



The Mapunapuna region of Honolulu during heavy rains.
(<http://starbulletin.com/2004/02/28/news/story1.html>)

Chapter 8

Malama o kekai, kekai o ke malama

“Take care of the ocean and the ocean will take care of you”

Climate Change and Sea-Level Rise

The Sun’s energy drives the weather and climate and heats Earth’s surface. In turn, Earth reradiates and reflects the energy back to space. Atmospheric *greenhouse gases* (water vapor, carbon dioxide, nitrous oxide, methane, and others) trap some of the outgoing energy, retaining heat like the glass panels of a greenhouse. If greenhouse gases increase in abundance, their ability to store heat increases, warming the atmosphere. Without this natural effect, Earth’s surface temperature would be about zero degrees F instead of its present 57°F¹ and life as we know it would not be possible. This is known as the *greenhouse effect*.

Measurements indicate that the amount of carbon dioxide and other greenhouse gases in the atmosphere have increased over the past century. Measurements also indicate that global atmospheric temperature has risen by approximately 1°F over the past century while precipitation (expected to increase in a warmer atmosphere) rose 5-10%. For instance, 2007 tied 1998 as the second warmest year on the instrumental record (extending back to 1850 or so).² This is remarkable considering that 2007 was a cool La Niña year and a time of low solar activity (the lowest in twenty years) and 1998 was a warm year with high solar activity that has been

dubbed the “El Niño of the century.”³ Long term temperature records of Earth’s surface (including the ocean) and atmosphere show a sustained warming trend over the past 50 years of approximately 0.23°F per decade.⁴

Scientific researchers who study the greenhouse effect connect the unusual global warming witnessed now to gas emissions from our use of fossil fuels. These emissions have caused an increase in heat-trapping carbon dioxide and methane in the atmosphere. A number of researchers using advanced mathematical models of atmospheric and oceanic circulation have shown that human carbon emissions are capable of causing (and the most likely reason for) the observed warming of the late 20th and early 21st centuries. This work is summarized in a series of reports by the Intergovernmental Panel on Climate Change (IPCC) that began in 1990.⁵ Researchers, additionally, have collected and published in peer-reviewed scientific literature, numerous observations of ocean warming, melting glaciers, reduced sea ice, changes in seasonality, shifts in the behavior of temperature sensitive species, and other evidence supporting the contention that Earth’s surface environment is experiencing the effects of global warming as a result of human atmospheric pollution.

Although the connection between human pollution and atmospheric warming cannot ever be indisputably proven, only inferred or correlated, a compelling case has been made by researchers that greenhouse gas emissions are an important factor driving the rise in temperature. This does not exclude the possibility of a natural component to climate change, but the most likely scenario is one that includes human production of greenhouse gases. In this discussion we assume that global warming is real, that it is driven by human contributions to atmospheric greenhouse gases, and that the surface environment in many places has begun to react to changes resulting from warming.

Some Observations

In order to figure out whether Earth is cooling or warming, scientists have used temperature data from land weather stations, satellite measurements, and ships.⁶ This data is analyzed to determine the average surface temperature of Earth for any year. For instance, climatologists at NASA's Goddard Institute for Space Studies (GISS) in New York City note that the eight warmest years in the GISS record (extending to 1880) have all occurred since 1998, and the fourteen warmest years in the record have all occurred since 1990.⁷ The highest global temperature record was set in 2005, and 2006 was the warmest year in the U.S.⁸

Scientists at the National Climatic Data Center note that global temperatures have increased about 1.33°F (plus or minus 0.32°F) since the late-19th century, and the linear trend for the past 50 years of 0.23°F (plus or minus 0.05°F) per decade is nearly twice that for the past 100 years. The warming has not been globally uniform. Some areas (including parts of the southeastern U.S. and parts of the North Atlantic) have, in fact, cooled slightly over the last century. The recent warmth has been greatest over North America and Eurasia between 40 and 70°N. Lastly, seven of the eight warmest years on record have occurred since 2001 and the 10 warmest years have all occurred since 1995.⁹

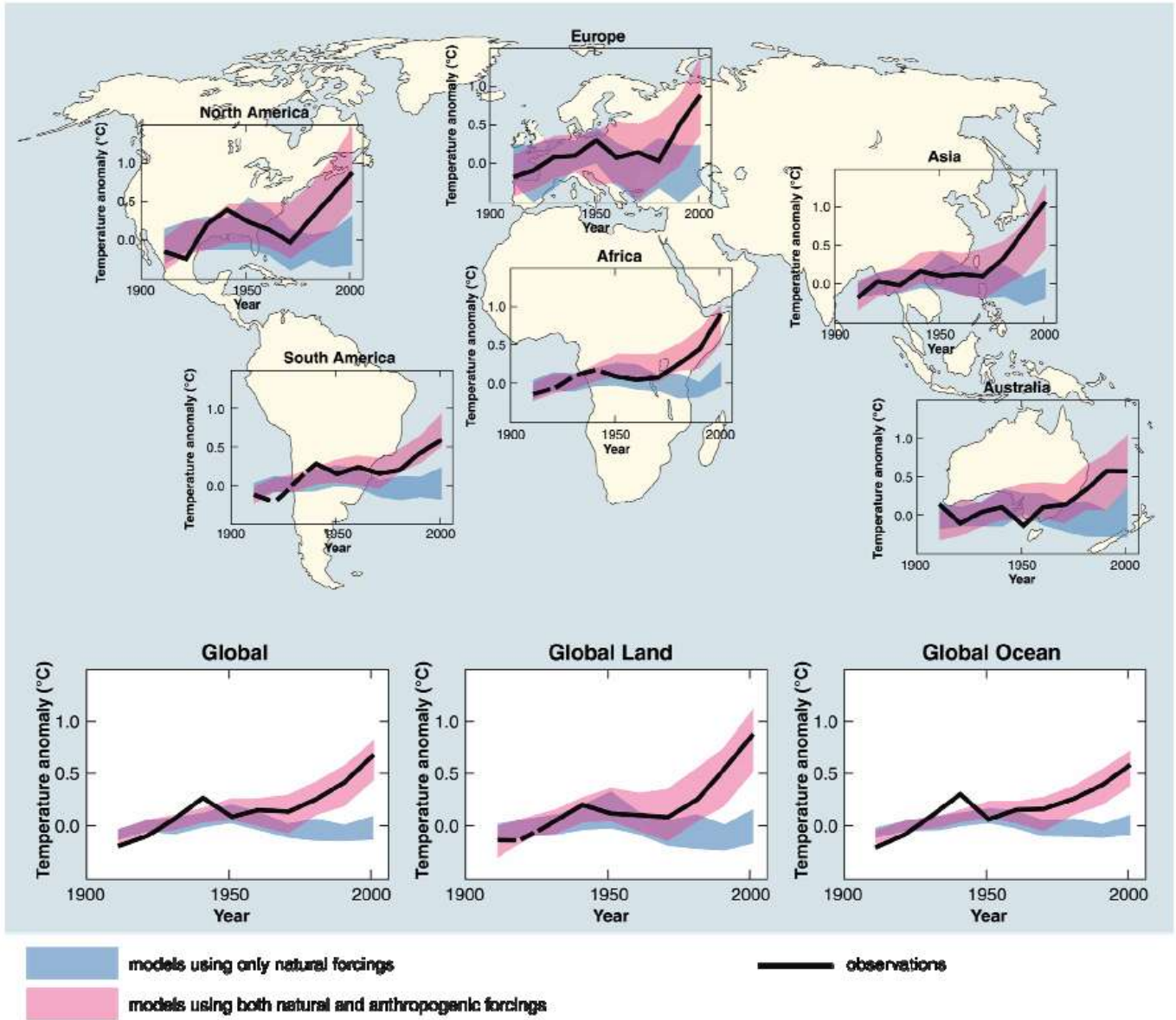
Since the industrial revolution, global concentrations of carbon dioxide (CO₂) have increased 30%, far exceeding the natural range over the past 650,000 years; methane (CH₄) has more than doubled, and nitrous oxide (N₂O) has risen by 15%.¹⁰ These increases in greenhouse gases have

enhanced the heat-trapping capability of Earth's atmosphere and caused important changes to air temperature.¹¹ Other research indicates that snow cover in the Northern Hemisphere and floating ice in the Arctic Ocean has decreased.¹² Globally, sea level has risen four to eight inches over the past century¹³ and has accelerated so that now it is rising at approximately one foot per century.¹⁴ Worldwide precipitation over land has increased and the frequency of extreme rainfall events has increased throughout much of the United States.¹⁵ Notably, models predict that had no human effect been forced on global climate, solar and volcanic processes likely would have produced global *cooling* over the same period in which we have witnessed global warming.

Researchers report a number of ecological changes have already occurred in the United States over the past century paralleled by increases in average U.S. temperature and changes in precipitation. Warmer temperatures have resulted in longer growing seasons at the national level, altered carbon cycling and storage in the Alaskan tundra, and increased frequency of fires and other disturbances in U.S. forests.¹⁶ Biologists report individual species such as Edith's Checkerspot Butterfly and the Red Fox have shifted north or to higher altitudes. Other species including Mexican Jays and Tree Swallows have experienced changes in the timing of reproduction, as have plants such as Forest Phlox and Butterfly Weed.¹⁷ While these changes illustrate efforts by species to adapt to a warming climate, these responses may alter competition and predator-prey relationships and have other unforeseen consequences.

Scientists hypothesize that changes in natural systems will continue and become even more apparent in the future, potentially resulting in degradation and loss of global biodiversity. With continued and more severe changes in the climate, the ability of wildlife to adapt through migration and physiological change will be increasingly limited. Furthermore, as species migrate with changing climate and adapt to new environments, animals will begin competing for habitat, potentially threatening the long-term survival of newly resident species as well as long-time inhabitants. The challenge is even greater when considered along with the broad range of other environmental threats currently affecting wildlife, such as habitat loss, environmental contamination, and invasive species as widely seen in Hawai'i.

Studies of climate change even suggest that humans began their impact on climate with the domestication of animals and early agriculture over the past 8,000 years.¹⁸ These activities occurred with the very dawn of our civilized communities. They produced sufficient greenhouse gas to prevent the natural decay of climate into the beginnings of a small ice age we would be enduring today because of reduced exposure to solar radiation due to Earth's orbital configuration with the sun. Comparison of the current climate with past episodes of similar climate preserved in ice cores¹⁹ show that concentrations of CO₂ started rising about 8,000 years ago, despite indications that natural trends should have been dropping. By about 5,000 years ago the same thing happened to methane, correlating to the expansion of rice agriculture (requiring wetland production). Without these unexpected increases, present-day temperatures in northern portions of North America and Europe would be cooler by five to seven degrees Fahrenheit; enough to threaten agriculture. Amazingly, a budding ice age, marked by the appearance of small ice caps in parts of northeastern Canada, would probably have begun several thousand years ago. Instead Earth's climate has remained relatively warm and stable in recent millennia because of the role of human agriculture. Where climate has been irregular, such as the "Little Ice Age", correlations to plague and other population lowering events further strengthen the link to land-use practices.²⁰



Simulating surface temperature using mathematical models (blue=natural factors only; red=natural and human factors combined), and comparing the results to measured changes (observations of temperature change=black line), can provide insight into causes of major changes. The simulations represented by the blue band were produced with only natural factors: solar variation and volcanic activity. Those shown in red were produced with anthropogenic factors: greenhouse gases and an estimate of sulphate aerosols combined with the natural factors. The red band shows that anthropogenic factors combined with natural factors best account for observed temperature changes.²¹

Climate Change in Hawai‘i

The U.S. Global Change Research Program studied the impacts of global change on U.S. islands in the Caribbean and Pacific. They list four areas of greatest concern: freshwater resources, public health and safety, ecosystems and biodiversity, and sea-level variability.²²



Generalized El Niño Predictions for the Pacific: Australia: dry with drought conditions in some locations; Cook Islands: dry conditions and possible drought; Fiji: lower than usual rainfall, threat of tropical storms/cyclones; Hawai‘i: dry, some colder-than-usual temperatures, high-surf conditions and coastal erosion; Kiribati: higher than normal rainfall; Micronesia: drought conditions in many locations, threat of tropical storms in Marshalls, FSM, Guam and Commonwealth of the Northern Marianas with coastal erosion and interior mudslides during storms; Papua New Guinea: lower than normal rainfall, drought in some provinces; Samoa & American Samoa: lower than average rainfall, threat of tropical storms/cyclones with coastal erosion; Solomon Islands: low rainfall, drought conditions; Tonga: lower than normal rainfall, threat of tropical storms/cyclones; Vanuatu: low rainfall, drought conditions.²³

In general, the report offers descriptions of potential effects that we should worry about, rather than direct observations of impacts or hard conclusions. Presumably, the lack of concrete conclusions will change as we move deeper into the 21st Century and impacts of global warming become more defined. Of course, if we wait until that time before formulating a response to the potential impacts of global warming, it will be too late to prevent the possibility of harmful results.

Among their findings they list the following:

- Pacific islands will possibly be affected by:
 - changes in patterns of natural climate variability (ENSO);
 - changes in the frequency, intensity, and tracks of tropical cyclones²⁴;
 - changes in ocean currents.
- Islands are very likely to experience increasing air and ocean temperatures and changes in sea level (including storm surges and sustained rise).
- Some climate model studies project that El Niño Southern Oscillation extremes are likely to increase with increasing greenhouse gas concentrations. Some models suggest more persistent El Niño-like conditions across the Pacific. This would lead to a reduction of fresh water resources in areas of the western Pacific, Micronesia, and the southwest tropical Pacific.
- The number of intense storms (hurricanes, typhoons, and heavy rain events) is likely to increase.²⁵ Hurricane wind speeds and rainfall rates are likely to increase with continued warming.²⁶
- There is significant uncertainty about how increasing global temperatures will affect hurricane and typhoon frequency and tracks.
- It is possible that climate change and the resulting sea-level rise will adversely affect water supplies in the future through more frequent droughts, floods, and saltwater intrusion into freshwater lenses.
- In both Caribbean and Pacific regions, a large percentage of people, infrastructure, and economic activities are located near the coast, leading to dense areas of vulnerability. It is possible that the frequency of extreme events may increase over the next few decades to a century thereby increasing the risk to public health and safety.
- Island biodiversity is threatened by invasive non-native plant and animal species, as well as urban expansion, resulting in the highest extinction rates of all regions of the US.
- Coral bleaching associated with El Niño, warming seawater events, and long-term chronic warming of surface waters has become widespread in both the Pacific and Caribbean since the 1990's.
- There is concern for increased extinction rates of mountain species that have limited opportunities for migration, and declines in forests due to floods, droughts, or increased incidence of pests, pathogens, or fire.
- It is possible that increases in the frequency or intensity of hurricanes would generally favor invasive species.
- The unique “cloud forests” located on some islands occupy a narrow geographical and climatological niche. A shift in temperature or precipitation patterns would cause this zone to shift upwards enough to be eliminated.

- Sea-level rise, both long-term and episodic, is already an extremely important issue for many Pacific islands. Sea-level rise results in coastal erosion, inundation, and saltwater intrusion into freshwater lenses and coastal agricultural zones.
- Future sea-level rise, both global and due to episodic events (such as extreme lunar tides, ENSO-related changes, storm surge, and peaks in sea level related to oceanic eddies) will increasingly contribute to negative consequences for island populations and ecosystems.²⁷

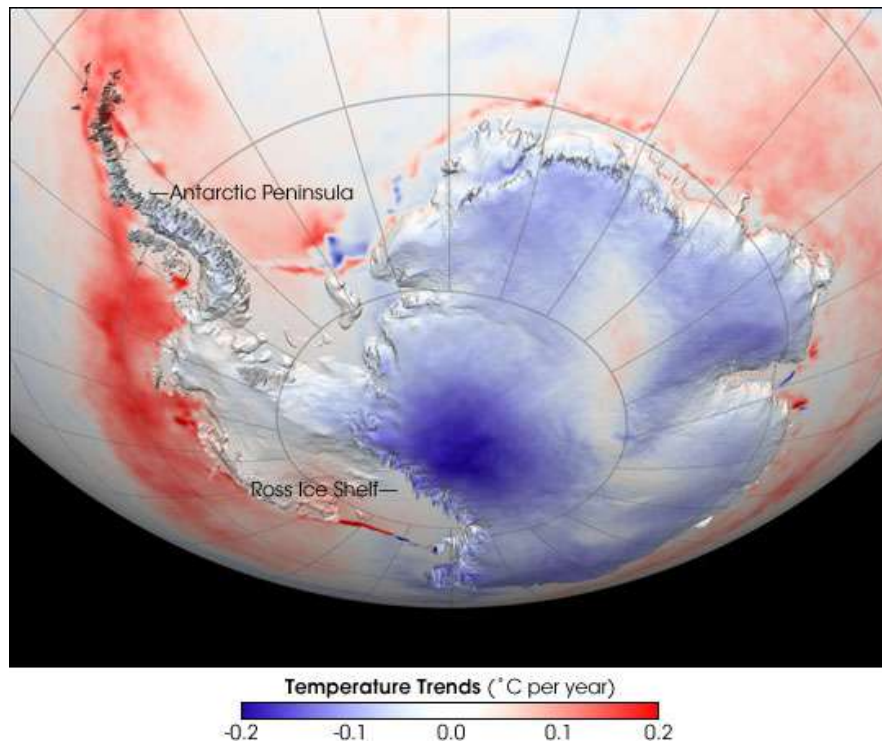
Sea-Level Rise Generally

The level of the sea is the product of several factors. For instance, when rain falls on the ground it may be absorbed into the groundwater system or run off the land into the ocean. Groundwater does not contribute to the volume of water in the oceans but changes in runoff may. In fact, the human activity of building dams on the world's major rivers has changed run-off characteristics such that we have trapped the equivalent of 1.2 inches of global sea-level rise in the world's reservoirs.²⁸ But with the world's major rivers now controlled by dams, this dodge is ended. Since human activities include withdrawing groundwater and discharging it to the sea, impounding runoff in reservoirs, changing seepage characteristics in urbanized watersheds, and otherwise altering natural controls on the water cycle, the result is a minor, but quantifiable, impact on global sea level.

Sea level is also influenced by heat. When the atmosphere heats, as it has in recent decades, the temperature of the upper layer of the ocean absorbs some of the heat. Researchers estimate that thermal expansion of ocean water is responsible for as much as 0.2 inches per decade of sea level rise over the 20th century compared to 0.7 inches per decade in the first decade of the 21st century.²⁹ As it warms, water expands, leading to a rise in sea level.

Heat in the atmosphere also leads to melting of glaciers and sea ice, a decrease in the extent of snow cover, and shifts between rainfall and snowfall. Glacier and snowmelt contribute to sea-level rise, whereas melting sea ice does not because it is already displacing its own weight or mass in the oceans. However, as sea ice retreats, more open water is exposed to absorb heat from the atmosphere and from the sun, further encouraging sea-level rise and contributing to heating of the arctic and Antarctic.

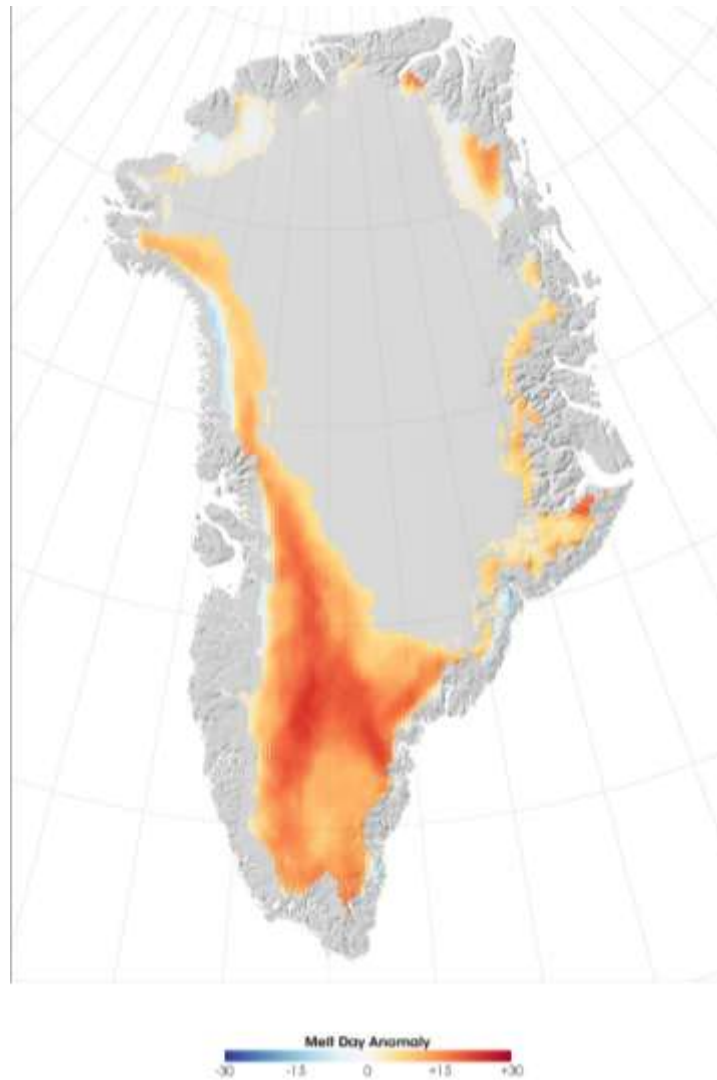
In West Antarctica, ice loss has increased by 59% in the early 21st century to about 132 billion metric tons a year.³⁰ The yearly loss along the Antarctic Peninsula has increased by 140% to sixty billion metric tons. The East Antarctic ice sheet, by far the largest region of the continent, is stable to slightly melting, experiencing melting along the coastal margin in warming seas and net snow accumulation in the hinterlands of the ice sheet. For the entire continent of Antarctica, there is net melting.³¹



The continent of Antarctica is experiencing warming in the area of West Antarctica, the Antarctic Peninsula, and among coastal waters. The region of East Antarctica is stable to slightly melting. Coastal ice sheets are melting due to warm coastal currents.³²

Until recently, the contribution of the Greenland continental glacier to sea-level rise has been unknown. Now, however, increased melting of the Greenland ice sheet has been observed and it is known that the pile of ice is getting smaller. The balance between annual ice gained and lost is in deficit and the deficiency tripled between 1996 and 2007.³³ In Greenland, the year 2007 marked a rise to record levels of the summertime melting trend over the highest altitudes of the Greenland ice sheet. Melting in areas above 6,560 feet rose 150% above the long-term average, with melting occurring on twenty-five to thirty more days in 2007 than the average in the previous nineteen years.³⁴ Scientists have found that glaciers in southern Greenland are flowing 30% to 210% faster than they were ten years ago, and the overall amount of ice discharged into the sea has increased from 5 cubic miles in 1996 to 13 cubic miles in 2005, an increase of 250%.

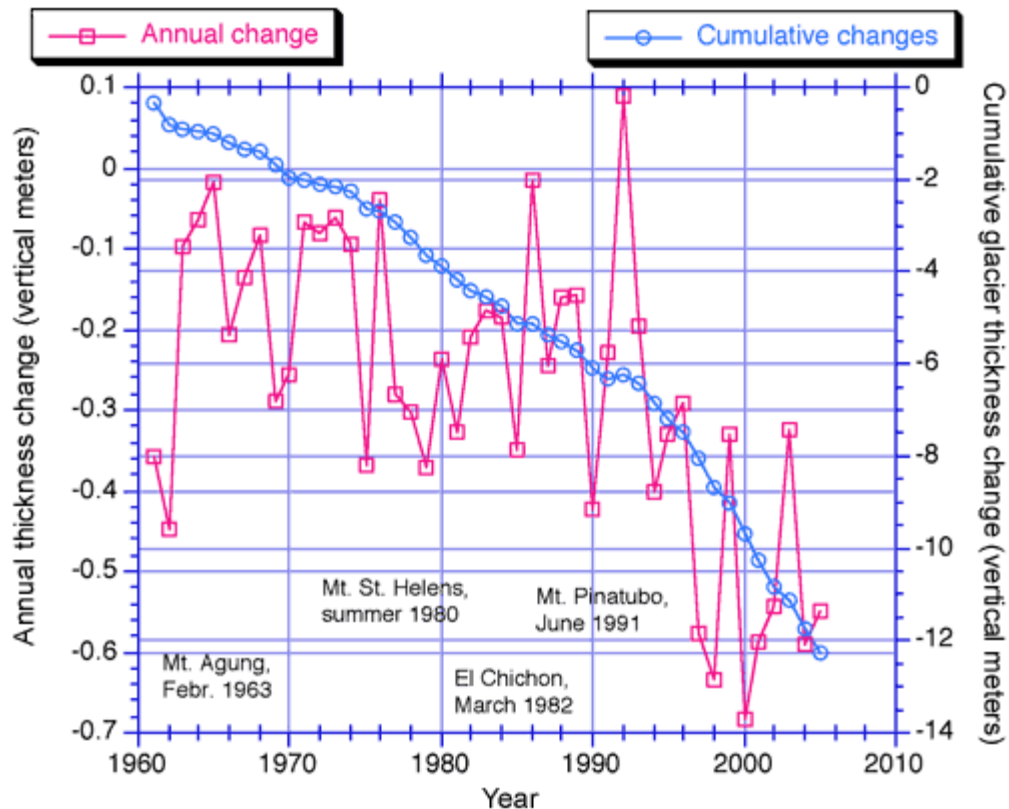
Greenland's contribution to average sea-level rise increased from 0.09 inches per decade in 1996 to 0.2 inches per decade in 2005. This accounts for between 20% and 38% of the observed yearly global sea-level rise.³⁵ Two-thirds of Greenland's sea level contribution is due to glacier dynamics (chunks of ice breaking off and melting), and one-third is from direct melting of ice. As glacier acceleration continues to spread northward from its current focus in southern Greenland, the global sea-level rise contribution from the world's largest island will continue to increase.



This map shows the Greenland melt anomaly, measured as the difference between the number of days on which melting occurred in 2007 compared to the average annual melting days from 1988-2006. The areas with the highest amounts of additional melt days appear in red, and areas with below-average melt days appear in blue. Although faint streaks of blue appear along the coastlines, namely in northwestern and southeastern Greenland, red and orange predominate, especially in the south.³⁶

Alpine and other types of mountain glaciers are also retreating. In fact for the millions of people in communities that depend on seasonal ice melting as a source of freshwater (such as Los Angeles and San Francisco), the retreat and eventual loss of these ice centers delivers a fundamental blow to the sustainability of urban neighborhoods. Mountain glaciers are retreating in every mountainous region of the planet and the cumulative mean thickness change has accelerated from about -6 to -13 feet in 1965 to 1970 to about -40 to -46 feet of change in the first decade of the 21st century.³⁷

Global Glacier Thickness Change



This shows average annual and cumulative alpine (mountain) glacier thickness change, measured in vertical meters, for the period 1961 to 2005. These results indicate that, in most regions of the world, glaciers are shrinking in mass. From 1961 to 2005, the thickness of "small" glaciers decreased approximately 12 meters, or the equivalent of more than 9,000 cubic kilometers of water.³⁸

Tide gauge data show that global average sea level rose between four and eight inches during the 20th century. But satellites that have been mapping the ocean surface for over 15 years have recorded accelerations in the rate of sea-level rise. The latest sea level research³⁹ shows an average increase in global mean sea level over *twelve inches per century from 1993-2008* (approximately 0.12 in/yr). This rate is more than fifty percent greater than the average rate of the last fifty years.⁴⁰

According to scientists from the National Snow and Ice Data Center in Boulder, ice cover in the Arctic Ocean, long held to be an early warning of a changing climate, shattered the all-time low record in the summer of 2007, and nearly matched it again in 2008. Although melting sea ice does not raise sea level, the loss of reflective sea ice and the increase in heat-absorptive ocean water will cause less sunlight to reflect back into space and more heat to be absorbed into the Arctic Ocean. Using satellite imagery, researchers now estimate that the summer Arctic ice pack covers 1.63 million square miles, equal to just less than half the size of the United States.⁴¹ This figure is about twenty percent less than the previous all-time low record of 2.05 million square miles set in September 2005.⁴² Scientists describe the loss as "astounding," the most dramatic

loss observed in the history of watching the arctic ice pack. Most researchers had anticipated the complete disappearance of the Arctic ice pack during summer months after the year 2070, but now they speculate that losing summer ice cover by 2030 – or even earlier – is not unreasonable.⁴³ Thus the stage is set for what scientists refer to as an “albedo flip.” Albedo is a measure of the reflectivity of Earth’s surface. That is, the former reflecting ice surface will become a strongly heat-absorbing body of water.

Past Sea Levels

Sea level has changed throughout Earth history and the past 130,000 years or so have seen especially dramatic changes. Because of an irregular pattern in Earth’s orbit around the Sun (known as *Milankovitch Cycles*⁴⁴), the amount of sunlight hitting our planet varies over time. These variations force Earth to experience times of reduced solar heating leading to cold spells including ice ages (“glacials”) where sea level was as much as 400 feet lower than today, and times of enhanced solar heating producing warm periods (“interglacials”) where sea levels are high including the interglacial we have enjoyed the past 10,000 years or so.

It is somewhat mysterious why the present interglacial has continued to be warm when the maximum solar radiation hitting the planet peaked 12,000 years ago and has since declined. As mentioned earlier, one intriguing hypothesis holds that early human farming activity altered natural patterns of carbon storage and produced an enhanced greenhouse effect beginning thousands of years ago.⁴⁵ For instance, clearing and burning of forested land by Neolithic cultures resulted in excess amounts of carbon dioxide entering the atmosphere and potentially tipping climate toward a warmer world. Likewise, farming of rice (wetland creation) in Southeast Asia and domestication of farm animals released excess methane in the earliest days of civilization. Methane and carbon dioxide are two of the most powerful greenhouse gases and may have prevented Earth from sliding into a cooling phase foreshadowed by natural decreases in solar insolation. In support of this idea is a record of human plagues, which decrease global population and allow cleared lands to reforest. The drawdown of atmospheric carbon dioxide this causes correlates to climatic coolings, such as the Little Ice Age, that characterize the past several thousand years. If this hypothesis is true, humans have been controlling climate much longer than we thought.

However, because of Milankovitch Cycles, today’s warmth has been seen before. In the last interglacial, which may have lasted over 20,000 years between 136,000 and 115,000 years ago, temperatures are thought to have been one or two degrees warmer than present and sea level as much as ten to twenty feet higher.⁴⁶ Notably, rates of sea-level rise may have reached five feet per century, perhaps prophesying the flooding that is to come later this century⁴⁷. Hawai‘i, and especially O‘ahu, contains a geologic record of the last interglacial sea level in the rock formation known among geologists as the “Waimanalo Limestone.”⁴⁸ This is found composing Popoia Island in Kailua Bay, along the rock shorelines of the Ewa Plain and the Waianae coast, and ringing the ocean along the north shore of Mokuleia on the way to Kaena Point.⁴⁹ This limestone unit is actually a fossil reef dating to the last interglacial and it contains fossilized coral heads, communities of molluscs and other invertebrates, and ancient algae. Studies of these same rocks and similar ones on Bermuda and the Caribbean have fueled the study of the last interglacial period.



The rock shores of Oahu preserve a record of high sea levels and warmer seas from the last interglacial period ca. 125,000 years ago.

Where did the high sea levels of the previous warm period come from? For years paleoclimatologists thought that only the West Antarctic ice sheet was large and unstable enough to raise global sea levels by such alarming magnitudes in the timeframe of a last interglacial. However, when scientists reconstructed the evolution of the Greenland ice sheet by combining numerical modeling with insights obtained from central Greenland ice-cores, they discovered that it was considerably smaller and steeper during the last interglacial, and plausibly contributed thirteen to eighteen feet to global sea-level.⁵⁰ They concluded that the high sea level during the last interglacial period most probably included a large contribution from Greenland meltwater and therefore should not be interpreted as evidence for a significant reduction of the West Antarctic ice sheet.

This finding suggests a major worry as a modern industrialized society threatened by sea-level rise this century should be focused on Greenland as an important contributor to the volume of the oceans⁵¹. This is especially worrisome as research has revealed that the Greenland ice sheet responds rapidly to changes in atmospheric temperature in the North Atlantic and Arctic⁵².

The last ice age peaked about 21,000 years ago. Ice ages and warm periods in recent geologic time are related to regular variations in Earth's orbit around the sun that determine the amount of heat the planet receives (the afore mentioned Milankovitch Cycles). In the transition to the present warm period, sea level rose rapidly between 15,000 and 6,000 years ago at an average rate of 0.4 in/yr. Based on geological data among Pacific islands, by 5,000 years ago sea level reached and then passed its present position rising a few feet above present.⁵³

Fossil shorelines around Polynesia indicate that the oceans flooded coastal regions between 5,000 and about 2,000 years ago. By the time the first discoverers stepped foot on Hawaiian shores (ca. 1,500 yrs ago), sea level was falling below this height and sandy coastal plains were

widening onto the newly opened sea floor. Although exact patterns are unclear, the period between approximately 2,000 and 500 years ago was characterized by a falling sea level among the islands of Oceania.⁵⁴ This time marked the exposure of many low-lying sandy coastal plains that became important Hawaiian community sites, including on Oahu: Waimanalo, Kailua, Waikiki, Kahana, Kaena, and elsewhere.

Sea level ceased falling a few centuries ago and has since been rising around the world. Local evidence of this rise in sea level, and the coastal erosion it engendered, is found in the form of stranded fossil beach ridges of sandstone in the shallow waters on many fringing reefs around Oahu.

Projected Sea Level Changes to 2100

The Intergovernmental Panel on Climate Change has predicted future sea-level changes to the year 2100.⁵⁵ They are not the first body to attempt this important exercise, nor are their latest results their first attempt. The latest IPCC estimate in 2007 forecast a range of global sea-level rise from seven to twenty-three inches by the end of this century. However, these projections are based on thermal expansion alone and do not include any component based on ice sheet behavior. Hence, they are widely understood to underestimate the potential for flooding due to rising seas by the end of the century.⁵⁶

Two studies published in 2007, both by German climate researcher Stefan Rahmstorf and colleagues, indicate a more likely scenario of future climate change and sea-level rise. In one study, Rahmstorf compared projections of future atmospheric warming and sea-level rise made in 1990 by the IPCC to observations of the same in 2006.⁵⁷ The results indicate that the climate system, in particular sea level, may be responding to global warming more quickly than models specify. While the observed carbon dioxide concentrations follow the model projections almost exactly, the temperature changes are in the upper part of the range projected by the IPCC; notably, since 1990 the sea level has been rising faster than even the extreme scenarios projected by the models. Rahmstorf found that the rate of rise for the past twenty years is 25% faster than the rate of rise in any twenty-year period in the preceding 115 years. In their conclusion, the authors state “Overall, these observational data underscore the concerns about global climate change. Previous projections, as summarized by IPCC, have not exaggerated but may in some respects even have *underestimated* the change, in particular for sea level.”⁵⁸

In his other paper in 2007, Rahmstorf estimates 21st century sea-level change on the historical relationship between 20th century temperature changes and sea-level changes.⁵⁹ He presents the empirical relationship that connects global sea-level rise to global mean surface temperature and proposes that, for time scales relevant to global warming, the rate of sea-level rise is roughly proportional to the magnitude of warming above the temperatures of the pre-Industrial Age. The study establishes a proportionality constant of 1.3 inches of sea-level rise per decade per 1.8°F of global temperature warming. When applied to future warming scenarios of the Intergovernmental Panel on Climate Change, this relationship results in a projected sea-level rise in 2100 of 1.6 to 4.6 feet above the 1990 level. On the basis of Rahmstorf’s research, and the documented accelerations in melting of both the Greenland and Antarctic ice sheets, many scientists find it highly likely that a sea level of approximately 3.3 feet (1 m) above present will be reached by the end of the 21st century.⁶⁰

This estimate is confirmed by a paper published in *Science* in 2008 that examines the physics of ice melting and thermal expansion of the seas. Authors conclude a most likely sea level scenario by the end of the century of 0.8 to 2.0 m with an emphasis on the lower area of this range.⁶¹ Clearly, a 1.0 m (3.3 ft) sea level rise is the best planning target for local coastal zone managers that can be offered today.

If greenhouse gas concentrations were stabilized today, sea level would nonetheless continue to rise for hundreds of years. After 500 years, sea-level rise from thermal expansion may have reached only half of its eventual level, which models suggest may lie within ranges of 1.6 to 6.5 feet. Glacier retreat will continue and the loss of a substantial fraction of Earth's total glacier mass is likely. Areas that are currently marginally glaciated are likely to become ice-free.⁶²

But it is unlikely that greenhouse gases will be stabilized soon, so we can probably count on additional atmospheric heating – and sea-level rise. Research published in the journal *Science* on March 24, 2006, proposed that Earth's warming temperatures may be on track to melt the Greenland and Antarctic ice sheets sooner than previously thought and ultimately lead to a global sea-level rise of at least twenty feet.⁶³ This is a number for another century, and another generation. They found that if the current warming trends continue, by 2100 Earth will likely be at least four degrees Fahrenheit warmer than present, with the Arctic at least as warm as it was nearly 130,000 years ago when the Greenland ice sheet was a mere fragment of its present size⁶⁴.

"This is a real eye-opener set of results," said study co-author Jonathan T. Overpeck of the University of Arizona in Tucson.⁶⁵ "The last time the Arctic was significantly warmer than present day, the Greenland Ice Sheet melted back the equivalent of about six to ten feet (two to three meters) of sea level." The research also suggests the Antarctic ice sheet melted substantially, contributing another six to ten feet (two to three meters) of sea-level rise. The ice sheets are melting already. The new research suggests the melting could accelerate, thereby raising sea level as fast, or faster, than 3.3 feet (one meter or forty inches) per century.

Scientific Reticence and Sea-Level Rise.

Global warming and its consequences present new challenges to modern society. Among these is a degree of uncertainty among scientists about how to communicate the dramatic environmental changes that may be in store. For example, in 2007 James Hansen of the NASA Goddard Institute for Space Studies published a paper about *scientific reticence* in *Environmental Research Letters*, an on-line science journal open to the public⁶⁶. He proposed that normally quite articulate scientists were reluctant to communicate the full threat of potentially large and damaging future sea-level rise out of a misplaced sense of scientific conservatism.

Reticence, he argues, prevents researchers from expressing their full understanding of the implications of global warming on human communities. He expresses the opinion that professional reserve and cautious judgment may be hindering the ability of society to recognize and respond to the signs of catastrophic future sea-level rise. This may lead to unnecessary future expense, damage, and even threats to public safety. In the words of the author "We may rue reticence, if it serves to lock in future disasters." He describes how a scientist who has made an important discovery may have concerns about the danger of 'crying wolf' and that this danger is more immediate in his mind than concern about the danger of 'fiddling while Rome burns'. He

cites studies of human behavior that show a preference for immediate over delayed rewards, which may contribute to irrational reticence even among rational scientists.

As reviewed earlier, the basis for catastrophic sea-level rise is compelling. Global sea level has accelerated, it is clearly responding to global warming of the atmosphere, and several studies converge on the likely reality that a 1 m rise by the end of this century is imminent. Most major cities of the world are located along coastlines because they were founded during the era of shipping. Low coastal lands often have average elevations less than 5 m and with population growth communities have expanded into the lowest-lying exposed portions of these areas, in many cases within 1 m of mean sea level. In Hawaii, tens of thousands of people make their homes and conduct their businesses in this vulnerable area threatened by sea-level rise. While scientific reticence may provide a safe alternative for the individual scientist, it threatens catastrophe on an uninformed public.

Higher Sea Levels in Hawai'i

In Hawai'i, sea-level rise is a particular concern. Riding on the rising water are high waves, hurricanes, and tsunami that will be able to penetrate further inland with every fraction of rising tide. The physical effects of sea-level rise fall into five categories. These are:

- Marine inundation of low-lying developed areas including coastal roads,
- Erosion of beaches and bluffs,
- Salt intrusion into ground water and surface ecosystems (including taro farming),
- Higher water tables, and
- Increased flooding and storm damage due to heavy rainfall.

At present, the potential range of impacts from any of these five has not been assessed in Hawai'i. This is because, until recently, estimates of future sea-level position continued to change on the international scientific stage and, it had been thought, until these centered on a widely agreed upon value, efforts gained by an exhaustive study are vulnerable to going quickly out of date. Now, however, studies reviewed above suggest that a rise of one meter (3.3 ft) is likely toward the end of this century. It must be recognized that the impacts of sea-level rise within our lifetime in Hawai'i are going to be significant and may lead to irreversible effects.

If a sea-level planning scenario were to be undertaken, a one meter threshold would be very appropriate and presently supportable from a scientific point of view. Whether this rise is reached in 50 years, or 100 years is somewhat irrelevant. The scenario will be achieved in any case and the potential impacts of that trend need to be examined sooner rather than later.

As the ocean continues to rise, natural flooding occurs in low-lying regions during rains because storm sewers back up with saltwater, coastal erosion accelerates on our precious beaches, and critical highways shut down due to marine flooding. The Mapunapuna industrial district of Honolulu adjacent to the airport is a good example. If heavy rains fall during monthly highest tides, portions of the region flood waist deep because storm drains are backed up with high ocean water. The undercarriages of trucks suffer a rust problem because floodwaters become salty at high tide. Even when it does not rain, portions of the area flood with salt water

as it surges up the storm drain into the streets and local workers report seeing baby hammerhead sharks in the two foot-deep pools.⁶⁷

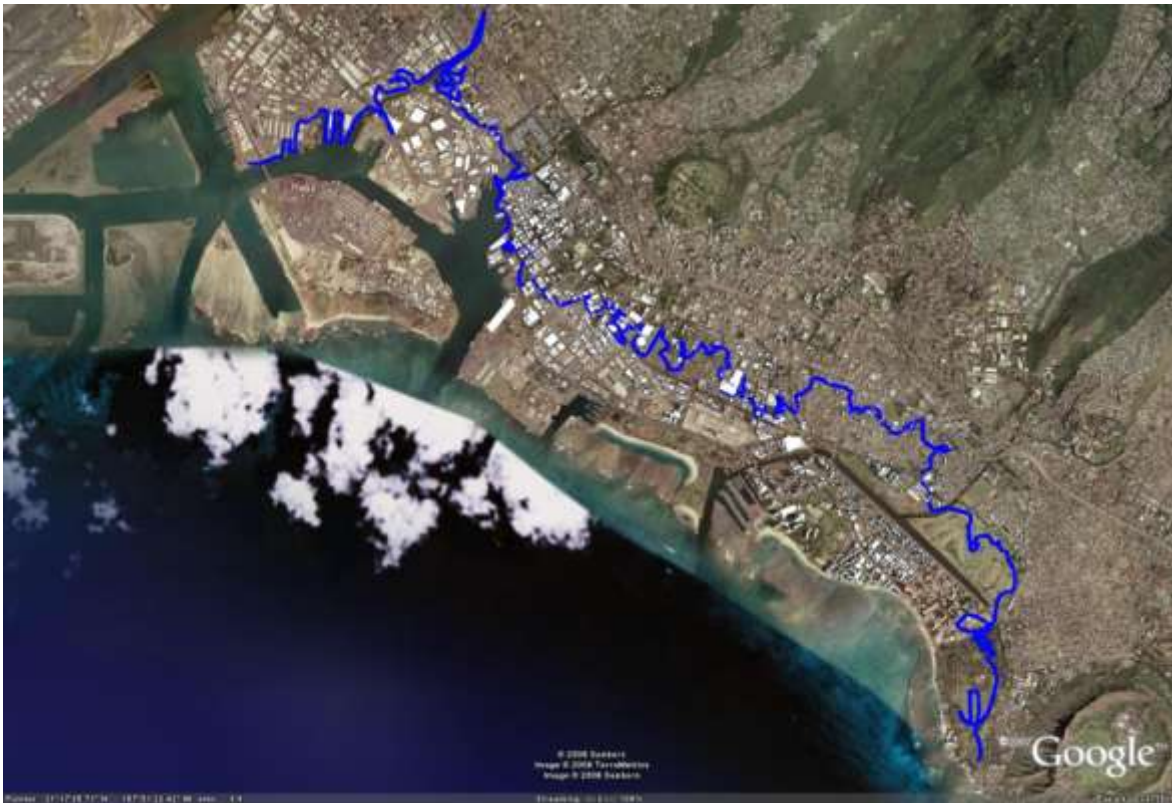
Signs of sea-level rise effects are widespread throughout the state. Not a year passes without some coastal roadways suffering temporary closure as high swell washes across them. These events prevent people from getting to work, to school, and from bringing emergency vehicles to those in need. If it has not happened already, it will not be long before someone's life is threatened because an ambulance or fire truck fails to render timely assistance because the road has been closed due to high waves. While the waves themselves are the apparent culprit, the operator behind the scene is several centuries of rising sea level that brings the oceans onto our coastal highways as well as the poor location of the infrastructure in the first place.

Another widespread sign of sea-level rise is the chronic erosion plaguing many sandy beaches in Hawai'i. A beach is an accumulation of sand on the coast and any action that impacts sand availability has the potential to cause erosion. This can include engineering structures that impede currents and waves that move sand, as well as seawalls that impound dune sand that would otherwise contribute to beach stability. A history of sand mining among the coastal dunes and beaches of Hawai'i contributes to the erosion problem, as does the over-fishing of species that make sand on the reef. But as bad as these problems are, it is the rising level of the oceans that unifies and extends these different effects and ultimately leads to extensive beach loss throughout Hawai'i and the world.

As unpredictable hazards such as hurricanes, heavy rains, high swell, and tsunamis continue to visit the islands, it would be wise to incorporate the impacts and uncertainties of sea-level rise into the planning and development of our coastal zone. We should not ignore nature by hoping that these hazards will not re-occur and that sea-level rise will stop. The question of *how* we live with them, and *if* we will reduce the likelihood of natural hazards becoming catastrophes, rests in our hands.

Using sensitive topographic data collected by a laser in the fuselage of an airplane, it is possible to map the contour line marking one meter above present day high tide in O'ahu. This "blue line" identifies the portion of our communities that will fall below high tide when seas reach the 1 m (3.3 ft) mark later in the century. This dramatic map has roughly 30 cm (12 in) accuracy. Those lands that border the ocean are highly vulnerable to inundation by seawater during high waves, storms, tsunami, and extreme water levels. Hotel basements will be flooded, ground floors will be splashed by wave run-up, and seawater will come out the storm drains on most of the streets in Waikīkī and along Ala Moana Boulevard. However, don't think that waves will be rolling down the streets and reaching the blue line. More likely, lands lying below sea level in the future will be temporarily dry at low tide and during arid summers. But they will have high water tables, standing pools of rainwater, and backed up storm drains when it rains and tides are high.

Beaches will be gone and we'll have built large seawalls lining most of our shores. Despite the wet conditions, most of the buildings will probably still be inhabited and residents will have to time their movement between the tides, just as they do today in Mapunapuna. In the McCully and Makiki areas residents won't see any seawater; instead they will see the wetlands of the 19th century reemerging as the water table rises above ground level in some areas.



The blue line marks the contour of high tide when sea level is 40 inches (1 m) above present. Lands makai of the line identify communities that are highly vulnerable to coastal hazards. These represent targets for redevelopment to increase resiliency following natural hazards.
[2 pg spread]

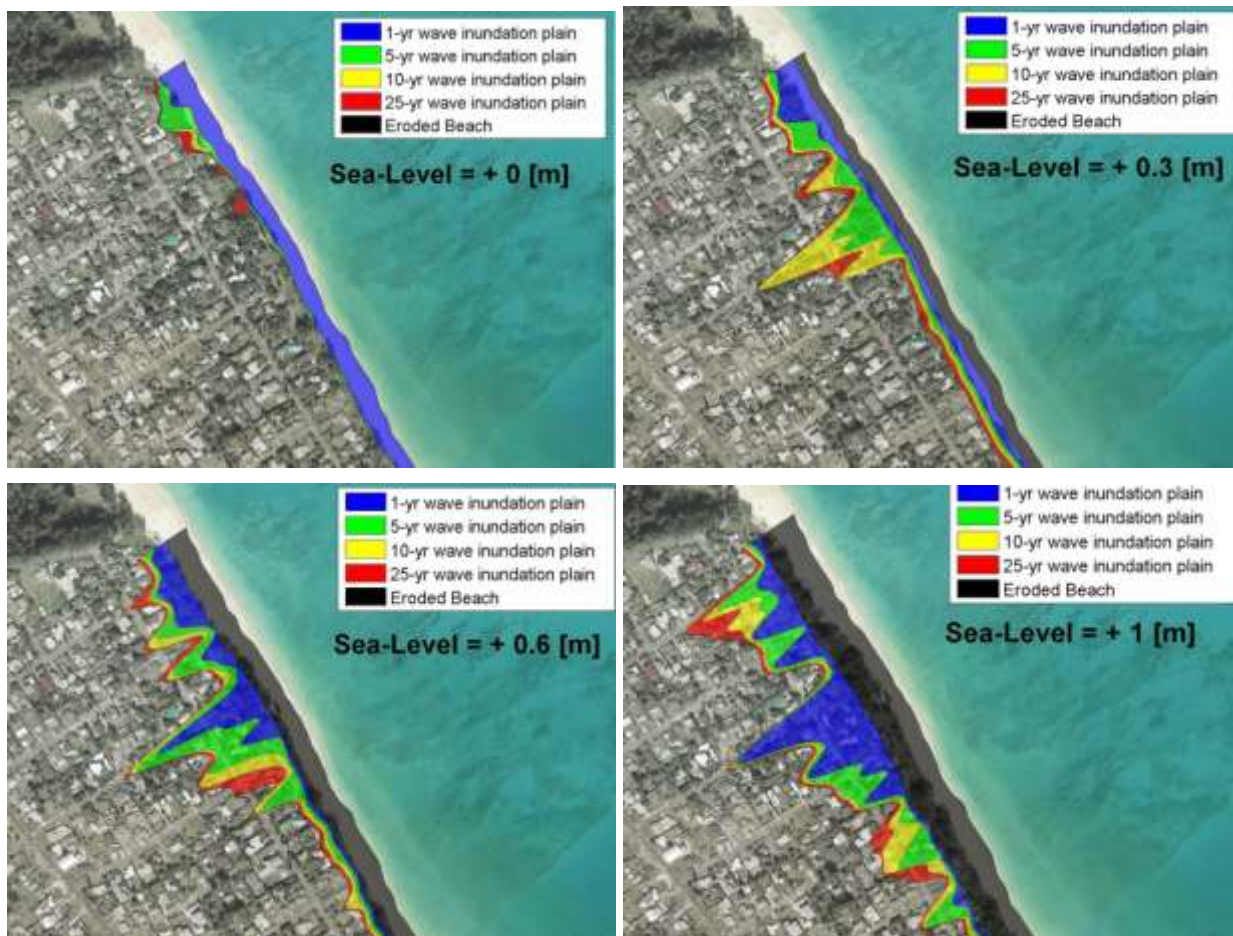
How to Respond?

How should we confront sea-level rise before it overwhelms our ability to adapt? Researchers should first map the blue line for the entire state. Second, between the coast and the blue line scientists need to exactly map and model the water table throughout the urban corridor in the vulnerable area. The water table should be instrumented and monitored with gauges the same way we monitor the sea level with tide gauges today. As we learn how the water table rises and falls with the tides, large waves, and rainfall, we will be able to more accurately map regions that are vulnerable to flooding from rising sea level in coming decades. In some areas the water table will crop out (break the ground surface) sooner than others and these are the places where planners and landowners need to focus a redevelopment and retreat strategy. By mapping the behavior of the water table it will become apparent which lands are most, and first, vulnerable, and which are least.

Researchers also need to develop an improved ability to predict what lands will be overtopped by high waves. The system of buoys that surrounds the islands provides us with an early warning of large waves arriving on our shores. Waves arrive in Hawaii from all directions of the compass. North swell arrive in the winter, south swell arrive in the summer, and trade wind waves and Kona storm-generated waves may arrive any time of the year. Hurricanes (see Chapter 11) are most likely in Hawaii in late summer and through the fall. All coastlines in Hawaii are vulnerable to wave overtopping. With several days advance notice, it is possible for

road crews to get outfitted, homeowners to shore up their homes, and communities to prepare for the high run-up of waves on eroded beaches and low roadways. By using combinations of wave run-up models, detailed topography of coastal lands, and knowledge of arriving waves, the disruption to our lives caused by these events can be predicted, and prediction is the first step to mitigation.

An additional step that will be important for coastal communities is to identify which of our beaches we value to the point of conserving them into the end of the century. Most of our beaches are lined by development in the form of roadways, housing tracts, and even urban corridors and business districts. As sea levels rise, these beaches will seek new sand sources and eroding coastal lands that are sand-rich will be a major source. If however, these lands are developed, history has taught us that, in Hawaii at least, sea walls will materialize and impound potential new sand sources.⁶⁸ These will slowly wipe-out the last beaches among our islands over the course of the century. In the next chapter we discuss this problem, and some potential tools to help manage it.



A simulation of the wave overtopping phenomenon suggests that when sea level rises approximately 0.6 m above present, rare flooding of our low-lying coastal communities will become a frequent event.⁶⁹

A Quiet Threat

The insidious thing about sea-level rise is its silence. Buried beneath the more obvious signals of daily tides, massive waves, storms and riptides, a couple tenths of an inch of sea-level rise in a year is not noticed. We see the ocean every day and over our lifetimes it appears the same. But this casual acceptance belies the truth. Episodes of high sea level are already hitting the Hawai'i coastline with a hidden one-two punch that we ultimately feel in our bank accounts and in the loss of our favorite shores. Take the following case study that happened on the Maui coast in late summer 2003.

The tides in Hawai'i are not large on a global scale. They range two feet or so between the daily high and low, and twice a month they reach up to 2.5 to three feet as the Sun, moon, and Earth align. In the heat of late summer they swell with the warm water and extend a few more inches upward. Bring in a summer swell event and the physics of the huge waves push seawater against the coast raising average sea-level position higher by an additional foot or so. Combine the effects of swell energy and seasonal heating, throw in the monthly spring high tides, and before you know it, high tide is reaching past the beach and onto our roadways and yards. Most beaches respond to this higher water by narrowing somewhat and experiencing some coastal erosion. As a seasonal event this usually falls within limits that residents of the south shores have learned to wait-out until the calm of the fall and winter.

These were the conditions on Maui's west shore through early summer 2003. But by mid-July something was different. Beaches narrowed as usual, and then wholly disappeared. Sharp cliffs of eroded land appeared on the waters edge. Palm trees, clumps of soil, and entire hedge rows on carefully manicured shorelines fell into the water. Beach paths, showers, and verandas were undermined by the lapping waves and subsided into muddy water. By mid-August it appeared that the erosion front would keep pushing landward into the front lawns and pool decks of hotels and timeshare condominiums. The very foundations of ten story visitor towers appeared vulnerable. Soon visitors and kama'aina alike were confronted with a scene of thousands of sand bags, teams of sweating workers, and noisy construction equipment shoring up the eroding coast.⁷⁰

Desperate pleas cascaded on state and county authorities for permits to install legal armaments to save the land. The state promoted the temporary use of steel plates driven into the sand to stop the onslaught. County planners balked at the jarring image of pile-drivers hammering in broad steel sheets on the delicate beaches. Scientists and engineers were recruited in the quest for answers and solutions. Angry phone calls between and among hotel operators, the mayor, county council members, state and county planners, native Hawaiians denied access to favored beaches, environmental groups, tourists, and timeshare owners crackled across the phone lines throughout the weeks of August and September. And then like magic, one day in October, the seas subsided and sands returned.

In the post-mortem analysis that followed this expensive and chaotic episode, one group of inquisitive specialists turned for an explanation to the tide gauge at Maui's Kahului Harbor. And they found what they were looking for: high sea level.

It turns out that during the spring and summer months of 2003 a series of *extreme tides* migrated through the Hawaiian Islands, culminating with the highest recorded sea levels in state history by late September and October. Considering that these extreme tides extended only two to eight inches above the mean sea-level position and lasted each for a month or two, the drama

of the Maui coast is eye-opening. Not waves, not storms, not currents, but short-lived and quiet, these high water levels plunged our system of coastal management into utter chaos, angry exchanges, and many hundreds of thousands of dollars of crisis spending.

Is the State of Hawai‘i ready to face sea-level rise? In a word, “No”, we flunked the practice drill.

The source of these water levels is an oceanographic phenomenon known as a “mesoscale eddy.” Mesoscale eddies are broad mounds of high water two or three times larger than the Big Island of Hawai‘i. With waters two to ten inches higher than the surrounding sea, these form in the tropical eastern Pacific and migrate toward Hawai‘i with regularity.⁷¹ Four eddies, each larger than the last, migrated through the islands between February and October of 2003. As ocean waters warmed and expanded into the late summer, and sets of large waves from the south arrived as usual throughout the season, the fragile sands of west Maui were stretched to the breaking point. The death blow arrived in the form of a strong eddy that began driving up sea level in late August, persisted throughout September and culminated in the first week of October with an all time high of Hawaiian sea level reaching eight inches above the average water levels of the earlier winter months.

A Coming Calamity

As sea level continues to rise, smaller eddies that previously passed un-noticed through the islands play an increasing role in de-stabilizing our shorelines. In time, extreme tides related to eddies will grow in frequency and magnitude until they become a permanent condition. Not because there will be more eddies. But because minor eddies we never noticed before will have increasingly dramatic impacts. In 2003, we were given a glimpse of our sea-level future. Was anyone watching?

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⁴ NOAA National Climatic Data Center, <http://www.ncdc.noaa.gov/oa/climate/globalwarming.html#q3>

⁵ The IPCC provides authoritative reviews of the state of climate science for national governments throughout the world. A key aspect of its work has been the production of major assessment reports in 1990, 1995, 2001, and 2007. For more information, see <http://www.ipcc.ch/>.

⁶ Climate Science, [2005 Warmest Year in Over a Century](http://www.climatechange.com.au/category/press-releases/press-climate-science/) (Jan. 27, 2006), <http://www.climatechange.com.au/category/press-releases/press-climate-science/>.

⁷ J.E. Hansen et al., [NASA GISS Temperature Analysis](http://cdiac.ornl.gov/trends/temp/hansen/hansen.html), <http://cdiac.ornl.gov/trends/temp/hansen/hansen.html>.

⁸ Temperature Analysis, supra note 7.

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¹¹ 2007 Summation, supra note 2.

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