Climate Change in Hawai'i

Pacific Islands Climate Education Partnership

You may have heard the term **climate change.** What does this term mean? What are the main climate features of Hawai'i? What is happening to the climate on our planet? What impacts of climate change are happening in Hawai'i? How can Hawai'i communities adapt to these impacts?

The purpose of this booklet is to discuss these questions and more.

Most fresh water in Hawai'i orginates with clouds that are produced by the orographic process.

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A. What are weather and climate?

To learn about climate change we need to understand the difference between weather and climate. **Weather** is the *short-term* condition of the **atmosphere** in a specific place, such as where you live. Is it raining today? Where is the wind blowing from and how strong is it blowing? Is the air hot or cool? How cloudy is the sky?

Climate is the *long-term* average weather pattern in a specific place or region. When scientists describe the climate in a place, they use measurements and observations of the weather that have been made over decades. The climate in a place has very big effects on the plants, animals, and people who live there. Ecosystems are especially sensitive as they evolve under a particular climate and when it changes, the ecosystem becomes stressed. If climate changes rapidly, some species may face **extinction**.

Hawai'i has a climate in which the weather patterns change from a wetter season (winter) to a drier season in the summer (**Figure 1**), although it can rain at any time of the year. Other places on our planet have climates where the weather changes significantly over the year. For example, many places have very cold snowy winters and very hot summers.

Weather in Hawai'i

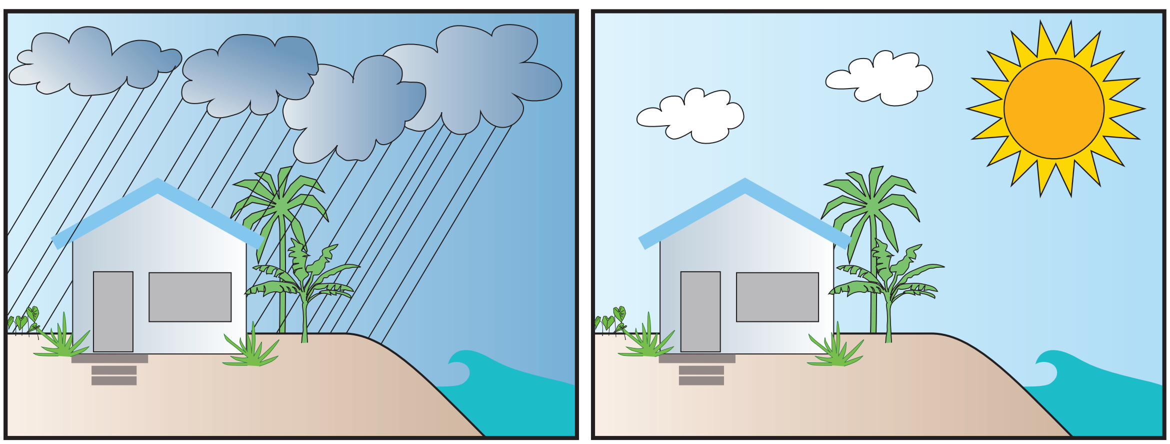


Figure 1 *In Hawai'i, the weather changes from a wetter season (winter) to a drier season (summer). Hawai'i's heaviest rains come from winter storms between October and April.*

Climate describes what kind of weather you can expect to happen. Weather describes what is actually happening. If you visit a place in the wetter season, you should expect that it would be rainy. However, on the days that you visit, the weather could actually be dry. It was probably rainy before you visited, and it will probably become rainy again after you leave.

B. What are the main climate features of Hawai'i?

Hawai'i's location, together with the rain, wind, seasons, and the variability of these, make the unique climate found in the islands. Each of these factors is discussed in detail on the following pages.

I. Location

The climate in Hawai'i is generally warm with windy conditions and lots of water vapor in the air. This is known as high **humidity**. The map (**Figure 2**) shows two factors that play the biggest roles in causing this climate:

- Hawai'i is located in the **tropics**;
- Hawai'i is surrounded by the ocean in all directions

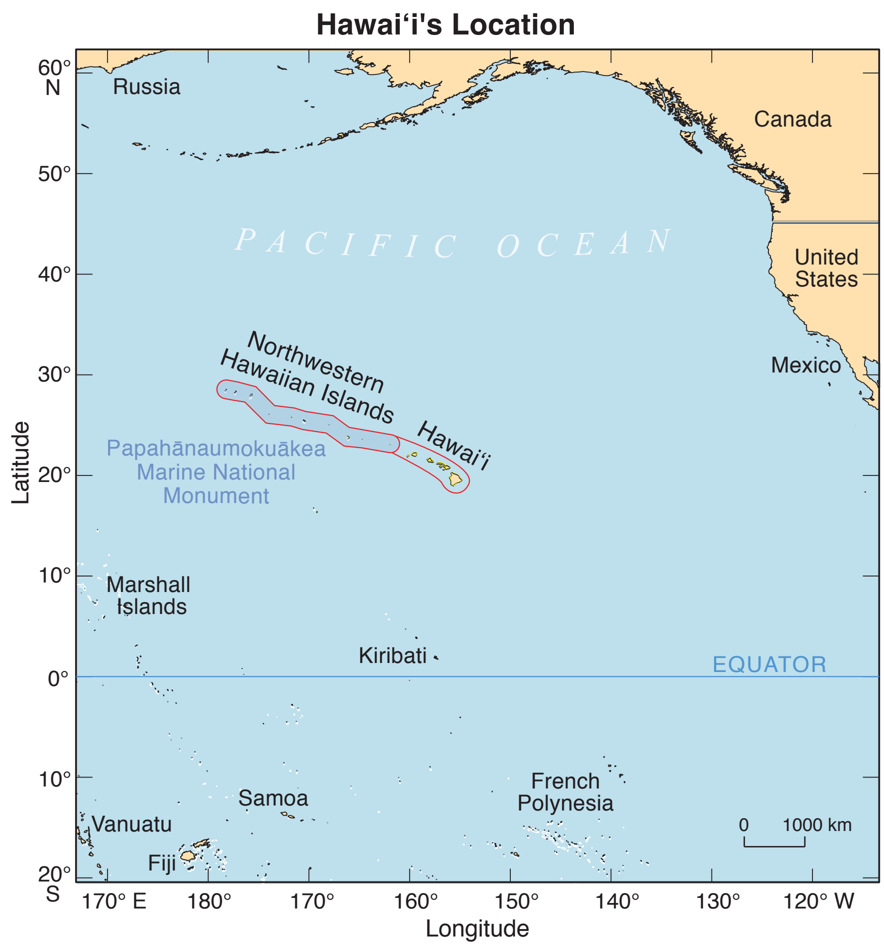


Figure 2 *Hawai'i is located in the tropics of the north central Pacific Ocean.*

Locations in the tropics get a lot more energy from the Sun than places that are farther away from the equator. This location is the main reason that Hawai'i is warm and humid. Temperatures range from daily highs of 85 - 90°F (29 - 32°C) during the summer months to 79 - 83°F (26 - 28°C) during the winter months[1]. Where most people live in Hawai'i (at lower elevations near the ocean), the temperature rarely rises above 90°F (32°C) or drops below 65°F (18°C). However, temperatures are cooler in the mountains at higher elevations. In fact, the three highest mountains (**Figure 3**) of Mauna Kea (13,800 ft, 4,205 m) and Mauna Loa

1 Climate of Hawaii, Wikipedia, 2015. Sanderson, M. (ed.), 1993, Prevailing Trade Winds: Weather and Climate in Hawaii. University of Hawai'i Press, Honolulu, 126pp. http://www.wrcc.dri.edu/narratives/HAWAII.htm

(13,680 ft, 4,170 m) on Hawai'i Island, and Haleakalā (10,023 ft, 3,055 m) on Maui are so high that they can receive snowfall even though they are located in the tropics.

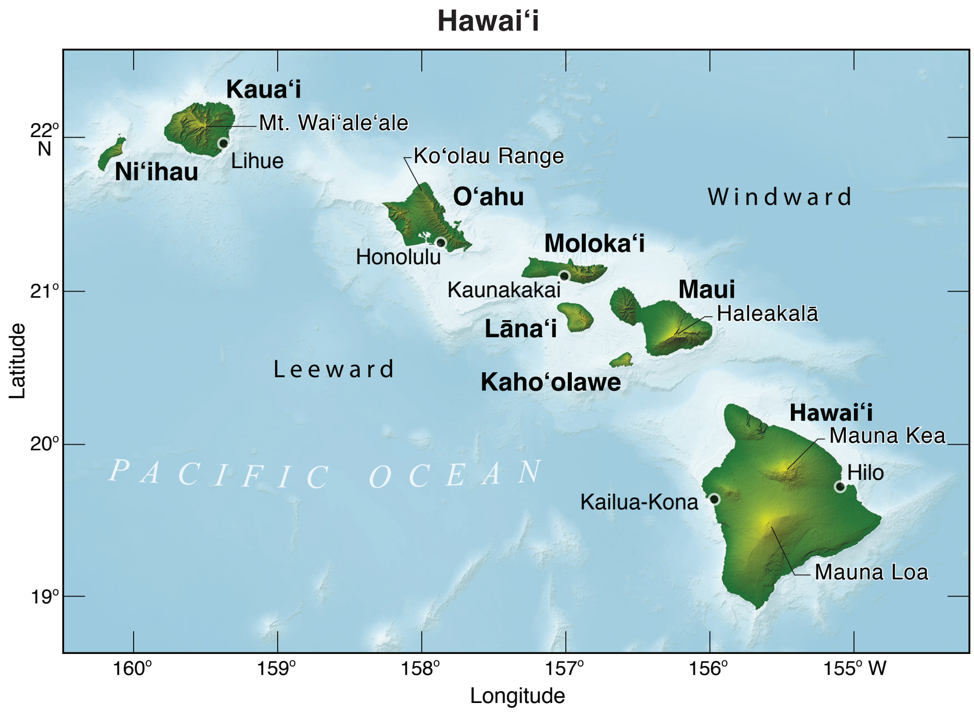


Figure 3 *The Hawaiian Islands are characterized by high rugged topography that is an important factor in determining the weather*

The Hawaiian Islands are made of steep volcanoes that extend into the cold air thousands of feet (hundreds of meters) above **sea level**. The air temperature in Hawai'i depends on your elevation and which side of an island you are on. Locations at high elevations are cooler than locations near sea level. In addition, because the mountains can block the normally windy conditions, windward and leeward sides of the islands can have different air temperatures (and rain patterns).

The ocean surrounding Hawai'i has a large influence on the climate. The average sea surface temperature varies throughout the course of the year by only about 6°F (3.3°C); from a low of about 74°F (23.3°C) between late February and March to a high near 80°F (26.6°C) in late September or early October. This creates a very stable climate that does not change as much as places outside the tropics where temperature can vary by several tens of degrees from one season to the next.

If the islands of Hawai'i did not exist, the average annual rainfall on the ocean surface in this location would be about 25 inches (63.5 centimeters). Instead, the actual average is about 70 inches (178 centimeters). The presence of the islands causes an additional 45 inches (114 centimeters) of rain that otherwise would not fall. The high topography of the volcanic islands is responsible for this added precipitation (see the next section). At Mt. Wai'ale'ale on Kaua'i, the annual average rain measures an extraordinary total of 486 inches (1234 centimeters, or over 40 feet). This is the highest recorded annual average rainfall in the world.

2. Types of Rain and Trade Winds

There are two main kinds of islands in the Pacific Ocean: high islands (such as the eight main Hawaiian Islands) and low islands (such as the atoll islands of Papahānaumokuākea Marine National Monument, and the Marshal Islands). Across the Pacific, communities of people on both kinds of islands have homes, grow food, go fishing, and drink fresh water. The fresh water that they have comes from the type of rain that falls where they are located.

From day to day, there are two common kinds of rain that fall in Hawai'i and other Pacific islands. One kind of rain happens everywhere: over the open ocean, on low islands, and on high islands. This kind of rain happens because warm air rises (a process called **convection**). Above the tropical Pacific Ocean, the rising warm air has so much water vapor in it that the water vapor condenses, and forms low clouds when it reaches the cooler air above it. The condensed water then falls as rain that is called **convective rain** (**Figure 4**).

Convective Rain at Waimānalo, O'ahu

Figure 4 *Convective rain occurs when moist warm air rises and the water vapor condenses, forms low clouds and then precipitates or falls as rain.*

High islands cause a second type of rain. When warm humid air is forced to rise up the slopes of a high island, the cool air it encounters causes the water vapor to condense, making clouds and rain. This is called **orographic rain** (**Figure 5**). Very often, the base of the clouds formed in this manner creates a clear horizon marking the transition where the rate of condensation increases so much that clouds form and rain precipitates.

Orographic Rain at Kualoa, O'ahu

Figure 5 *Orographic rain occurs when warm humid air is forced to rise up the slopes of a high island and the cool temperatures it encounters causes the water vapor to condense, making clouds and rain.*

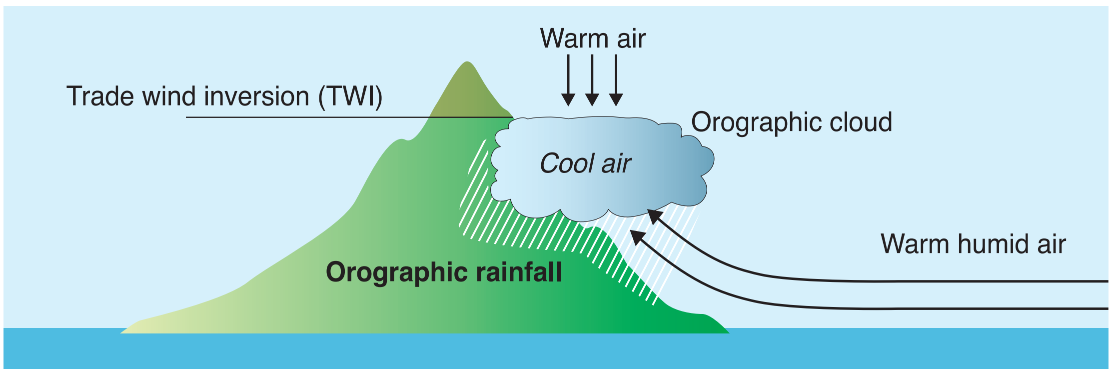
As mentioned earlier, high mountains in Hawai'i get more rain than coastal areas. This is because air is much colder up the slopes of a high mountain compared with the air at sea level. When warm, humid air blowing in from the ocean hits a mountain, that air is forced upward into the colder mountain areas. As the air becomes colder, its water vapor condenses from the gas state into the liquid state, and forms water droplets. These water droplets become clouds, supported by upward rising air currents, from which rain falls on the island.

Low atoll islands, such as found in Papahnaumokuākeā and throughout Micronesia and Polynesia, are usually made of coral sand and gravel. Low islands do not cause humid air to condense because these islands do not have tall topography that extends into the cold air at high elevations. The main source of fresh water on a low island comes from convective rain that moves across the ocean and happens to pass over the island. Both convective rain and orographic rain result from air at higher elevations being cooler, and thereby causing more condensation. The difference is that orographic rain comes from mountains forcing the air to quickly rise, while convective rain results from warm air rising due to being less dense than cold air.

The increase in rainfall that occurs as you climb to higher elevations ends, however, when you reach the **Trade Wind Inversion** (TWI) level (**Figure 6a**). The TWI can be seen as the top of the mountain cloud layer, at typically between 4,000 and 8,000 feet (1219 to 2438 meters) of elevation. The inversion forms when warm dry air from higher in the atmosphere sinks over the Hawaiian Islands and encounters cooling air rising up the slopes of the mountains. This condition of dry warmer air above cooler air causes cloud formation to stop. Conditions above the TWI are very dry and the environment of the highest peaks in Hawai'i, such as on Mauna Kea, Mauna Loa, and Haleakal'i, are **arid** as a result (**Figure 6b**).

Cloud and Rain Formation on High Islands

a.



b.

Figure 6a. *Warm dry air from the upper atmosphere often sinks over the Hawaiian Islands. This air stops the rise of the cooler air that has been forced up the mountain. This phenomenon is called the Trade Wind Inversion (TWI).* **b**. *The tops of these orographic clouds show the position of the TWI on the slopes of Mauna Kea, Hawai'i. Note how dry the land is by the lack of vegetation.*

The TWI is formed by warm air that is carried from the equator by currents high in the atmosphere. This air sinks to the ocean surface in the region around Hawai'i and forms an important belt of wind that blows across the ocean surface called the **trade wind**. The trade wind is discussed in a latter section of this booklet.

The rain and trade winds, combined with Hawai'i's rugged topography, are critical factors in its **hydrologic cycle**. Because the Islands' towering peaks and cliffs form a barrier to the moisture-laden trade winds, as this air rises against the island the falling temperature allows condensation to outpace **evaporation**, forming familiar rain clouds. Thus, among the ridge tops and on the **windward** sides of the islands (the sides facing east or northeast), orographic rain falls from these clouds and runs down the volcanic slopes. Porous, permeable lava and layers of volcanic cinder store the waters that seep underground. Windward slopes and mountainous peaks, lying below the TWI, that face into the trade winds, are the sites of greatest rainfall. These locations recharge underground **aquifers** from which residents draw precious freshwater, and that feed streams that nourish wetlands and lowland taro-agriculture, before eventually flowing into the ocean.

Because most rain falls on the ridges and windward sides of the islands, **leeward** areas tend to be semi-arid or arid. For instance, the annual rainfall averages 20 inches (50 centimeters) and less in leeward coastal areas while at the other extreme the annual average exceeds 300 inches (762 centimeters) along the windward slopes.

3. Seasons and Variability

The weather and climate in Hawai'i have been observed and analyzed since the first arrival of humans, and have been scientifically measured for over a century. Hawai'i experiences several climate patterns, in addition to being generally warm and humid. One of the most important patterns is that during the year there are two seasons, a wetter season that is cooler and a drier season that is warmer.

Native Hawaiians have long recognized these two seasons. **Kau** (May through September) is the fruitful season when the sun is more directly overhead, the weather is warmer, widespread rainstorms are rare, and winds from the northeast and east, the trade winds, are most reliable. **Ho'oilo** (October through April) is the season when the sun is in the south, the weather is cooler, and the trade winds are most often interrupted by other winds (**Table 1**).

Table 1 Seasonal Patterns in Hawai'i

Feature	Kau (May-September)	Ho'oilo (October – April)
Sun position	More directly overhead	To the south
Wind	Persistent trade winds	Intermittent trade winds
Rain	Drier	Wetter
Temperature	Warmer	Cooler

Table 1 *Seasonal climate patterns in Hawai'i.*

In most parts of the tropics, rainfall is highly variable from one year to another and Hawai'i is no exception. **Figure 7** shows the yearly rainfall in inches measured at Honolulu International Airport between the years 1948 and 2014. Note that the amount of rain changes a lot from year to year. Some years had 40 inches (102 centimeters) or more of rain, while other years

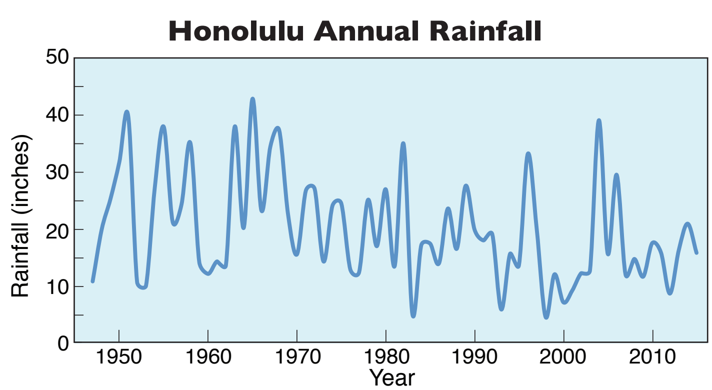


Figure 7 *The amount of rainfall in Hawai'i has a lot of variability from one year to the next.*

had 10 inches (25.4 centimeters) or less of rain. This kind of change in rainfall is also a natural feature of the climate in many Pacific islands that are near the equator. Scientists say that the amount of rainfall has a lot of **variability**[2] (natural change from year to year).

Even in areas of very high rainfall, with monthly averages above 10 inches (25.4 centimeters), the rainfall in any particular month may double or triple from one year to another, and there may be occasional months with only one or two inches (2.5 to 5 centimeters) of rain.

Rainfall variability is far greater during Ho'oilo, when occasional storms may envelop entire islands or parts of islands and contribute appreciably to rainfall totals. For both Hilo and Honolulu, the Ho'oilo variability in January rainfall is about 10 times greater than the Kau variability in August rainfall. Hilo in general tends to get much more rain than Honolulu, but they both have the same seasonal change towards wetter and more variable rain in Ho'oilo compared with Kau.

4. Regional Wind and Rain Patterns

The trade winds are an important aspect of the weather and climate in Hawai'i. They are created at the **North Pacific High**, an area to the northeast of Hawai'i where air that has cooled sinks through the atmosphere onto the ocean surface. When air sinks through the atmosphere, it creates an area of high atmospheric pressure on Earth's surface. This movement creates the trade winds, as the air will flow away from the high pressure toward areas of lower pressure.

The North Pacific High rotates in a clockwise direction (**Figure 8**) creating winds that travel to the west and southwest. These winds become the trade winds that blow across the tropical Pacific region to Micronesia and beyond.

The North Pacific High Creates the Trade Winds

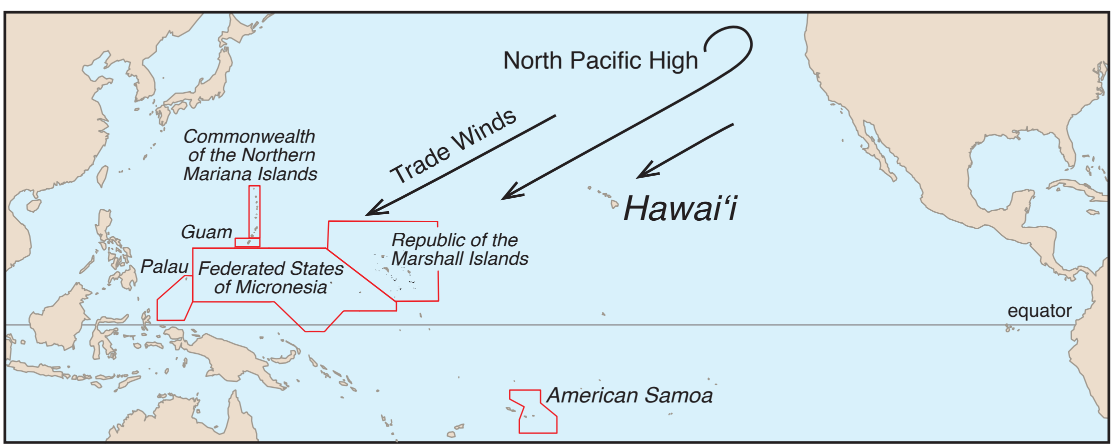


Figure 8 *The North Pacific High is a high-pressure region in the atmosphere that is located to the northeast of Hawaii. Air in the North Pacific High rotates in a clockwise direction making the trade winds that travel outward toward the west and southwest.*

The east to west trade winds play a large role in the climate of the tropical Pacific Ocean, including Hawai'i. These winds can change during a climate pattern called the **El Niño Southern Oscillation**

2 To learn more about climate variability see the PCEP booklet "Pacific Climate Variability" http://pcep.prel.org/resources/pacific-climate-variability/

(ENSO). ENSO is a periodic fluctuation in sea surface temperature across the central and eastern tropical Pacific Ocean, ranging anywhere from 1.8°F to 5.4°F (1°C to 3°C) compared to normal. In addition to significantly affecting the Pacific islands, ENSO has big effects on climate in very distant locations around the world.

There are 3 types of ENSO patterns.

- When the winds are normal it is called a **neutral** year.
- When the trade winds are stronger than normal, scientists call it a **La Niña** year.
- When trade winds are weaker than normal, or absent, scientists say that it is an El Niño year.

Table 2 summarizes the differences between neutral years, El Niño years, and La Niña years.

Table 1 ENSO Conditions and the Effects of ENSO Changes in Hawai'i

Feature	Neutral ENSO Year	El Niño ENSO Year	La Niña ENSO Year
Wind	Normal east to west trade winds	Weaker than normal with occasional westerly winds	Stronger than normal trade winds
Rainfall	Usual amounts of rainfall with normal variability	As El Niño develops there is more rainfall than normal. As El Niño comes to an end, Hawai'i tends to be drier than usual, and can experience drought	Hawai'i may be wetter than usual but this pattern seems to be changing as recent La Niña years have brought less than normal rain
Sea Level	Usual sea level with normal tide variability	Ocean level is near to slightly above normal. High surf on north shores of islands that can cause coastal erosion and flooding	Ocean level may be slightly below normal with normal tide variability

Table 2 *The effects of ENSO conditions in Hawai'i*

In aneutral year (normal conditions), the ocean water around Hawai'i tends to be similar temperature as waters in the central and eastern portions of the Pacific Ocean. Normal levels of evaporation and winds provide for typical amounts of rain that, in the past decade, has trended toward increasing **drought** (an extended period of dry conditions).

In an El Niño year, trade winds are weaker than normal or absent. This allows warm ocean water to migrate away from the western tropical Pacific toward the eastern Pacific Ocean. Sea surface temperatures in Hawai'i are higher than normal and there may be more **tropical cyclones** than usual. In the western and central Pacific (where Hawai'i is located), there may be more rainfall than normal as El Niño conditions grow and develop. But as an El Niño comes to a close, conditions are usually drier and there is a greater chance of drought.

In a La Niña year, Hawai'i tends to experience colder than usual sea surface temperatures. Strong trade winds blow across the ocean surface toward the tropical southwest Pacific. This raises the level of the ocean in that region and can cause **coastal erosion** (land loss due to wave action) and damaging floods during **king tides** (the highest tides of the year) in the Republic of the Marshall Islands, the Federated States of Micronesia, and Republic of Palau. In Hawai'i, sea level position is not strongly affected by ENSO, but rainfall is. La Niña years tend to have more rainfall than normal. However, this appears to be changing as recent La Niña years have brought less than normal rain.

The signature of El Niño and La Niña years is the temperature of the sea surface in the central and eastern Pacific Ocean around the equator. During an El Niño year, the temperature is warmer than average, and during a La Niña year, the temperature is cooler than average (**Figure 9**).

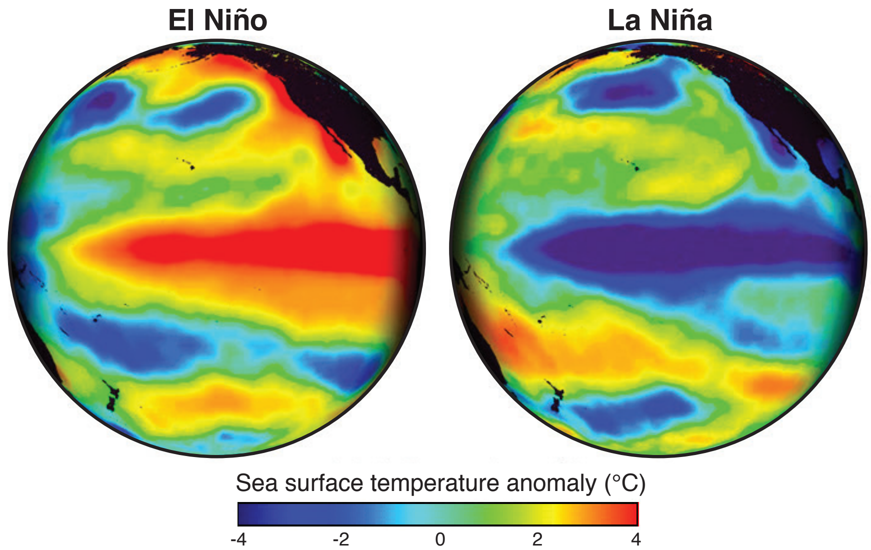


Figure 9 *These maps of the Pacific Ocean show the changing sea surface temperature, relative to the average, during El Niño and La Niña years.*

5. Extreme Weather Events

Extreme weather events are another important climate feature in Hawai'i. An extreme weather event is the kind of weather that can cause a lot of damage and problems for ecosystems and people. The main extreme weather events that happen in Hawai'i are droughts, tropical cyclones, and intense rainstorms.

i. Drought

Despite relatively high annual rainfall amounts in certain locations (Mt. Wai'ale'ale, Kaua'i; Ko'olau Range on O'ahu; and others), Hawai'i suffers the negative effects of drought almost every dry season. Studies[3] in Hawai'i show a declining amount of rainfall over the past century, which has accelerated in the past 3 decades. During drought, wildfires increase, grasslands and certain tree species tend to dry out and defoliate or lose their leaves, stream flow is reduced, and Hawai'i water wells show a decrease in water level.

Ranching, crop irrigation, aquatic ecosystems, and plant communities all experience water-related stress during times of drought. Every three or four years, the drought is especially severe. Droughts typically occur in the drier season months of January through June, especially in the last 6 months or so of an El Niño year.

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3 Giambelluca, T.W., Diaz, H.F., Elison Timm, O., Takahashi, M., Frazier, A.G., and Longman, R. 2011. Regional climate trends in Hawai'i. American Geophysical Union Fall Meeting, San Francisco, December 2011.

During particularly strong El Niño drought, rainfall can decrease during the dry season and the length of the dry season can be extended. The worst recorded drought was in 1998, when Hawai'i received significantly less than the average rainfall. The El Niño in 2015 was strong and the drought in 2016 was severe.

It is not clear how drought will change in the future. Some climate models predict an increase in the strength and frequency of future El Niño conditions, which suggests that drought will increase as well. Models also predict that wet places will get wetter and dry places will get dryer, but that overall, Hawai'i will experience dryer conditions. This poses an adaptation challenge to Hawai'i's water managers and policy makers to develop new water recovery and delivery systems that protect the natural resources of the ahupua'a and ensure people can access water on all inhabited areas of the islands.

ii. Tropical Cyclones

Very strong storms in the equatorial Pacific Ocean region are called "tropical cyclones" (**Figure 10**). Tropical cyclones have strong, damaging wind and very heavy rainfall that leads to flooding. Tropical cyclones that arrive in the Hawaiian Islands usually form off western Mexico and Central America in the warm coastal waters of the eastern Pacific. The hurricane season officially starts on June 1 and extends through November 30. However, the stormiest period generally falls from July through September.

Three Hurricanes Near Hawaii, August, 2015

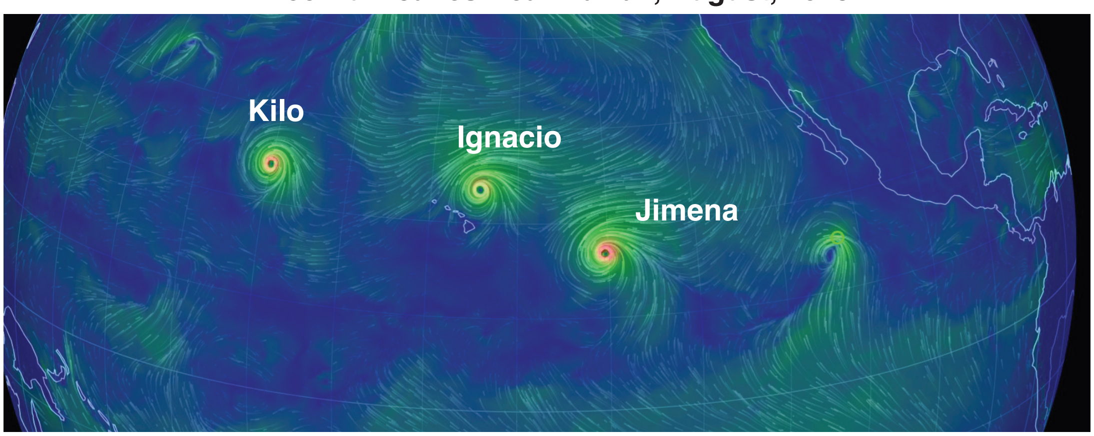

Figure 10 *In late August, 2015 there were 3 hurricanes in the region of Hawai'i: Kilo, Ignacio, and Jimena. The Pacific hurricane season of 2015 set a new record for number of tropical cyclones in a single season – 15.*

Tropical cyclones are classified into 3 types on the basis of their wind speed. The 3 types are as follows:

• **Hurricane**: An intense tropical weather system with a well-defined circulation and sustained winds of 74 miles (119 km) per hour or higher. In the western Pacific, hurricanes are called typhoons; in the Indian Ocean, they are called cyclones.

• **Tropical storm:** An organized system of strong thunderstorms with a defined circulation and maximum sustained winds of 39 to 73 miles (63 to 117 km) per hour.

• **Tropical depression:** An organized system of clouds and thunder storms with defined circulation and maximum sustained winds of 38 miles (61 km) per hour or less.

In Hawaiʻi, although hurricanes have not been historically common, when storms do approach and hit an island the results can be catastrophic. [4] This is largely because Hawaiʻi's communities have not taken sufficient steps to protect themselves, to factor in the potential for violent winds in the design of buildings, to build up and away from potential storm surge, to bury power lines, and to plan for the days to weeks of isolation and power failure that develops immediately after a storm has hit.

Many factors affect the level of tropical cyclone activity from year to year. Chief among them is the state of the El Niño Southern Oscillation in the Pacific. Moderate to strong El Niño years are correlated with increased tropical cyclone activity in the waters around Hawaiʻi and the occurrence of late season storms. Cyclones are least frequent in La Niña years.

During the development of the 2015 El Niño, the Central Pacific around Hawaiʻi experienced a record-setting 15 tropical cyclones, 6 of which reached hurricane strength, but luckily, none of them made landfall among the islands. Scientists[5] have concluded that because of climate change, future El Niño's occurrences will be stronger and more frequent. This suggests that Hawaiʻi may experience increased exposure to tropical cyclones as global warming continues.

iii. Intense Rainstorms

In 2015, while one of the strongest El Niño's in history was developing, Honolulu experienced 11 days of record-setting rainfall in August, September, and November. The city also experienced 9 months of below average rainfall that same year, revealing one of the key features of climate change and El Niño's, that both drought and rain intensity tend to increase.

Deluges of rain that greatly exceed average levels of rainfall, but tend to end quickly, characterize intense rainstorms. These downbursts of rain fall at a rate of several inches per hour, far surpassing more normal rainfall rates of 0.1 (light) to 0.3 (heavy) inches of rain per hour. The impact of these events is to cause short-term **flash floods** that overwhelm the drainage capacity of our roads, buildings, and developed areas. For instance, torrential rain caused problems for Oahu drivers and businesses in September 2015 when major thoroughfares quickly flooded and caused traffic to come to a halt. Water overflowed onto sidewalks, making it difficult for drivers to see the road and curb. During intense rainstorms, the amount of rainfall is enough to fill storm drain pipes, so that in low lying areas, as rain continues to fall, flooding of over 3 feet (90 centimeters) can develop because drainage is insufficient. This amount is enough to cause businesses to close and streets and highways to shut down.

Climate change is projected to cause an increase in the number and intensity of future El Niño's. Thus drought and intense rainstorms can also be expected to increase in Hawaiʻi.

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4 Fletcher, C.H., et al., 2010, Living on the Shores of Hawaiʻi. University of Hawaiʻi Press, ISBN 978-0-8248-3433-3: http://www.uhpress.hawaii.edu/p-6497-9780824834333.aspx

5 Cai, W., et al., 2014, Increasing frequency of extreme El Niño events due to greenhouse warming. Nature Climate Change 4, pp. 111-116.

6. Summary of Main Climate Features of Hawai'i

Table 3 is a summary of the main climate features in Hawai'i.

Table 3 Main Climate Features

- Rain produced by convection and orographic processes
- Warm and humid days and nights all year in low elevation areas
- Wetter and drier seasons
- Cool conditions at high elevations with variable amounts of precipitation depending on orographic effect and trade wind inversion.
- Lots of variability in annual amounts of rain with a long-term trend of declining rainfall
- Lots of variability in wind speed and wind direction
- Extreme weather events: drought, tropical cyclones, and intense rainstorms
- Strong influence by climate conditions known as El Niño, La Niña and the North Pacific High
- Breezy with trade winds normally blowing east to west

Table 3 *The main features of the climate in Hawai'i.*

C. What is happening to the climate on our planet?

Our planet has been around for a very long time, more than four billion years. During that time, the climate of the planet has changed many times. Sometimes, the climate has been very cold, with large amounts of ice covering most of the land and even large parts of the ocean. Sometimes, the climate has been very warm when even the polar regions had little or no ice.

1. Global Warming Caused by Burning Fossil Fuels

For the past 10,000 years, Earth's climate has been very comfortable for people and for the ecosystems we know. But now, the climate is beginning to change because of human activities, especially because we burn fossil fuels: oil, coal, and natural gas, made of fossil plankton and plants. Since our human activities are causing the global air temperature to become warmer, this change is often called **global warming,** and global warming is causing climate change.

We use oil to make the fuel that provides the power for transportation, such as gasoline and diesel fuel for cars, boats and trucks. People also burn fossil fuels to make electricity (**Figure 11**). When we burn oil and coal and natural gas, the burning produces gases, especially carbon dioxide (CO_2), that traps heat in the atmosphere. Other human activities are also producing gases that go into the atmosphere and trap heat. These include cutting down forests and growing large numbers of cows, chickens, and pigs for food. This trapping of heat in the atmosphere is causing Earth's air temperature to get warmer which is changing the climate.

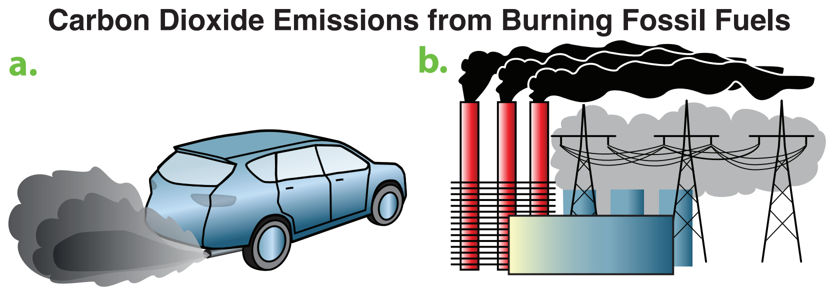

Figure 11 *When we burn fossil fuels (oil, coal and natural gas), cut down forests, and grow many animals as a food source, they produce gases (such as carbon dioxide [CO_2] and methane [CH_4]) that stay in the atmosphere and trap heat, causing global warming.* **a**) *Oil is used to make gasoline and diesel fuel to run cars and trucks.* **b**) *Oil, coal and natural gas are burned to make electricity.*

There are two special characteristics of carbon dioxide accumulation that are of particular concern. 1) Once carbon dioxide is released into the atmosphere significant amounts of it will stay there for many centuries essentially causing permanent climate change. 2) Humans are releasing so much carbon dioxide so rapidly that it is causing very fast climate change. This means that many plant and animal communities will not have enough time to adjust to the changes. In some cases, this will cause extinction, and once living organisms go extinct, they never come back. Researchers have estimated that if global warming exceeds 3° to 4°F (about 2°C) above historic natural levels, 20 to 30% of Earths species will be at increased risk of extinction.

Although human communities may be able to adapt to a changing climate, many ecosystems will be permanently damaged. This can have negative impacts on human communities because we depend on natural ecosystems for many things including clean water, food, natural materials for construction, and the very oxygen that we breath.

2. Global Climate Change

The graph of average global air temperature over the past century shows that the global air temperature has been increasing (**Figure 12**). The temperature data are collected from weather stations around the world. Weather stations collect information on the cloudiness, air temperature, rainfall, wind, air pressure and other characteristics of the weather. By continuously collecting data over a few decades, these measurements also describe the climate, and **climate variability** of a place.

Weather patterns vary a lot from year to year. However, over all the years in the graph, there is a clear trend that Earth's climate has been getting warmer. Fifteen of the top 16 warmest years have occurred since the start of this century. Global temperatures in the last ten years are significantly higher than they have been for any other ten-year period and the hottest years on record are 2014 and 2015.

Over the past 100 years, Earth's temperature has increased about 1.55°F (0.86°C). While this amount may not seem very much to us, it is actually a lot for planet Earth. A decrease in global temperature of about 10°F (5.6°C) can cause an ice age. In the geologic past when Earth's average temperature was 10°F higher, most of Earth's ice was gone and sea levels were 100 feet (30 meters) higher.

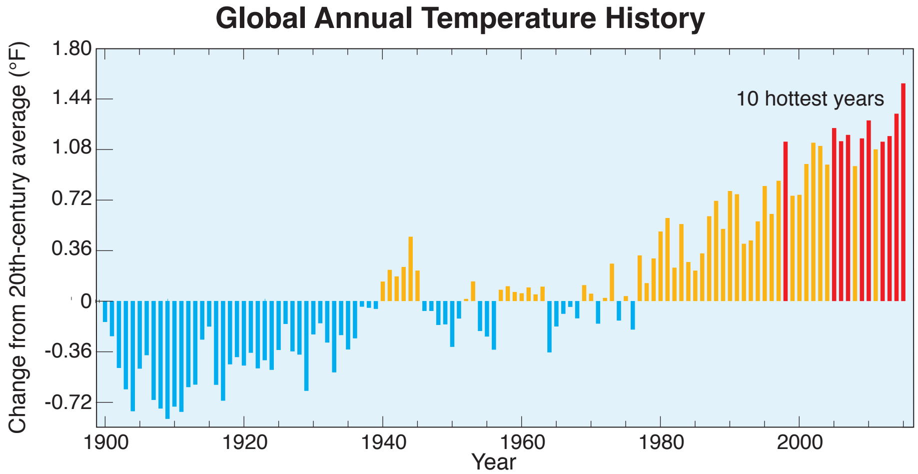

Figure 12 *The annual average temperature of the air at Earth's surface, 1900-2015.*

The higher global temperatures cause many other changes to weather patterns and conditions on the planet. As a result, scientists tend to use the broader term "climate change" to describe this. **Table 3** provides a list of global climate changes that are happening because of global warming.

Table 3 Global Climate Changes

- Air and ocean temperatures are warming.
- Glaciers everywhere in the world are melting.
- The oceans are getting more acidic.
- Sea level is rising.
- Ecosystems, both on land and in the oceans, are moving away from current locations toward locations that are not as hot. This is disrupting natural ecosystem processes such as seasonal migrations, food webs, mating, predator-prey relationships, and others.
- Warm seasons, including dry periods, are starting earlier and lasting longer.
- More of the planet is having tropical climate.
- Rain patterns are changing. Generally, wet places are getting wetter (flooding) and dry places are getting dryer (drought). This is causing increased flooding and well as more drought.
- Tropical cyclones are shifting poleward and increasing in intensity.
- Periods of extreme heat (heat waves) are more frequent and more intense.
- Global food production and clean water availability are threatened.
- Human health is threatened by heat-related illness and wider ranges of vector-borne diseases such as dengue fever.

Table 3 *Global climate changes resulting from higher air temperatures.*

These and many other observations show that Earth's climate system is rapidly changing because of global warming. Global climate change affects Hawai'i in many ways. The rest of this booklet focuses on the changes that are already happening and the climate changes that are projected to happen. We will also discuss what people in Hawai'i can do to help protect themselves from the damaging effects of climate change.

D. What impacts of climate change are happening in Hawai'i?

As shown in **Figure 13**, the four most important impacts (damages) of climate change in Hawai'i are:

- Higher air and ocean temperatures
- Sea-level rise
- Increasing exposure to tropical cyclones
- Changing rain patterns
- Ocean acidification

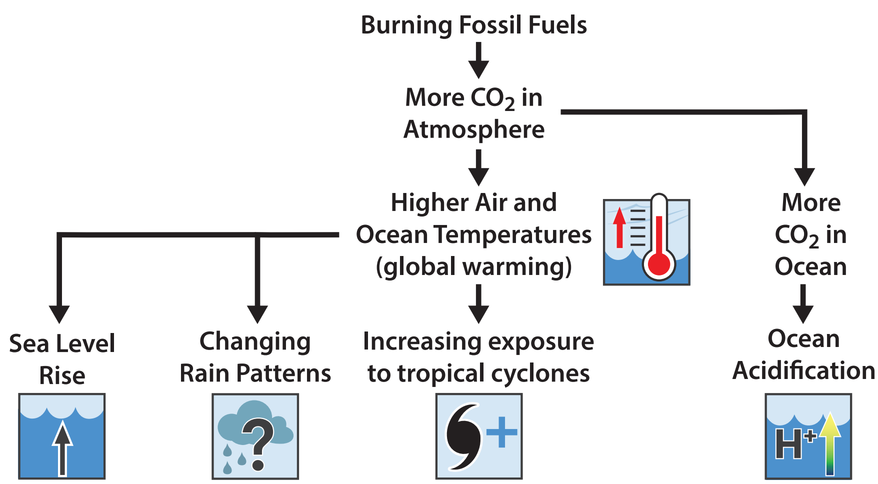

Figure 13 *Human activities, mainly burning fossil fuels, cutting down forests, and increasing the number of animals used for food, are putting more heat-trapping gases, especially carbon dioxide (CO_2) and methane (CH_4), into the atmosphere. These activities are causing global warming. The five major impacts of climate change in Hawai'i are shown with a graphic image next to each one.*

I. Sea-Level Rise

Global warming means that air and ocean temperatures are warmer. These higher temperatures can directly harm ecosystems and human communities. For instance, warmer ocean water is an unhealthy condition for coral reefs and fish. In addition, these higher temperatures are causing one of the most serious climate impacts: **sea-level rise.** [6]

Higher ocean temperatures cause the oceans to have a larger volume.[7] Thus, the ocean surface rises. This accounts for about 1/3 of the amount of global sea-level rise today. Higher

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6 For more information on sea-level rise see the PCEP booklet "Sea-level rise in the U.S. Affiliated Pacific Islands" at http://pcep.prel.org/resources/sea-level-rise-in-the-u-s-affiliated-pacific-islands-usapi/

7 When something gets warmer, it expands (gets larger) in size. This increase in size happens with solids, liquids, and gases.

air temperatures also cause mountain glaciers to melt, and this water flows into the ocean (accounting for another 1/3 of global sea-level rise). The last 1/3 of global sea-level rise comes from melting ice on Greenland (**Figure 14**) and Antarctica. As a result of warming seawater and melting ice, oceans have a higher volume, and sea levels around the world are rising and flooding coastal areas.

Greenland Annual Melting

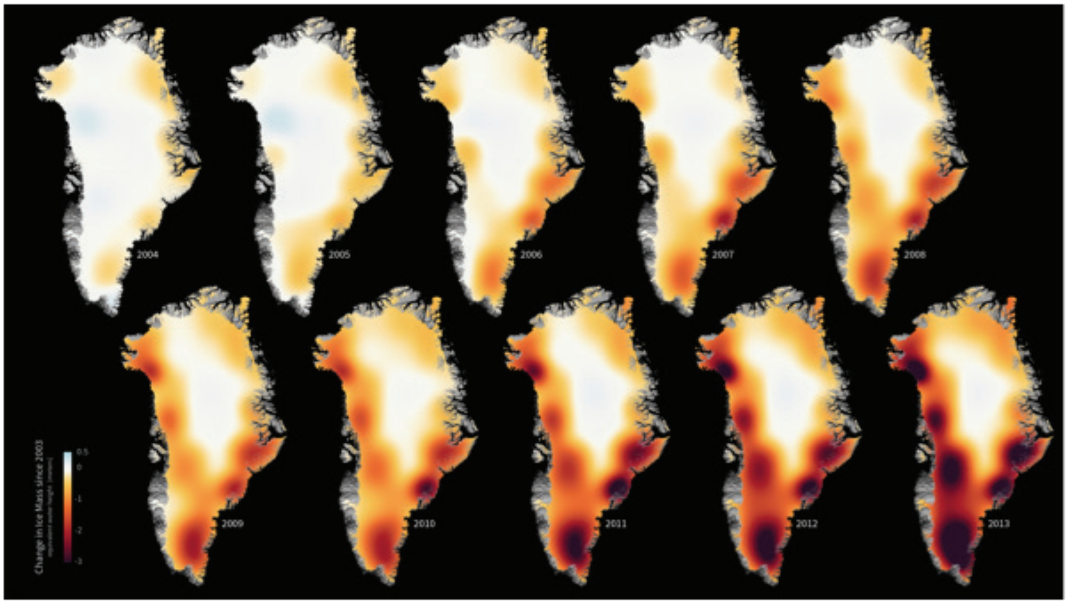

Figure 14 *This sequence of images records the melting of ice on Greenland from 2004 (top left) to 2013 (bottom right). Darker colors indicate net lowering of the surface elevation of the ice sheet as a result of melting over the 10-year period; darkest red is elevation loss of 9.8 ft (3 m). The greatest melting of ice occurred over southeastern Greenland.*

Sea level has risen over the last century on each island in Hawai'i at rates varying from 0.5-1.3 inches (1.5-3.3 centimeters) per decade[8]. Accelerating rates of sea-level rise have been detected in global sea level data. Rates of rise are projected to continue to accelerate, resulting in a 1-3 foot (0.3-1 meter) rise, or more, by the end of the century. Some studies indicate that if we continue to emit greenhouse gases into the atmosphere at the same rate that we have been for the past few decades, the West Antarctic Ice Sheet may collapse and sea level might rise twice as much as currently projected.

Sea-level rise will cause the ocean to come over the land more often and with more strength. This coastal inundation will cause more erosion, leading to the degradation of coastal ecosystems, beach loss, and increasing damage to infrastructure in low-lying areas.

During heavy rainstorms, high sea level that floods drainage systems and raises the groundwater table can prevent the rain from draining off the land, causing even more flooding. Sea-level rise is one of the most damaging impacts of climate change, especially for island communities.

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8 Climate Change Impacts in Hawai'i, 2014, University of Hawai'i at Mānoa, Sea Grant College Program, http://seagrant.soest.hawaii.edu/CCIH

2. Changing Rain Patterns

The amount of rainfall that Hawai'i receives has been declining over the past century and the rate of decline has increased in the past 30 years. Fresh water delivered by rain is essential to life in the islands. We use it to irrigate agriculture, in manufacturing, for daily household activities, in businesses throughout the state, and of course for drinking. A decrease in rainfall could reduce groundwater aquifer recharge and freshwater supplies, negatively influence agriculture as well as ecosystems in rivers and streams, and threaten plant and animal communities in our watersheds.[9]

Several types of observations have been recorded with regard to rain patterns among Hawaiian watersheds. Rainfall has become less intense for some locations on the islands of O'ahu and Kaua'i, but has increased in intensity in the eastern regions of the island of Hawai'i. Honolulu experienced intense rainstorms, leading to flash floods, during the El Niño that occurred in 2015. The probability of intense rainstorms rises during El Nino years. The island of Hawai'i has experienced longer periods of drought with an increasing trend in the annual length of dry periods from 1980-2011 when compared to the period 1950-1970. Instrument records that monitor the amount of water flowing in streams throughout the state show a decrease in the amount of groundwater that contributes to stream flow. This decline in stream flow ranges from 20 to 70 percent depending on watershed.

How will these trends play out in future years? Climate change, natural variability, complex topography, changing land use, and other factors make it very difficult to definitively project future rainfall patterns in Hawai'i. Some regions could experience greater drought, while other regions could experience unprecedented flooding (**Figure 15**). Climate models suggest that Hawai'i is projected to experience overall drying, decreased winter rain in dry areas, and a longer and drier dry season. It is important for governments and communities to be prepared for declining rainfall, increasing drought, and increasing rain intensity in some locations. These various patterns are not mutually exclusive. For instance, if rains become more intense in some locations during El Niño years, the possibility of damaging floods increases. But in the same year, the period of drought may become longer and dryer.

Flooding in Honolulu

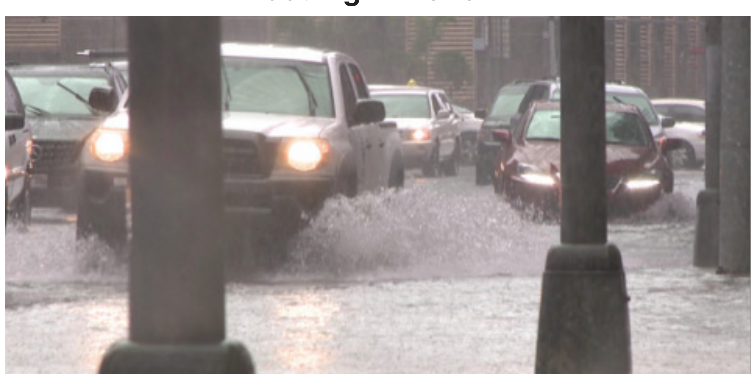

Figure 15 *Flash flooding occurred in downtown Honolulu during the El Niño of 2015.*

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9 Climate Change Impacts in Hawai'i, 2014, University of Hawai'i at Mānoa, Sea Grant College Program, http://seagrant.soest.hawaii.edu/CCIH

3. Increasing Exposure to Tropical Cyclones

Global warming is increasing Hawai'i's exposure to tropical cyclones (**Figure 16**). One study[10] predicts that there will be more frequent tropical cyclones in the waters near Hawai'i. This is not necessarily because there will be more storms forming in the east Pacific; rather, it is projected that storms will follow new tracks, shifted away from the equator, that bring them into Hawaiian waters more often.

Hurricane Inki Damage

Figure 16 *Hurricane Iniki was the most powerful hurricane to strike Hawaii in recorded history. With winds of 145 miles per hour (233 km/hr) it made landfall on September 11, 1992. Iniki caused about $1.8 billion in damage and 6 deaths.*

Another study[11] documents a shift in the zone of maximum wind intensity toward the poles, away from the equator. This is worrisome as, historically, most tropical cyclones in our region pass to the south of Hawai'i. Thus, if the zone of maximum wind intensity shifts away from the equator, these storms may follow new tracks that are shifted to the north, and are thereby more likely to impact Hawai'i.

In yet another study[12], computer models project that a warmer world will see more frequent, and more intense El Niño's. El Niño years are characterized by higher numbers of tropical cyclones in the North Central Pacific where Hawai'i is located. For instance, in the El Niño of 2015, there were 15 tropical cyclones in the region, a record-breaking number. With these

10 Murakami, H., Wang, B., Li, T., and Kitoh, A., 2013, Projected increase in tropical cyclones near Hawai'i. Nature Climate Change, v. 3, August, pp. 749-754.

11 Kossin, J.P., Emanuel, K.A., and Vecchi, G.A., 2014, The poleward migration of the location of tropical cyclone maximum intensity. Nature, v. 509, May, pp. 349-352.

12 Cai, W. et al. (2015) Increasing frequency of extreme El Niño events due to greenhouse warming. Nature Climate Change 4, 111–116 (2014) doi:10.1038/nclimate2100

storms following new tracks that are closer to the Hawaiian islands, and with increasing numbers of storms during El Niño years (which are going to occur more frequently), Hawai'i is experiencing increased exposure to tropical cyclones.

4. Higher Air and Ocean Temperatures

The global average surface temperature in 2015 was the warmest on record and reached 1.55°F (0.86°C) above the pre-industrial era. This was 20% hotter than the next hottest year and was due to a combination of a strong El Niño and human-induced global warming. The years 2011-2015 have been the warmest five-year period on record, with many extreme weather events – especially heat waves – influenced by climate change.

The rate of warming air temperature in Hawai'i has dramatically increased in recent decades. Currently, the air is warming at 0.3°F (0.17°C) per decade, four times faster than half a century ago. This can lead to **heat waves**, expanded ranges for pathogens and invasive species, thermal stress for the natural flora and fauna of the islands, increased demands for electricity, increased wildfires, and potential threats to human health.

Globally, the oceans have been absorbing more than 90% of the extra energy that has accumulated in the climate system from human emissions of greenhouse gases, resulting in higher water temperatures and sea levels. Sea surface temperatures have warmed 0.13 to 0.41°F (0.07-0.23°C) per decade in the Pacific for the last 40 years.[13] Today, the oceans absorb heat at twice the rate they did two decades ago.[14] Ocean warming is accelerating, and may increase another 2.3 to 4.9°F (1.3-2.7°C) before the end of the century. Warming sea surface temperatures can influence ocean circulation, nutrient distribution, the tendency for coral communities to experience bleaching, and the nature of predator-prey relationships in the marine food chain. Warming sea surface temperatures will also intensify weather patterns in Hawai'i. The potential for marine ecosystem disruption is significant.

5. Ocean Acidification

Ocean acidification (**Figure 17**) is another major impact caused by higher carbon dioxide (CO_2) levels. When carbon dioxide dissolves in the ocean, it forms a weak acid. As excess carbon dioxide in the atmosphere dissolves in the ocean, it changes the acid-base chemistry of the ocean and causes seawater to become more acidic. pH is the scientific measure of the acid-base condition. A lower pH value indicates more acidic conditions. Therefore, the signature of ocean acidification is a steadily decreasing pH value. The projected total change in pH shown in Figure 17 would represent about a doubling of the ocean's acidity.

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13 Australian Bureau of Meteorology and CSIRO. 2011. Climate Change in the Pacific: Sci. Assessment and New Research. V1: Reg. Overview. V2: Country Reports. http://www.cawcr.gov.au/projects/PCCSP/

14 Glecker, P.J., et al. (2016) Industrial era global ocean heat uptake doubles in recent decades. Nature Climate change. doi:10.1038/nclimate2915

Observed and Projected Ocean Acidification

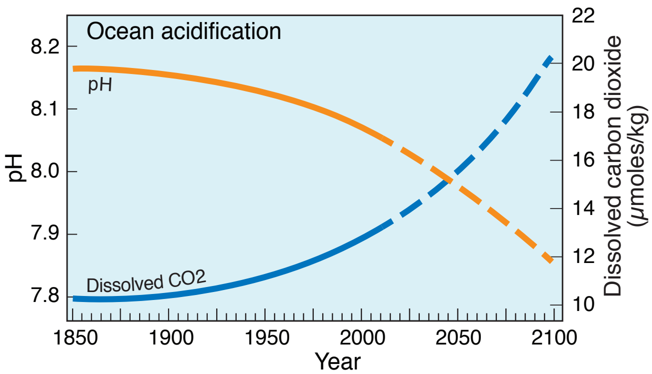

Figure 17 *CO_2 mixes with seawater to form carbonic acid, making the oceans more acidic, which threatens marine ecosystems, food supply, and the economies of coastal communities. Dissolved carbon dioxide has been increasing and pH has been falling (solid lines). The dotted lines represent projections of future effects based on continuing current greenhouse gas emissions.*

An estimated 30 to 40% of the carbon dioxide from human activity released into the atmosphere dissolves into oceans, streams, and lakes. Ocean acidification is considered an impact of climate change because it is caused by the same increase in carbon dioxide that causes the other climate change impacts. Ocean acidification harms many of the same marine ecosystems, especially coral reefs, plankton, and shellfish that are additionally harmed by higher ocean temperatures.

Many chemical reactions, including those that are essential for life, are sensitive to small changes in pH. In humans, for example, normal blood pH ranges between 7.35 and 7.45. A drop in blood pH of 0.2-0.3 can cause seizures, comas, and even death. Similarly, a small change in the pH of seawater can have harmful effects on marine life, impacting food webs, chemical communication, reproduction, and growth.

So far, ocean pH has dropped from 8.2 to 8.1 since the industrial revolution, and is expected by fall another 0.3 to 0.4 pH units by the end of the century. If we continue to add carbon dioxide at current rates, seawater pH may drop another 120% by the end of this century, to 7.8 or 7.7, creating an ocean more acidic than any seen for the past 20 million years or more.

The building of skeletons in marine creatures is particularly sensitive to acidity. Marine creatures such as plankton, corals, mollusks, fish, and others build their skeletons out of calcium carbonate ($CaCO_3$), which is highly vulnerable to acidic conditions. Lower pH makes building skeletons more difficult and may even cause calcium carbonate to dissolve in seawater. Many types of important marine organisms are threatened by lower pH: mussels, clams, urchins, starfish, coral, zooplankton (such as pteropods and foraminifera), coralline algae, fish (fish develop a potentially fatal blood condition called acidosis), and others. A major fear among scientists is that disruptions to plankton and krill (a tiny crustacean) will ripple throughout the marine food chain (including whales, seals, penguins, and others) and have far-reaching and serious negative impacts to the entire ocean biosphere.

6. El Niño

An El Niño year is different than a calendar year. Typically, an El Niño year begins in the summer, peaks in the winter, and ends the following summer. Some El Niño's are unusually strong such as the ones that occurred in 1998/1999 and 2015/2016. Others are more moderate such as in 2007/2008 and 2010/2011. There are also weak El Niño's, which we experienced in 1995/1996, 2000/2001, and 2011/2012. Climate scientists predict that because of climate change, strong El Niños may occur with greater frequency. This could potentially have important implications for Hawai'i.

The effects of these different types of El Niño's can be quite noticeable in Hawai'i and may have a clear impact on our weather and ocean conditions. Generally speaking, when a powerful El Niño develops (such as in 1998/1999 and 2015/2016), seven types of events may occur in Hawai'i that have significant impacts on local ecosystems and human communities. These seven are: heat waves, extreme rainfall, failure of the trade winds, an active hurricane season, large waves from the north, drought, and high sea surface temperatures that can produce coral bleaching.

Because climate scientists predict that as the atmosphere warms strong El Niño's are going to occur more frequently and with greater strength, Hawai'i may expect to see these seven types of events more often in the future. Each of these has particular characteristics that require that human communities take steps to adapt to the changing conditions.

i. Heat Waves

Worldwide, record hot days now outnumber record cold days by a factor of 12 to 1. These conditions set the stage for heat waves, and scientists have predicted that by mid-century extremely high temperatures observed once in 20 yrs will occur every 2 to 4 yrs. The trend of increasing heat waves is more pronounced in Hawai'i during the summer months at the beginning of a strong El Niño.

In 2015, the average temperature at the Honolulu Airport was 1.2°F above normal, and there were 25 record-setting warm days yet only 4 record setting cold days. Hot summer days generally peak in the period August – October and can lead to sweltering heat that drives people to run their air conditioning at home all night long. This puts unusual stress on the ability of utility companies to supply enough electricity to meet the high demand, and in 2014 and 2015 the Hawaiian Electric Company issued public warnings requesting homeowners to turn off their air conditioning at night.

This excessive demand for electricity can lead to a blackout, a dangerous situation where there is no electricity available. These are exactly the conditions that have unfortunately caused fatalities in other urban areas around the world during a heat wave. It has been estimated that more than 140,000 people have died in heat waves since 2000. The very old, the very young, and those who are ill, are highly vulnerable to heat-related stress and during a blackout the lack of air conditioning in tall buildings, hospitals, schools, and other such locations, as well as the lack of electricity for the police and fire departments, can produce potentially deadly situations. Hawai'i should plan for these conditions, as in a warmer world, with stronger El Niños, heat waves are increasingly likely to occur.

ii. Extreme Rainfall

Worldwide, the incidence of extreme rainfall has increased 12%. The El Niño of 2015/2016 brought 11 days of record-setting rainfall to Honolulu causing flash floods, impassable roads, and shuttered businesses in many neighborhoods. According to the National Oceanographic and Atmospheric Administration, in August 2015, the Honolulu Airport's monthly total of 7.63 inches (19.38 cm) of rain was 1363% of average rainfall and more than double the previous August record of 3.74 inches (9.5 cm) set in 2004. Intense rainfall in low-lying communities is especially dangerous. Dramatic flooding, stalled traffic, and damaged buildings, can make entire neighborhoods inaccessible, potentially isolating the young, elderly, and ill from caregivers, medical supplies, food, and water.

Many Hawai'i communities, including much of Honolulu, sit at low elevation along the shoreline. Normally, rainfall does not accumulate and cause flooding because a system of drainage pipes diverts the runoff into the ocean. However, Hawai'i has experienced slowly rising sea level for at least the past century and seawater is now flooding up into these pipes and blocking the rainwater from going into the ocean. This problem is especially bad at high tide, which occurs twice each day. When heavy rainfall occurs, there is little or no drainage under these conditions and flash floods develop. With more powerful El Niño's expected in the future, and continuing sea level rise blocking the drainage system, flooding such as this may worsen in the future.

iii. Failure of Trade Winds

Strong El Niño years are characterized by a general failure of the trade winds in the summer, fall, and winter period. On hot days this can promote heat wave conditions. Overall, because the trade winds provide a critical component of our rain, a lack of trade winds promotes drought and drying that stresses ecosystems, damages agriculture, and can threaten our freshwater supplies.

iv. Active Hurricane Seasons

There is a positive correlation between years with active hurricane seasons and strong El Niño's. In 2015, the North Central Pacific, the region where Hawai'i is located, had 15 tropical cyclones. In a typical year the average is only 4 to 5, and the previous record high was in 1992 and 1994 when there were 11 storms in both years.

Global warming is causing certain changes to hurricanes. Hurricanes are becoming more violent. They are larger, with higher wind speeds, and they produce more rainfall. Research has shown that, worldwide, the region of maximum winds associated with tropical cyclones is shifting toward the poles. This is alarming news for Hawai'i since these storms have historically passed to the south of Hawai'i. Should they migrate to the north, the Hawaiian Islands are likely to experience increased exposure to their devastating consequences, especially as they are associated with strong El Niño years.

v. Large Winter Waves

Every winter Hawai'i is exposed to large ocean waves that approach from the north and northwest. These are produced by storms in the North Pacific Ocean that stir the water and send these large waves in all directions. During strong El Niño years these storms are more powerful than usual and thus the waves they produce are typically the highest on record. These waves cause all kinds of damage to the shorelines they hit. They erode coastlines and beaches, undermine roads and seawalls, flood homes and buildings, and snarl traffic on narrow roads when they run-up onto the pavement and block traffic. These waves will cause increasing amounts of damage and mayhem as sea level continues to rise throughout the 21st century. Coastal landowners and public agencies should prepare for these problems to grow worse in time, and to be especially pronounced during El Niño years.

vi. Drought

Drought is a chronic and troublesome problem in Hawai'i, at one time or another affecting virtually every part of the state. Drought reduces crop yields, diminishes livestock herds, desiccates streams, irrigation ditches and reservoirs, depletes groundwater supplies, and leads to forest and brush fires. Drought tends to worsen during El Niño years.

Around the world, warmer air temperatures have increased drought by 10%. In Hawai'i, rainfall has been decreasing for the past century and the rate of decrease has accelerated in the past 30 years. Now, statewide, data indicate there has been a 6% decrease in the amount of rain that falls each year. These trends promote drought in Hawai'i. 2015 had 9 months of below average rainfall and the spring and summer of 2016 most of the state experienced severe to moderate drought conditions.

vii. High Ocean Temperatures and Coral Bleaching

Ocean temperatures around Hawai'i are typically cooler than in other tropical areas. This is because Hawai'i is located along the northern edge of the tropics, we generally have strong trade winds to encourage water circulation, and cloudy conditions all help to keep the water temperature in a comfortable range for coral reefs. But during El Niño years, the sea surface temperature in the central and eastern Pacific will increase by several degrees. Combined with a breakdown in the trade winds, this can lead to conditions that cause **coral bleaching**.

Coral bleaching occurs when coral expel algae that live in their tissues. These algae give corals their many colors, and so it causes the coral to turn completely white (bleached). Under normal conditions the algae provide a partnership with corals where in they produce, through photosynthesis, certain nutrients that the corals need to survive. Scientists believe that when coral become stressed, such as by extreme sea surface temperatures, pollution, or other impacts to their environment, the coral expel these algae and continue to live for weeks to months afterwards, reacquiring the algae once the stress is relieved.

Hawai'i does not experience bleaching often. But the powerful El Niños of 1998/1999 and 2015/16 caused coral bleaching throughout the state, and into the northwest Hawaiian Islands as well. Bleaching does not necessarily spell disaster for a reef, but if stressful conditions related to high water temperatures persist for many months, it does typically result in the death of a coral. Humans place stress on coral reefs, which can compound the effects of El Niño. Pollution, overfishing, and physical contact with coral all lead to damaged ecosystems that are thereafter more vulnerable to the negative effects of high water temperatures. If we hope for coral reefs to survive future strong El Niño events, it makes sense to remove the stresses we place on them from our activities in adjacent watersheds and coastal waters.

7. Trade Winds

The prevailing northeast trade winds have decreased in frequency over the past 40 years. These winds are responsible for much of the orographic and convective rainfall that provides Hawai'i with freshwater. The decreasing trade winds would likely lead to less precipitation and enhance the formation of heat waves and coral bleaching.

8. Terrestrial Ecosystems

The watersheds of Hawai'i are characterized by a number of species, such as the Hawaiian honeycreeper and the Haleakalā silversword, that are found nowhere else in the world. Changes in the wind, rain, and air temperature threaten the extent of the native habitats and unique ecosystems that support these species.

As a result of climate change, critical conditions may diminish, pests, diseases, and invasive species may expand, and ecosystems may shift upslope and decline in size. Higher elevations are feeling the stress of these changes and lower elevations are seeing the emergence of new habitats that previously did not exist in the Hawaiian Islands. Changes in rainfall that include flooding drought, wildfires, and soil erosion are among the major threats.

Rising air temperatures in Hawai'i, which have shown an accelerating upward trend over the past 40 years, are changing fastest at higher elevations. Among the impacts of this are a decrease in the difference between the nightly low temperature and the daily high temperature, which is an important factor for many terrestrial species. Consequently, heat stress experienced during the day, is less easily relieved at night. Hawai'i is projected to continue warming, with a range of 4 to 5°F (2.2 to 2.8°C) for high emissions scenarios by the year 2085.

E. How do these climate change impacts harm ecosystems and human systems in Hawai'i?

Many people think that humans should protect the natural world. All five of the climate change impacts shown in Figure 13 (higher temperatures, sea-level rise, exposure to tropical cyclones, changes in rainfall, and ocean acidification) harm Hawaiian ecosystems. These impacts harm the organisms that live there and the human communities that get many benefits from these ecosystems. These benefits include cultural and spiritual values, food, and income from fishing and tourism (**Figure 18**).

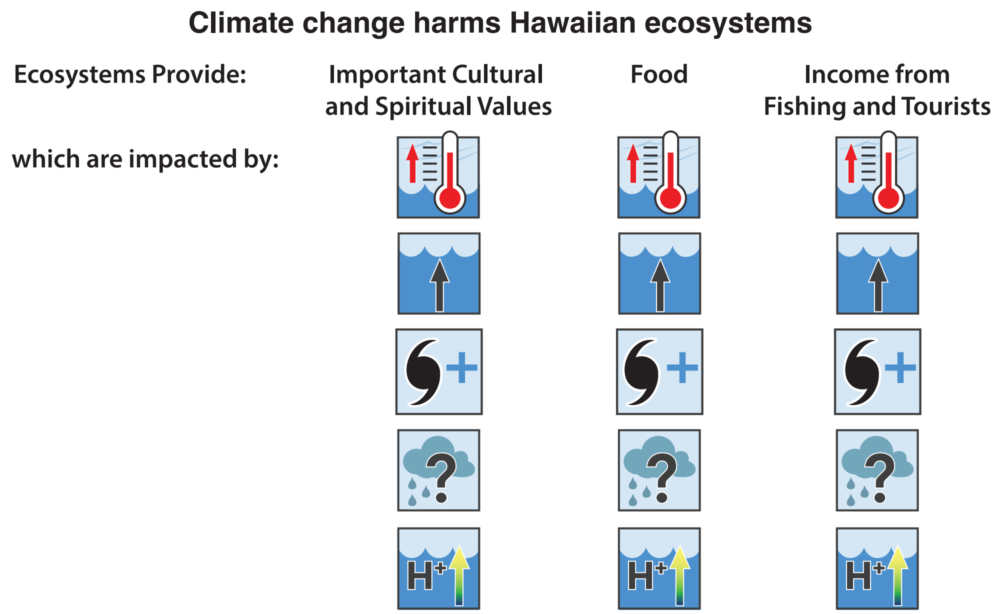

Figure 18 *Higher air and ocean temperatures, Sea-level rise, tropical cyclones, changing rainfall patterns, and ocean acidification all damage major services that are provided by ecosystems.*

In addition, climate changes harm the human systems that people depend upon for their homes, food, fresh water, and transportation (**Figure 19**).

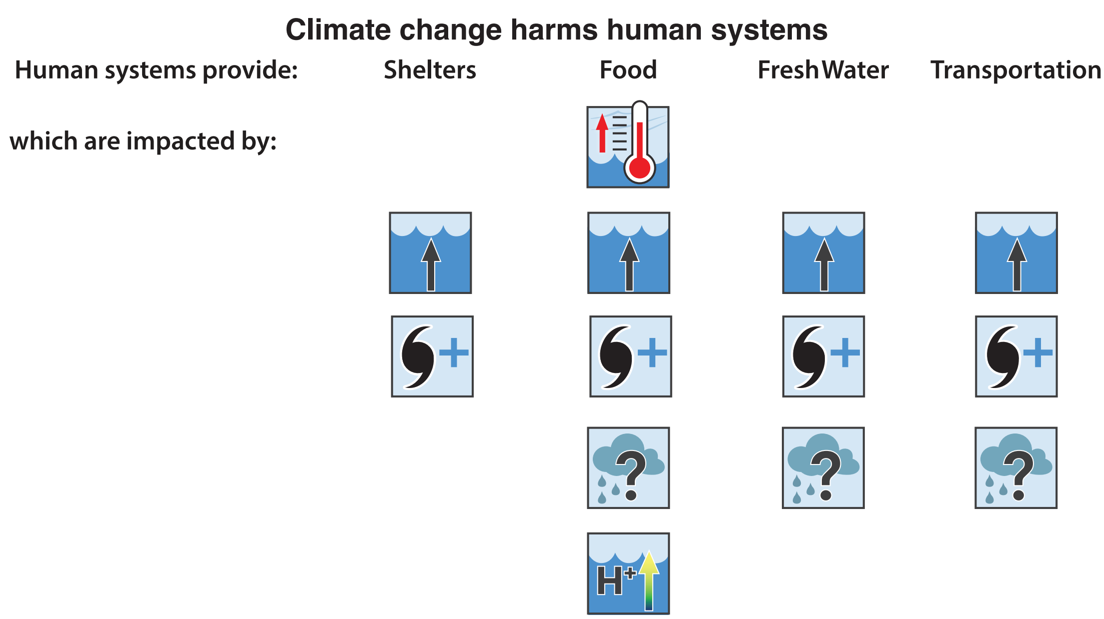

Figure 19 *Climate change damages major services that are provided by human systems.*

I. Ocean Acidification and Warming

Often, the different impacts of climate change harm the same ecosystem or human system and cause more damage than either would by itself. For example, higher ocean temperatures and ocean acidification both harm local marine ecosystems such as coral reefs (**Figure20**). Corals are very sensitive to increases in temperature. In the North Pacific, sea surface temperatures have been rising, on average, by about 0.22°F (0.12°C) per decade. Warmer ocean water can lead to coral bleaching, and damage to local marine ecosystems and fishing.

Warming and Acidification on Reefs

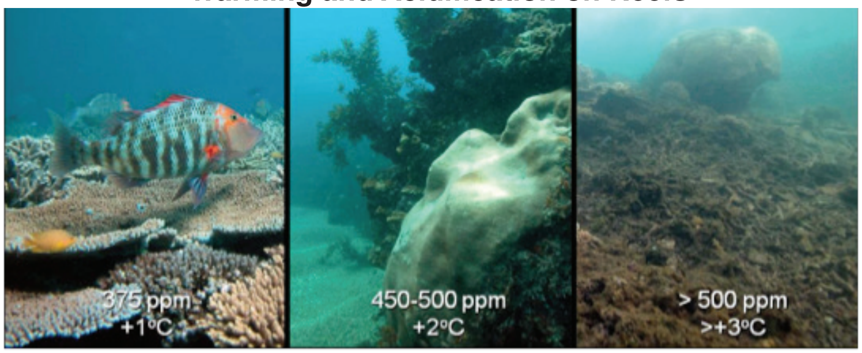

Figure 20 *The combined impacts of ocean acidification and warming harms the coral, plankton, and other organisms that use calcium carbonate to make their shells and the reef. Shown are 3 scenarios of atmospheric CO_2 concentrations in ppm (parts per million) and air temperatures with the associated state of reef health. Reefs progress from coral and fish dominated ecosystems to algae dominated.*

The outside hard parts of many shelled organisms, such as plankton, and coral are made of carbon combined with calcium and oxygen in a solid form called calcium carbonate ($CaCO_3$). As the ocean becomes more acidic, it is much more difficult for many marine organisms to make and keep their hard calcium carbonate shells.

Global Coral Bleaching, 2015

Figure 21 *For the third time in recorded history, a massive coral-bleaching event unfolded in 2015 throughout the world's oceans, stretching from Hawai'i to the Indian Ocean and the Atlantic. Here, a scientist examines bleached coral in American Samoa.*

In 2015, as a result of a growing El Niño event and record ocean temperatures in the Pacific, the National Oceanic and Atmospheric Administration declared the third global coral bleaching event ever on record (**Figure 21**). One quarter of all sea animals spend time in coral reef environments during their life cycle. Since plankton and coral are very important for marine ecosystems, the combined impacts of ocean warming and acidification can also decrease the populations of many marine organisms that do not live in reefs.

2. Sea-Level Rise

Sea-level rise is especially important since it harms essential Hawaiian ecosystems and human systems. Sea level has been increasing in Hawai'i at about 0.06 inches per year (1.5 mm/yr or 6 inches per century). This may not seem like a very rapid increase, but its effects can quickly add up year after year.

For instance, 70% of the beaches in Hawai'i have been classified as chronically eroding, and long-term sea-level rise over several decades is one reason why this is happening. Sea-level rise causes beach erosion (**Figure 22**), flooding during **high tide**, and increases the vulnerability of coastal communities to flooding from storm surge and tsunamis. Sea level is expected to continue rising, perhaps by more than 3 feet (1 meter) by the end of this century.

Coastal Erosion, Oahu

Figure 22 *Sea-level rise causes coastal erosion, which can damage beaches, cause land loss, and threaten coastal communities.*

This increase in sea level means that anything that makes the ocean waves reach farther inland (such as a high tide, a tsunami, or a large storm) will cause more flooding than when the sea level was lower. For example, the next tropical cyclone to pass over the islands will generate a storm surge that is likely to do more flood damage than it would have if sea level had not been rising.

3. Human Health

As warming air and ocean temperatures impact the resilience and sustainability of natural ecosystems, humans are exposed to growing threats to their own health.

The most fatal form of climate change is a heat wave. Heat waves are prolonged periods of excessively hot weather that may be accompanied by high humidity. These are especially dangerous when hot conditions linger for days to weeks, which they tend to do in summer months. Nighttime temperatures under these conditions may not provide sufficient relief to the ill, elderly, and young who suffer the most. Drought and food shortages may develop under especially protracted conditions.

Because of continuous demand for air conditioning, local energy systems may fail during a heat wave. Electricity blackouts such as this are especially harmful and may lead to fatalities. For example, the European heat wave of 2003 led to the hottest summer on record in Europe since 1540. The event produced health crises in several countries and, in combination with drought, resulted in food shortages in parts of Southern Europe. The European heat wave death toll was placed at more than 70,000. Nine out of the 10 deadliest heat waves in recorded history have occurred since 2000.

In Hawai'i's rapidly warming climate, there may be increased levels of vector-borne diseases, water-borne diseases such as cholera, fish poisoning, heat-related illness, mental health problems, respiratory disease, and other non-communicable diseases. Increased injury and death from tropical cyclones may also increase. Some diseases such as dengue fever have developed in Hawai'i with increased frequency.

Dengue fever is spread by mosquitoes, and is correlated with wet, warm conditions. Climate change can lead to increased availability of stagnant water and shorter incubation periods for vectors, such as mosquitoes. In 2001 and 2002, Maui experienced an outbreak of dengue fever during a period of warmer, wetter weather. In November of 2015, Hawai'i Island was declared under a federal travel advisory as over 90 cases of dengue fever developed within a period of a few weeks. Hawai'i may be especially vulnerable to these types of diseases because of the high volume of foreign visitors and imports.

Increased storminess may also cause an increase in polluted runoff. Polluted runoff associated with excessive storm water can contain sewage and other contaminants from overflowing sewage pipes, commercial products used in and around homes, gardening chemicals, and wastes from common animals. These flow into coastal waters and can produce coral disease, nutrient contamination, anoxic conditions, mud pollution, and the growth of marine pathogens. Ciguatera, leptospirosis, and other water-borne infectious diseases are expected to increase in occurrence in a wetter, warmer Hawai'i.

F. How can Hawai'i communities adapt to the impacts of climate change?

We use the term **climate adaptation** to describe the things that people, communities and governments can do to help protect themselves from harmful climate impacts. A Pacific Island community that has planned and implemented climate adaptation strategies for their ecosystems, food supplies, homes, roads, and water supplies will suffer less damage and recover more quickly from climate change impacts.

Plants and animals living in Pacific Island ecosystems are adapted to the current conditions, such as temperatures and rainfall patterns. Since temperatures normally do not change very much over the course of a year, many local plants and animals have never experienced the higher temperatures that may be happening already and that are predicted to happen even more in the future.

Changes in sea level (**Figure 23**) and rainfall, more tropical cyclones, higher temperatures, salt from ocean flooding, and a more acidic ocean all can cause very significant damage to land and marine ecosystems.

In addition to the stress from climate change impacts, these ecosystems are often already being harmed by other human actions. Activities such as polluting land or water, cutting down too many trees, catching too many fish, disturbing reefs, and replacing natural environments with industrial development all harm local ecosystems.

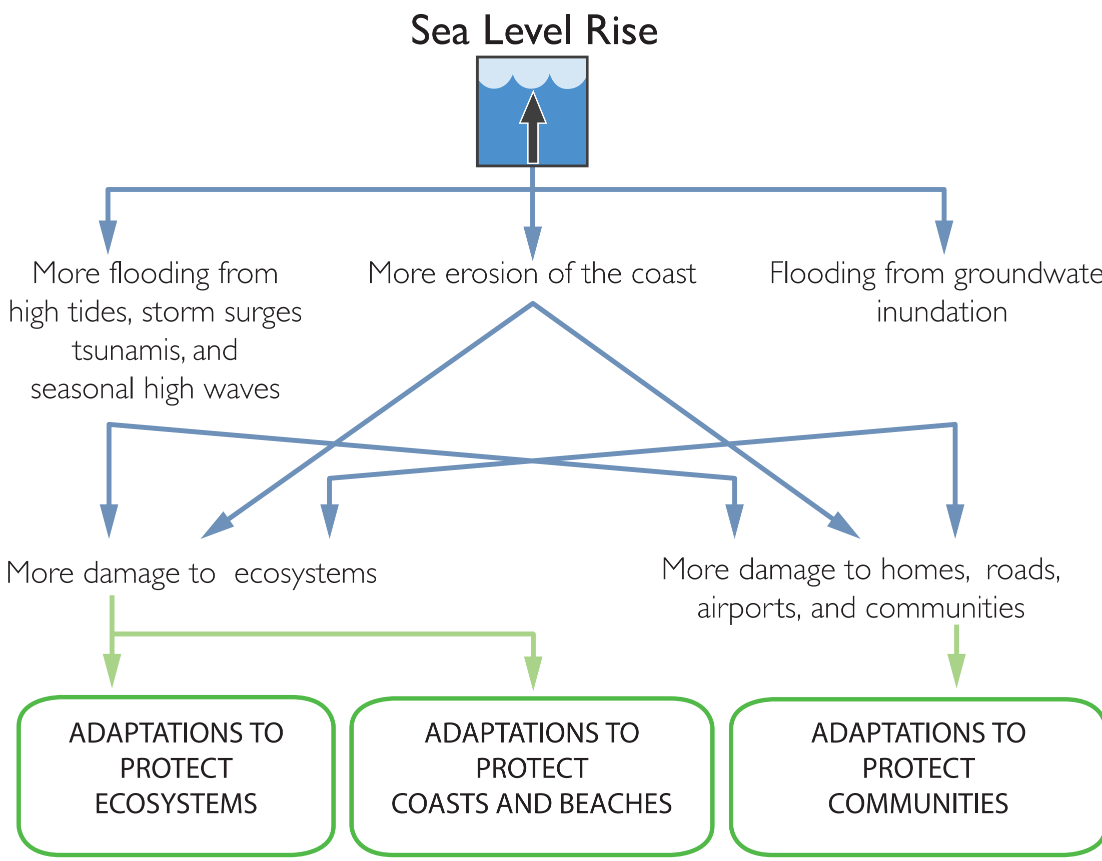

Figure 23 *Impacts of sea-level rise and kinds of adaptation strategies.*

Ecosystems that are close to their natural condition are more resilient with respect to climate change. This means that they are damaged less by climate changes and can recover faster than ecosystems that are harmed by other human activities. The best climate adaptations for ecosystems are activities that help the ecosystems return to and keep their natural conditions. These activities include preventing and removing pollution, and carefully managing human interactions with the ecosystem such as logging, fishing, altering the reef, and tourism.

Because ecosystems provide so many important benefits to island communities, these ecosystem adaptations also increase the resilience of human systems. In addition, human systems (such as homes, getting freshwater, getting food, and transportation) require other adaptation actions. These adaptation actions generally make the human systems more flexible, efficient and sustainable. In other words, these climate adaptations for human systems are:

- **Flexible** Giving the communities more ways to meet their needs
- **Efficient** Adapting in ways that provide the maximum benefits for the cost
- **Sustainable** Relying more on island resources than on outside resources

Communities on islands have fewer choices and resources to reduce the impacts of climate change than do communities on continents. Low coastal settings lack the higher elevations that can provide much more security with respect to avoiding flooding, getting fresh water, growing food, and building roads. If the impacts of climate change continue to increase, the islands in Hawai'i, their way of life and their ecosystems, will become increasingly threatened.

In general, there are three kinds of climate adaptation activities that can help make people, communities, and ecosystems safer with respect to rising sea levels and other climate impacts. These kinds of adaptation activities are:

- Protecting local ecosystems to help these ecosystems be more resilient,
- Increasing the resiliency of the communities' physical systems such as homes, roads, water supplies, and food supplies,
- Making the community's cultural systems stronger and healthier so people in the community effectively plan and implement climate adaptation strategies that work for that community.

These climate adaptations can help make life in Hawai'i safer and more comfortable for more years into the future.

Glossary

Aquifer An underground layer of water-saturated rock from which fresh water can be obtained for human use such as irrigation, drinking, and in manufacturing.

Arid A very dry climate in a place.

Atmosphere The envelope of gases that surrounds Earth. The atmosphere contains the air that we breathe, and the weather that we experience.

Climate The weather conditions prevailing in an area in general or over a long period. The climate is the long-term average condition of the weather over 30 years or so.

Climate Adaptation Adaptation is any action that reduces the vulnerability of social and biological systems to climate change and thus offset the effects of global warming. Even if emissions are stabilized relatively soon, global warming and its effects will last many years, and adaptation will be necessary to the resulting changes in climate.

Climate Change A change in global or regional climate patterns, in particular a change apparent from the mid to late 20th century onwards and attributed largely to the increased levels of atmospheric carbon dioxide produced by the use of fossil fuels.

Climate Variability Changes in climate that are caused by oceanographic and atmospheric influences. Climate is described as the average, long-term condition of the weather. As implied by the word "average," conditions vary in being sometimes wetter, dryer, colder, warmer, or windier.

Coastal Erosion Wearing away and loss of beaches and land due to waves. Coastal erosion gets worse when sea-level rises.

Convection Convection is the movement of heat that is carried by the motion of a fluid (such as air or water) when the heated fluid moves away from the source of heat. Convection occurs because hot air (or hot water) expands, becomes less dense, and rises.

Convective Rain Convection involves the upward movement of warm air. If this warm air has a lot of water vapor, the water vapor readily condenses and forms clouds. The clouds produce rain that falls as showers that can rapidly change in intensity. We call this convective rain. This rain falls over a limited area for a relatively short time because convective clouds aren't very wide. Most rain in the tropics seems to be convective.

Coral Bleaching Bleaching is a state of stress when coral loses its color and turns completely white because it has expelled algae that live in its tissue. These algae give the coral color as well as nutrients. Coral can only survive for a few months without these algae and so this marks a state of high distress for the coral and is potentially deadly. Bleaching often occurs because the water temperature is too high, but other stresses can cause bleaching as well.

Drought An extended period of little rainfall.

El Niño A natural climate event, lasting typically less than 1 year, which occurs in the Pacific when the normal trade winds weaken (or die). This causes warm water in the western tropical Pacific to surge into the central and eastern Pacific. El Niño can cause temporary global changes in the climate and weather.

El Niño Southern Oscillation (ENSO) Refers to a Pacific climate event that has two states: El Niño and La Niña. These states govern the movement of a large body of warm water to the eastern (El Niño) or western (La Niña) regions of the tropical Pacific Ocean. ENSO states cause strong climate and weather variability around the globe.

Extinction Extinction is when a group of organisms, usually a species but could include higher level taxonomic groups such as genus, go out of existence such that there are no members of the group any longer in existence on Earth.

Evaporation When a liquid turns into a gas.

Flash Flood Rapid flooding of low-lying areas caused by heavy rain associated with a severe thunderstorm, hurricane, tropical storm, or intense rainstorm.

Global warming When the air in the lowest portion of the atmosphere (the troposphere) gets significantly warmer than normal. Global warming is caused by an increase in the amount of heat-trapping greenhouse gases when humans burn fossil fuels (coal, petroleum, natural gas) for energy. Other types of greenhouse gases produced by humans also contribute to the problem.

Heat Wave A prolonged period of excessively hot weather, often accompanied by high humidity. Often these conditions pose a health threat to human communities.

High Tide High tide is the highest level reached by the tide. The tide is the alternating rising and falling of the sea, usually twice in each day, due to the gravitational attractions on the ocean by the moon and sun.

Ho'oilo The Hawaiian season (October through April) when the sun is in the south, the weather is cooler, and the trade winds are most often interrupted by other winds.

Humidity Humidity is the amount of water vapor in the air. Water vapor is the gaseous state of water and is invisible. Humidity indicates the likelihood of precipitation, dew, or fog. Higher humidity also reduces the effectiveness of sweating in cooling the body by reducing the rate of evaporation of moisture from the skin.

Hurricane A hurricane is a tropical cyclone with sustained winds of at least 74 miles per hour (119 km/h).

Hydrologic Cycle The hydrologic cycle is a description of the pathways that water follows as it is naturally recycled. The hydrologic cycle begins with the evaporation of water from the surface of the ocean. As moist air is lifted, it cools and water vapor condenses to form clouds. Moisture is transported around the globe until it returns to the surface as precipitation, which enters a drainage system (a watershed) or infiltrates into the ground.

Kau The Hawaiian season (May through September) when the sun is more directly overhead, the weather is warmer, widespread rainstorms are rare, and trade winds (from the northeast and east) are most reliable.

King tide A term that describes an unusually high tide, usually the highest tides of the year. King tides may cause flooding on low-lying coastal lands.

La Niña A natural climate event, lasting typically less than 1 year, which occurs in the Pacific when the trade winds grow stronger than normal. This causes a body of warm water to accumulate in the western tropical Pacific and is an opposite state to El Niño.

Leeward Locations that are sheltered from the prevailing winds. In Hawai'i, leeward sides are typically the south and west shores of the islands.

Neutral A year in which ENSO conditions are neither in the El Niño or La Niña states.
North Pacific High An area of high atmospheric pressure to the northeast of Hawai'i that generates the trade winds.

North Pacific High A semi-permanent area of high atmospheric pressure where air sinks to the ocean surface and spins in a clockwise manner. It is located northeast of Hawaii and west of California. It is strongest during the northern hemisphere summer and shifts towards the equator during the winter. It is responsible for Hawaii's persistent trade winds.

Ocean Acidification The ongoing decrease in the pH of Earth's oceans, caused by the absorption of carbon dioxide (CO2) from the atmosphere. An estimated 30–40% of the carbon dioxide from human activity released into the atmosphere dissolves into oceans, rivers and lakes.

Orographic Rain Orographic rain occurs when humid air is forced upwards over rising terrain, such as a mountain, into colder air at higher elevations. Colder air can hold much less water vapor than the same volume of warmer air. Cooling air increases condensation, leading to the formation of clouds that yield rain

Sea level The average level of the surface of the ocean.

Sea-level rise When the average level of the surface of the ocean rises, especially as a result of global warming that melts glaciers (increasing the amount of water in the ocean) and warms the ocean (causing ocean water to expand, upwards).

Trade wind A wind blowing steadily toward the equator from the northeast in the northern hemisphere or the southeast in the southern hemisphere, especially at sea.

Trade Wind Inversion The trade wind inversion is the level at which cloud formation by orographic condensation ends because of overlying dry warm air. [1]

Tropics The tropics is a region on Earth surrounding the equator. Its northern extent is a line of latitude called the Tropic of Cancer in the Northern Hemisphere (23.43721°N) and its southern extent is a line of latitude called the Tropic of Capricorn in the Southern Hemisphere ((23.43721°S). The tropics region is characterized by warm temperature and humid conditions throughout the year.

Tropical cyclone A rotating system of strong winds, clouds and thunderstorms that produce heavy rain. Tropical cyclones are organized around a center, or eye, where there is low air pressure. Tropical cyclones cause storm surge and are responsible for severe damage where they make landfall in human communities.

Tropical Depression A tropical depression is an organized system of clouds and thunderstorms with a defined air circulation and maximum sustained winds of less than 39 miles (63 kilometers) per hour.

Tropical Storm A localized, very intense low-pressure wind system, forming over tropical oceans and with winds 39 to 73 miles per hour.

Variability The extent to which some occurrence changes frequently but then returns to an average state.

Weather The state of the atmosphere at a place and time with regard to heat, dryness, sunshine, wind, rain, clouds and other factors.

Windward Facing the wind or on the side facing the wind.

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1 The warm air is usually associated with the descending limb of a circulation cell known as the Hadley Cell, which originates in equatorial latitudes and transports moist warm air toward the poles. The descending limb of the Hadley Cell is located at approximately 30o latitude.

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Photographs

Page 1. Photograph of orographic clouds, Oahu, Hawai'i.
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Figure 4. Photograph of convective rain, Waimanalo, Hawai'i.
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Figure 5. Photograph of orographic rain.
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Figure 6b. Photograph of Mauna Kea.
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Figure 9. Maps of Pacific sea surface temperature during La Niña and El Niño.
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Figure 10. Three storms in the Pacific Ocean.
https://earth.nullschool.net

Figure 14. Elevation decrease on Greenland.
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Figure 15. Photo of flash flooding in Honolulu.
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Figure 16. Photo of Hurricane Iniki damage.
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Figure 17. Ocean acidification.
http://www.climatecentral.org/gallery/graphics/ocean-acidification-more-co2-more-acidic

Figure 20. Photo of reef scenarios.
Hoegh-Guldberg, O., et al., 2007, Coral reefs under rapid climate change and ocean acidification, Science 318.

Figure 21. Photo of bleached reef.
https://www.washingtonpost.com/news/energy-environment/wp/2015/10/08/scientists-say-a-dramatic-worldwide-coral-bleaching-event-is-now-underway/

Figure 22. Photo of coastal erosion.
Sea Grant College, University of Hawai'i

For more information about climate change in Hawai'i and globally, see the following publications:

1) 3rd National Climate Assessment, May 2014, U.S. Global Change Research Program, http://www.globalchange.gov/

2) Climate Change Impacts in Hawai'i, 2014, University of Hawai'i at Mānoa, Sea Grant College Program, http://seagrant.soest.hawaii.edu/CCIH

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