolonged impact when they occur along with high tides and moderate-sized waves. In September 2003, a westward propagating circulating eddy was associated with the highest daily (average of hourly measurements) water level and highest monthly value ever recorded in Honolulu (Figure 4-4a, shown since 1932). Due to its large size, slow passage, and circulation characteristics (clockwise from a high sea surface in its center), the eddy raised sea levels by about 6 inches (15 cm) for nearly two months starting in late July 2003 (Figure 4-4b) (Firing & Merrifield, 2004).

During this period, there were numerous daily extremes (Figure 4-5, left), defined as daily maximum heights (based on hourly values) exceeding the 99th percentile relative to the long-term trend over 1980–2010 (black line in Figure 4-4a). Sea level peaked the last week of September (highest daily mean on September 28), when the seasonal cycle of sea level is also highest (typically more than 8 cm [3.15 inches] higher than its low in April/May) due to normal seasonal surface heating and related thermal expansion of the upper ocean. Also contributing to this absolute maxima, but in a more subtle manner, was the slow rise in relative sea level over the past century (about 0.059 inches/year or 1.5 mm/yr).

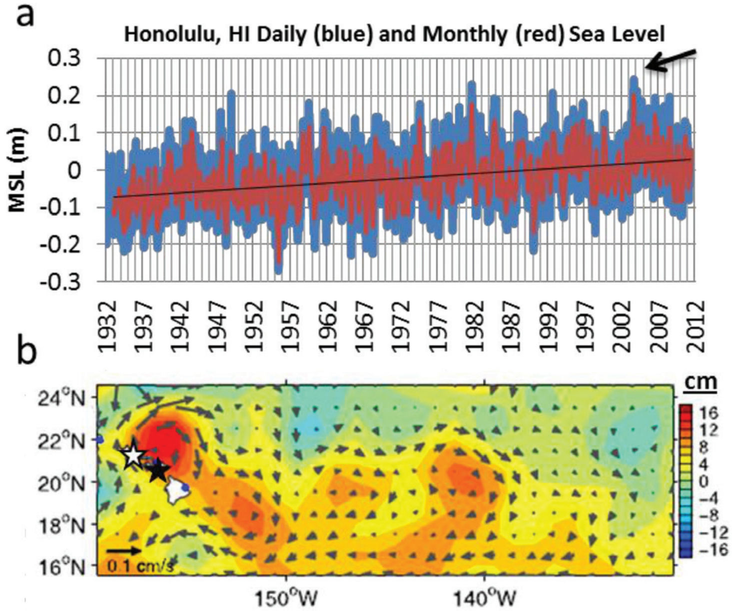


Figure 4-4 (a) Daily and monthly mean sea levels at NOAA Tide Gauge Honolulu (white star in (b)) are shown relative to the 1983–2001 mean sea level (MSL). The black line indicates the long-term relative sea-level rise (about 1.5 mm [0.059 in]/year); the arrow indicates the September 2003 event. (b) The gridded altimeter sea-surface height (SSH, contours in centimeters (cm), and mean circulation (vectors) for August 7, 2003, reveals the eddy directly north of the Hawaiian Islands. 0.1 m = 10 cm = 3.94 in. (Data in Figure 4-4a from NOAA; Figure 4-4b © 2004 American Geophysical Union. Reproduced/modified from Firing & Merrifield [2004] by permission of American Geophysical Union.)

This eddy was not necessarily a rare or unique event; in fact, there have been numerous eddies, which can be tracked by satellite altimeter (Figure 4-5, right). Eddies have been observed to originate far to the east of the Hawaiian Islands as well as in the lee (west) of the islands themselves. They are thought to form in response to changes in regional wind forcing related to El Niño- Southern Oscillation (ENSO) and from instabilities within the prevailing westward-flowing North Equatorial Current (Mitchum, 1995; Firing & Merrifield, 2004; Chen & Qiu, 2010). Although eddies occur on an inter-annual basis, they generally produce extreme events only when they combine with seasonal high tides and waves. Although storms have always caused flooding on low-lying islands of the Pacific, the concern today is that sea-level rise related to longer-term climate conditions will combine with storms to cause even more frequent and more damaging floods in the years ahead.

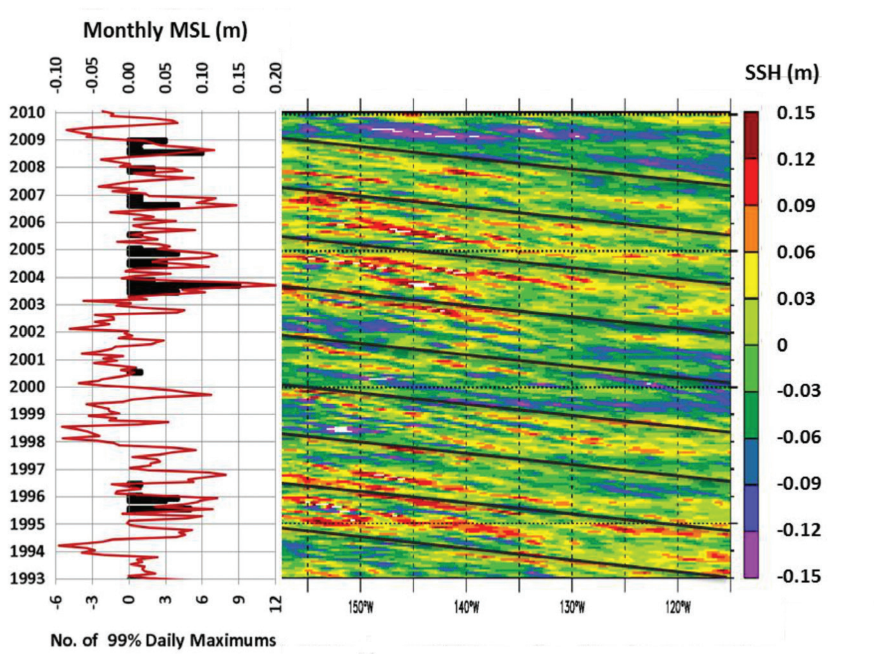


Figure 4-5 A time-longitude plot of SSH anomalies (right) along the altimeter track at 21.3°N shows that when high monthly mean sea levels at Honolulu (left, right line) are recorded, they often appear to originate further east along the same latitude range (right, eddies as red contours moving westward over the x-axis as time progresses on the left y-axis). 0.1 m = 0.33 ft. (©2004 American Geophysical Union. Reproduced/modified from Firing & Merrifield [2004] by permission of American Geophysical Union.)

FOCUS ON ADAPTATION

Case Study 5

Mapping sea-level rise in Honolulu

Dolan Eversole (Sea Grant, University of Hawaiʻi at Manoa),
Charles Fletcher (SOEST, University of Hawaiʻi at Manoa)

Rising sea levels along Hawaiʻi's coastlines will exacerbate many other episodic coastal hazards such as storm surge, tsunami, and hurricane inundation. The threat of rising ocean levels calls for strong leadership and proactive measures from federal, state, and local governments. Mapping the potential impact of sea-level rise (SLR) provides a basis for developing adaptation guidelines and choosing among a range of coastal land-use policy tools (Culver et al., 2010; Codiga & Wager, 2011). Maps allow communities to assess what needs protection and what form protection should take. Based on stakeholder workshops, agency surveys, and analysis by researchers at the University of Hawaiʻi, Codiga and Wager conclude that Hawaiʻi is likely to experience a sea-level rise of around 1 foot by 2050 and around 3 feet by the end of this century (Figure 5-1). Local and regional decision makers, land-use planners, and managers should consider this forecast as a guideline for development planning (e.g., SLR Policy Toolkit, *http://seagrant.soest.hawaii.edu/publications*).

Figure 5-1 Waikīkī District: Areas shaded in blue on the left lie at or below 0.3 m above the current high-tide line; areas shaded in blue on the right lie at or below 0.9 m above the current high-tide line. The thin white line is the current shoreline. (Courtesy of University of Hawaiʻi Coastal Geology Group.)

Using these estimates combined with digital elevation models, the University of Hawaiʻi Coastal Geology Group has developed maps to help visualize the impact of elevated sea level on the island of Oʻahu (see figures below). This work suggests that segments of shoreline and numerous low-lying inland areas will fall below the high-tide line later in the century as sea levels rise.

Low-lying areas that are not submerged will be increasingly vulnerable to inundation by high waves, storms, tsunami, coastal flooding, and extreme tides. Along the shoreline, the impacts are already being observed, including beach erosion and waves reaching over seawalls and other structures with increased frequency and magnitude. In areas of Honolulu and Waikīkī within five to eight blocks of the ocean, there is the potential for basements to flood, ground floors to be splashed by storm wave runup, sea water to come out of the storm drains, and flooding following heavy rains.

FOCUS ON IMPACTS

Case Study 6

Climate change threatens Hawaiian forest birds

Stephen E. Miller (USFWS)

In Hawai'i, geographic isolation has prevented the natural establishment of mammals, terrestrial reptiles, amphibians, and many insect species, such as biting mosquitoes. Isolation has also facilitated the spectacular evolutionary radiation of Hawaiian honeycreepers from a single small flock of North American finches into more than 50 species and subspecies of endemic forest birds (Pratt, 2009).

With the arrival of humans came the clearing of forests and the introduction of non-native species and their diseases. More than 40 mosquito species have been captured in Hawai'i, and six have become established, most recently in 2004 (LaPonte & Burgett, 2005). The southern house mosquito was the first to arrive in Hawai'i in 1826 (Atkinson & LaPointe, 2009b). It is the vector for avian malaria and avian pox. The malaria parasite arrived later with the introduction of non-native birds, probably around 1871. These introduced birds are the perfect avian malaria host: they show no signs of infection and remain infectious for long periods of time.

Case Study 6 Photo 1 The '*Apapane* honeycreeper, seen here at Hawai'i Volcanoes National Park, is one of the only remaining, relatively abundant species of Hawaiian honeycreepers. (Courtesy of Simon Bisson.)

Habitat loss, predation, and competition have taken their toll on Hawaiian honeycreepers, but this trio of invasive species—alien birds, malaria, and mosquitoes—were, and still are, a major threat to the honeycreepers' long-term survival. Almost all of these birds are vulnerable to avian malaria, with mortality rates as high as 65% to 90% after being bitten by a single infective mosquito (Atkinson & LaPointe, 2009a, 2009b). Of the 50 species and sub-species of endemic Hawaiian honeycreepers, only 22 have survived the combined effects of habitat loss, disease, predation, and competition from alien species. The most recent victim, the *Po'ouli*, became extinct in 2004 (Pratt, 2009).

Mosquitoes and avian malaria do not do well in Hawai'i's cooler high elevations. Below 13°C (about 55°F), the malaria parasite cannot complete its maturation cycle, so the disease cannot be transmitted. In addition, the southern house mosquito, which transmits avian malaria, is active at night when temperatures are cooler. Consequently, the prevalence of avian malaria in native forest birds is low above

1,500 m (about 5,000 feet) (Atkinson & LaPointe, 2009a). At lower elevations, mosquitoes and malaria are abundant, and most honeycreepers can no longer survive in the warm mesic and wet forests that were once ideal habitats. Hawai'i's cool, high mesic and wet forests have become their last refuge. But today, climate change threatens to open up these refuges to avian malaria.

As climate change warms the air, the range of mosquitoes will expand upslope, and infective malaria parasites will develop at high elevations. Currently, at higher elevations, avian malaria transmission is seasonal, occurring during the warm summer and fall when mosquito populations are at a maximum. Thus, the cooler winter months and night temperatures are critical to the survival of honeycreepers.

As global warming raises air temperatures, their seasonal high elevation refuge will shrink and eventually disappear (Figure 6-1) (Benning et al., 2002; Atkinson & LaPointe, 2009a). It is likely that the spread of mosquitoes and avian malaria (as well as avian pox) into the high elevations of Hawai'i will eventually lead to the extinction of many, perhaps all, of the honeycreepers that currently survive in these areas.

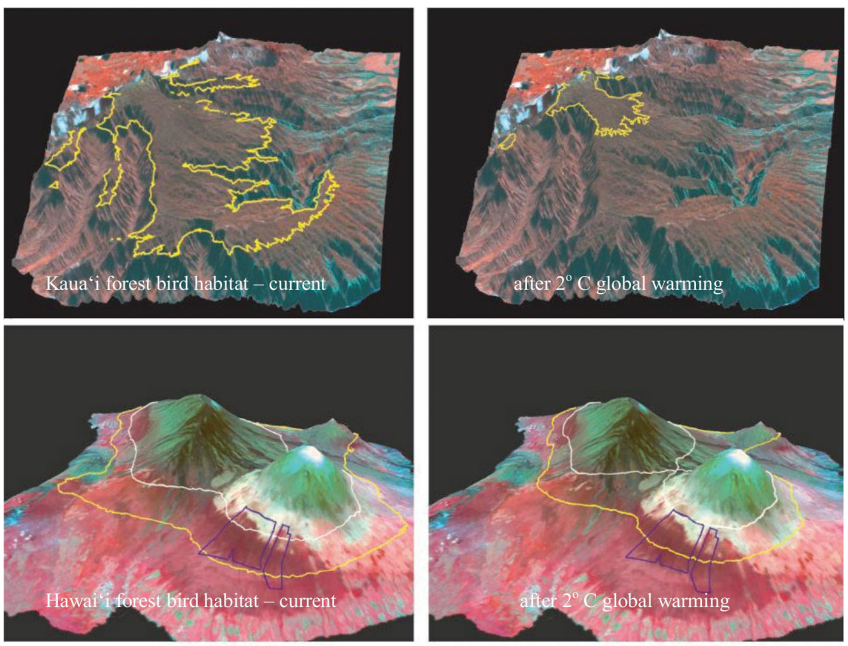


Figure 6-1 Projected changes in the location of the forest cover in relation to 17°C (yellow) and 13°C (white) isotherms under current conditions and with a 2°C warming of the climate. Changes are shown for Hakalau Forest National Wildlife Refuge (blue boundary) on Hawai'i, and the Alakai swamp region on the island of Kaua'i. (From Benning et al., 2002.)

Current temperatures at high elevations in Hawai`i have risen about 0.26°C per decade averaged over the day and night. But of greater concern is the rise in night-time temperatures, when the southern house mosquito is most active. These have risen about 0.44°C (0.79°F) per decade since 1975 (Giambelluca et al., 2008). As a result, the prevalence of avian malaria in Hawaiian forest birds at Hakalau Forest National Wildlife Refuge (1,500 to 2,000 m; 5,000 to 6,500 feet elevation) on the island of Hawai'i has risen from 2.1% to 5.4% over the past decade (Freed et al., 2005). The prevalence of avian malaria at high elevations on Kaua'i has risen as much as 30% over the past decade (Atkinson & Utzurrum, 2010).

High-elevation forest restoration is needed to expand the upward range available to these forest birds. This will require addressing long-standing problems with invasive plants and animals. And there is hope for some Hawai'i honeycreepers. Natural resistance to avian malaria has developed in one species, the *Hawai'i amakihi,* which is now more abundant in low-elevation forests with high levels of mosquitoes and avian malaria than at disease-free high-elevation sites (Woodworth et al., 2005; Kilpatrick et al., 2006). The hope is that good habitat management can help other honeycreepers develop resistance to avian malaria (Kilpatrick, 2006). Unfortunately, the rate of warming in Hawai'i may not give these birds enough time to develop resistance. Without human assistance, global warming combined with avian malaria may overwhelm Hawaiian honeycreepers and other forest bird species.

FOCUS ON IMPACTS

Case Study 7

Fish populations respond to climate conditions

Deanna Spooner (PICCC)

Fishing is a way of life in the Pacific Islands. Subsistence fishers ply the waters of every inhabited shore as well as many uninhabited ones; seafood consumption is high, providing a primary protein source; and fishing is prominent in cultural traditions. There are many stories, chants, and songs about fish and fishing throughout the Pacific region. In Polynesia, the most famous perhaps are those of Maui and his legendary fishing hook.

Oh the great fish hook of Maui!
Manai-i-ka-lani ' made fast to the heavens' its name;
An earth-twisted cord ties the hook.
Engulfed from the lofty Ka'uiki.
Its bait the red billed 'Alae,
The bird made sacred to Hina.
It sinks far down to Hawai'i,
Struggling and painfully dying.
Caught is the land under the water,
Floated up, up to the surface,
But Hina hid a wing of the bird
And broke the land under the water.
Below, was the bait snatched away
And eaten at once by the fishes,
The Ulua of the deep muddy places.

"Chant of Kuali'i," ca. 1700 AD
(Westervelt, 1910)

Case Study 7 Photo 1 Fish hook collection, Bishop Museum, Honolulu, Hawai'i. (© 2008 Debbi Long, "hooked," used under a Creative Commons Attribution-NonCommercial-ShareAlike license.)

In addition to their importance to traditional practices and food security for island communities, open-ocean fish populations in the Pacific play an increasingly dominant role in global fish production. The Western Pacific Regional Fishery Management Council estimates the annual catch of skipjack tuna (*Katsuwonus pelamis*), yellowfin tuna (*Thunnus albacares*), bigeye tuna (*T. obesus*), and South Pacific albacore tuna (*T. alalunga*) at about 2.7 million metric tonnes. These tuna species are highly migratory and range throughout the Pacific, and adults tolerate a relatively wide range of conditions (Brill, 1994).

Yet, climatic conditions greatly influence the productivity and geographic range of Pacific tuna populations (Miller, 2007).

Tuna have been shown to respond to El Niño-Southern Oscillation (ENSO) events. Sea-surface temperature influences tuna productivity and optimal development through different life stages (Lehodey et al., 1997; Lehodey, 2001; Lu et al., 2001). ENSO-related shifts create a disadvantage for local fishers who, unlike large-scale commercial fleets, cannot follow the tuna to more productive waters thousands of miles away.

Due to projected ocean warming and other climate-associated changes in marine ecosystem productivity, it is projected that over the 21st century, tuna distributions "are likely to shift progressively towards the central and eastern Pacific" (Bell et al., 2011) (Figure 7-1). Currently, in the Western North Pacific sub-region, the domestic tuna fisheries of the Federated States of Micronesia and the Republic of the Marshall Islands are valued at \$2.67 million and \$2.44 million annually, respectively (Bell et al., 2011). The contribution of tuna fisheries to these economies may well lessen as the projected shift in populations takes place.

The complexity of marine ecosystems makes it difficult to predict how climate change will alter discrete "strands" of the food web upon which tuna and other large pelagic fish depend. There are indications that, in addition to changes in sea-surface temperature, changes in ocean circulation and ocean chemistry will heavily influence productivity throughout the region (Le Borgne et al., 2011; Polovina et

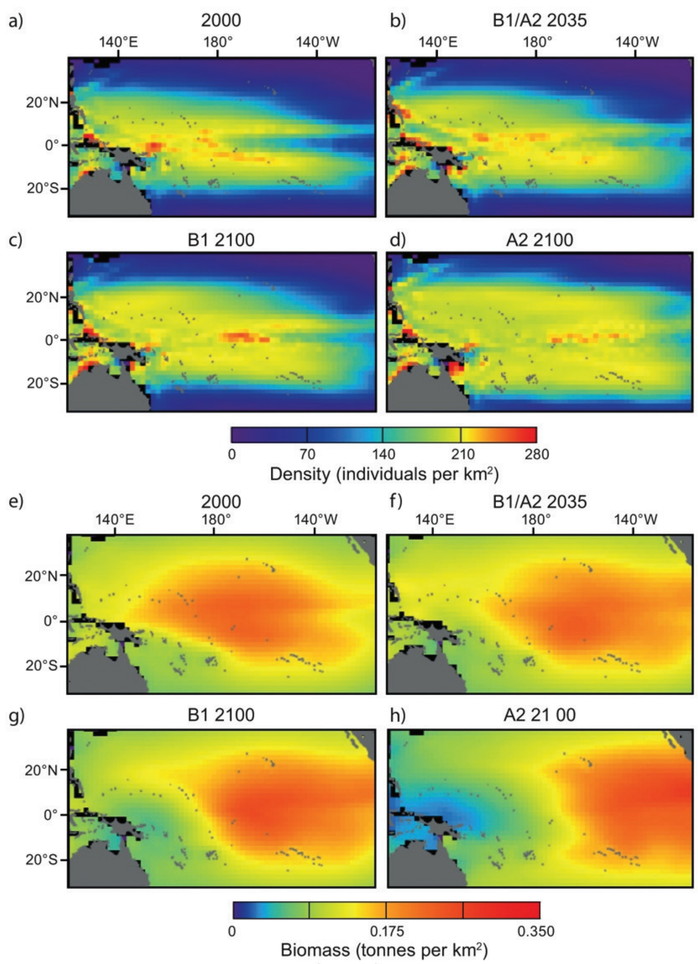


Figure 7-1 Projected distributions (density) for skipjack tuna larvae recruits from the SEAPODYM model (a) in 2000; (b) under the B1/A2 emissions scenario in 2035; (c) under B1 in 2100; and (d) under A2 in 2100. Also shown are estimates of total biomass (tonnes per square kilometer) of skipjack tuna populations based on average (1980–2000) fishing effort in (e) 2000; (f) under B1/A2 in 2035; (g) under B1 in 2100; and (h) under A2 in 2100. (From Lehodey et al., 2011.)

al., 2011). By the end of this century, the total primary production and fish catch is projected to increase by 26% in the subtropics and decrease by 38% and 15% in the temperate and the equatorial zones, respectively (Polovina et al., 2011). This projected decrease, in combination with shifting fish populations, may have a significant and unequal economic impact on Pacific Island sub-regions. One cannot place a monetary value, however, on how these projected changes in pelagic fisheries will impact the Pacific Island way of life.

FOCUS ON IMPACTS

Case Study 8

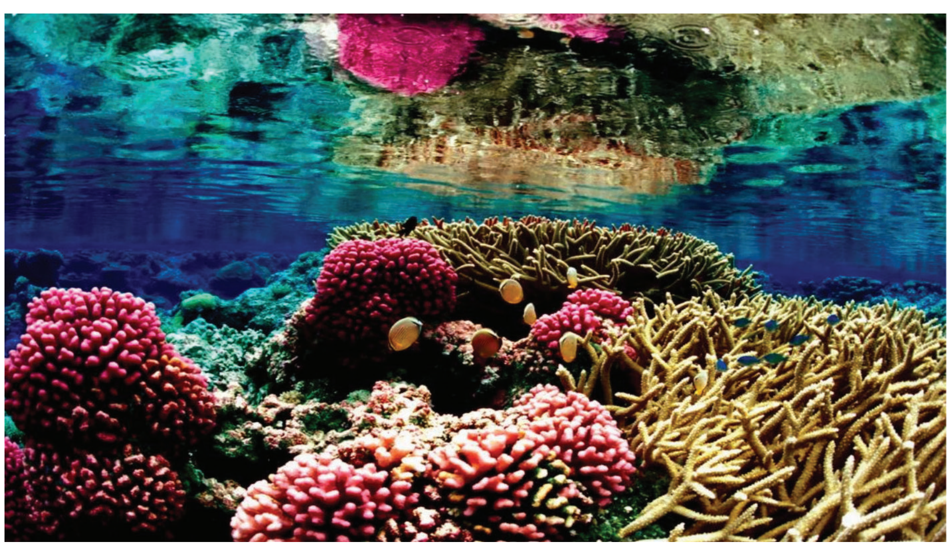
Pacific coral reef management in a changing climate

Britt Parker (NOAA CRCP)

Tropical coral reefs are among the most productive and diverse ecosystems in the world: thousands of species coexist in a complex structure built by living corals. Coral ecosystems are of particular ecological, economic, and cultural importance in the Pacific Islands region, and this region supports the majority of coral reefs within the United States' jurisdiction.

These ecosystems are declining due to a plethora of human impacts, including overutilization, land-based pollutants, introduced invasive aquatic species, and climate change. Two climate-related phenomena in conjunction pose a potentially catastrophic threat to the long-term survival of coral reef ecosystems in the Pacific Islands region: rising sea-surface temperatures (SSTs) and changes in ocean chemistry.

Over the past 30 years, periods of elevated SST have become more commonplace, often correlating with coral bleaching (Donner, 2011). Coral bleaching occurs when water temperatures rise 1° to 2°C (1.8° to 3.6°F) above the warmest normal summer temperatures and persist over three to four weeks or more. This stress can cause the corals to expel their crucial, colorful symbiotic algae and thus turn white (hence the name "bleaching"). Intense coral bleaching is often followed by coral death, though corals can recover from mild bleaching events.



Case Study 8 Photo 1 A healthy tropical Pacific coral reef, Palmyra Atoll National Wildlife Refuge. (Courtesy of J. Maragos, USFWS.)

Coral bleaching is becoming more frequent as the oceans warm (Hoegh-Guldberg, 1999). Coral bleaching in 1998 and 2010 caused large-scale coral deaths in reef systems around the globe, with the 1998 event heavily impacting Palau in the Western North Pacific sub-region, and Palmyra Atoll in the Central North Pacific sub-region (Turgeon et al., 2002). In the Republic of Palau, nearly one-half (48%) of 946 surveyed colonies were totally bleached, and a further 15% were partially bleached (Bruno et al., 2001). Coral bleaching has also been observed elsewhere in the Micronesian, Marianas, Samoan, and Hawaiian archipelagos. The *Reefs at Risk Revisited* report (Burke et al., 2011) predicts that by 2050 many of the reefs in the Pacific will bleach annually. This frequency of bleaching is worrying because it allows little time for corals to recover. Annual summer bleaching has already been reported from American Sāmoa (Fenner & Heron, 2008).

Adding to the stress of high temperatures is the increasing acidification of the ocean, caused by rising levels of carbon dioxide in the air that is absorbed by sea water. One of the impacts of ocean acidification is that less carbonate is available in the form necessary for coral reefs to build their calcium carbonate skeletons. The skeletons that these small coral polyps build are a fundamental building block of coral reef ecosystems. Based on the rate of coral loss reported over the past 20 years, and the projected effects of more frequent coral bleaching and ocean acidification, average coral cover throughout the Pacific is expected to decline to 15% to 35% by 2035 compared with 20% to 40% in 2007 (Bruno & Selig, 2007; Hoegh-Guldberg et al., 2011).

Coral reef managers have few options for preventing or reducing coral bleaching because it is not possible to cool large masses of sea water. They can focus on increasing the potential resilience of reefs by reducing human impacts such as overfishing, sediment and pollutant runoff, and invasive species. In addition, early-warning systems that predict coral bleaching and monitor the effects on reef ecosystems have made it possible to identify which reefs are perhaps more resistant to bleaching and have a better chance of recovery.

In an effort to expand the range of management options, researchers in American Sāmoa are testing technologies that could cool selected, important reefs and shade them from strong sunlight. Seasonally high temperatures at a particular reef on the island of Tutuila cause predictable coral bleaching (Fenner & Heron, 2008), creating an ideal test site. Initial tests have shown that reducing peak water temperatures by about 1.0°C (1.8°F) enables two sensitive species of coral to regain and retain their healthy color during periods of thermal stress (Figure 8-1). In a second set of experiments, shading was found to restore healthy color in bleached coral. In conjunction with strategies for reducing land-based stress, these and other management tools may provide Pacific Island communities with new, localized conservation measures to help combat the effects of global climate change on their valuable coral reef resources.

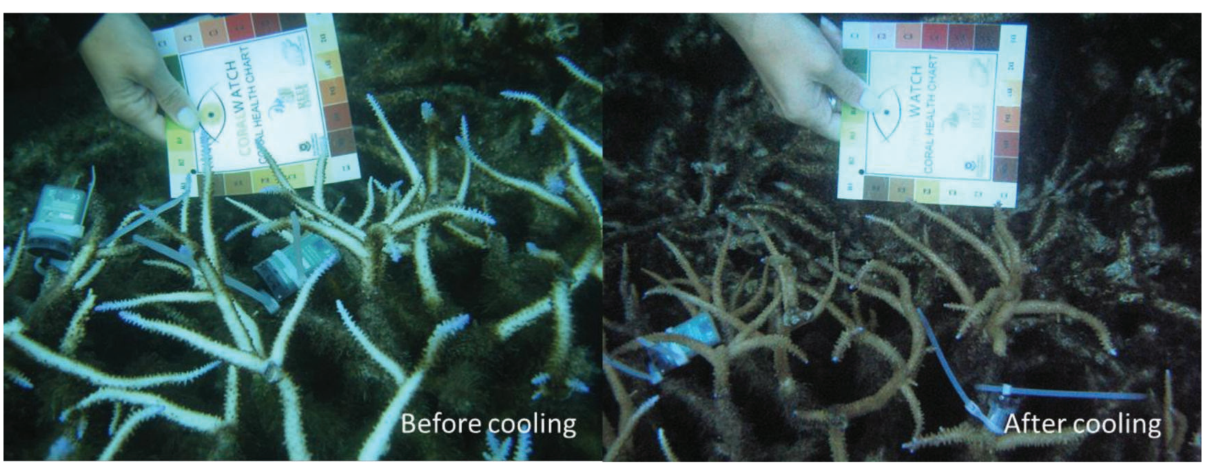


Figure 8-1 Bleached *Acropora* corals before (left) and after (right) treatment with cooled seawater for 24 hours, Tutuila, American Samoa. (Courtesy of B. Von Herzen, Climate Foundation.)

References

Arata, J. A., Sievert, P. R., & Naughton, M. B. (2009). *Status assessment of Laysan and Black-footed Albatrosses, North Pacific Ocean, 1923-2005* (US Geological Survey Scientific Investigations Report No. 2009-5131). Retrieved from http://pubs.usgs.gov/sir/2009/5131/

Atkinson, C. T., & LaPointe, D. A. (2009a). Ecology and pathogenicity of avian malaria and pox. In M. T. K. Pratt, M. C. T. Atkinson, M. P. C. Banko, M. J. D. Jacobi, & M. B. L. Woodworth (Eds.), *Conservation biology of Hawaiian forest birds: Implications for island avifauna* (pp. 234–252). New Haven, CT: Yale University Press.

Atkinson, C. T., & LaPointe, D. A. (2009b). Introduced avian diseases, climate change, and the future of Hawaiian honeycreepers. *Journal of Avian Medicine and Surgery*, *23*(1), 53–63. doi:10.1647/2008-059.1

Atkinson, C. T., & Utzurrum, R. B. (2010). *Changes in prevalence of avian malaria on the Alakai'i Plateau, Kaua'i. Hawai'i, 1997-2007* (Hawaii Cooperative Studies Unit Technical Report No. HCSU-017). University of Hawaii at Hilo. Retrieved from http://hilo.hawaii.edu/hcsu/documents/ TRHCSU017AtkinsonChangesinPrevalenceofAvianMalariaFINAL.pdf

Bell, J. D., Adams, T. J. H., Johnson, J. E., Hobday, A. J., & Sen Gupta, A. (2011). Pacific communities, fisheries, aquaculture and climate change: An introduction. In J. D. Bell, J. E. Johnson, & A. J. Hobday (Eds.), *Vulnerability of tropical Pacific fisheries and aquaculture to climate change* (pp. 1–48). Noumea, New Caledonia: Secretariat of the Pacific Community.

Benning, T. L., LaPointe, D., Atkinson, C. T., & Vitousek, P. M. (2002). Interactions of climate change with biological invasions and land use in the Hawaiian Islands: Modeling the fate of endemic birds using a geographic information system. *Proceedings of the National Academy of Sciences*, *99*(22), 14246–14249. doi:10.1073/pnas.162372399

Brill, R. W. (1994). A review of temperature and oxygen tolerance studies of tunas pertinent to fisheries oceanography, movement models and stock assessments. *Fisheries Oceanography*, *3*(3), 204–216. doi:10.1111/j.1365-2419.1994.tb00098.x

Bruno, J. F., Siddon, C. E., Witman, J. D., Colin, P. L., & Toscano, M. A. (2001). El Niño related coral bleaching in Palau, Western Caroline Islands. *Coral Reefs*, *20*(2), 127–136. doi:10.1007/s003380100151

Bruno, J. F., & Selig, E. R. (2007). Regional decline of coral cover in the Indo-Pacific: Timing, extent, and subregional comparisons. *PLoS ONE*, *2*(8), e711. doi:10.1371/journal.pone.0000711

Burke, L., Reytar, K., Spalding, M., & Perry, A. (2011). *Reefs at risk revisited*. Washington, DC: World Resources Institute. Retrieved from http://www.wri.org/publication/reefs-at-risk-revisited

Chen, S., & Qiu, B. (2010). Mesoscale eddies northeast of the Hawaiian Archipelago from satellite altimeter observations. *Journal of Geophysical Research*, *115*, C03016. doi:10.1029/2009JC005698

Codiga, D., & Wager, K. (2011). *Sea-level rise and coastal land use in Hawai'i: A policy tool kit for state and local governments*. Honolulu, HI: Center for Island Climate Adaptation and Policy. Retrieved from http://icap.seagrant.soest.hawaii.edu/sites/seagrant.soest.hawaii.edu/files/publications/icap-sealevelrisetoolkit_web-1_2.pdf

Commission on Water Resource Management. (10 June 2010). *'lao ground water management area high-level source water-use permit applications and petition to amend interim instream flow standards of Waihe'e River and Waiehu, 'lao, & Waikapu Streams contested case hearing* (CCH-MAO6-Ol). Retrieved from http://hawaii.gov/dlnr/cwrm/cch/cchma0601/CCHMA0601-02.pdf

Culver, M. E., Schubel, J. R., Davidson, M. A., Haines, J., & Texeira, K. C. (Eds.). (2010). *Proceedings from the Sea Level Rise and Inundation Community Workshop, 2009 Dec 3-5*. Lansdowne, MD: sponsored by the National Oceanic and Atmospheric Administration and US Geological Survey. Retrieved from http://www.csc.noaa.gov/publications/inundation-workshop.pdf

Donner, S. D. (2011). An evaluation of the effect of recent temperature variability on the prediction of coral bleaching events. *Ecological Applications, 21*(5), 1718–1730. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/21830713

Fenner, D., & Heron, S. F. (2008). Annual summer bleaching of a multi-species coral community in backreef pools of American Samoa: A window on the future? *Proceedings of the 11th International Coral Reef Symposium, 2008 July 7-11* (pp. 1289–1293). Ft. Lauderdale, FL. Retrieved from http://www.nova.edu/ncri/11icrs/proceedings/files/m25-04.pdf

Firing, Y. L., & Merrifield, M. A. (2004). Extreme sea level events at Hawaii: Influence of mesoscale eddies. *Geophysical Research Letters*, *31*, L24306. doi:10.1029/2004GL021539

Fletcher, C. H., & Richmond, B. M. (2010). *Climate change in the Federated States of Micronesia: Food and water security, climate risk management, and adaptive strategies*. Honolulu, HI: University of Hawai'i Sea Grant College Program. Retrieved from http://seagrant.soest.hawaii.edu/sites/seagrant.soest.hawaii.edu/files/publications/1webfinal_maindocument_climatechangefsm.Pdf

Flint, B., Leary, P., & Klavitter, J. (2011). Briefing paper to the US delegation to the Agreement on the Conservation of Albatrosses and Petrels (ACAP) presented at the Population Status and Tends and Breeding Sites Working Group meeting, Guayaquil, Ecuador.

Freed, L. A., Cann, R. L., Goff, M. L., Kuntz, W. A., & Bodner, G. R. (2005). Increase in avian malaria at upper elevation in Hawai'i. *The Condor*, *107*(4), 753. doi:10.1650/7820.1

Giambelluca, T. W., Diaz, H. F., & Luke, M. S. A. (2008). Secular temperature changes in Hawai'i. *Geophysical Research Letters*, *35*, L12702. doi:10.1029/2008GL034377

Giambelluca, T. W., Chen, Q., Frazier, A. G., Price, J. P., Chen, Y.-L., Chu, P.-S., Eischeid, J., et al. (2011). *The rainfall atlas of Hawai'i*. Retrieved from http://rainfall.geography.hawaii.edu

Hamlin, S. N., & Takasaki, K. J. (1996). *Water-quality reconnaissance of ground-water in the inhabited outer islands of Chuuk State, Federated States of Micronesia, 1984-85* (US Geological Survey Water-Resources Investigations Report No. 96-4180). Retrieved from http://pubs.er.usgs.gov/usgspubs/wri/wri964180

Hawai'i County. (2010, August). Hawai'i County water use and development plan update. Retrieved from http://hawaii.gov/dlnr/cwrm/planning/wudpha2012.pdf

Hezel, F. X. (2009). High water in the low atolls. *Micronesian Counselor*, *#76*. Retrieved from http://www.micsem.org/pubs/counselor/frames/highwaterfr.htm

Hoegh-Guldberg, O. (1999). Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research*, *50*(8), 839. doi:10.1071/MF99078

Hoegh-Guldberg, O., Andréfouët, S., Fabricius, K. E., Diaz-Pulido, G., Lough, J. M., Marshall, P. A., & Pratchett, M. S. (2011). Vulnerability of coral reefs in the tropical Pacific to climate change. In J.D. Bell, J. E. Johnson, & A. J. Hobday (Eds.), *Vulnerability of tropical Pacific fisheries and aquaculture to climate change* (pp. 251–296). Noumea, New Caledonia: Secretariat of the Pacific Community. Retrieved from http://www.publish.csiro.au/nid/126/paper/MF99078.Htm

Kilpatrick, A. M. (2006). Facilitating the evolution of resistance to avian malaria in Hawaiian birds. *Biological Conservation*, *128*(4), 475–485. doi:10.1016/j.biocon.2005.10.014

Kilpatrick, A. M., LaPointe, D. A., Atkinson, C. T., Woodworth, B. L., Lease, J. K., Reiter, M. E., Gross, K., et al. (2006). Effects of chronic avian malaria (Plasmodium relictum) infection on reproductive success of Hawaii Amakihi (Hemignathus virens). *The Auk*, *123*(3), 764–774. doi:10.1642/0004-8038(2006)123[764:EOCAMP]2.0.CO;2

LaPonte, D., & Burgett, J. (2005). *Mosquitoes in Hawai'i* (Position Paper No. 2005-02). Honolulu, HI: Hawai'i Conservation Alliance. Retrieved from http://hawaiiconservation.org/files/content/resources/publications/position_papers/mosquitos.pdf

Le Borgne, R., Allain, V., Griffiths, S. P., Matear, R. J., McKinnon, A. D., Richardson, A. J., & Young, J. W. (2011). Vulnerability of open ocean food webs in the tropical Pacific to climate change. In J. D. Bell, J. E. Johnson, & A. J. Hobday (Eds.), *Vulnerability of tropical Pacific fisheries and aquaculture to climate change* (pp. 189–250). Noumea, New Caledonia: Secretariat of the Pacific Community.

Lehodey, Patrick. (2001). The pelagic ecosystem of the tropical Pacific Ocean: Dynamic spatial modelling and biological consequences of ENSO. *Progress in Oceanography*, *49*(1-4), 439–468. doi:10.1016/S0079-6611(01)00035-0

Lehodey, P., Bertignac, M., Hampton, J., Lewis, A., & Picaut, J. (1997). El Niño Southern Oscillation and tuna in the western Pacific. *Nature*, *389*(6652), 715–718. doi:10.1038/39575

Lehodey, P., Hampton, J., Brill, R. W., Nicol, S., Senina, I., Calmettes, B., Pörtner, H. O., et al. (2011). Vulnerability of oceanic fisheries in the tropical Pacific to climate change. In J. D. Bell, J. E. Johnson, & A. J. Hobday (Eds.), *Vulnerability of tropical Pacific fisheries and aquaculture to climate change* (pp. 433–492). Noumea, New Caledonia: Secretariat of the Pacific Community.

Lu, H.-J., Lee, K.-T., Lin, H.-L., & Liao, C.-H. (2001). Spatio-temporal distribution of yellowfin tuna *Thunnus albacares* and bigeye tuna *Thunnus obesus* in the Tropical Pacific Ocean in relation to large-scale temperature fluctuation during ENSO episodes. *Fisheries Science*, *67*(6), 1046–1052. doi:10.1046/j.1444-2906.2001.00360.x

Marshall Islands drought assistance continues. (1998, April 7). *Pacific Islands Report*. Retrieved from http://archives.pireport.org/archive/1998/april/04-08-02.htm

Merrifield, Mark A., & Maltrud, M. E. (2011). Regional sea level trends due to a Pacific trade wind intensification. *Geophysical Research Letters*, *38*, L21605. doi:10.1029/2011GL049576

Miller, K. A. (2007). Climate variability and tropical tuna: Management challenges for highly migratory fish stocks. *Marine Policy*, *31*(1), 56–70. doi:10.1016/j.marpol.2006.05.006

Mitchum, G. T. (1995). The source of 90-day oscillations at Wake Island. *Journal of Geophysical Research, 100*(C2), 2459–2475. doi:199510.1029/94JC02923

Oki, D. S. (1999). *Geohydrology and numerical simulation of the ground-water flow system of Kona, Island of Hawaii* (US Geological Survey Water-Resources Investigations Report No. 99-4073). Retrieved from http://pubs.er.usgs.gov/publication/wri994073

Oki, D. S. (2004). *Trends in streamflow characteristics at long-term gaging stations, Hawaii* (US Geological Survey Scientific Investigations Report No. 2004-5080). Retrieved from http://pubs.usgs. gov/sir/2004/5080/

Oki, D. S., & Meyer, W. (2001). *Analytical versus numerical estimates of water-level declines caused by pumping, and a case study of the Iao aquifer, Maui, Hawaii* (US Geological Survey Water-Resources Investigations Report No. 00-4244). Retrieved from http://pubs.usgs.gov/wri/wri00-4244/

Polovina, J. J., Dunne, J. P., Woodworth, P. A., & Howell, E. A. (2011). Projected expansion of the subtropical biome and contraction of the temperate and equatorial upwelling biomes in the North Pacific under global warming. *ICES Journal of Marine Science*, *68*(6), 986–995. doi:10.1093/icesjms/fsq198

Pratt, T. K. (2009). Origins and evolution. In T. K. Pratt, C. T. Atkinson, P. C. Banko, J. D. Jacobi, & B. L. Woodworth (Eds.), *Conservation biology of Hawaiian forest birds: Implications for island avifauna* (pp. 3–24). New Haven, CT: Yale University Press

Presley, T. K. (2005). *Effects of the 1998 drought on the freshwater lens in the Laura Area, Majuro Atoll, Republic of the Marshall Islands* (US Geological Survey Scientific Investigations Report No. 2005-5098). Retrieved from http://pubs.usgs.gov/sir/2005/5098/

Sweet, W. V., Zervas, C., & Gill, S. (2011). *Seasonal variability of storm surge and high water events within the Hawaiian Islands*. Poster presented at the 12th International Workshop on Wave Hindcasting and Forecasting & 3rd Coastal Hazards Symposium, 2011 October 30–November 4, Kohala Coast, Hawai'i.

Takasaki, K. J., & Mink, J. F. (1985). *Evaluation of major dike-impounded ground-water reservoirs, Island of Oahu* (US Geological Survey Water-Supply Paper No. 2217). Retrieved from http://pubs.er.usgs.gov/publication/wsp2217

Turgeon, D. D., Asch, R. D., Causey, B. D., Dodge, R. E., Jaap, W., Banks, K., Delaney, J., et al. (2002). *The state of coral reef ecosystems of the United States and Pacific Freely Associated States: 2002*. Silver Springs, MD: National Oceanic and Atmospheric Administration/National Ocean Service/National Centers for Coastal Ocean Science. Retrieved from http://ccma.nos.noaa.gov/ecosystems/coralreef/coral2002/

Wannier, G. (2011). Threatened island nations: Summary of legal issues. *Climate Law Blog*. Columbia Law School, Center for Climate Change Law. Retrieved from http://blogs.law.columbia.edu/climatechange/2011/07/11/threatened-island-nations-summary-of-legal-issues/

Westervelt, W. D. (1910). *Legends of Maui—a demi god of Polynesia, and of his mother Hina.* Honolulu: Hawaiian Gazette.

Woodworth, P. L., Atkinson, C. T., LaPointe, D. A., Hart, P. J., Spiegel, C. S., Tweed, E. J., Henneman, C., et al. (2005). Host population persistence in the face of introduced vectorborne diseases: Hawaii Amakihi and avian malaria. *Proceedings of the National Academy of Sciences*, *102*(5), 1531–1536. doi:10.1073/pnas.0409454102

This collection of case studies was developed by the Pacific Islands Regional Climate Assessment (PIRCA), and is part of Climate Change and Pacific Islands: Indicators and Impacts, which is being published as one of a series of technical inputs to the National Climate Assessment (NCA) 2013 report. These case studies illustrate current climate impacts and adaptations across the Pacific Islands region. Real-world examples of the implications of climate risks for Pacific Islanders are described in diverse sectors, including agriculture and food security, human health, environmental policy, coastal infrastructure, and native ecosystems. The case studies highlight how information about the changing climate can be used to support decision making. The PIRCA is a collaborative effort engaging federal, state, and local government agencies, non-government organizations, academia, businesses, and community groups to inform and prioritize their activities in the face of a changing climate.

Cover photos: (*Top*) View from Makapuʻu Point on the Island of Oʻahu in Hawaiʻi, courtesy of Zena N. Grecni. (*Middle Left*) Tropical Pacific coral reef, Palmyra Atoll National Wildlife Refuge, courtesy of J. Maragos. (*Middle Right*) Pacific fish hook collection, Bishop Museum, Honolulu, Hawaiʻi, © 2008 Debbie Long, "hooked", used under a Creative Commons Attribution-NonCommercial-Share-Alike license. (*Bottom*) Clouds around Mt. Konahuanui in the Koʻolau Mountain Range, Oʻahu, courtesy of Zena N. Grecni.

Acknowledgments

Primary responsibility for the PIRCA is shared by: the Pacific Regional Integrated Sciences and Assessments (RISA) program, funded by the US National Oceanic and Atmospheric Administration (NOAA) and supported through the East-West Center; NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) National Climatic Data Center (NCDC); Pacific Climate Information System (PaCIS); and the Pacific Islands Climate Change Cooperative, funded by the US Fish and Wildlife Service. The editors extend special acknowledgment to the many experts who presented research, discussed findings, and authored or reviewed sections of the full report.

ISLANDPRESS