Future Climate Change:

Impact on Pacific Islands and Resources

Investigating Impacts of Projected Climate Change on Hawaii

October 23, 2013

- Begin Research

Plea from Director Kahuna of the Pacific Islanders Council on Climate Change

Welcome fellow scientist! We are in great need of your expertise and services. Our scientific director - Dr. Humuhumunukunukuku Apua'a or "Dr. Humu" as we call him - has gone missing. He was charged with investigating the potential future impacts of climate change on Pacific Islands and more specifically Hawaii and was collaborating with the Intergovernmental Panel on Climate Change (IPCC). Seems that he went out on one of his unannounced surfing adventures and hasn't been seen for days. He is always doing these things...

Anyway, one of our remote climate station attendants found his surf board on the beach with a huge bite mark!!! We fear the worst and have sent out a search crew, but Dr. Humu has pressing research that must be finished.

You have been selected to investigate the future impact of climate on Pacific Island environments and resources. This mission is critical given that millions of Pacific Islanders depend on your investigation and assessment of our collective futures. Do Pacific Islanders need to begin enacting drastic measures immediately to mitigate potential future climate change impacts to their islands...? Your investigation will help answer these questions.

There are two letters (links on the right) we found digging around Dr. Humuhumunukunukuku Apua'a's Hawaii lab that you need to read before embarking on your investigation. I hope these will give you some idea about the potential scope of the problem. Unfortunately, Dr. Humu's lab is such a mess we weren't able to find much else, so you will have to formulate your own

Lab Letters

Letter to Dr. Humu from the IPCC Director
Read letter >

Dr. Humu draft letter to Council warning about Climate Change
Read letter >

conclusions about global climate change and the potential impact to us Pacific Islanders.

Good luck!

Mr. Kahuna - Director of the Pacific Islander Council on Climate Change

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Chapter 1 - Overview of Climate Change

Introduction

Before embarking on your determination of the future impacts of climate change on Pacific islands and their resources, let us first look at the current state-of-understanding of past climate change. It is from this understanding of the past changes in climate that we can hope to have a better idea or be able to better predict what will happen in the future regarding climate.

What is climate change?

Climate change refers to a change in the average temperature, precipitation, winds, and other aspects of the climate system. Weather, on the other hand, describes the constantly changing atmospheric circulation (including storms and the hurricanes) on a daily to weekly basis.

Paleoclimate evidence from ice cores, tree rings, and other natural recorders reveals that large, abrupt changes in the Earth's past climate such as in temperature and precipitation have occured. The changes have occurred over decades to centuries, sometimes affecting small regions, entire hemispheres, or the entire globe. The past abrupt changes are massive compared to anything we have experienced since humans have been keeping records of climate for the past 150 years. What if these abrupt climate changes were to occur in the future? Would ecosystems that we count on be affected? How would humans adapt? These questions and concerns motivate a vigorous ongoing research effort to understand the changes of the past and eventually to predict future abrupt climate change.

Chapter 1 is divided into three sections:

- (A) Historical Climate Change,
- (B) Comparing Ancient to Current Climates, and
- (C) Has the Earth's Climate Changed Over the Past 1,000 Years?

For a brief introduction on climate and global warming, watch these NASA Videos (Real Player is necessary to view):

- Turning up the Heat &
- The Earth is Running a Fever

After watching these videos, proceed to A. Historical Climate Change

Chapter 1 - A. Historical Climate Change

Introduction

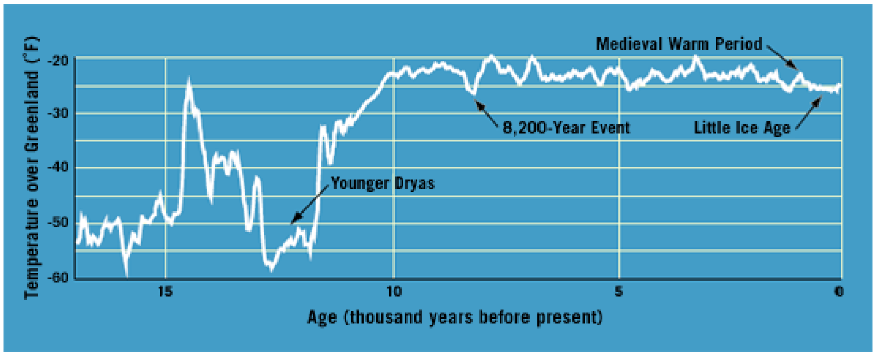
Measurements of climate using modern instruments have produced a record of the last 150 years or so. In order to reconstruct changes in the climate system further back in time than 150 years, scientists use natural archives of climatic and environmental changes, such as ice cores, tree rings, ocean and lake sediments, corals, and historical evidence. Scientists call these records "proxies" because, although the proxies are not usually direct measures of temperature or other climatic variables, they are affected by temperature. Therefore, the changes in the proxies preserved in the historical record can give us an idea of what the climate was in the distant past.

Climate Story

Climate has profoundly impacted and shaped the lives of humans over their entire existence. In turn, we humans, via our activities, have impacted local and regional climate and also now even perhaps the global climate. Beginning around 10,000 years ago, the Agricultural Revolution (which led to more abundant and easier obtained sources for food) and resultant growth in population altered the local and regional climate of many regions around the world including islands. For example, as huge tracks of forest were felled to make way for agriculture (in this example to grow crops) to support growing populations, the pre-Agricultural Revolution Mediterranean hydrological cycle and thus climate was altered from a wet to the present relatively dry climate.

In the past half-century, we humans have increased our monitoring of various aspects or indicators of climate change to understand further how climate not only changes, but also to predict what impact these changes might have on the world around us. One area of monitoring focus has been on greenhouse gases. Atmospheric levels of gases, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), and sulfate (SO_4) aerosols have all been sampled and concentrations recorded for the past half-century or longer. The measured increases in atmospheric concentrations of these gases and aerosols along with historical comparisons from proxy records have led the world's community – on local, regional, national, and international levels – to consider the potential climatic implications of past, current, and future increases in greenhouse gases.

There are many records of the Earth's past climate. The one below depicts the air temperature above Greenland for the past 20,000 years. Temperature is on the y-axis and years before present on the x-axis. The graph shows the last major glaciation of the "Younger Dryas" about 12,500 years ago (notice the large drop in temperature) followed by the subsequent relative warm period for the past 10,000 years. The "Little Ice Age", occuring around from 1550 to 1850 is a small deviation to colder temperature in an otherwise relatively warm era of the past 10,000 years. What have we humans done over the past 100 to 200 years to perturb this our Earth's climate system?



In this case study, we will investigate:

(1) the science behind how greenhouse gases change the climate;

(2) the evidence of how we humans have changed the greenhouse gas concentrations through our activities;

(3) our global response to reduce future climatic impacts from our acitivities; and

(4) the impacts of projected human-induced climate change on the islands of Hawaii and specifically Oahu.

Now proceed to B. Comparing Ancient to Current Climates

Lab 1: Temperature Trends

Do you find evidence for climate change with the following data set?

Self Check 1A

Click above to proceed to a self check on this chapter.

Climate and Water Resource Case Study

Chapter 1 - B. Comparing Ancient to Current Climates

Introduction

How can we compare climates of ancient Earth with our current climate? Well, on the short-term (say over the past 100-200 years) we can use instrument measurements (e.g. thermometer, rainfall gauge, tide gauge, etc.) that humans have recorded. However, to be able to compare present climate with those more distant in the past requires other methods (for example, the proxy records initially discussed in Chapter 1A).

Paleoclimatology is the study of climate prior to the widespread availability of records of temperature, precipitation and other instrumental data. We are really interested in the last few thousand years because this is the best dated, best sampled part of the past climatic record. So these past few thousand years can help us establish the range of natural climatic variability in a period prior to global-scale (not just regional scale such as the human impact on Mediterranean climate) human influence-change, which has only occurred since the last 100-200 years (e.g. since the industrial revolution).

Paleoclimate Proxies

Environmental recorders are used to estimate past climatic conditions and thus extend our understanding far beyond the 100+ year instrumental record. "Proxy" records of climate have been preserved in tree rings, locked in the skeletons of tropical coral reefs, extracted as ice cores from glaciers and ice caps, and buried in laminated sediments from lakes and the ocean.

Tropical Corals Reefs:

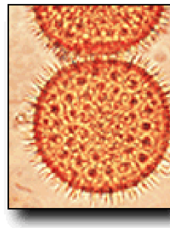
Corals build their hard skeletons from calcium carbonate ($CaCO_3$), a mineral created from dissolved calcium (Ca) and carbonate (CO_3) in sea water. The carbonate contains isotopes of oxygen, as well as trace metals, that can be used to determine the temperature of the water in which the coral grew long ago. These temperature recordings can then be used to reconstruct the climate at the time when the coral lived.

Learn more about the study of corals and past climate by visiting:

- NOAA's Coral Paleoclimatology Site.

Read the following sections at the site: (1) "Corals and the threat of global climate change" ; (2) "Collecting Coral Cores" - make sure you watch the quicktime movie of the coral sampling; and (3) "Data from a few reefs around the world".

Fossil Pollen:

All flowering plants produce pollen grains. The pollen grains distinctive shapes can be used to identify the type of plant that created them. Since pollen grains are well preserved when they sink and are buried in sediment at the bottom of a pond, lake or ocean, an analysis of the pollen grains in each layer of sediment tell us what kinds of plants were growing at the time the sediment was deposited. We can then make a good guess at what the climate was like when the pollen grain was buried based on the type of plant pollen found in each layer.

To learn more about fossil pollen and the past climate, please visit the following:

- Fossil Groups: Spores and Pollens, U.S. Geological Survey (USGS)

Read the section on "What are Spores and Pollen Grains?" How small are these spores and pollen grains?

Tree Rings:

Since tree growth is influenced by climatic conditions, patterns in tree-ring widths, density, and isotopic composition reflect variations in their surrounding climate. In temperate regions (regions where there is a spring, summer, fall, and winter) where there is a distinct growing season, trees generally produce one ring a year, and thus record the climatic conditions of each year. Trees can grow to be hundreds to thousands of years old and can contain single year records of climate for centuries to over a thousand years.

To learn more about tree rings and past climate please visit the following:

- Laboratory of Tree Ring Research at the University of Arizona

Read the section "Tree Rings Basics" at the University of Arizona site.

Ice Cores:

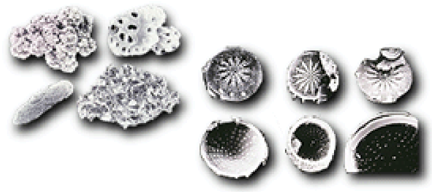
Located high in mountains and in polar ice caps, ice has accumulated from snowfall over many thousands to hundred of thousands of years. Scientists can drill through this deep ice and collect ice cores from areas in Greenland and Anarctica. These cores contain things such as dust, air bubbles, or isotopes of oxygen, that can be analyed to interpret the past climate of that area.

To learn more about ice cores and past climate visit the following site:

- The Secrets of the Ice: An Antarctic Expedition

Make sure to read the entire website.

Ocean & Lake Sediments:



Billions of tons of sediment accumulate at the bottom of the ocean and lake basins each year. Scientist drill cores of sediment from the basin floors and bring them back the surface to analyze. Ocean and lake sediments have imbedded in them tiny fossils that are used to interpret past climates.

To learn more about ocean & lake sediments can be used to determine past climate, please visit the following:

- Ocean Drilling Program- funded by NSF with 22 international partners
- IMAGES- International Marine Global Changes Study international collaboration

Now proceed to C. Has the Earth's Climate Changed Over the Past 1000 Years?

Lab 2: Time Cycles and Tree Rings

How to use tree rings to study time and climate.

Self Check B1

Click above to begin self check on this chapter.

Chapter 1 - C. Has Earth's Climate Changed over the Past 1000 Years?

Introduction

Beginning in the 1970's, paleoclimatologists (people that study the history of Earth's climate) began constructing a blueprint of how the Earth's temperature changed over the centuries before 1850 and the widespread use of thermometers. Out of this effort emerged an preliminary understanding of the last 1000 years of climate, based on the limited data from tree rings, historical documents, sediments and other proxy data sources. Today, over 25 to 30 years later, many more paleoclimate records are available from around the world, providing a much improved view of past changes in the Earth's temperature.

Boreholes and Past Climate

In the last few years, there has been a major breakthrough in our understanding of global temperature change over the last 400 to 1000 years. Several different but important studies, published in scientific journals, have revolutionized what we know about the 20th century in the context of the last six centuries.

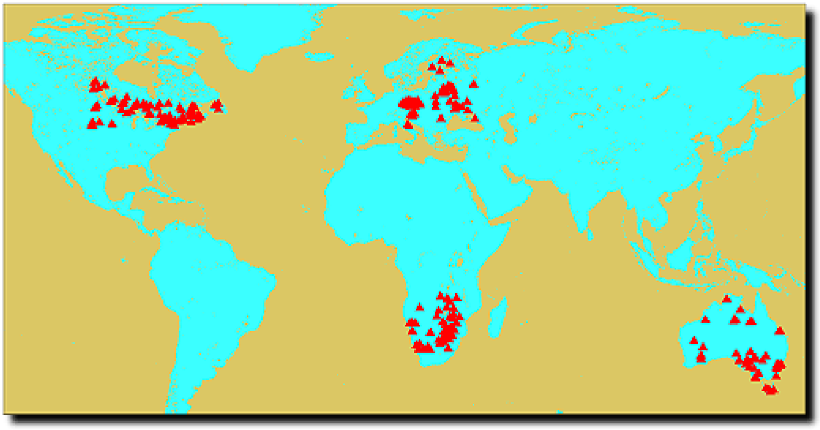
Although each of the temperature reconstructions are different (due to differing calibration methods and historical data used), they all show some similar patterns of temperature change over the last several centuries. Most striking is the fact that each record reveals that the 20th century is the warmest of the entire record, and that warming was most dramatic after 1920.

The similar characteristics among the different paleoclimatic records provides greater confidence in the following important conclusions:

- Dramatic global warming has occurred since the 19th century.
- The recent record warm temperatures in the 1990's are indeed the warmest temperatures the Earth has seen in at least the last 1000 years.

One of the more interesting recent studies of past climate uses boreholes. Dr. Pollack's research group at the University of Michigan recently constructed a climate record using totally different paleoclimate proxies than those used in many other studies. In their study, underground temperature measurements were examined from a database of over 350 bore holes (holes that are dug deep into the ground) in eastern North America, Central Europe, Southern Africa and Australia (see the figure below). Using this unique approach, Pollack's group found that the 20th century to be the warmest of the past five centuries, thus confirming the results of other earlier studies.

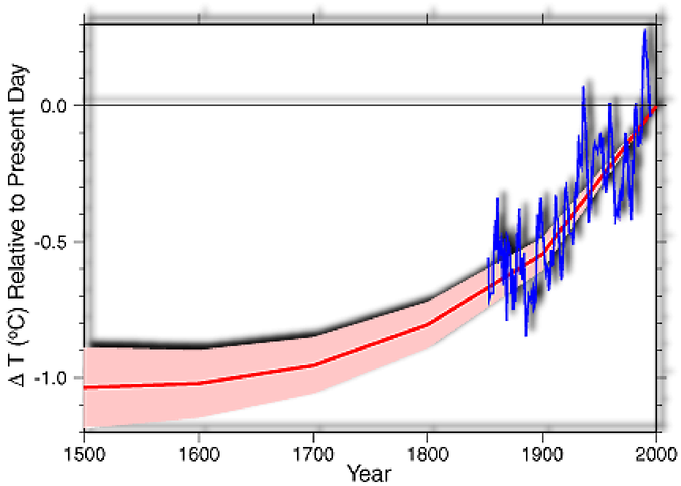
Figure. Location of boreholes used in temperature reconstruction.



LOCATIONS - POLLACK ET AL.

The methods used to generate bore hole temperature reconstructions do not permit annual (yearly) or decade (every 10 years) resolution, but only the century-scale (100 year) trend in temperatures over the last several centuries. Nonetheless, this record, totally independent of data and methods used in other studies, shows the same thing: the Earth is warming dramatically.

Figure. Temperature derived from borehole data (the blue line). The y-axis value is the difference in past temperature compared to present day temperature. The x-axis is the year in the past. The red line is an average past temperature constructed from many different types of proxy data. The pink area around the red line is the error associated with the data used to calculate the average temperature (red line).



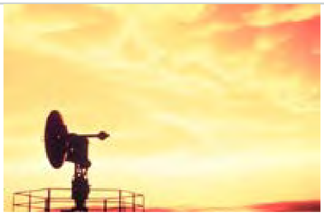
POLLACK RECONSTRUCTION

Now proceed to Chapter 2. Introduction: Greenhouse Effect and Climate Change

Self Check 1C

Click above to begin self check on this chapter.

Chapter 2 - Introduction: Greenhouse Effect and Climate Change



Introduction

Although the two words are sometimes used interchangeably, there are important differences between weather and climate. For a brief overview of these differences, click here.

Weather's variability occurs quickly, in the period of hours and days, and while extremes between high and low temperatures or abrupt storms can occur on such small time scales, they are influenced by longer-term climatic forces.

Scientists are finding that even with as much information as they have gathered about current and past weather and climates, it is difficult to predict weather beyond an 11 to 14 day time horizon.

Weather and Climate Factors

Weather and climate are influenced by a variety of factors such as:

- astronomical factors such as the tilt of the Earth's axis
- planetary albedo (reflectivity of the planet surface and clouds)
- fluctuations in solar energy (variation in energy output from the sun)
- the climate character of a region
- the time of year/season
- the time of day
- chemical composition of the atmosphere, both natural (for example changes due to volcanic activity) and anthropogenic (a fancy way of saying human) impacts such as heat from cities, agriculture practices, and the burning of fossil fuels.

There are many factors influencing climate variability and climate change. As an introduction to how future climate change will impact the Pacific Region and island states, we will briefly survey these factors.

Chapter 2 - A1. Climate System Forcings: Solar Energy

Introduction

There is a wealth of data on past climates. For example, you have seen already that deep sea sediments and ice cores provide proxies for long-term temperature records. By examining these proxies, the composition and chemical changes in atmospheric gases as well as temperatures of the planet can be determined during last the several hundred thousands of years. Cores of sediments and sedimentary rocks contain fossils that also provide insights to past climate. Analyses of tree rings provide records of precipitation, temperature, and soil moisture for the last several thousand years. It is from all these records along with our current understanding of atmospheric and oceanic science that we obtain our climate projections of the future. This section discusses the major factors that influence global climate change and global climate variability.

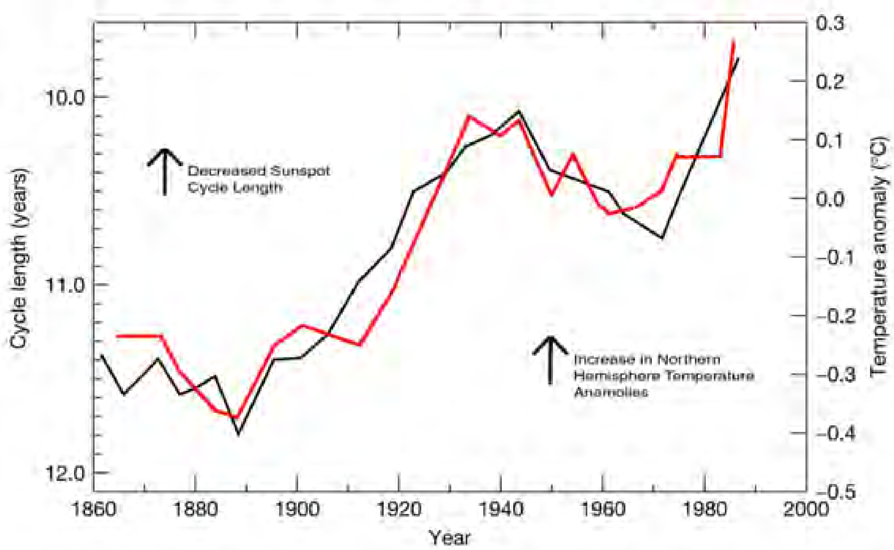
Climate System Forcings

At this point, it is necessary to discuss the difference between climate change and climate variability as often these terms are used interchangeably, which can confuse our discussion about the Earth's projected future climate. Climate variability refers to relatively short-term variations (months to years) in the natural climate system, such as the El Niño Southern Oscillation Cycle. Variability implies shifts about some mean point. Climate change (as used in the Intergovernmental Panel on Climate Change volumes) refers to long-term changes from decades to centuries that are associated with changes in concentrations of greenhouse gases. These changes are often viewed as unidirectional -- at least over relatively long time scales. Global climatic change involves unidirectional changes in climatic features over the entire globe and may either be amplified or lessened by climate variability. As an example, long-term climate change in the Pacific Basin may be amplified or lessened by the El Niño Southern Oscillation.

Fluctuations in Solar Energy

The amount of energy radiated by the sun fluctuates. For 500 years, astronomers have observed visible changes on the sun's surface such as sunspot activity. This sunspot record indicates that there is an approximately 11-year cycle in the number of sunspots visible on the sun's surface. Furthermore, when sunspots are in abundance, an increase in solar emissions from the darker sunspots and the sun's polar regions is observed. When sunspot activity is minimal, these solar emissions are less intense. This correlation between changes in sunspot activity and solar emissions has been confirmed by satellite observations over two complete sunspot cycles. Solar radiation that hits the top of the Earth's atmosphere has been measured to vary by 2.5 watts over the 11-year sunspot cycle. Such a change in incoming solar radiation could result in a variation of Earth's temperature by 0.1^{o} C in response to the 11-year variation in the intensity of the sun's radiation. The linkages between sunspot variation, the sun's strength, and the Earth's climate are uncertain at a decadal (every ten years) to century (every 100 years) time scale. It is interesting to note that there exists a significant correlation between the northern hemisphere land temperature record for the last 100 years and the length of sunspot cycle (Figure 1). In other words, decreased sunspot cycle length matches very well with increase in northern hemisphere temperature.

Figure 1. Correlation between the variation of the sunspot cycle length (solid dark line, left hand scale) and Northern Hemisphere land temperatures anomalies (red line, right hand scale) from 1861 to 1989. The temperature anomalies are the deviations in temperatures relative to the period of 1951 to 1980. Note that as the sunspot cycle length decreases, the temperature increases.


Decreased Sunspot Cycle Length
Increase in Northern Hemisphere Temperature Anamolies
Cycle length (years)
Temperature anomaly (°C)
Year
10.0
11.0
12.0
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
−0.5
1860
1880
1900
1920
1940
1960
1980
2000

Chapter 2 - A2. Climate System Forcings: Earth Orbital Parameters

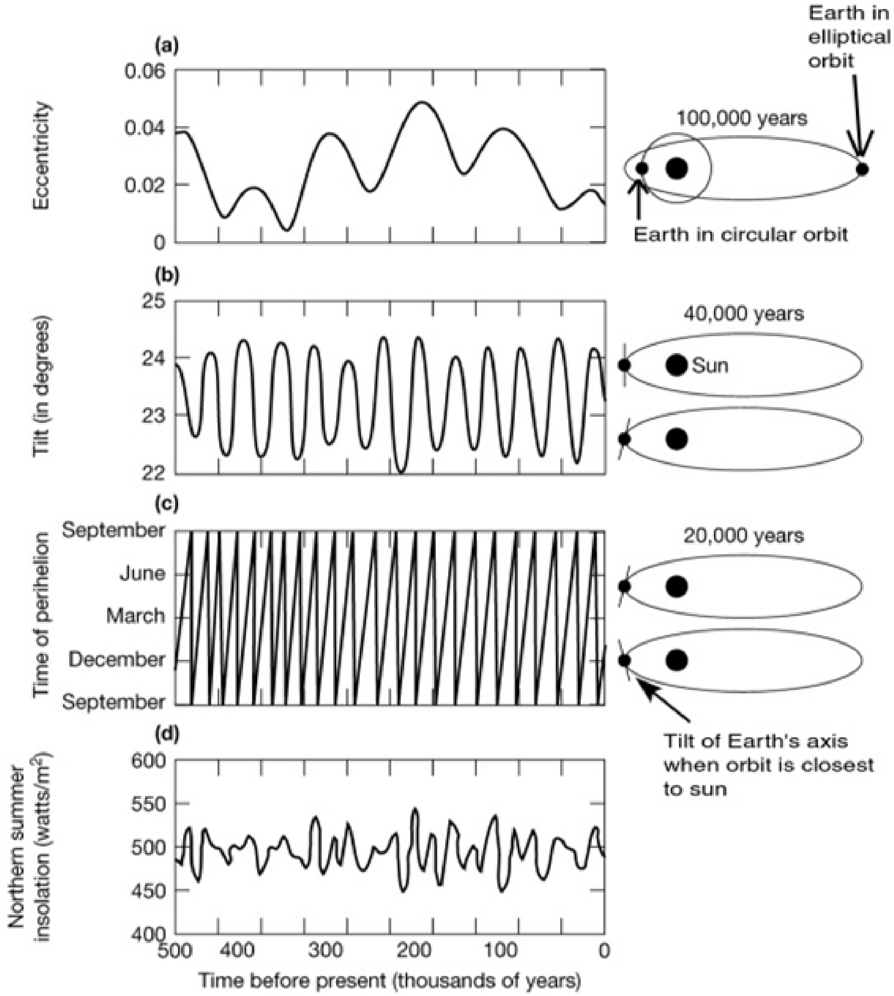
Introduction

There is a wealth of data on past climates. For example, you have seen already that deep sea sediments and ice cores provide proxies for long-term temperature records. By examining these proxies, the composition and chemical changes in atmospheric gases as well as temperatures of the planet can be determined during last the several hundred thousands of years. Cores of sediments and sedimentary rocks contain fossils that also provide insights to past climate. Analyses of tree rings provide records of precipitation, temperature, and soil moisture for the last several thousand years. It is from all these records along with our current understanding of atmospheric and oceanic science that we obtain our climate projections of the future. This section discusses the major factors that influence global climate change and global climate variability.

Orbital Parameters of the Earth

The amount of radiation received from the sun and its distribution on the Earth's surface varies with the relative position between the sun and the Earth. These natural variations in the Earth's orbit impact the planet's climate and appear to set the conditions for the cooler and warmer periods of glacial and interglacial (non-glacial) stages. Figure 2 depicts the three parameters that describe the Earth's orbit around the sun: (1) eccentricity, (2) axial tilt (or obliquity), and (3) time of perihelion (or precession). In 1920, Milutin Milankovitch proposed a theory that changes in climate cycles of glacial-interglacial periods were initiated by both the amount and the distribution of radiation received from the sun. Every 100,000 years or so, these orbital parameters vary in such a way to reduce the amount of sunlight energy received at midlatitudes in the northern hemisphere. This reduction in sunlight energy and is thought to lead to the onset of an ice age due to reduced warming of the Earth's surface.

Figure 2. Earth's orbital paramenters: (a) eccentricity, (b) tilt (c) time of perihelion, and (d) amount of solar radiation received in the Northern Hemisphere between 60 and 70 degrees as a function of these three parameters.



The Milankovitch theory of climate change during the last 1.6 million years theorizes that the onset of ice ages is due to variations in three orbital parameters of Earth. In Figure 2, the eccentricity (a) is the degree to which Earth's orbit departs from a circle. Times of maximum eccentricity are separated by roughly 100,000 years. The tilt angle (b) is the angle between Earth's axis and a line perpendicular to the plane of the orbit of the planet. The time of perihelion (c) involves the tilt of Earth's axis at its closest approach to the sun. The cycles of tilt and time of perihelion are roughly 40,000 and 20,000 years, respectively. The calculated amount of sunlight (d) received at 60^{o} to 70^{o} north latitude during the summer (summer insolation, July) is based on the cycles of variation of these three orbital parameters.

Chapter 2 - A3. Climate System Forcings: Planetary Albedo

Introduction

There is a wealth of data on past climates. For example, you have seen already that deep sea sediments and ice cores provide proxies for long-term temperature records. By examining these proxies, the composition and chemical changes in atmospheric gases as well as temperatures of the planet can be determined during last the several hundred thousands of years. Cores of sediments and sedimentary rocks contain fossils that also provide insights to past climate. Analyses of tree rings provide records of precipitation, temperature, and soil moisture for the last several thousand years. It is from all these records along with our current understanding of atmospheric and oceanic science that we obtain our climate projections of the future. This section discusses the major factors that influence global climate change and global climate variability.

Planetary Albedo

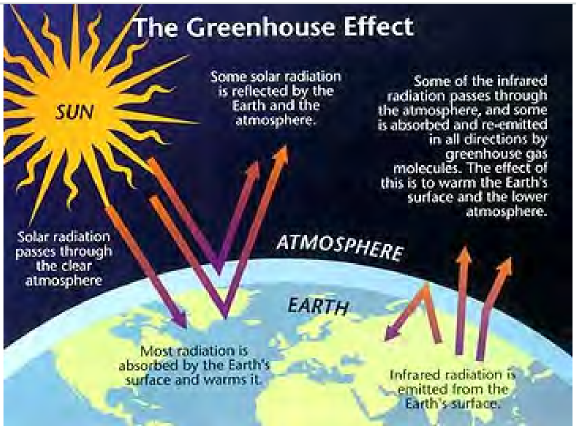
The albedo or reflectivity of the Earth's surface affects the planet's heat budget and thus the climate of the planet. Things such as, but not limited to, aerosols, clouds, ice, snow, water, land, plant surfaces, asphalt, and concrete all contribute to the Earth’s albedo. Aerosols are small airborne particles that can be derived from natural environmental sources – for example, volcanoes, wildfires, windblown soil dust, land and ocean emissions of biologically produced gases, and sea-salt spray – or they can be emitted from human sources – for example, spray cans, industry, etc. The size and distribution of the aerosols determine whether the surface temperature of the Earth increases or decreases. Generally, the larger the number of aerosol particles, the greater the aerosol cooling effect due to the increased amount of heat radiated or reflected back to space. Aerosols will be discussed in more depth in the next section of Chapter 2 - B. Greenhouse Effect.

Ice and snow surfaces have a very high albedo. When sunlight strikes ice or snow, most of the light and heat energy is reflected. Assuming other factors influencing climate are held constant, the greater the area of Earth’s surface covered by ice, snow, glaciers, sea ice, etc. the more energy is reflected back to space and the cooler the planet's climate. Deserts and other non-vegetated areas have albedos less than that of ice and reflect only half of the radiation they receive. Liquid water in oceans and lakes has a very low albedo and absorbs most of the radiation received and is warmed in the process. Land and aquatic plants absorb almost all incoming radiation. An increase of vegetation coverage with all other climate factors held constant would lead to an increase in the temperature of the planet.

Self Check on 2A1, 2A2, and 2A3

Click above to begin self check on sections A1, A2, and A3.

Chapter 2 - B1. Greenhouse Effect: Atmosphere Structure



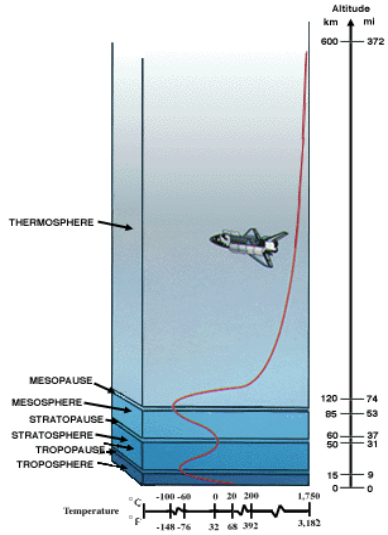
Introduction

The current concern about the greenhouse effect and climate stems from the amounts of greenhouse gases that are being released into the atmosphere from the burning of fossil fuels, deforestation, agricultural and industrial practices, release of synthetic chlorofluorocarbons, and other humankind activities. Accumulation of these heat-absorbing greenhouse gases in the atmosphere can result in an enhanced greenhouse effect and consequent global warming amplified by human activities. The concern is that an enhanced greenhouse effect may elevate global temperatures above levels that have not occurred for hundreds of thousands of years. The degree to which the accelerating rate of increase of greenhouse gases in the atmosphere will impact our climate is a topic of much debate and uncertainty because of the many variables that are involved in the climate system and their feedbacks.

Atmospheric Structure - Troposphere and Stratosphere

The global atmosphere extends 500 kilometers (310 miles) above the Earth's surface from the lower troposphere to the upper exosphere (Figure 3). The atmosphere has evolved ever since the Earth was formed and along with the ocean is responsible for heat being distributed throughout the globe and thus is a principal driver of climate and weather. Climate and weather have much in common, but are not the same. Weather is an everyday experience representing the sum total of atmospheric variables in a particular region for a short duration. Climate is a long-term composite of day-to-day weather conditions and atmospheric variables in a region. The atmospheric variables that drive climate and weather are solar energy, humidity, precipitation, atmospheric pressure, and wind currents. It is very important that you clearly understand the difference between the two, so for a more detailed discussion, go to the NASA website (click here).

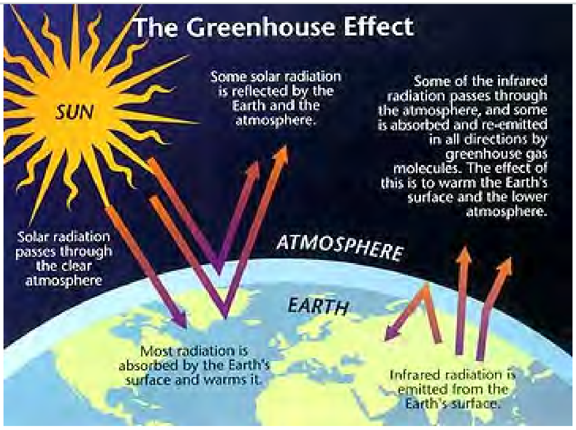
Figure 3. Atmosphere Structure. The red line is the atmospheric temperature in both Celsius (^oC) and Fahrenheit (^oF), which is measured on the x-axis. The y-axis is the altitude given in both miles (m) and kilometers (km).



The troposphere is the lowermost atmospheric region and it extends from the surface of the earth to about 12 kilometers above the surface. The tropospheric boundary layer is the lower 1 kilometer or so of the troposphere right above the Earth where mixing and frictional effects between the land and atmosphere are most dramatic. The troposphere is well-mixed due to the turbulence in this region caused by the radiant heating of the below earth's surface. In the lower troposphere, the air temperature is generally warmer near the surface and cooler above causing an unstable situation. The warmer, less dense (relatively light air compared to the colder denser air above) air rises and the cooler, more dense (relatively heavy compared to the warm air below) air wants falls towards the Earth's surface. Note in Figure 2 how the atmospheric temperature decreases from the earth surface to the troposphere/stratosphere boundary. In the troposphere, the weather system of clouds, surface winds, and water vapor circulates around the planet and is capped by the stratosphere.

The stratosphere extends from about 12 to 48 kilometers above the Earth. Ultraviolet radiation from the sun is absorbed and therefore blocked by ozone (O_3) in the top two-thirds of the stratosphere between approximately 24 to 48 kilometers. This region is the ozone layer that protects life on the planet from UV radiation. The overproduction of ozone by natural processes is kept in check by the destruction of ozone by solar radiation and gases. The absorption of ultraviolet light by ozone is what warms the upper two-thirds of the stratosphere, which is why in Figure 3 the temperature increases from the lower stratosphere to the upper stratosphere. It is actually as warm or even warmer in the upper stratosphere due to ultraviolet radiation absorption than it is at Earth's surface! This warmer mid-to-upper stratosphere then effectively "caps" the cooler lower troposphere, which is one reason why we have a habitable climate at the earth's surface.

Chapter 2 - B2. Greenhouse Effect: Atmosphere Energy Absorption



Introduction

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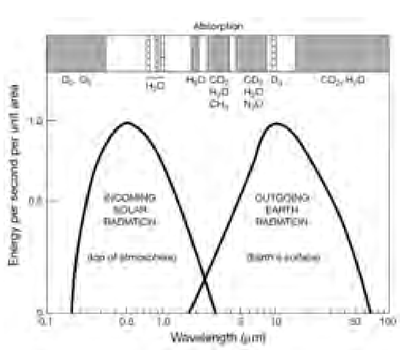
Atmospheric Absorption of Energy

The sun primarily provides the energy that drives the Earth's climate and weather by influencing atmospheric and surface processes (click here to see a related discussion of the Electromagnetic Spectrum - Box 1). The temperature of the surface of the sun is approximately 5480 ^{o}C and the radiation energy from the sun travels through space and impacts the Earth's atmosphere. This radiation energy is primarily in the form of visible, short wave (ultraviolet), and long wave (infrared) radiation. Some of the sun's energy is reflected back to space by the outer atmosphere, but the remainder of energy passes through the space-atmosphere boundary.

Figure 4. Illustration of relationship between radiation intensity and incoming solar radiation at the top of Earth's atmosphere and outgoing Earth radiation. (Note: Much of the incoming shortwave UV solar radiation is absorbed by oxygen (O_2 and O_3) in the upper atmosphere. The outgoing long wavelength radiation emitted by the Earth is partially to totally absorbed by the greenhouse gases of water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and tropospheric ozone (O_3).



The atoms and molecules that make up the atmosphere absorb the different types of radiation (visible, ultraviolet, and infrared) to varying degrees (see Figure 4). Oxygen, in the form of O_2 (diatomic oxygen) and O_3 (triatomic oxygen, ozone), is the most important absorber of incoming radiation in the atmosphere. High in the atmosphere, diatomic oxygen (O_2) absorbs radiation with wavelength less than 240 nanometers (240 x 10 meters) and at lower altitude ozone (O_3) absorbs radiation within the globally encircling stratospheric ozone layer with wavelengths mainly between 200 to 300 nanometers (200 to 300 x 10^{-9} meters). This incoming solar radiation is actually strong enough to break bonds holding the diatomic oxygen (O_2) and ozone (O_3) molecules together causing the molecule to split. Here are some equations representing those reactions.

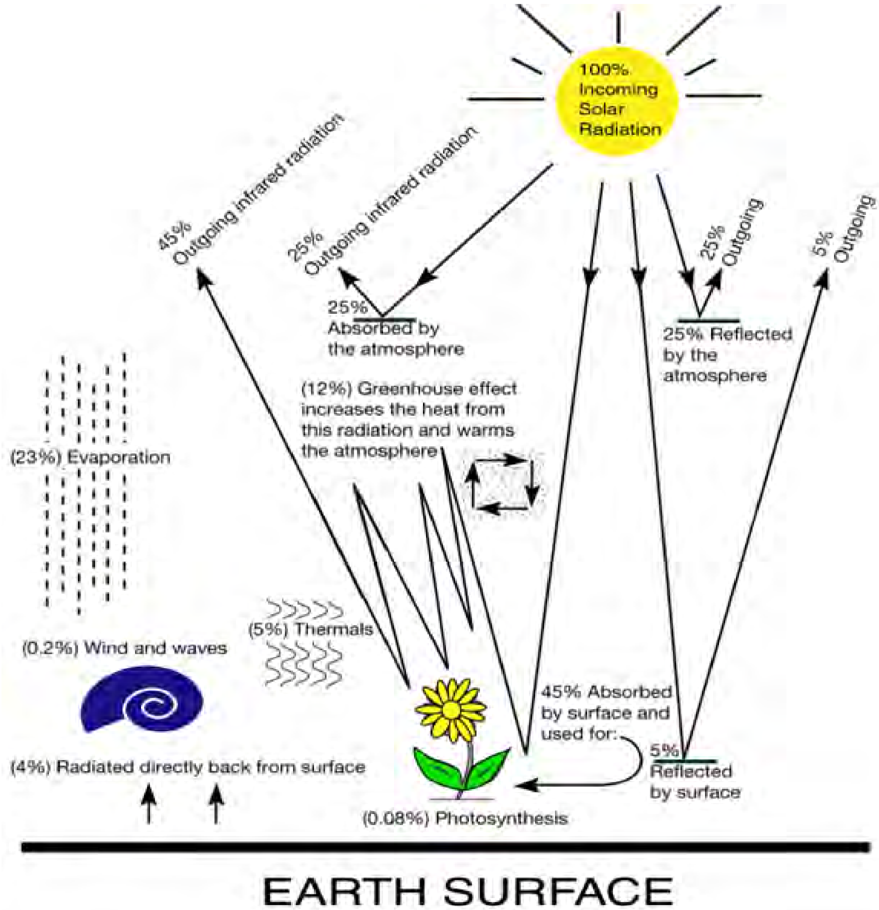
O_2 + solar radiation = O + O (1)

and

O_3 + solar radiation = O_2 + O (2).

Most ozone in the atmosphere occurs in the stratosphere. The absorption of solar radiation by ozone in the stratosphere is the source for heat in the stratosphere and mesosphere (see Figure 3). The ozone also absorbs and blocks most ultraviolet radiation below 300 nanometers. As solar radiation continues to penetrate the atmosphere and gets closer to the Earth's surface, it is scattered, reflected, and absorbed by air molecules, clouds, and various types of particles. Of the incoming solar radiation that hits the boundary between the Earth's atmosphere and outer space, about 30% is reflected back to space by atmospheric clouds and the Earth's surface, 25% is absorbed by the atmosphere and reradiated back to space, and 45% is absorbed by the surface of land and ocean (Figure 5). The temperature of the Earth's surface and lower atmosphere is higher than would be expected for a planet the distance of the Earth from the sun. This is because of the insulating qualities of the greenhouse gases in the Earth's atmosphere. When short wavelength radiation from the sun is not intercepted by the outer atmosphere or the ozone layer, it penetrates to the surface of the planet, is absorbed by the Earth's surface, and it is reradiated back as energy of a longer wavelength (infrared radiation) because the Earth is much cooler than the sun. Water vapor, carbon dioxide and other greenhouse gases absorb and trap this longer wavelength radiation leading to a natural warming of Earth's surface and the lower atmosphere (see Figure 6). So it important to realize that the greenhouse gases don't trap incoming short wave radiation, but rather the long wave radiation that is emitted by the Earth's surface due to absorbing the short wave radiation.

Figure 5. Earth's radiation budget. Incoming solar radiation is shortwave, ultraviolet, and visible radiation; outgoing Earth radiation is long wave infrared radiation.



The quantity of carbon dioxide residing in the atmosphere affects the amount of heat retained in the atmosphere and this in turn impacts climate. The more carbon dioxide (CO_2) in the atmosphere, everything else being equal, the warmer the climate will be. Nitrous oxide (N_2O), water vapor (H_2O, the most important greenhouse gas), methane (CH_4) and other gases have effects similar to those of carbon dioxide in controlling the amount of heat retained by the atmosphere. This overall process is the natural greenhouse effect. Without the naturally occuring greenhouse gases in the Earth's atmosphere, the planetary surface temperature would be –18 ^{o}C. This is 33 ^{o}C cooler than its present average of 15 ^{o}C (see Box 2: Solar and Earth Radiation and the Greenhouse Effect). If there were no naturally occuring greenhouse gases, the Earth would likely be entirely covered in ice and so life as we know it would not exist.

Chapter 2 - B3. Greenhouse Effect: Gas Concentration

Introduction and Overview
A1. Climate System Forcings: Solar Energy
A2. Climate System Forcings: Orbital Parameters
A3. Climate System Forcings: Planetary Albedo
B1. Greenhouse Effect: Atmosphere Structure
B2. Greenhouse Effect: Atmosphere Energy Absorption
B3. Greenhouse Effect: Gas Concentration
C1. Greenhouse Gases: Carbon Dioxide
C2. Greenhouse Gases: Methane
C3. Greenhouse Gases: Nitrous Oxide
D1. Greenhouse Gases: CFCs
D2. Greenhouse Gases: HFCs, PFCs, and SF_6
D3. Greenhouse Gases: Aerosols

Chapter 2 Labs

Lab 3: CO_2 used to school

Chapter 2 Self Checks

Self Checks: 2A1, 2A2, 2A3
Self Checks: 2B1, 2B2, 2B3
Self Checks: 2C1, 2C2, 2C3
Self Checks: 2D1, 2D2, 2D3

Course Reference Links

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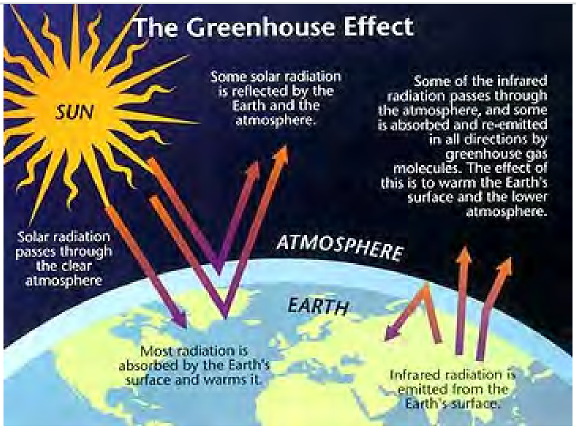

Introduction

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Atmospheric Gas Concentration

So how do we measure the quantity of carbon dioxide in the earth's atmosphere? An important concept in the discussion about greenhouse gases is concentration and it is the way we measure the quantity of gases in the atmosphere. Concentration is simply how much of a particular stuff is in all the stuff. Confused? Well, a simple example would be a mixture of brown and white rice grains. The brown rice concentration would be the number of brown rice grains divided by the total number of rice grains (brown grains plus white grains). Concentration can be given in a variety of units with mass and volume being most popular. A more technical definition is that concentration is calculated by the fraction of the total of a subsubstance made up of one component. Concentrations have a variety of units, but for our purposes one of the most important is parts per "something" where "something" usually is thousands, millions, billions, or trillions. The following abbreviations are used for these units:

ppm = parts per million by weight, mass, or volume

ppb = parts per billion by weight, mass, or volume

ppt = parts per trillion by weight, mass, or volume

Sometimes, there is a "v" that follows - e.g ppmv - which means parts per million by volume.

Self Check on 2B1, 2B2, and 2B3

Click above to begin self check on 2B1, 2B2, and 2B3.

Chapter 2 - C1. Greenhouse Gases: Carbon Dioxide (CO_2)

Introduction

Many chemical compounds found in the Earth's atmosphere act as "greenhouse gases." These gases allow sunlight to enter the atmosphere freely. When sunlight strikes the Earth's surface, some of it is reflected back towards space as infrared radiation (long wave radiation). Greenhouse gases, which allow the shorter wave radiation to pass through, absorb this longer wave infrared radiation. The absorption of the radiation causes the molecules of the greenhouse gases to vibrate more than they were, which then heats the atmosphere. Over time, the amount of energy sent from the sun to the Earth's surface should be about the same as the amount of energy radiated back into space by the Earth. This would result in the temperature of the Earth's surface roughly constant. Many gases in the atmosphere exhibit these "greenhouse" properties. Some of them occur in nature and are not human creations (for example, gases such water vapor, carbon dioxide, methane, and nitrous oxide), while others are exclusively human-made (for example, gases used for aerosols).

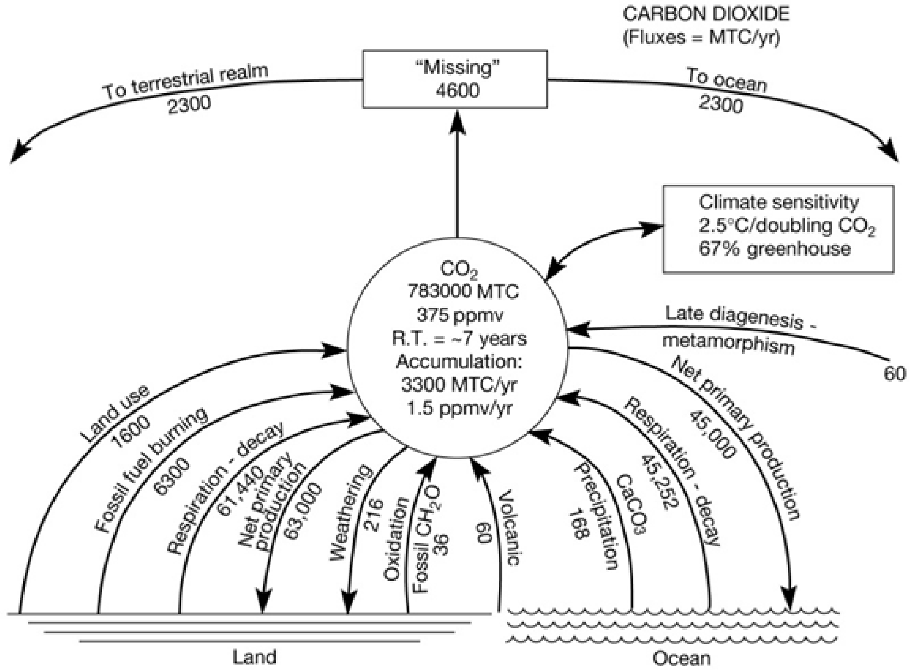
Greenhouse Gases - CO_2, CH_4, and N_20

In this first section studying greenhouse gases, we will investigate carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_20). All these gases contribute to the natural background greenhouse effect. They are also being impacted by human activities which results in a human-induced greenhouse forcing. It is important to understand that the total greenhouse effect is a combination of natural and human-induced forcings.

Carbon Dioxide - CO_2

The natural carbon cycle involves the cycling of carbon through the reservoirs of the lithosphere, hydrosphere, atmosphere, and biosphere over a wide range of time and space scales. Some of the processes involved in carbon cycling have gone on throughout most of the history of the planet and variations in some of the fluxes in the cycle are responsible for changes in atmospheric carbon dioxide. Figure 6 shows the processes (for instance fossil fuel burning) and their rates or fluxes (in the case of fossil fuel burning = 6300 million metric tons of carbon per year) that involve the transfers of carbon at the Earth's surface and alter the amount of carbon dioxide in the Earth's atmosphere.

Figure 6. Global biogeochemical cycle of carbon as carbon dioxide. Rates or fluxes (denoted by arrows) between land, ocean, and atmosphere reservoirs are in millions of metric tons of carbon (MTC) per year. The reservoir size of carbon dioxide is in millions of tons of carbon. The "Missing" is the amount of global CO_2 emissions taken up by the ocean and terrestrial realms. The relative amount of "Missing" uptake by ocean and terrestrial realm, split evenly in this representation, is still debated although it appears now that the terrestrial realm is a slightly bigger sink for the excess CO_2.

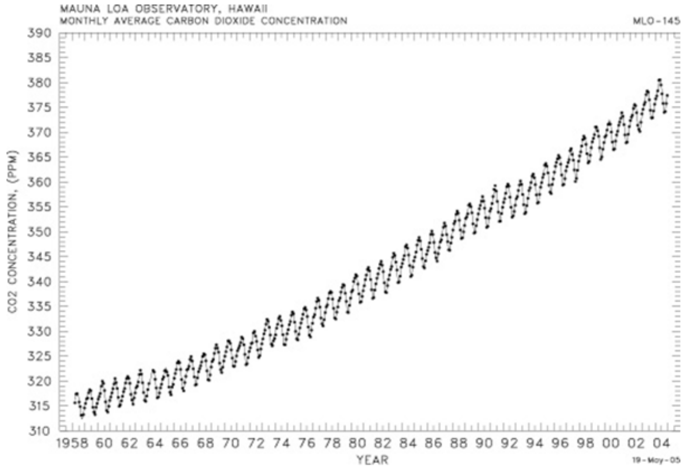


On short times scales – years to thousands of years – volcanoes, plants, animals, natural forest and grass fires, and decaying organic matter contribute carbon dioxide to the atmosphere. Photosynthesis takes carbon dioxide out of the atmosphere and stores it as carbon in the tissues of plants. Atmospheric carbon dioxide concentration has varied from about 200 parts per million by volume in recent glacial periods to 300 parts per million by volume during interglacial periods. So there is more carbon in the atmosphere during the warmer interglacial periods (300 parts per million) than during the cooler glacial period (200 parts per million). The warm Eemian-Sangamon interglacial period of 125,000 years ago had an atmospheric carbon dioxide content of 280 parts per million by volume while the Wisconsin ice age glaciation 18,000 years ago had an atmospheric carbon dioxide content of 180 parts per million by volume.

Fossil fuel burning is the major source of anthropogenic (this means human) produced carbon dioxide to the atmosphere. The world's use and reliance on this energy source will impact the composition of the atmosphere far into the twenty-first century. Carbon dioxide is also released to the atmosphere by land use practices such as deforestation, which has been occurring for the past 10,000 years. During the 1990s, an estimated 1 to 2 billion tons of carbon per year were put in to the atmosphere from land use practices. The carbon system is currently difficult to balance in terms of inputs and outputs (see "Missing" in Figure 6). Of great importance is to determine where all the carbon is going that is emitted from human activities. Of the 7.9 billion tons of carbon per year emitted by human activities in the 1990s, 3.3 billion tons remained in the atmosphere leaving 4.6 billions tons per year unaccounted. Scientists have now determined that the oceans and land biomass each take up roughly half of the 4.6 billion tons.

Charles Keeling of Scripps Institution of Oceanography in 1958 began a continuous sampling of atmospheric carbon dioxide at the Mauna Loa Observatory on the island of Hawaii (Figure 7). The trend in atmospheric carbon dioxide, supported by other like measurements at other locations around the world, demonstrates without question that in the past 50 years atmospheric carbon dioxide concentration has increased by more than 15%. Atmospheric carbon dioxide measurements (primarily from measurements of atmospheric gas composition taken from air bubbles trapped in ice cores many years ago and thus are a record of atmospheric carbon dioxide concentration at the time) demonstrate that atmospheric carbon dioxide levels have increased by 32% since pre-industrial time.

Figure 7. Mauna Loa CO_2 curve. The y-axis is atmospheric CO2 concentration and the x-axis is the year. Note how the concentration increases from 1955 at 315 parts per million to 2005 at around 375 parts per million. Also note the yearly saw-toothed up-and-down pattern caused by the photosynthesis and respiration of the Northern Hemisphere land biosphere - primary plants and trees. In the summer, global atmospheric CO_2 levels drop because of photosynthesis and uptake of CO_2 by plants and trees to make material in the northern hemisphere. In the winter, the global CO_2 levels rise because of respiration and decay of the plant and tree material by bacteria which converts plant and tree carbon into CO_2 which goes back into the atmosphere. These data are collected at the Mauna Loa observatory.



Lab 4: CO_2 used to school.

How much CO_2 would you use if you took a vehicle to school every day?

Chapter 2 - C2. Greenhouse Gases: Methane (CH_4)

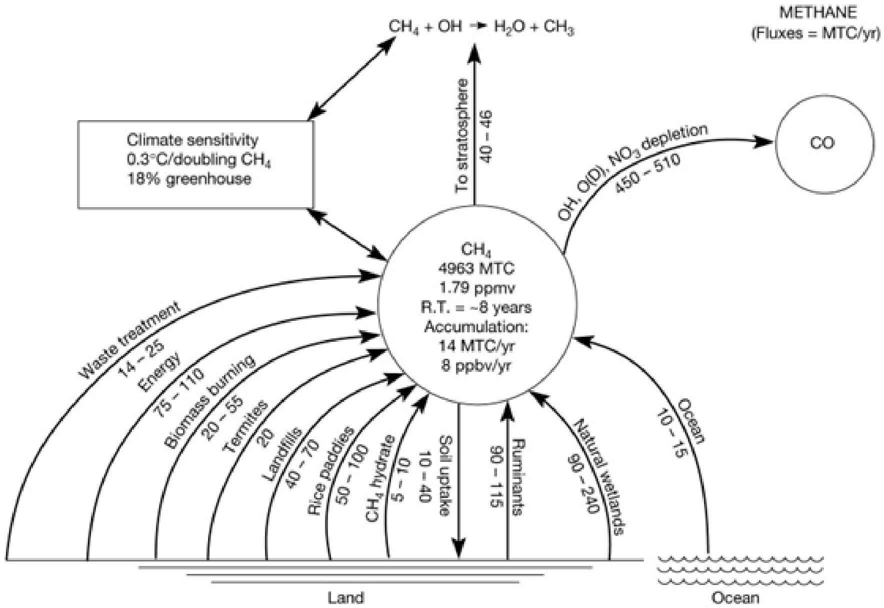
Introduction

Many chemical compounds found in the Earth's atmosphere act as "greenhouse gases." These gases allow sunlight to enter the atmosphere freely. When sunlight strikes the Earth's surface, some of it is reflected back towards space as infrared radiation (long wave radiation). Greenhouse gases, which allow the shorter wave radiation to pass through, absorb this longer wave infrared radiation. The absorption of the radiation causes the molecules of the greenhouse gases to vibrate more than they were, which then heats the atmosphere. Over time, the amount of energy sent from the sun to the Earth's surface should be about the same as the amount of energy radiated back into space by the Earth. This would result in the temperature of the Earth's surface roughly constant. Many gases in the atmosphere exhibit these "greenhouse" properties. Some of them occur in nature and are not human creations (for example, gases such water vapor, carbon dioxide, methane, and nitrous oxide), while others are exclusively human-made (for example, gases used for aerosols).

Methane - CH_4

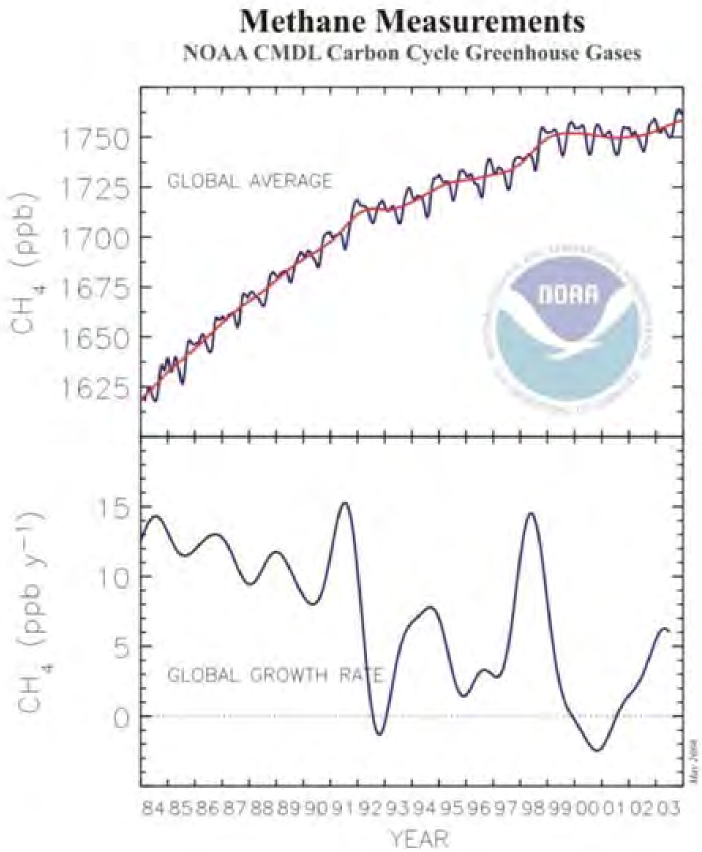
Methane (CH_4) is a very effective greenhouse gas. While its atmospheric concentration is much less than that of carbon dioxide, methane is 20 times more effective at trapping infrared radiation! The atmospheric residence time of methane is approximately 8 years. Residence time is the average time it takes for a molecule to be removed, so in this case for every molecule of methane that goes into the atmosphere it stays there for 8 years until it is removed by some process. The methane biogeochemical cycle is shown in Figure 8. The global processes and fluxes of methane are difficult to measure and thus the atmospheric sources and sinks are difficult to balance. It is estimated that up to 60% of the current methane flux from land to the atmosphere is from activities that are related to human society. Some of these activities include emissions from fermentation processes associated with livestock, from cultivated rice paddies, from fossil fuel and biomass burning, and from landfills. Methane concentrations have been increasing steadily for the past 200 years, although the rate of increase is declining. Over this time period, atmospheric methane concentrations have more than doubled (Figure 9).

Figure 8. The biogeochemical cycle of methane. Fluxes are in millions of tons of carbon per year, and the reservoir size of methane is in millions of tons of carbon.



Of future concern to the issue of global warming is the methane stored in cold environments such as peat bogs in tundra biomes and methane hydrates (frozen methane-ice compounds) found in permafrost regions and in sediments beneath the sea of continental margins. If the climate were to significantly warm, the methane tied up in these areas and forms could be released when those forms melt resulting in a positive feedback (a positive feedback is a process or mechanism that amplifies a change in a system) to global warming.

Figure 9. (Top plot) Global average atmospheric methane concentrations. The y-axis is atmospheric concentration of methane in parts per billion (ppb). The a-xis is the year of the measurement from 1984 to 2003. The red line is an average value line and the blue line is the actual measurement, which varies on yearly basis just like carbon dioxide. (Bottom plot) Methane growth rate which tells how much the concentration of methane increased year to year in the atmosphere. The y-axis is the yearly growth rate in parts per billion per year (ppb y^{-1}) and the x-axis is the year from 1984 to 2003. For example, 1991 and 1998 had increases in atmospheric methane of about 15 parts per billions per year.


Methane Measurements
NOAA CMDL Carbon Cycle Greenhouse Gases
GLOBAL AVERAGE
CH_4 (ppb)
1750
1725
1700
1675
1650
1625
NOAA
GLOBAL GROWTH RATE
CH_4 (ppb y^{-1})
15
10
5
0
84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 00 01 02 03
YEAR

Chapter 2 - C3. Greenhouse Gases: Nitrous Oxide (N_2O)

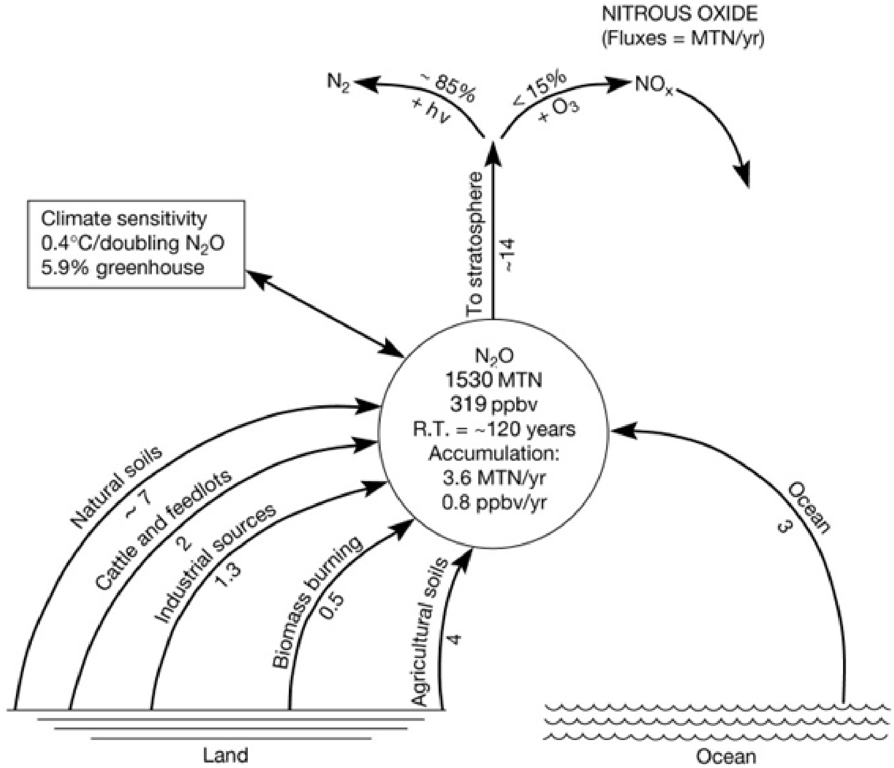
Introduction

Many chemical compounds found in the Earth's atmosphere act as "greenhouse gases." These gases allow sunlight to enter the atmosphere freely. When sunlight strikes the Earth's surface, some of it is reflected back towards space as infrared radiation (long wave radiation). Greenhouse gases, which allow the shorter wave radiation to pass through, absorb this longer wave infrared radiation. The absorption of the radiation causes the molecules of the greenhouse gases to vibrate more than they were, which then heats the atmosphere. Over time, the amount of energy sent from the sun to the Earth's surface should be about the same as the amount of energy radiated back into space by the Earth. This would result in the temperature of the Earth's surface roughly constant. Many gases in the atmosphere exhibit these "greenhouse" properties. Some of them occur in nature and are not human creations (for example, gases such water vapor, carbon dioxide, methane, and nitrous oxide), while others are exclusively human-made (for example, gases used for aerosols).

Nitrous Oxide - N_2O

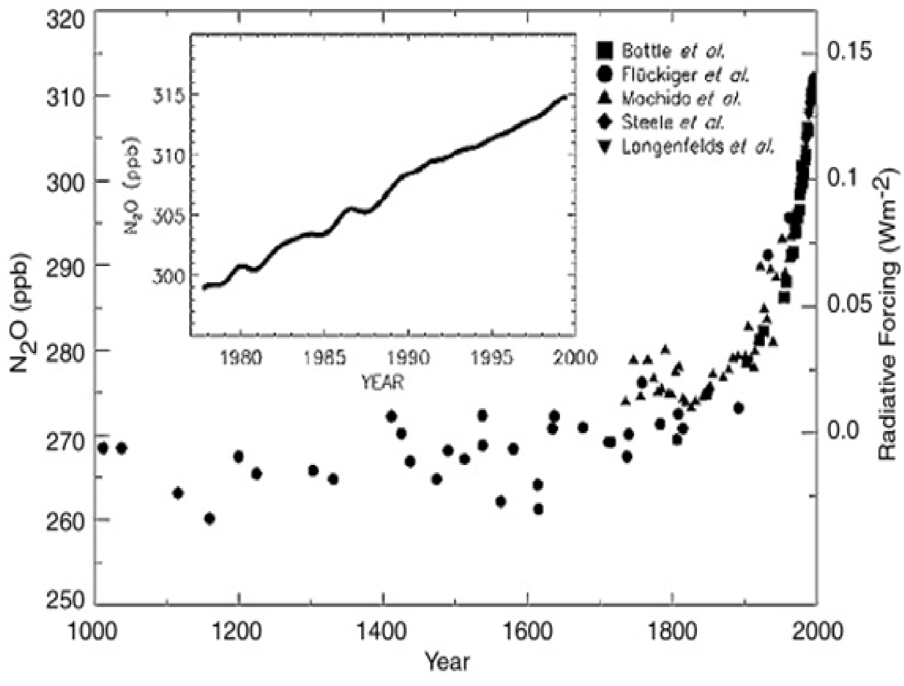
Nitrous oxide (N_2O) gas should not be confused with nitric oxide (NO) or nitrogen dioxide (NO_2). Neither nitric oxide nor nitrogen dioxide are greenhouse gases, although they are important in the process of creation of tropospheric ozone which is a greenhouse gas. There are several sources of nitrous oxide, both natural and anthropogenic (human), to the atmosphere with many of these sources difficult to measure. Because of this, there is general agreement that the atmospheric sources and sinks of nitrous oxide are difficult to bring into balance. Figure 10 shows the global biogeochemical of nitrous oxide involving transfers between Earth's surface and atmosphere.

Figure 10. The global biogeochemical cycle of nitrous oxide. The major processes and fluxes involve transfer of nitrogen as nitrous oxide between the atmosphere and the surface of the Earth. Fluxes are millions of tons of nitrogen (MTN) per year, and the reservoir size of nitrous oxide is in millions of tons of nitrogen.



Natural production of nitrous oxide is from microbial activity in soils and in the ocean and after nitrous oxide production by the microbes the gas goes to the atmosphere. Human production of nitrous oxide is primarily due to combustion of fossil fuels, biomass burning, industrial production of nitric acid, and application of fertilizers to agricultural crops. Nitrous oxide enhances the greenhouse effect just as carbon dioxide does by capturing reradiated infrared radiation from the Earth's surface and subsequently warming the troposphere (lower atmosphere). It is chemically inert in the troposphere and stays in the troposphere for about 120 years before moving into the stratosphere where it ultimately leads to destruction of stratospheric ozone. The atmospheric nitrous oxide concentration has been growing due to human activities (Figure 11).

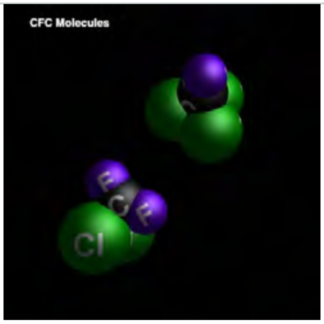
Figure 11. Atmospheric nitrous oxide concentrations over time. There are two plots of nitrous oxide concentration over time with the main plot from the year 1000 to the year 2000 and the subplot from about the year 1980 to the year 2000. The left y-axis for both plots is nitrous oxide concentration in parts per billion and the y-axis for both plots is the year. The right y-axis for the main plot is a measure of the warming effect [in Watts (W) per square meter (m^{-2})] of the nitrous atmospheric concentration. For example, an atmospheric concentration of 300 ppb warms the Earth by 0.1 Watts per square meter.



Self Check on 2C1, 2C2, and 2C3

Click above to begin self check on 2C1, 2C2, and 2C3.

Chapter 2 - D1. Greenhouse Gases: CFCs



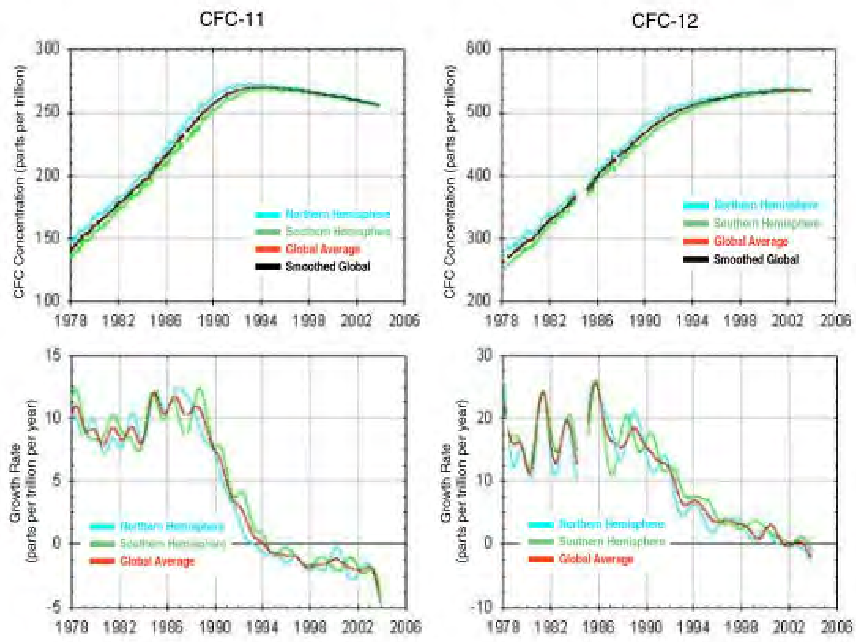
Introduction

Chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and aerosols are very important greenhouse gases. CFCs, HFCs, and PFCs are all human made and are not produced by any other process but our activities. Chlorofluorocarbons (CFCs) are nontoxic, nonflammable chemicals containing atoms of carbon, chlorine, and fluorine. They are used in the manufacture of aerosol sprays, blowing agents for foams and packing materials, as solvents, and as refrigerants. CFCs owe their existence to accidents that occurred in the early 1900s. Refrigerators in the late 1800s and early 1900s used the toxic gases, ammonia (NH_3), methyl chloride, and sulfur dioxide, as refrigerants. After a series of fatal accidents in the 1920s when methyl chloride leaked out of refrigerators, a search for a less toxic replacement begun as a collaborative effort of three American corporations - Frigidaire, General Motors, and Du Pont. CFCs were first synthesized in 1928 by Thomas Midgley, Jr. of General Motors, as safer chemicals for refrigerators used in large commercial applications.

Chlorofluorocarbons - CFCs

Halocarbons are the carbon-based compounds that contain chlorine, fluorine, bromine, or iodine. The compounds that only contain carbon, chlorine, and fluorine are called chlorofluorocarbons (CFCs). Chlorofluorocarbons are exclusively of industrial origin and have only been around for the past 60 years! Chlorofluorocarbons are exceptionally strong greenhouse gases and are also responsible for the destruction of stratospheric ozone. The most publicized of these compounds are those used as coolants in refrigeration and air conditioners, as propellants in spray cans and similar products, and as solvents for industrial purposes. Chlorofluorocarbons are far less abundant than carbon dioxide in the atmosphere, but they are 10,000 times more powerful as a greenhouse gas and can remain in the atmosphere for more than 45 to 100 years. Figure 12 shows the atmospheric concentrations of chlorofluorocarbons. Chlorofluorocarbons are regulated under the 1987 Montreal Protocol and are therefore not addressed in the 1997 Kyoto Protocol.

Figure 12. Two different CFC (CFC-11 and CFC-12) concentrations and growth rates from Northern Hemisphere (NH) and Southern Hemisphere (SH). Note the higher concentrations in the NH, the source of major emissions of CFCs to the atmosphere form human activities before the Montreal Protocol, relative to the SH and the decrease in the growth rate of the two gases in the atmosphere since the late 1980s. CFC concentration given in parts per trillion by volume (pptv).



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Chapter 2 - D2. Greenhouse Gases: HFCs, PFCs, and SF_6

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B1. Greenhouse Effect: Atmosphere Structure
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D1. Greenhouse Gases: CFCs
D2. Greenhouse Gases: HFCs, PFCs, and SF_6
D3. Greenhouse Gases: Aerosols

Chapter 2 Labs

Lab 3: CO_2 used to school

Chapter 2 Self Checks

Self Checks: 2A1, 2A2, 2A3
Self Checks: 2B1, 2B2, 2B3
Self Checks: 2C1, 2C2, 2C3
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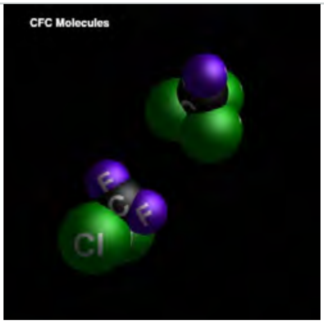

Introduction

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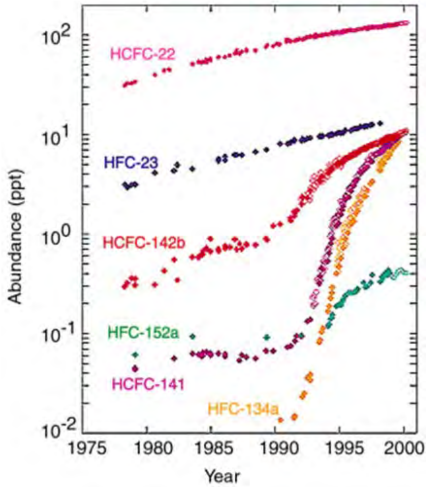
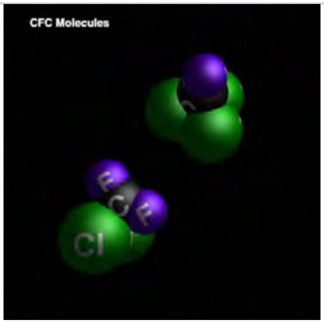
Hydrofluorocarbons - HFCs, Perfluorocarbons - PFCs, Sulfur Hexafluoride - SF_6

Hydrofluorocarbons (composed of hydrogen, fluorine, and carbon) and perfluorocarbons (composed of fluorine and carbon) have been created for industrial applications and been adopted as ozone safe replacements for chlorofluorocarbons and thus are growing in atmospheric concentration (Figure 13). Even though hydrofluorocarbons and perfluorocarbons are emitted in relatively small quantities, they have a disproportionate effect on the greenhouse effect. As a greenhouse gas, the most potent hydrofluorocarbons and perfluorocarbons are 11,700 times and 7000 to 9000 times per molecule as effective as a molecule of carbon dioxide, respectively. Also, perfluorocarbons have relatively long atmospheric lifetimes (up to 50,000 years). Rated as the most powerful greenhouse gas ever released to the atmosphere, sulfur hexafluoride is used as an electric insulator, heat conductor, and a freezing agent. In comparison to one molecule of carbon dioxide, the global warming potential of one sulfur hexafluoride molecule is approximately 24,000 times greater. Sulfur hexafluoride has now been banned from use due to its global warming potential.

Figure 13. Hydrofluorocarbons (HFCs) and hydrochlorofluorocarbons (HCFCs) atmospheric concentrations.. Concentrations given in parts per trillion (ppt).


HCFC-22
HFC-23
HCFC-142b
HFC-152a
HCFC-141
HFC-134a
Abundance (ppt)
10^2
10^1
10^0
10^{-1}
10^{-2}
1975 1980 1985 1990 1995 2000
Year

Chapter 2 - D3. Greenhouse Gases: Aerosols



Introduction

Chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and aerosols are very important greenhouse gases. CFCs, HFCs, and PFCs are all human made and are not produced by any other process but our activities. Chlorofluorocarbons (CFCs) are nontoxic, nonflammable chemicals containing atoms of carbon, chlorine, and fluorine. They are used in the manufacture of aerosol sprays, blowing agents for foams and packing materials, as solvents, and as refrigerants. CFCs owe their existence to accidents that occurred in the early 1900s. Refrigerators in the late 1800s and early 1900s used the toxic gases, ammonia (NH_3), methyl chloride, and sulfur dioxide, as refrigerants. After a series of fatal accidents in the 1920s when methyl chloride leaked out of refrigerators, a search for a less toxic replacement begun as a collaborative effort of three American corporations - Frigidaire, General Motors, and Du Pont. CFCs were first synthesized in 1928 by Thomas Midgley, Jr. of General Motors, as safer chemicals for refrigerators used in large commercial applications.

Aerosols

Aerosols are very small airborne particles, either liquid or solid, that can be produced naturally from volcanoes, wildfires, windblown dust of soils, land and ocean emissions of biologically produced gases, and sea-salt spray. The size and distribution of the aerosols are critical to their influence on climate and there is great spatial and temporal variability in aerosol concentrations. In addition, aerosols overall have short atmospheric lifetimes, which suggests that they should not be considered or relied upon to act in such a way as to offset long-term greenhouse warming. Generally speaking, the larger the number of aerosol particles, the greater the amount of the sun's radiation is reflected back in to space and thus aerosols most likely produce a cooling effect on climate. Aerosols can cool by (1) reflecting incoming radiation back to space, and (2) serving as cloud condensation nuclei for certain cloud types that reflect radiation back to space.

An example of the global cooling effect that aerosols can have on climate is the 1815 eruption of Tambora volcano in Indonesia. The dust and aerosol produced by the eruption entered the stratosphere and reduced the solar radiation reaching the planet. In 1816, because of late snows and continuous rains, Europe experienced a year without a summer. The cool conditions continued in Europe for three years after the eruption resulting in massive crop failures, subsequent starvation, and near collapse of society in Europe.

Biological emissions of sulfur gases from the land and ocean surface also can lead to creation of aerosols in the atmosphere and hence affect climate. These emissions are dominated by dimethylsulfide (DMS), hydrogen sulfide (H_2S), and carbonyl sulfide (OCS). The biogenic gases can be oxidized to sulfur dioxide gas in the atmosphere and then to sulfate aerosol.

The major source of cloud condensation nuclei in the atmosphere above the ocean is dimethylsulfide gas escaping the sea surface. The magnitude of the dimethylsulfide flux is related to ocean (via phytoplankton) primary production and bacterial degradation of the organic products derived from primary production. One hypothesis put forth related to the feedback between dimethylsulfide emissions and climate is that if the Earth warms, then phytoplankton production will increase. This increase would lead to an increased flux of dimethylsulfide to the atmosphere, which in turn would result in more formation of sulfate aerosols and thus cloud condensation nuclei. The increased production of cloud condensation nuclei and therefore degree of cloudiness would lead to reflection of solar radiation and hence to cooling of the atmosphere (specifically the troposphere). This is a negative feedback (a negative feedback is a process or mechanism that diminishes a change in a system) to global warming.

Industry, biomass and fossil fuel burning and the resultant emission of sulfur dioxide can lead to formation of sulfate aerosols that contribute to tropospheric sulfate aerosols (Figure 14). These aerosols potentially could have a cooling effect on climate. It has been argued that the enhanced anthropogenic emissions of sulfur dioxide to the atmosphere, especially in the northern hemisphere, have helped cool the planet during the twentieth century. If this is true, the cooling effect may have offset part of the expected temperature increase owing to anthropogenic emissions of greenhouse gases to the atmosphere, especially over industrialized areas (Figure 15).

Figure 14. Earth surface-atmosphere global biogeochemical cycle of oxidized sulfur species. Sulfur dioxide (SO_2) released from the land surface to the atmosphere reacts with hydroxyl radical (OH) to form sulfate (SO_4) aerosol. Sulfate aerosol, directly or indirectly, potentially exerts a cooling influence on the climate. Flux values are in units of million tons of sulfur per year. Note how large the combustion flux (due to human activities) is compared to the natural process of volcanism, which is the emission from volcanic activity.

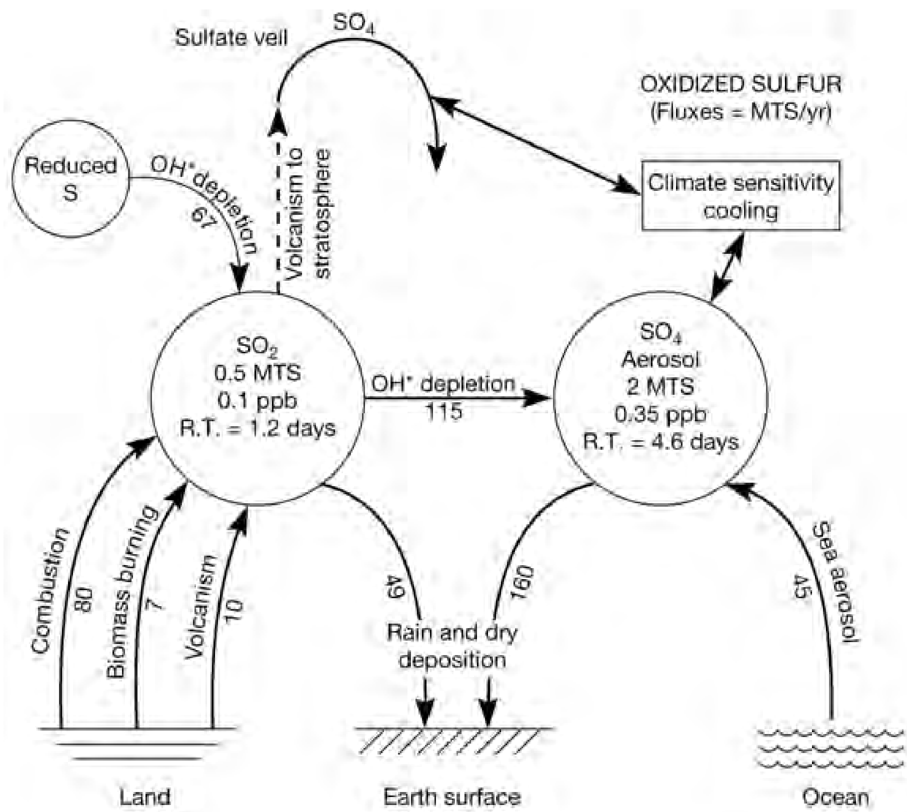
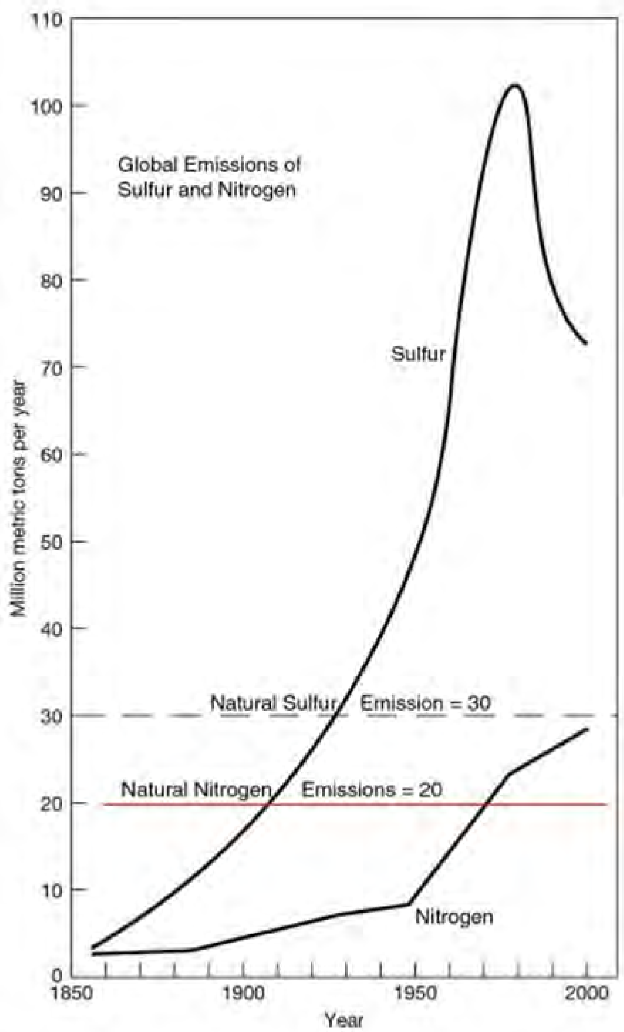


Figure 15. Annual anthropogenic global emissions of sulfur and nitrogen as SO_x and NO_x to the atmosphere from the burning of fossil fuels, and for sulfur from the smelting of sulfide ores from 1860 to 2000. An estimate of the natural biological sulfur flux (dashed line) and natural nitrogen flux (red line) to the atmosphere is given for comparison.



Summary

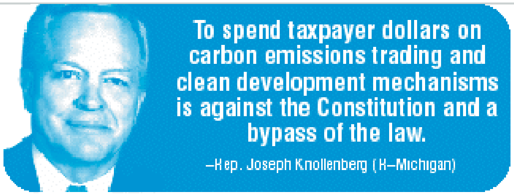
The current concern about the greenhouse effect and climate stems from the amount of greenhouse gases that are being released into the atmosphere from the burning of fossil fuels, deforestation, agricultural and industrial practices, release of synthetic chlorofluorocarbons, and other humankind activities. Accumulation of these heat-absorbing greenhouse gases in the atmosphere can result in an enhanced greenhouse effect and consequent global warming induced by human activities. The concern is that an enhanced greenhouse effect may elevate global temperatures above levels that have not occurred for hundreds of thousands of years. The degree to which the accelerating rate of increase of greenhouse gases in the atmosphere will impact our climate is a topic of much debate and uncertainty because of the many variables that are involved in the climate system and their feedbacks.

In an effort to determine what effects these human-induced changes to greenhouse gas concentrations could have on climate, sophisticated computer models have been developed by the scientific community and are continually refined. In 1990, 1995, and 2001 the Intergovernmental Panel on Climate Change released three reports intended to provide information on not only how climate has changed over human times, but also how it might change in the future, and given the range of projected future change, what would be the resultant impacts – e.g., environmental, economic, social, political, etc. – for the world's population. The climate forecasts in these reports are based upon the projections from large-scale global climate models. The first two Intergovernmental Panel on Climate Change reports, and their climate forecasts, led to the 1997 Kyoto Protocol, which is discussed in the next chapter - Chapter 3.

Self Check on 2D1, 2D2, and 2D3

Click above to begin self check on 2D1, 2D2, and 2D3.

Chapter 3 - What is the world doing about climate change?



Introduction

As evidence was building that we humans were altering our environment and even perhaps the climate, many nations of the world decided to begin addressing these issues through the United Nations. The **United Nations Framework Convention on Climate Change** (**UNFCCC** or **FCCC**) is an international environmental treaty produced at the United Nations Conference on Environment and Development (UNCED), informally known as the Earth Summit, held in Rio de Janeiro in 1992. The treaty aimed at reducing emissions of greenhouse gas in order to combat global warming.

The treaty as originally framed set no mandatory limits on greenhouse gas emissions for individual nations and contained no enforcement provisions; it is therefore considered legally non-binding.

Rather, the treaty included provisions for updates (called "protocols") that would set mandatory emission limits. The principal update is the Kyoto Protocol, which has become much better known than the UNFCCC itself.

Kyoto Overview

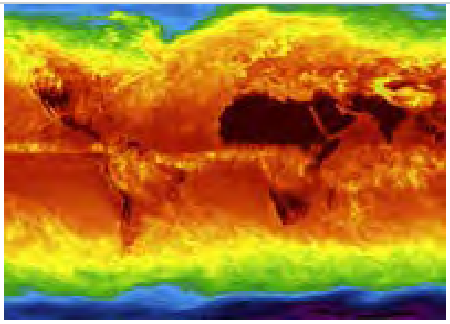
The Kyoto Protocol is an amendment to the United Nations Framework Convention on Climate Change (UNFCCC). Countries that ratify this protocol commit to reduce their emissions of carbon dioxide and five other greenhouse gases, or engage in emissions trading if they maintain or increase emissions of these gases.

The objective of the Kyoto Protocol is the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system".

The Intergovernmental Panel on Climate Change (IPCC) has predicted an average global rise in temperature of 1.4°C (2.5°F) to 5.8°C (10.4°F) between 1990 and 2100 (click here to see the report). Some current estimates indicate that even if successfully and completely implemented, the Kyoto Protocol will not provide a significant reduction in temperature despite the large cut in emissions. Because of this, many critics and environmentalists question the value of the Kyoto Protocol, should subsequent measures fail to produce deeper greenhouse gas emission cuts in the future.

Proponents also note that Kyoto is a first step (click here to read article), as requirements to meet the UNFCCC will be modified until the objective is met, as required by UNFCCC Article 4.2(d).

Chapter 3 - A. Kyoto Protocol



Introduction

The average temperature of the earth's surface has risen by 0.6 degrees C since the late 1800s. It is expected to increase by another 1.4 to 5.8 ^{o}C by the year 2100 -- a rapid and profound change. Even if the minimum predicted increase takes place, it will be larger than any century-long trend in the last 10,000 years.

The principal reason for the increase in global temperature is a century and a half of industrialization: the burning of ever-greater quantities of oil, gasoline, and coal, the cutting of forests, and the practice of certain farming methods.

These activities have increased the amount of "greenhouse gases" in the atmosphere, especially carbon dioxide, methane, and nitrous oxide. Such gases occur naturally -- they are critical for life on earth; they keep some of the sun's warmth from reflecting back into space, and without them the world would be a cold and barren place. But due to increasing quantities the greenhouse gases are pushing the global temperature to artificially high levels and thus altering the climate. The 1990s appear to have been the warmest decade of the last thousand years.

Kyoto Protocol

In an effort to mitigate (meaning to reduce or make less severe) many of the problems associated with human-induced amplification of the greenhouse effect and climate change, including the impacts on island nations and states, the United Nations Framework Convention on Climate Change (UNFCCC) was adopted and opened for signing in 1992 at the Rio Earth Summit. The convention called for signatory countries to strive to return their individual CO_2 emissions back to 1990 levels by the year 2000 and also established the Conference of Parties (COP). The United States refused to make the terms of the agreement legally binding. In 1994, it was decided that the Convention would enter into force 90 days after the receipt of the 50th ratification. In 1995, the first Convention of Parties (COP-1) took place in Berlin with delegates agreeing that the United Nations Framework Convention on Climate Change proposed greenhouse reductions commitments were inadequate, but no agreement was reached over new emission targets. The Intergovernmental Panel on Climate Change climate scientists released their Second Assessment Report in 1995 and these findings become a major impetus for negotiations that eventually resulted in the 1997 Kyoto Protocol.

The 1997 Kyoto Protocol is a legally binding international agreement that commits signatory countries to reducing their global emissions of greenhouse gases. The Kyoto Protocol becomes legally binding when ratified by 55 nations and in addition that these nations represent 55% of the 1990 carbon dioxide emissions by the 39 industrialized countries. As of mid-2004, 122 countries representing 44% of the total 1990 carbon dioxide emissions had signed the protocol. There were thus more than enough countries that had ratified the agreement for it to go into effect, but these nations did not represent 55% of the 1990 carbon dioxide emissions. At that time, both the United States and Russia had not ratified the Kyoto Protocol and one of the two nations needed to ratify it before the 55% of the 1990 carbon dioxide emission goal could be met and the Kyoto Protocol would become a globally binding agreement. This is because of these nations' relative contributions to the 1990 carbon dioxide emissions (United States = 36% of 1990 emissions; Russia = 17% of 1990 emissions).

In 2001, the United States stated it would not sign the agreement – even though the U.S. government accepts climate change as a fact – because of the restrictions it felt the protocol placed on industry and world economic growth.

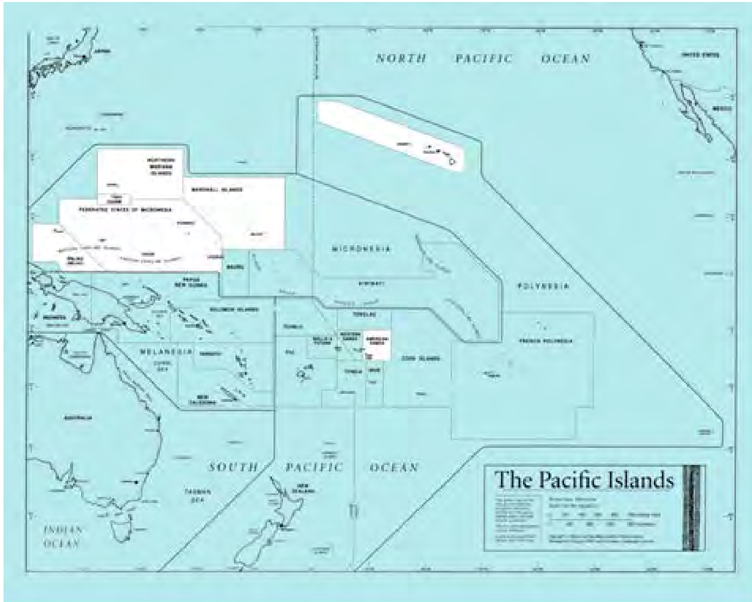
The U.S. instead is promoting policies meant to support new and emerging energy and climate protection technologies. Russia initially indicated it would sign the agreement, retracted that promise, and then sent mixed signals about its intentions. It too, as the U.S., took the stance that if the Kyoto Protocol was enacted, it would retard future economic growth. In a turn of events though, Russia announced in late 2004 that they were going to ratify the agreement. On November 18, 2004 the 90 day countdown to the Kyoto Protocol's entry into force was triggered by the receipt of the Russian Federation's instrument of ratification by the United Nations Secretary-General. The Protocol became legally binding on its then 128 Parties on February 16, 2005. The developing countries are not included within the protocol, despite the fact that greenhouse gas emissions from these countries will exceed those of the developed, industrialized world by 2010. The Kyoto Protocol requires that the 39 industrialized nations involved in the protocol reduce their greenhouse gas emissions by a specified annual percentage of their 1990 emissions by 2008-2012. The average overall reduction is targeted to be approximately 5%, but the percentages vary from country to country – e.g., U.S. is 7%, European Union is 8%, New Zealand is no change. Australia and New Zealand are allowed to increase their emissions by 8 and 10%, respectively. As of May 2006, the United States has yet to sign the Kyoto Protocol.

The emissions of the following six gases are included in the protocol: carbon dioxide (CO_2), nitrous oxide (NO_x), methane (CH_4), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). Each country's emission limit is based on a greenhouse forcing-weighted sum of the six gases, which takes into account the relative impact and abundance that each of the six gases has on global warming. Sinks for gases are also included in the protocol. An example is that if a country demonstrates that carbon is being stored in its forests because of planting trees, this carbon storage will be entered as a negative value into the country's net emissions counting as a reduction and credit against emissions. Because the protocol will influence most major sectors of the world economy, it is considered to be the most far-reaching agreement on environment and sustainable development ever adopted.

The 1997 Kyoto Protocol, based on the 1990 and 1995 Intergovernmental Panel on Climate Change (IPCC) reports, is necessarily global in scope. The regional effects of a future enhanced greenhouse effect on climate variables of temperature, precipitation, storm variability, and on sea level rise, etc. are difficult to resolve with global models due to their course spatial resolution. In other words, the global climate models look at large global space scale changes and do not have the resolution to look at regional and local effects. An analogy would be that if you are taking pictures of a beach, your camera (the global climate model) will be able to resolve the beach (the global climate space scale), but not the individual grains of sands (regional and local climate space scale). So, in conjunction with global models, regional models have to be constructed that can not only take into account global processes, but also regional to local one to resolve changes on the regional space scale.

In 2001, The Pacific Islands Regional Assessment Group (PIRAG) on behalf of the U.S. Global Change Research Program (USGCRP) published the report *Preparing for a changing climate: The potential consequences of climate variability and change*. The Pacific Islands Regional Assessment Group focused on the consequences of climate variability and change on the American Flag Pacific Islands including Hawaii, Guam, American Samoa and the Commonwealth of the Northern Mariana Islands (CNMI), and the U.S.-affiliated Pacific Islands, which include the Federated States of Micronesia (FSM: Yap, Pohnpei, Kosrae and Chuuk), the Republic of the Marshall Islands (RMI), and the Republic of Palau (Figure 16).

Figure 16. Pacific Island Map.



In the Pacific Islands Regional Assessment Group report, the effects of changing climate on sea-surface temperatures, precipitation, and sea level in the Pacific region were modeled using two models: the Canadian Center for Climate Modeling and Analysis (CGCM1) and a similar general circulation model used by the United Kingdom's Hadley Centre for Climate Prediction and Research (HADCM2). The CGCM1 and HADCM2 results were compared to two model results (A2 and B2) generated by the Intergovernmental Panel on Climate Change *Special Report on Emission Scenarios* (SRES). Both of these models are capable of resolving regional scale processes, which makes them useful for discussing future climate impacts on Pacific Islands.

Lab 5 : How many automobiles?

How many automobiles?

Lab 5 : Calculate emissions

Calculate your personal greenhouse gas emissions using this calculator

Self Check 3A

Click here to begin self check on 3A.

Chapter 4 - Investigating Regional and Local Projected Change

Introduction

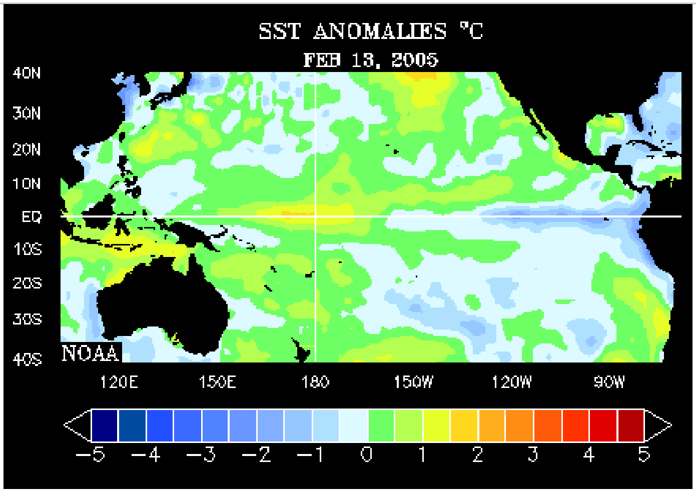
The Pacific Islands Regional Assessment Group report discussed the results of the two regional climate models that look approximately 100 years into the future. These models use a future greenhouse-gas emission scenario which is equivalent to a 1% rate of annual increase in carbon dioxide and a commensurate changes in sulfate aerosols for the century. The rate of carbon dioxide emission increase is based on rates of observed emission increases modified by estimates of how the current sources of emissions are likely to change in the future; as such, it is deemed plausible as a “business as usual” case with little policy intervention anticipated in the future from world governments to stop emissions.

Carbon dioxide increases in these two models cause warming by limiting outgoing long-wave radiation from the Earth’s surface in the absence of a simultaneous reduction of incoming solar radiation. Increases in sulfate aerosol concentrations produce a net cooling over regions where sulfur emissions are greatest, generally corresponding to industrial regions in the midlatitudes of the northern hemisphere. The effect of the sulfate aerosols, which is the reflection of solar radiation back away from the Earth’s surface, is taken into account in these two models. The radiative forcing (radiative forcing is the change in the balance between radiation coming into the atmosphere and radiation going out) of sulfate aerosols resulting in cooling is less than the forcing of carbon dioxide and thus warming of the globe is projected for the future.

Since the results from both models were generally consistent, we will only focus on the Hadley HADCM2 results. The HADCM2 results were also compared to the two model runs (A2 and B2) described in the Intergovernmental Panel on Climate Change *Special Report on Emission Scenarios*. These Intergovernmental Panel on Climate Change models represent an average of nine “state-of-the-science” global, coupled climate models from groups in the U.S., Canada, Germany, Australia, U.K., and Japan.

Two time periods (2025-2034 and 2090-2099) were projected using the HADCM2 model to study future changes in temperature, rainfall, storminess, and sea level for the Pacific region. The 2025-2034 results are termed “short-lead” and the 2090-2099 results are termed “long-lead”. The long-lead results are more speculative than the short-lead results. During these two time periods, there were two seasons analyzed [December-January-February (DJF) and June-July-August (JJA)]. These months were chosen because they represent two seasonal extremes.

Chapter 4 - A. Sea Surface Temperature



Introduction

With global climate models, it is possible to project how future increases in atmospheric greenhouse gas concentrations will impact sea surface temperatures (the top few meters of ocean that are in contact with the atmosphere). It is much more difficult to predict how the ocean's temperature will vary below the sea surface because this has to do with global ocean circulation.

As you can see from the above animated figure, sea surface temperature varies in a complex way. Note that this animation shows the sea surface temperature anamoly and not the actual sea surface temperature. The anamoly is how much the temperature varies or is different from an average value. For instance, if the average temperature in Honolulu in May is 75^{o} C and the temperature on May 10th is 77^{o} C, then the anamoly is +2^{o} C for May 10th. The sea surface temperature anamoly is dependent upon many factors such as how much sunlight energy is being received at the earth's surface (solar insolation).

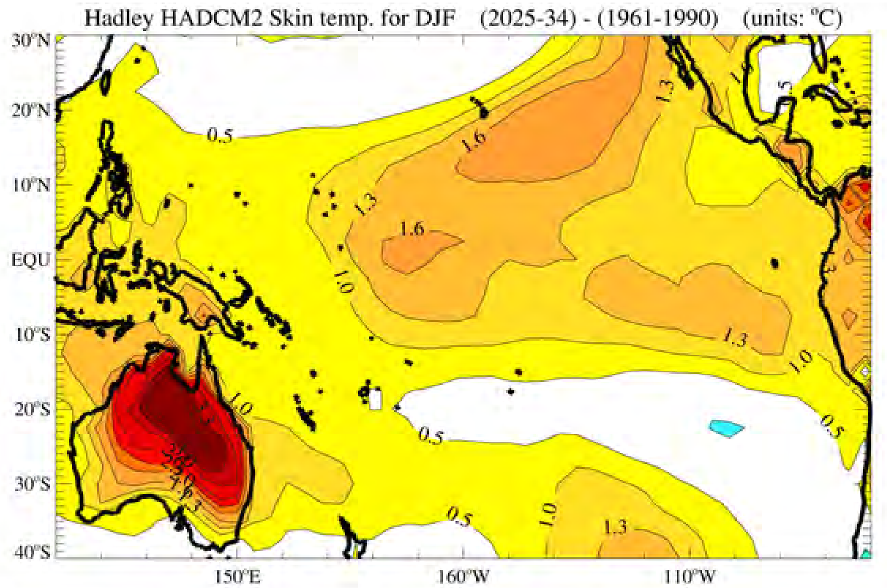
Seasonal changes in solar insolation (the change in the distance and angle between the sun and the earth cause the change in solar insolation, which is discussed in Chapter 2) vary the amount of incident radiation (which heats the water) the surface of the ocean receives and also the large scale atmosphere circulation (high and low pressure systems). These large scale atmospheric pressure cells can alter how water moves around the Pacific ocean and thus how heat is distributed (see section on El Niño and La Niña for more discussion).

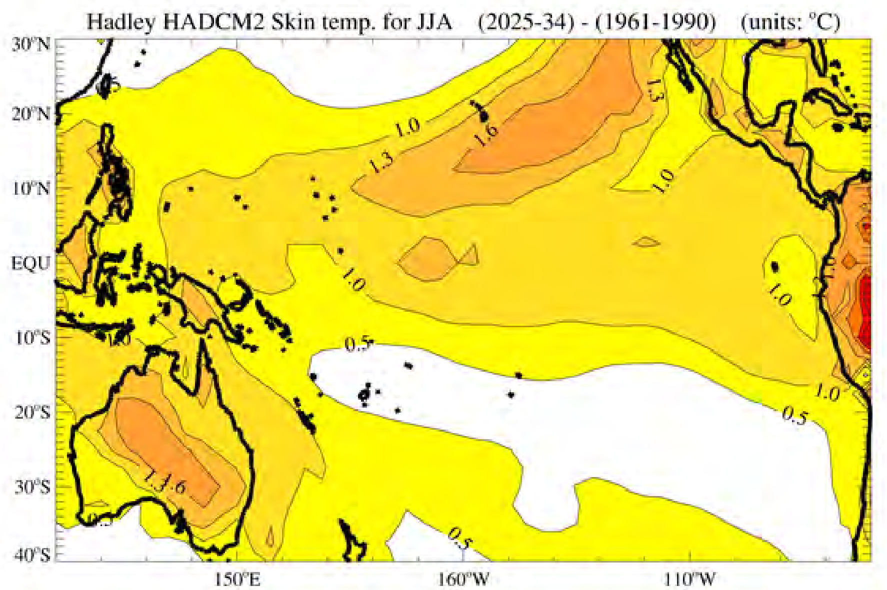
The Sun's Radiation and Sea Surface Temperature

Gradual warming of the sea-surface temperature (SST) and the air temperature near the sea surface is projected to occur for both the short and long-term results (Figure 17). The projected increase is about 1^{o} C (1.8^{o} F) for 20 to 45 years. Looking at the projections, warming will be greatest in the following Pacific regions: (I) along and slightly south of the equator extending from the international dateline on the west to the South American coast on the east and (II) east-northeastward from the equatorial Central Pacific to the United States-Mexico border and the southwest coast of the United States. Note the warming in the equatorial East Pacific, which is projected to be greater during the peak El Niño season of December-January-February.

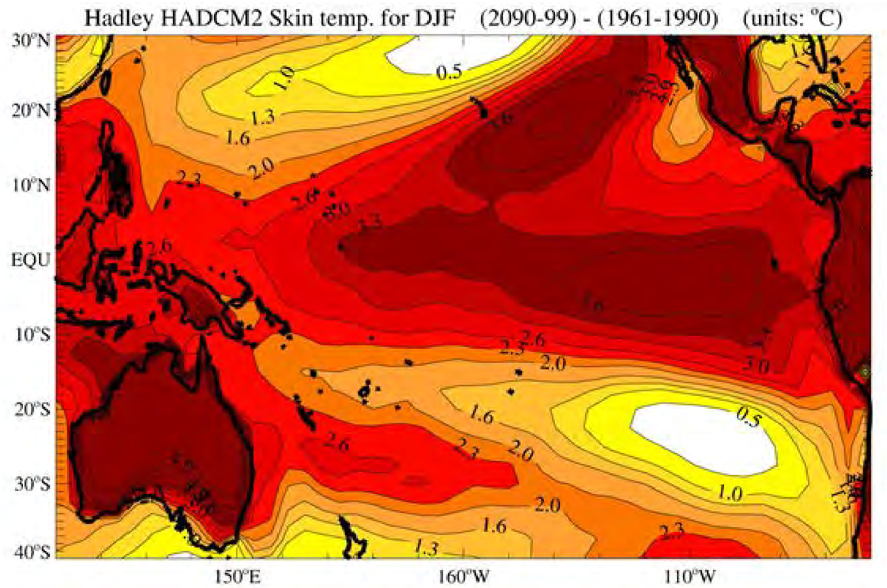
Figure 17. Projected changes in skin temperature (SST over ocean and surface–air temperature over land) difference for (A) the short-term results (the model's 2025-2034 average minus the 1961-1990 base period average) and (B) the long-term results (2090-2099 average minus the 1961-1990 base period) for the seasons December-January-February and June-July-August, in ^{o} C.

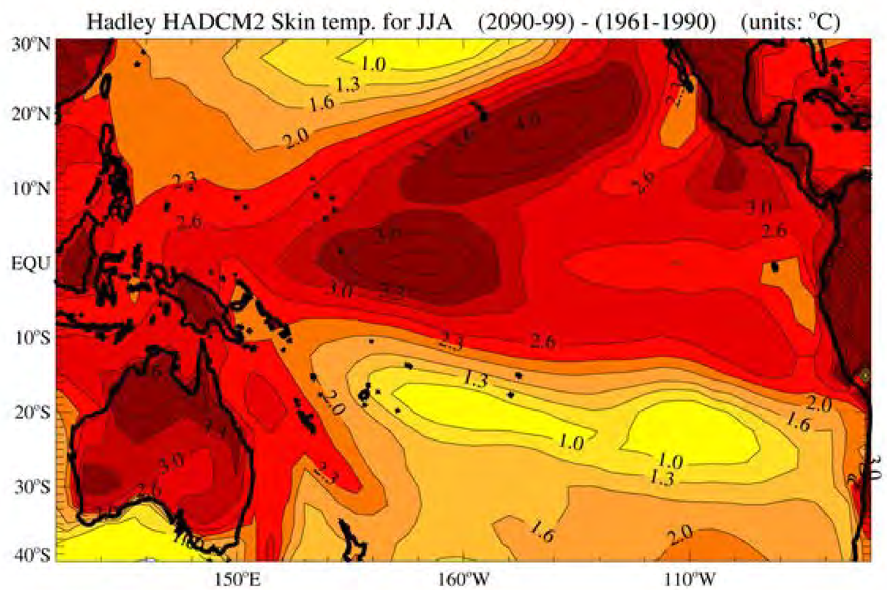
(A)





(B) Long-term results (2090-2099)





Self Check 4A

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Chapter 4 - B. Rainfall

Introduction

Precipitation, in this case rain, is the primary source of fresh water to Pacific islands. Without this precipitation, islands would be unihabitable and unable to support humans. In the past 5 years in parts of Hawaii, especially the more northern major islands of Kauai and Oahu, there has been episodes of consistent and heavy rainfall over long periods - e.g. November, 2003 through February 2004 and January 2005 through April 2005. While this intense rain is critical to the long-term habitability of the islands, it also can cause many problems such as flooding, property damage, sewage spills, beach closings, road damage, crop damage, etc. that can be expensive. Long-term climate change can alter regional and local seasonal precipitation patterns. Global and regional climate models attempt to project how future changes in temperature, atmospheric gas composition and content, cloud cover and other earth surface and atmosphere properties will impact rainfall patterns. We will now look at such projections for the Hawaiian Islands.

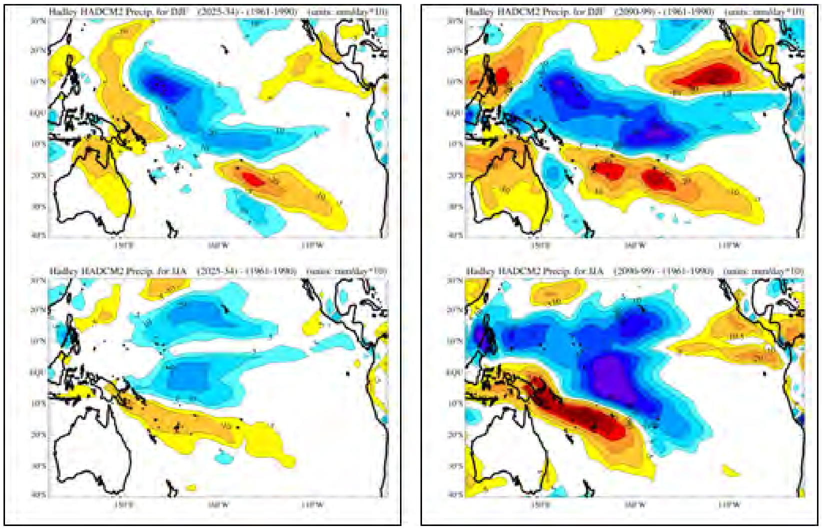
Climate Changes and Rainfall

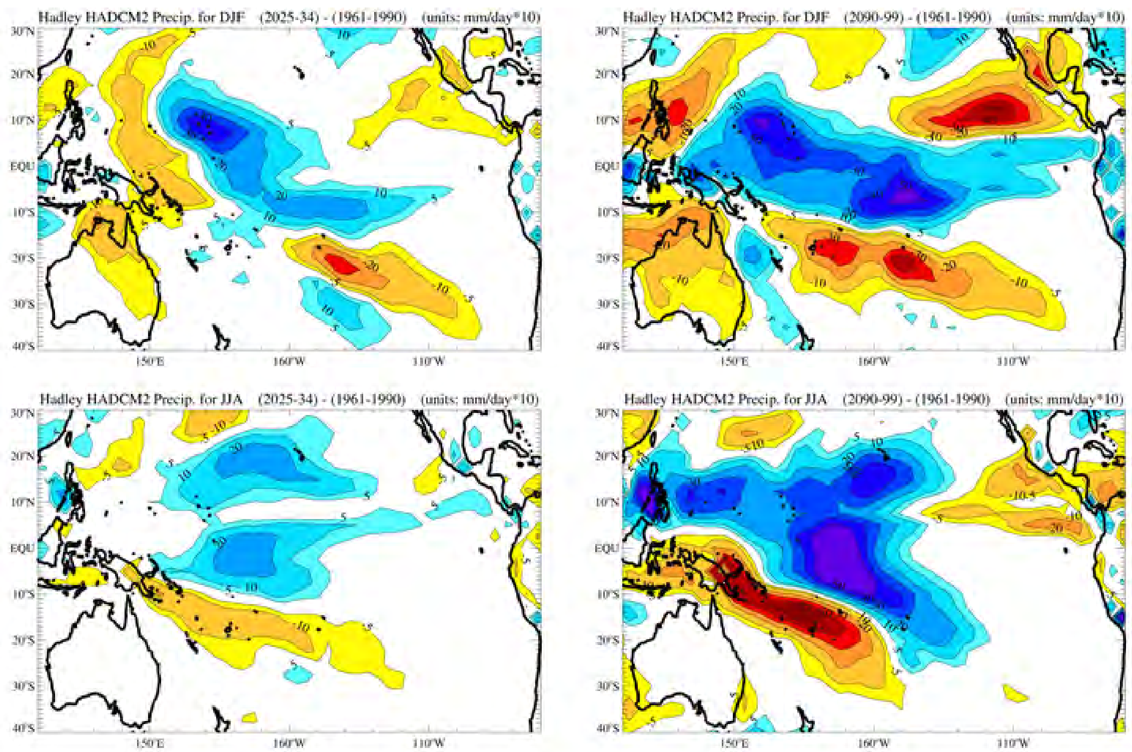
With the projected increase in temperature from the climate models comes increased precipitation due to the fact that warmer water produces more moisture and the atmosphere above a warmer ocean surface can absorb and hold more moisture. This is why warmer areas with available moisture are humid, such as the Hawaiian Islands. The equator around the dateline is the most likely candidate for increased precipitation since the sea-surface temperature is warm enough to support convection and thus cumulus cloud growth and precipitation. Increased sea-surface temperature in these areas would result in more convection and rainfall.

Convection refers to the process of cloud formation and precipitation associated with areas where warm tropical air rises through the atmosphere and, as it expands and cools, leads to the formation of clouds. As a results, weather patterns tend to be disturbed in these areas. In the tropics, warm air rises to the top of the troposphere and moves off toward the poles. Areas where colder air tends to move downward through the atmosphere and then toward the equator compliment these areas of rising air movement. As a general rule, weather in areas of sinking air tends to be dry and relatively calm.

Overall, the projections (Figure 18) suggest that variation in the rainfall pattern will be seasonal with the biggest change coming in the northern hemisphere summer months of June, July, and August. During the northern hemisphere summer months, increased rainfall is projected to occur along a line from the equator to the Hawaiian Islands. Less change in rainfall is projected during the winter months because ocean temperatures are cooler and thus less apt to support convection. Model projections for 2025-2034 June, July, and August indicate that areas of increased rainfall extend to 10^{o} S. The projections for the period 2090-2099 June, July, and August show this area extending farther south to between 15 and 20^{o} S with the largest increases in precipitation along a line extending from the Republic of the Marshall Islands in the north to Tahiti in the south. The regions near 10^{o} N and to the west of the dateline (180^{o}) would also receive substantially greater precipitation in the long-term results compared to the short-term results.

*Figure 18. Projected changes in total precipitation change for 2025-2034 and 2090-2099 in units of millimeters per day*10 (centimeters per day).*





During the southern hemisphere summer months of December, January, and February, model projections for 2025-2034 indicate some large areas of enhanced rainfall. The primary area is along a broad band extending from 10° N and 160° E through the equatorial dateline and southeast to near 10° S and 130° W. This already considerable region of enhanced precipitation is further enlarged in the projection for 2090-2099 with increased rainfall extending farther east along the equator and accompanied by large increases in the proximity of the Marquesas Island. This area of increased precipitation also extends westward to the most western of the islands of Micronesia.

Decreased precipitation could be experienced in all seasons in areas near the equator east of about 140° W. Rising, warm, moist air must ultimately come down and therefore areas of rising air that usually produce clouds and rainfall alternate with neighboring areas of sinking air that tend to be relatively dry. Due to this phenomenon, areas of decreased precipitation could also spread pole ward of the most rapidly warming equatorial regions (e.g., north of the Hawaiian Islands) negatively affecting many of the islands west of Hawaii, and tropical South Pacific Islands farthest off the equator but west of French Polynesia.

The projected rainfall scenarios are not as well known as the temperature projections and as such should be carefully considered. The exact location of borders between adjacent regions of projected enhanced or suppressed rainfall is uncertain and will be further addressed when the regional model results are compared with results from the multimodel ensemble experiments. Some of the areas near the regional boundaries made alternately wetter and drier by El Niño also bound the areas of the rainfall effects of climate change; examples of such locations are Apia in Samoa and Niualakita in southern Tuvalu.

Self Check 4B

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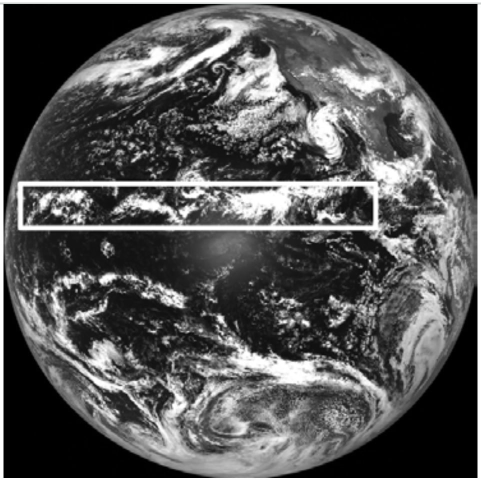
Chapter 4 - C. Intertropical Convergence Zone



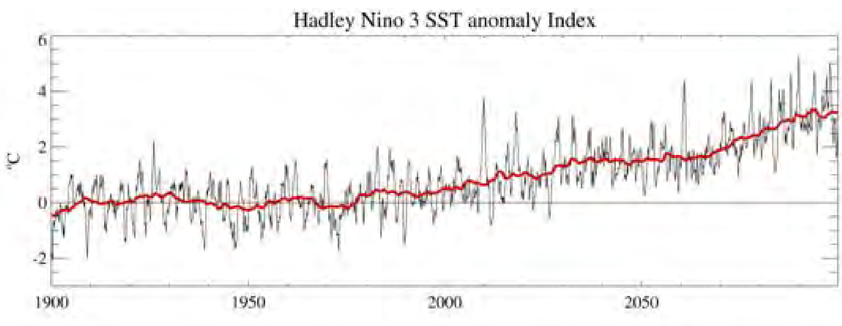
Introduction

When geologists use the term "convergence zone", they are discussing the region where two tectonic plates are colliding, with one plate sliding beneath the other. The result is geological turbulence: fault zones that produce earthquakes, and generated heat that gives rise to explosive volcanoes. When meteorologists use the term "convergence zone", they are describing a phenomenon in the atmosphere which works in an analogous fashion but is referring to air masses colliding. Near the equator, warm air rises and colder air moves in beneath it. As the warm air rises, it forms huge bands of clouds and thunderstorms over the ocean, an area called the Intertropical Convergence Zone, or ITCZ. A picture of the ITCZ is bounded by a white box in the figure to the left.

Sea Surface Temperatures and the Atmosphere

In the short- and long-term models, the pattern of increased sea-surface temperatures along the equatorial Central and Eastern Pacific suggests a greater tendency for El Niño-like conditions with sea-surface temperatures steadily warming in the Central and Eastern equatorial Pacific Ocean. Increased precipitation in the aforementioned region is indicative of both the short- and long-term December, January, and February warming patterns seen in the model results (Figure 17). Anomalies (or difference from the average tempeature) of sea-surface temperatures in the Niño-3 region (defined as 5^{o} N to 5^{o} S and 150^{o} W to 90^{o} W) are useful in measuring the strength of El Niños and La Niñas. The value of the Niño-3 sea-surface temperature anomaly index over time from the Hadley model (Figure 19) shows a general warming trend from present day through 2099. Over this interval and in this region, the average sea-surface temperature increases by roughly 3^{o} C (5.4^{o} F). It should be remembered that the characteristics or behavior of the El Niño Southern Oscillation could change with the overall warming of the atmosphere and ocean. If so, this would complicate and create uncertainty about the details of future climate conditions in the Pacific.

Figure 19. Monthly SST anomaly time series for the period 1900-2099. The El Niño 3 region is defined as 5 ^{o}N to 5 ^{o}S and 150 ^{o}W to 90 ^{o}W, with the base years for the climatology defined as 1950-1979. The thick red line is the 10-year running average. Units are in ^{o}C.

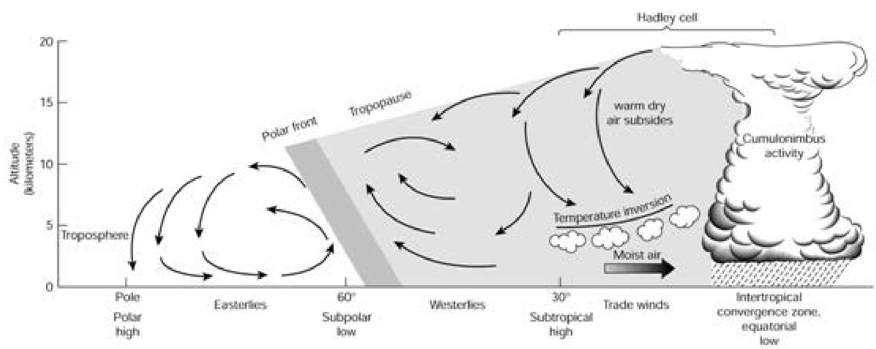


Regarding the short and long-term model results in terms of the natural Pacific climate variability and El Niño Southern Oscillation, it is useful to discuss how the atmosphere and ocean interact and thus impact climate. Both the

Intertropical Convergence Zone and the El Niño Southern Oscillation are consequences of the atmosphere and ocean systems interacting, play a role in climate variability, and thus may be impacted by climate change.

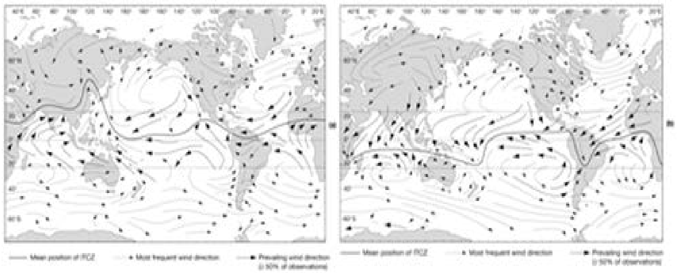
The air-sea interactions are important to the transfer of energy and mass between the oceans and atmosphere. Both atmospheric and ocean circulation are driven by heating at low latitudes (near the equator) and high latitude cooling (near the poles). Heat is absorbed by the planetary surface at low latitudes and is transferred poleward in both the northern and southern hemispheres. The equatorial region is a barrier to the exchange of materials between the the northern and southern hemisphere atmosphere. It is also a barrier to water, salt, and heat exchange at the ocean's surface. The large solar radiation input (due to the equator being closer to the sun) to the tropics leads mainly to heating of the ocean surface. In turn, the air above the surface ocean is heated, expands, and becomes less dense. This reduction in density causes the air to rise owing to convection. A region of low pressure develops because the mass of the overlying atmosphere in the tropics is reduced. The "void" left by the rising, warm, and moist air is replaced by air that moves toward the equator from higher latitudes. This region is called the Intertropical Convergence Zone. It is the zone along which the trade wind systems of the Northern and Southern Hemispheres meet (Figure 20).

Figure 20. Longitudinal cross section through the lower 20 kilometers of Earth's atmosphere from the polar region to the equator showing general vertical air circulation patterns.



Heating of the tropical ocean surface causes evaporation of water. The water vapor rises and cools at higher elevations in the atmosphere, leading to the formation of clouds. Thus, the region of the Intertropical Convergence Zone is characterized by cloudiness and heavy precipitation. The zone of the Intertropical Convergence Zone is particularly intensely developed in the western Pacific. Here a warm water pool of surface water is found with mean temperatures of about 31^{o} C! The average water temperature in Hawaii is around 24^{o} C. On average, the Intertropical Convergence Zone is also a region of intense atmospheric convection and the wettest part of the tropics. This surface ocean warm pool and the associated zone of heavy rainfall are important to the dynamics of El Niño-Southern Oscillation events. The Intertropical Convergence Zone shifts seasonally. During the northern hemisphere summer, the ITCZ shifts northward as the Asian continent is warmed more than the adjacent ocean (Figure 21a). The warm continental air rises, and air is drawn from the ocean toward the land. The zone of heavy rainfall expands northwestward from Indonesian into India and Southeast Asia. Southerly winds blowing from the oceans toward India and Southeast Asia are dominant at this time (Figure 21a). This is the time of the Southwest Monsoon (May to September). During the northern hemisphere winter, the reverse is true when the air above the Asian continent becomes very cold (Figure 21b). An intense high-pressure region develops in the atmosphere above continental Asia. The flow of air is from the continent toward the ocean. This is the time of the Northeast Monsoon (November to March).

Figure 21. The average prevailing wind directions at Earth's surface during the Northern hemispheric summer (a, July) and winter (b, January). The solid black line shows the Intertropical Convergence Zone position and its change with season.



(a) (b)

Self Check 4C

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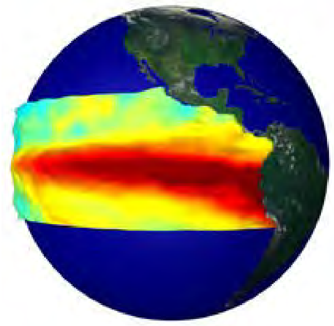
Chapter 4 - D. El Niño and La Niña



Introduction

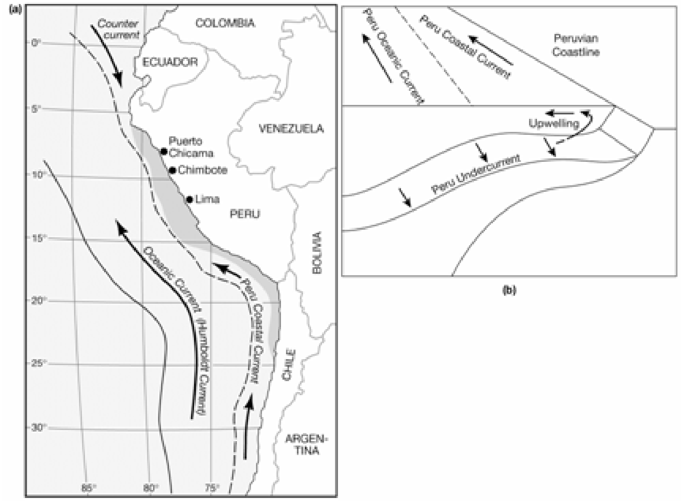
Fishermen who fish the waters of the Pacific off the coast of Peru and Ecuador have known for centuries about El Niño. On average, every three to seven years during the months of December and January, fish in the coastal waters off of these countries virtually vanish, causing the fishing business to come to a standstill. South American fishermen have given this phenomenon the name El Niño, which is Spanish for "the Christ Child," because it comes around the time of Christmas. During an El Niño, the physical relationships between wind, ocean currents, oceanic and atmospheric temperature, and biosphere break down into destructive patterns that are second only to the march of the seasons in their impacts to weather conditions around the world. La Niña is the opposite of El Niño and is characterized by unusually cold surface water temperatures in the equatorial Pacific. Below is a table of the recorded El Niño events.

El Niño Years			
1902-1903	1905-1906	1911-1912	1914-1915
1918-1919	1923-1924	1925-1926	1930-1931
1932-1933	1939-1940	1941-1942	1951-1952
1953-1954	1957-1958	1965-1966	1969-1970
1972-1973	1976-1977	1982-1983	1986-1987
1991-1992	1994-1995	1997-1998	

Regional and Global Climate Disturbance

The El Niño Southern Oscillation (ENSO) phenomenon in the Pacific Ocean has regional (Pacific Basin) and global ecological and climatic impacts. The El Niño Southern Oscillation cycle is comprised, among other things, of a range of surface water temperature conditions: (1) extreme warm conditions (El Niño), (2) normal or average surface conditions, and (3) extreme cold conditions (La Niña). During non-El Niño conditions – e.g., La Niña or normal surface water conditions – cool currents flow north along the coastline of Peru and Chile. These currents are named the Peru Oceanic and Coastal Currents (Figure 22).

Figure 22. (a) Peru Coastal Current and Oceanic Current; (b) Peru Undercurrent and upwelling.



The Peru Oceanic Current extends to a depth of 700 meters (2296 feet) and can be as wide as 600 kilometers and the Peru Coastal Current runs close to the coastline and is 200 meters (656 feet) deep and 200 kilometers (124 miles) wide. Beneath these two currents lies the southward flowing Peru Undercurrent and to the north is the Peru Countercurrent. The prevailing southeast trade winds usually blow approximately parallel to the Peruvian coastline. This results in the movement of the surface currents in the direction of the west. This westward movement of the surface waters gets replaced by water from below (this is termed "upwelling") from a depth of 40 to 80 meters (131 to 262 feet) at a speed of 1 to 3 meters (3.3 to 9.8 feet) per day. This upwelling water is rich in nutrients and stimulates biological production in surface waters. The upwelled nutrient-rich water comes from below the nutricline. The nutricline is the water depth below which nutrients are abundant and have not been consumed by primary production in the layer of surface water.

About every 3 to 7 years, an El Niño occurs that usually lasts 1 to 2 years or sometimes longer. El Niño means “the Christ Child” and is so named because the phenomenon usually begins around Christmas. El Niño is a time when the warm low salinity waters of the west Pacific extend far to the east and bathe the coast of central South America in warm (up to 10 ^{o}C warmer), nutrient-poor water. This western Pacific water is transported to the Peruvian coast by the Peru Countercurrent, which overrides the Peru Coastal Current because it is less dense (being both warm and low salinity) than the water of the coastal current. This nutrient-poor layer of water on the order of 30 meters (98 feet) thick comes to reside along the Peru coast. Due to the layer’s thickness, upwelling water no longer comes from below the nutricline but from within the nutrient-poor water layer above the nutricline. So during an El Niño if upwelling occurs, the upwelled water is low in nutrients and biological production is suppressed. At the same time that this warm nutrient poor water comes to reside off the Peru coast, trade wind intensity may decrease substantially. This reduction in trade wind intensity reduced the offshore movement of the surface water and the subsequent upwelling of below water.

In addition to changes in ocean upwelling and circulation, El Niño can impact rainfall and temperature patterns around the world (see Figure 23a). La Niña conditions are shown in Figure 23b. El Niño events are usually responsible for warm, dry winters in the northern United States and wet winters in the southern United States, torrential rains and flooding in coastal South America and parts of Asia, droughts in Africa, Australia, and the Hawaiian Islands, unusual tropical cyclone activity, and failure of the monsoon in Asia.

Figure 23a. El Niño rainfall and temperature patterns.

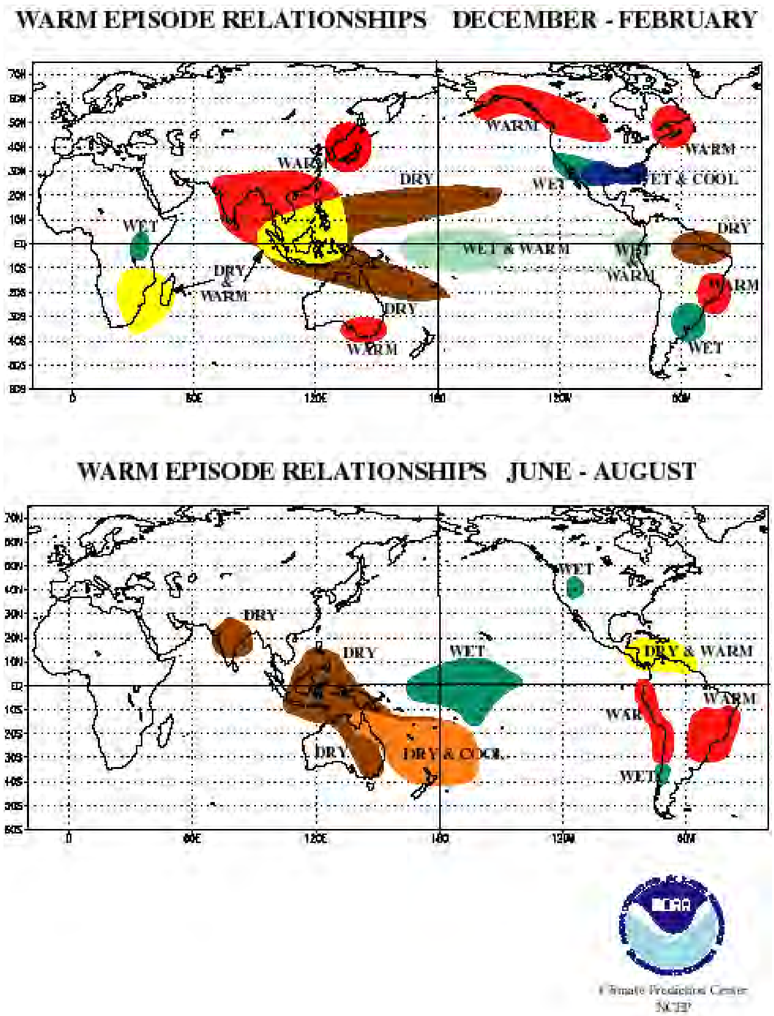
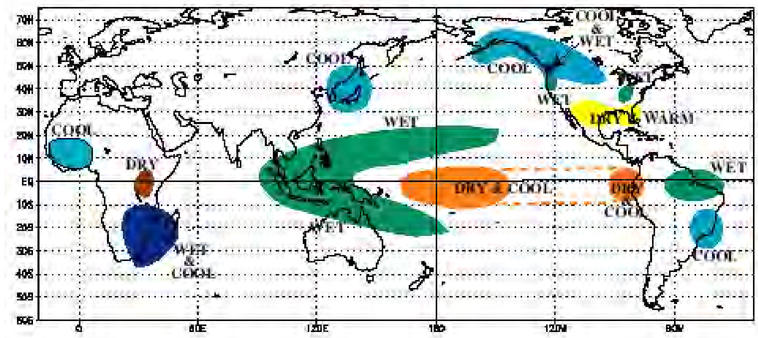
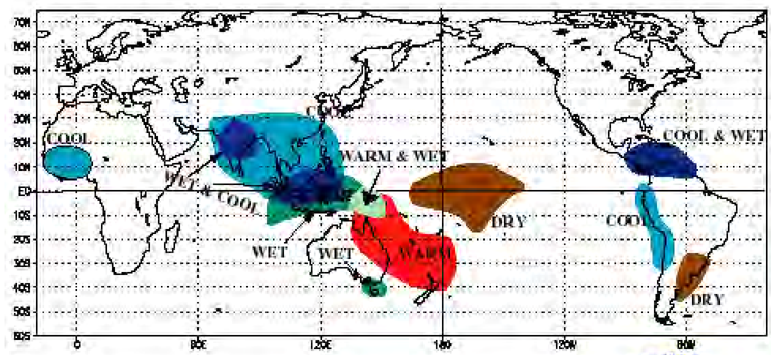


Figure 23b. La Niña rainfall and temperature patterns.

COLD EPISODE RELATIONSHIPS DECEMBER - FEBRUARY



COLD EPISODE RELATIONSHIPS JUNE - AUGUST



Climate Prediction Center
NCEP

When the more usual situation of the cool currents offshore Peru return (normal conditions or La Niña conditions), upwelling returns, biological productivity increase, the anchovies return, the birds feed, the fish and bird stocks increase. There has been considerably less research done on the cold extreme (La Niña) of the El Niño Southern Oscillation and its climatic implications compared to El Niño. The impacts of cold events on meteorological conditions throughout the world depend on the intensity of the La Niña event, but are less well known than the impacts of El Niño events. There are geologic records of El Niño events attesting to the fact that the events have been happening for about 5000 years. These records suggest that prior to 5000 years ago there was a warm background climate without El Niño episodes. Since then the cooler background climate of the past 5000 years has been conducive to the spawning of El Niño events. A question that is of concern to scientists studying the current environmental issue of global climatic change is: What might happen to the El Niño – La Niña cycles if there is a global warming induced by the accumulation of greenhouse gases in the atmosphere from human activities? There is some evidence that global warming might lead to conditions in the Pacific region that are like that of an extended El Niño event.

In Hawaii, El Niño tends to bring dry winters. Drought is more likely during El Niño years, especially during the October-March period which is traditionally the wettest time of the year. This association is well known in the Hawaiian Islands. In general, in all these regions, La Niña climate effects are approximately, but not exactly, opposite to El Niño climate effects. During the 1997-1998 El Niño, water rationing was implemented on the islands of Maui and Hawaii. Wildfires on Maui and the island of Hawaii were also prevalent problems due to the drought. For the Republic of the Marshall Islands and its island Majuro, El Niño tends to bring dry winters and drought conditions. During the 1997-1998 El Niño, Majuro was under a severe drought. The drought was so severe that measures such as water rationing, installation of a desalination plant, and emergency aid were required to sustain the population. El Niño conditions also tend to bring an enhanced threat of tropical cyclone activity to the Republic of the Marshall Islands. During the 1992-1993 El Niño, severe coral bleaching (bleaching is a result of a coral losing its symbiotic algae – zooxanthellae – that impart color to the coral and provide nutrition to the coral without which the coral will ultimately die animate or illustrate) was observed in the lagoon around Majuro killing up to half of many coral colonies . Table 1 summarizes the predicted precipitation impacts of El Niño and La Niña on the islands of Majuro and Oahu.

Table 1. Predicted ENSO Precipitation Impacts to Oahu, Hawaii and Majuro Atoll, Republic of the Marshall Islands.

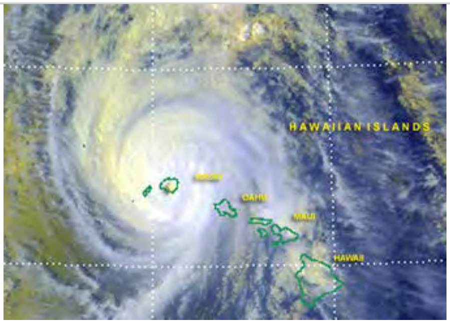
	Winter (December – February)		Summer (June – August)	
	Majuro	Oahu	Majuro	Oahu
El Niño	Dryer	Dryer	Normal	Normal
La Niña	Wetter	Wetter	Normal	Normal

National Geographic has put together a review of the El Niño phenomenon, click here if you would like to view it.

Self Check 4D

Click above to begin the self check for 4D.

Chapter 4 - E. Tropical Cyclones



Introduction

Millions of lives were changed by the record-setting 2005 Atlantic hurricane season - a "worst case scenario" for the United States. The 27 named tropical storms beat the old record of 21 in 1933. Five hurricanes (Dennis, Katrina, Ophelia, Rita and Wilma) and three tropical storms (Arlene, Cindy and Tammy) directly impacted the country: destroying lives, demolishing homes and wrecking the landscape. More than a thousand people lost their lives and many more were left battered, broken, displaced or homeless. Entire neighborhoods were wiped out by the combination of strong winds, heavy rain, storm surge and floodwaters.

While an active hurricane season was anticipated by meteorologists and experts at the National Hurricane Center, the destruction and sheer number of storms was simply overwhelming. Many residents, particularly in the southeastern U.S., were under a state of alert that lasted for months. As early as late July, more than a month before the peak of the season, seven storms had already formed, including two Category 4 storms that formed in rapid succession (Hurricanes Dennis and Emily). Typically the waters of the Gulf of Mexico are too cool at that point in the season to support such storms. However in 2005, warmer-than-normal sea surface temperatures combined with hurricane paths over very warm ocean currents which enabled many storms to rapidly intensify.

Hurricane Katrina was the costliest hurricane to ever strike the U.S. with at least $80 billion in damage, and two other 2005 hurricanes (Wilma and Rita) made the top 10. Levees failed after Katrina made landfall east of low-lying New Orleans on the morning of August 29, inundating the city with floodwaters. The scenes along the Louisiana, Mississippi and Alabama coasts were terrible: entire neighborhoods wiped out; debris rotting on the sides of streets; families sleeping in tents; sickness due to mold, mildew, and rot; and the loss of human life, centuries-old landmarks and industry. With more than 1300 deaths in four states, Katrina was also the deadliest U.S. hurricane since 1928.

Climate Change and Tropical Storms

The ocean water temperature that is generally required to generate tropical cyclones is 28 ^{o}C (82.4 ^{o}F). Cyclones, typhoons, or hurricanes (all terms that describe the same phenomena) form when the sea surface temperature exceeds 28 ^{o}C, which is primarily during the period of midsummer to early fall in the northern hemisphere. In the western part of the North Pacific Ocean, the water can be warm enough to spawn typhoons in winter. The warm tropical ocean supplies abundant moisture to the storm system. The release of large amounts of latent heat from the condensation of atmospheric water vapor into rain warms the atmosphere. Because warm air weighs less than cold air, the air pressure drops, and an initial low-pressure disturbance may intensify. As the low-pressure disturbance develops, the convergence of air leads to the rise of more warm air and increased release of latent heat sometimes to the point that a hurricane forms.

Tropical cyclone activity in the eastern Pacific generated off the western coast of Central America and Mexico has been limited over the past 30 years with most of the activity and source for cyclones in the western tropical Pacific. The western tropical Pacific cyclonic generating region extends farther east during El Niño events resulting in an increased threat of cyclones for the more eastern islands. It extends farther east due to the movement of the warm surface water from the western Pacific to the eastern Pacific. Cyclone development usually occurs west of the dateline (180^{o}) both north and south of the equator. After developing, the cyclones are pushed west by the trade winds. After moving west, they are pushed pole ward and ultimately eastward, threatening islands well off the equator such as Guam, the Republic of the Marshall Islands, and the Hawaiian Islands.

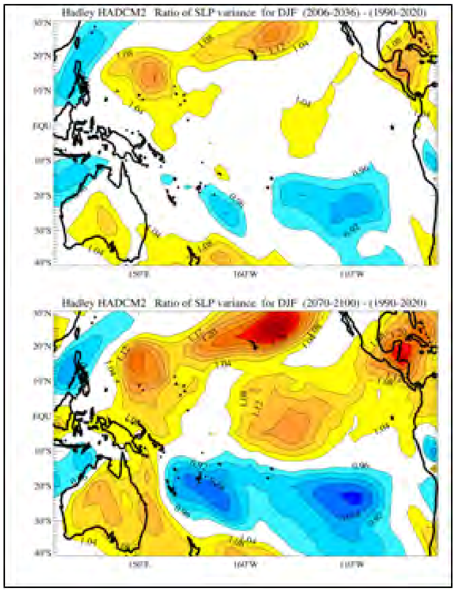
With climate change and subsequent warming, the warm water region that is normally confined to the western equatorial Pacific will likely move eastward into regions that only have warm waters during El Niño events. The projected result from this eastward movement of warm water is a gradual increase in the frequency of tropical cyclones for islands in the central and east-central Pacific on either side of the equator such as the Hawaiian Islands. Far western Pacific storm frequencies may not decrease as they would presently during El Niño events as sea-surface temperatures there will also be increasing, even if at a slower rate. Due to the projected increase in western-Pacific sea-surface temperature, the storm frequency could increase slightly. Researchers are investigating possible interactions between hurricane frequency and El Niño. El Niño is a phenomenon where ocean surface temperatures become warmer than normal in the equatorial Pacific. The below chart below shows the anomaly associated with the 1997-1998 El Niño. In general, warm El Niño events are characterized by more tropical storms and hurricanes in the eastern Pacific and a decrease in the Atlantic, Gulf of Mexico and the Caribbean Sea. The 1997-98 El Niño event agreed with this theory. In 1997, the Atlantic Ocean had 7 named storms, of which 3 became hurricanes and only one of them intense. Each of these figures were below average yearly values. The average hurricane season is compared against the average El Niño season below.

Table. Comparison of average storm activity in non-El Niño and El Niño years.

	Atlantic		**Eastern Pacific**	
	Average	El Niño Avg.	Average	El Niño Avg.
Named storms	9.4	7.1	16,7	17.6
Hurricanes	5.8	4.0	9.8	10.0
Intense Hurricanes	2.5	1.5	4.8	5.5

Large scale mid-latitudinal storms are a function of the frequency and intensity of cyclonic activity. These storms cause large changes in sea-level pressure on short time scales and so seasonal differences in sea-level pressure can be used to indicate storminess. Figure 24 shows the projected changes in the ratio of sea-level pressure for the two periods 2006-2036 and 2070-2100) compared to a baseline period of 1990-2020. The model projects increased storminess from 2006-2036 in a region extending north and east of the Hawaiian Islands to the area north of the Federated States of Micronesia and east of the Commonwealth of the Northern Mariana Islands. For that same region in 2070-2100, the storminess is amplified and also enlarged to encompass the entire Hawaiian Islands as well as most of the Federated States of Micronesia and Republic of the Marshall Islands. The equatorial region between 100^{o} W and the dateline is also expected to experience more storminess from 2070-2100. Between 10^{o} and 30^{o} S in the southern hemisphere, storminess is projected to decrease for regions between 170^{o} E and 90^{o} W. This region includes Fiji and the French Polynesian Islands.

Figure 24. The ratio of SLP variance for DJF for the period 2006-2036 compared to 1990-2020 and the period 2070-2100 compared to 1990-2020. Higher ratios (>1) indicate more storminess in the future periods.



Self Check 4E

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Chapter 4 - F. Sea Level: Part 1

Introduction

Global sea level and the Earth's climate are closely linked. The Earth's climate has warmed about 1°C (1.8°F) during the last 100 years. As the climate has warmed following the end of a recent cold period known as the "Little Ice Age" in the 19th century, sea level has been rising about 1 to 2 millimeters per year due to the melting of ice caps, ice fields, and mountain glaciers in addition to the thermal expansion of ocean water (as water gets warmer, it expands and therefore takes up more space). If present trends continue, including an increase in global temperatures caused by increased greenhouse-gas emissions, many of the world's mountain glaciers will disappear. For example, at the current rate of melting, all glaciers will be gone from Glacier National Park, Montana, by the middle of the next century. In Iceland, about 11 percent of the island is covered by glaciers (mostly ice caps). If the present rate warming continues, Iceland's glaciers will decrease by 40 percent by 2100 and virtually disappear by 2200.

Most of the current global land ice mass is located in the Antarctic and Greenland ice sheets (Table 1).

Table 1: Some physical characteristics of ice on Earth.

	Glaciers	Ice caps	Glaciers and ice caps	Greenland ice sheet	Antarctic ice sheet
Number	>160,000	70			
Area (10^6 km^2)	0.43	0.24	0.68	1.71	12.37
Volume (10^6 km^3)	0.08	0.10	0.18	2.85	25.71
Sea-level rise equivalent (meters)	0.24	0.27	0.50	7.2	61.1
Accumulation (sea-level equivalent, mm/yr)			1.9	1.4	5.1

(modified from IPCC, 2001 http://www.grida.no/climate/ipcc_tar/wg1/412.htm#tab113)

Complete melting of these ice sheets could lead to a sea-level rise of about 70 meters, whereas melting of all other glaciers could lead to a sea-level rise of only one-half meter.

Climate Change and Sea Level Rise

While global sea level rise is of concern to all coastal areas, this is especially the case for low lying Pacific Island nations. Some entire Pacific nations and archipelagos have maximum elevations of only a few meters above sea level making them especially vulnerable to sea level rise. For these atolls (click here for a short description of atolls and their formation), a relatively small sea level rise could affect a large fraction of the island surface area. Sea level rise can result in loss of low-lying coastal agriculture areas, ecosystems, and human settlements via erosion and inundation. Sea level rise can also impact fresh water supplies for islands, which may already be under stress from lack of rainfall due to climate change and further exacerbated by increasing population. Elevated sea level conditions could also amplify the damaging effects of tropical cyclones and their associated storm surges.

The animations below show the flooding in major cities as global warming raises sea levels and possibly leads to increased frequency and strength in storms. They show that as sea levels rise, even relatively weak storms will be able to do a great deal of damage. To see what would happen to the following cities with sea level rise, click on the city. You will need Windows Media Player to view the movies and they are quite large (around 4Mb), so they could take some time to load.

New York: Animation shows flooding that would occur as the result of the storm surge from a Category II hurricane, combined with a projected sea level rise of 2.2 feet (0.7 meters) anticipated over the coming century. According to the National Hurricane Center, from 1900-1996 the Atlantic coast of the U.S. between Florida and Maine has experienced 78 hurricane strikes of Category II or greater.

Miami: Shows flooding that would occur as the result of projected sea level rise of slightly over 1 1/2 feet (.6 meters) and storm surge from a 100-year storm, which will occur every 10 years by the end of the century.

Washington, DC: Animation shows flooding that would occur as the result the storm surge from a Category II Hurricane, combined with a projected sea level rise of 2.5 feet (0.75 meters) anticipated over the coming century. According to the National Hurricane Center, from 1900-1996 the Atlantic coast of the U.S. between Florida and Maine has experienced 78 hurricane strikes of Category II or greater.

Sea level rise and climate change can accelerate beach erosion and also have impacts on natural structures – e.g., mangroves and coral reefs – that serve to protect shorelines. While it is uncertain what the impacts of sea level rise would be on mangroves, the potential loss of coral reefs due to sea-surface temperatures rising above the coral's preferred temperature could jeopardize the natural protection from storm surge, wave activity, and long-term sea level rise afforded by a reef framework.

The worldwide sea level change shown in Figure 26 represents thermal expansion of ocean surface waters and alpine and valley glacial melt adding water to the ocean. However, the change does not take into account ice sheet melt because of the uncertainty of the net effect of climate change on Antarctic and Greenland ice sheets. Sea level rise can vary from location to location due to differences in local heating and thermal expansion of water. For example, waters around the equator will expand more due to heating than waters off Alaska. The projection of future sea level rise is heavily dependent upon which future emission scenario is used to drive the climate change model. Using the entire range of future emission scenarios (in other words, what we think the low and high estimates of future global emissions of carbon dioxide and other greenhouse gases), the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios projected a sea level rise of between 9 and 88 centimeters (3.5 and 34.7 inches) by the completion of the 21st century. Table 2 provides some historical context for sea level trends at some Pacific islands.

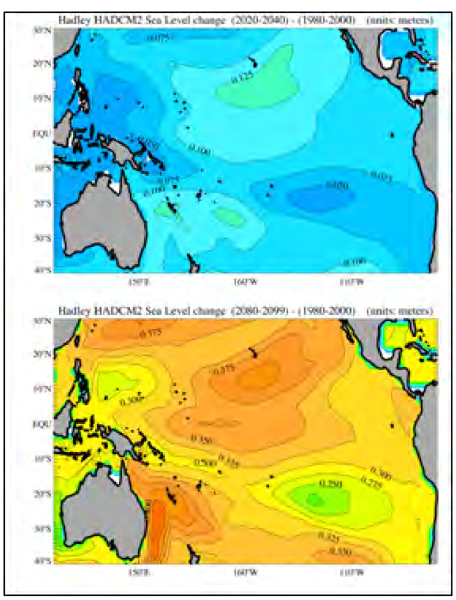
Table 2: Mean Sea Level Trends at Selected Pacific Island Stations (in centimeters)

Location	Rate of Change	Record Duration	Total Change
Hawaii			
Honolulu Hilo Nawiliwili Kahului Mokuoloe	1.5 +/- 0.2 cm/decade 3.4 +/- 0.5 cm/decade 1.5 +/- 0.4 cm/decade 2.1 +/- 0.5 cm/decade	1905-1999 1927-1999 1954-2000 1950-1999	11.10 +/- 1.84 cm 24.48 +/- 3.60 cm 6.90 +/- 1.84 cm 10.29 +/- 2.45 cm

	1.0 +/- 0.5 cm/decade	1957-1999	4.20 +/- 2.10 cm
Guam	0.0 +/- 0.6 cm/decade	1948-1999	0.00 +/- 3.06 cm
American Samoa Pago Pago	1.6 +/- 0.6 cm/decade	1948-1999	8.16 +/- 3.06 cm
CNMI/Saipan	-0.1+/- 2.2 cm/decade	1978-1999	-0.21 +/- 4.62 cm
Marshall Islands Majuro Kwajelein Wake	2.5 +/- 1.0 cm/decade 0.9 +/- 0.4 cm/decade 1.8 +/- 0.5 cm/decade	1968-1999 1946-1999 1950-1999	7.75 +/- 3.10 cm 4.77 +/- 3.10 cm 8.82 +/- 2.45 cm
Federated States of Micronesia Pohnpei Kapingamarangi Yap	1.6 +/- 1.8 cm/decade -1.6 +/- 2.3 cm/decade -1.4 +/- 1.8 cm/decade	1974-1999 1978-1999 1969-1999	4.00 +/- 4.50 cm -3.36 +/- 4.83 cm -4.21 +/- 5.40 cm
Republic of Palau Malakal	-0.4 +/- 1.8 cm/decade	1969-1999	-1.20 +/- 5.40 cm

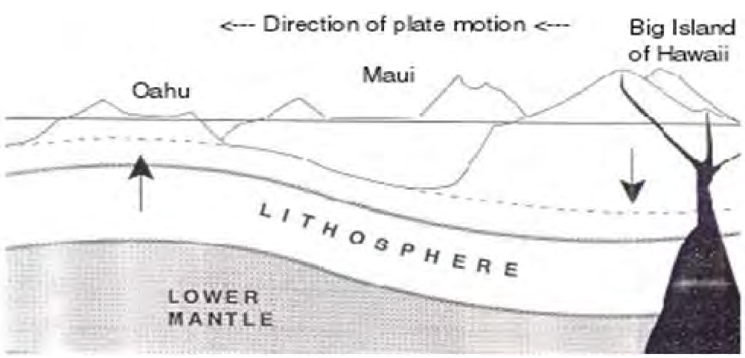
Original data for this table provided by Mark Merrifield, University of Hawaii.

Figure 26. Sea level rise for the period 2020-2040 minus 1980-2000 and the period 2080-2099 minus 1980-2000.



Finally, it should be noted that the islands of Hawaii are moving up and down -- albiet slowly over the time frame of the next 100 years - which can change relative sea level. This motion is not be important in sea level change for the Hawaiian Islands for the next hundred years though, but it is interesting to investigate anyway. The plate the Hawaiian Islands ride on (called the Pacific Plate) moves up and down due to lithospheric (plate) flexure. This flexure is a result of the loading of the plate, or lithosphere, where the Island of Hawaii (e.g., the Big Island) is located. The weight of the Island of Hawaii, the largest of the Hawaiian Islands, bearing down on the underlying plate causes the plate to be pushed downward (Figure 27). In response, this distorts the surrounding plate resulting in the upward movement of the plate portion under Oahu, which is approximately 400 kilometers (249 miles) from the Big Island. This upward plate motion during the past 125,000 years uplifting Oahu has ranged between 0.02 to 0.06 millimeters (0.0008 to 0.002 inches) per year. The impact of even the upper limit of these uplift rates over the next 100 years would be at most 6 millimeters and is therefore not necessary to factor in regarding near future climatically-driven sea level change. To learn why lithospheric flexure and earthquakes are associated and thus why the Big Island of Hawaii has many more earthquakes than Oahu, click here.

Figure 27. Lithospheric flexure under the massive volcanic accumulation that is the Big Island of Hawaii cause compensatory arching at a radius of approximately 400 kilometers (248 miles) resulting in the uplift of the island of Oahu.



Although we have not spent any effort to go in depth describing plate tectonics to see a movie of global plate motion over the past 750 million years, click here. This should give you a better idea of how slow plates move (remember these are plate motions over millions of years) and general plate motion. To see the movie replayed, click "refresh" or "reload" on the browser.

Lab # : Drowning New York!

Explore hazards presented to New York City by storm surge and sea level rise that occur due to global warming. Evaluate different claims as to the nature and cause of global warming. Read and interpret storm surge frequency diagrams. Review the 'pro' and 'con' opinions of advocacy groups and compare their modes of reasoning with a set of criteria drawn up to distinguish acceptable from non-acceptable types of argumentations.

Self Check 4F

Click here to begin the self check for 4F.

Chapter 5 - Consequences of Projected Climate Change

Introduction

The climate models previously reviewed predict short and long-term changes in sea-surface temperature, rainfall, the El Niño Southern Oscillation phenomenon and storm variability, and sea level for the Pacific Basin. These changes have implications for Pacific inhabitants and the entire world. Examples of impacts of past climate events include the recorded El Niño's of 1986-1987, 1991-1992, 1997-1998, and 2002-2003. The economic cost of the 1982-1983 El Niño at the time was estimated to be over 8 billion U.S. dollars. The economic cost of Hurricane Katrina (in 2005) is projected upwards of 70-80 billion U.S. dollars with approximately 1,300 people killed. Large-scale climate events, such as El Niño, and large scale weather events, such as hurricanes, may both have their impacts amplified by global climate change.

Future Impacts of Climate Change on Pacific Islands - Oahu, Hawaii

The islands of Hawaii are located in the Pacific Basin. The Pacific Basin area is easily large enough to fit all the presently exposed land surface area on Earth (58 million square miles). In other words, the surface area of the Pacific Basin is greater than the combined areas of North America, South America, Europe, Asia, Africa, Greenland, and Antartica. Of the roughly 30,000 islands in the Pacific, the Hawaiian Island of Oahu is one of the most developed, populated, and isolated as the nearest continental land mass is over 2,400 miles away. Climate change will play a significant role in the changes in temperature, precipitation, sea level variations that the islands of Hawaii experience.

Climate and Water Resource Case Study

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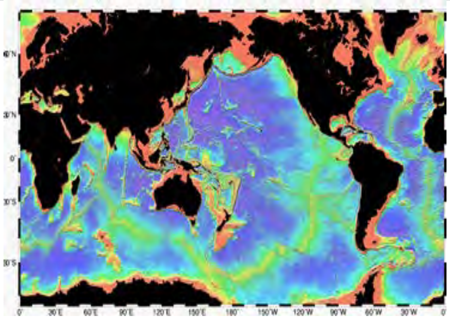
Chapter 5 - A. Pacific Basin Overview



Introduction

All 58 million square miles of the Earth's land area would easily fit inside the Pacific Basin. There are roughly 30,000 islands in the Pacific Basin and the Pacific Ocean has served as a passageway interconnecting the island inhabitants. While there are cultural similarities and differences among the inhabitants of these small island states, the one thing they share is susceptibility to climate change and variability. For example, climate change and variability can impact the following Pacific island attributes to varying degrees: soil and coastal zone formation, hydrology, susceptibility to storm systems, and components of biogeography such as population density, species density, and distribution. The degree to which climate change and variability will impact Pacific islands depends upon a variety of factors such as the island's geology, area, height above sea level, extent of reef formation, and freshwater aquifer size.

Pacific Island Variety

The Pacific Islands are difficult to characterize geomorphically (and include atolls, volcanic islands, continental islands, limestone islands, and mixtures of all these geomorphologies. Half of the Caroline Islands and 80% of the Marshall Islands are atolls. These atolls may only be above sea level by a few feet making them extremely susceptible to changes in sea level and storm activity and their impacts on the water table of the atoll. At the other extreme, volcanic islands such as the islands of Hawaii can peak at over 3,962 meters (13,000 feet) above sea level. Island landforms are not solely the product of their geological history. In the Pacific, climatic and oceanographic forces can alter island landforms. Changes in rainfall and water table level are important processes in this respect.

Islands are impacted by the interplay between their geology and climatological and oceanographic processes. Compared to other types of islands found in the Pacific, high volcanic islands like the Hawaiian islands tend to have larger surface areas, more groundwater, better soils for farming, and overall a more diverse resource base. Compared to high volcanic islands, low-lying atolls that are only a few meters above sea level are prone to drought and erosion and have very limited natural resources. High Pacific islands generally can support the growth of tropical forests given their warm temperatures, moisture, and soils whereas atolls generally do not support dense vegetation due to poor soil composition and hydrological constraints.

Pacific island landscapes and biodiversity are varied. Warm temperatures and moisture have supported the growth of tropical rainforest on many islands, particularly the high islands. While even relatively small islands can host a diversity of forest types, atolls generally do not support dense forest vegetation inpart because of the poor soil composition and lack of fresh water. The atolls are basically a coastal zone because the boundary between land and ocean constantly fluctuates throughout the year. Mangrove forests fringe some islands in locations where fresh water from runoff and salt water from the ocean mix. Oceanic islands tend to have lower levels of biodiversity and species found on them are more likely to be endemic, which means the species are native and restricted to that island. Island species are more susceptible to disruption from introduced species.

One example of how island species are susceptible to disruption from the introduction of foreign species is the the Puerto Rican coqui frog's introduction to the Hawaiian Islands -- specifically the Big Island of Hawaii. The coqui frog was accidentally introduced into Hawai'i from Puerto Rico around 1988. Aside from being a major noise nuisance, the frogs pose a threat to Hawai'i's island ecosystem. Coqui frogs have a voracious appetite that puts Hawai'i's unique insects and spiders at risk. They can also compete with endemic birds and other native fauna that rely on insects for food. The frogs are quite adaptable to the different ecological zones and elevations in the state and have been found from sea level to 4,000 feet elevation (at sites in Volcano on Hawai'i). Scientists are also concerned that an established coqui frog population may serve as a readily available food source if (or more likely when) brown tree snakes are accidentally introduced in Hawai'i.

Since their introduction to the Big Island within the last 10 years their numbers have ballooned, they have infested Maui and have been sighted on both Oahu and Kauai. Coqui populations have grown in the last 15 years from presumably a single infestation to over 200 on the Big Island alone. They are also present on Maui (40 or more infestations), O`ahu (5 sites) and most recently on Kaua`i (1 site, subject of an eradication effort with citric acid in June 2003). Puerto Rico averages 40 frogs (reproductively mature adults, not including juveniles) per 20 x 20 m plot compared to greater than 200 in Big Island plots, primarily because of the lack of predators (owls, snakes, tarantulas, scorpions) in Hawai'i.

Some effects of the frogs include:

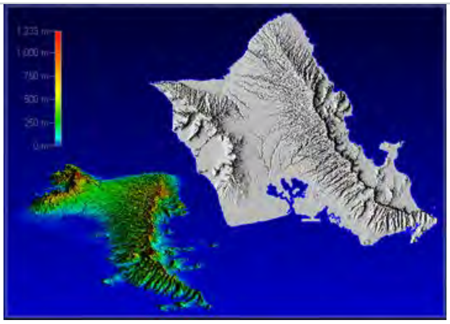
- Loud annoying calls that disturb sleep (click here to hear the frog's call)
- May prevent the export of infested goods to areas with "No Pest" policies
- Potential vector of nematodes in certified nurseries
- Competition with Hawaiian birds for insect prey
- Predation on Hawaiian insects and spiders
- Could boost mongoose and rat populations by serving as an unlimited food source
- Would provide an abundant food source for more damaging, potential invaders such as the brown treesnake

The lack of biodiversity makes island ecology extremely sensitive to climatological change. The Hawaiian Islands, although they comprise less than 0.002% of the total land area of the United States, are home to nearly 30% of the nation's endangered species. The ecosystems of the Pacific islands support more rare, endangered and threatened species than anywhere else on earth. The Pacific marine environment comprises an enormous and largely unexplored resource, including the most extensive and diverse reefs in the world, the deepest oceanic trenches and relatively intact populations of many globally threatened species including whales, sea turtles, dugongs and saltwater crocodiles. The high islands support large tracts of intact rainforests that are hosts to unique communities of plants and animals, many species of which are found nowhere else in the world, many more waiting to be discovered and described scientifically. For the small islands, this diversity is the result of thousands of years of physical isolation from continental landmasses; this enabled many island faunal species to evolve independently of relatives in other land masses resulting in a high level of endemism, which according to some reports exceed 80% in many islands.

Self Check 5A

Click here to begin the self check for 5A.

Chapter 5 - B. Oahu Overview



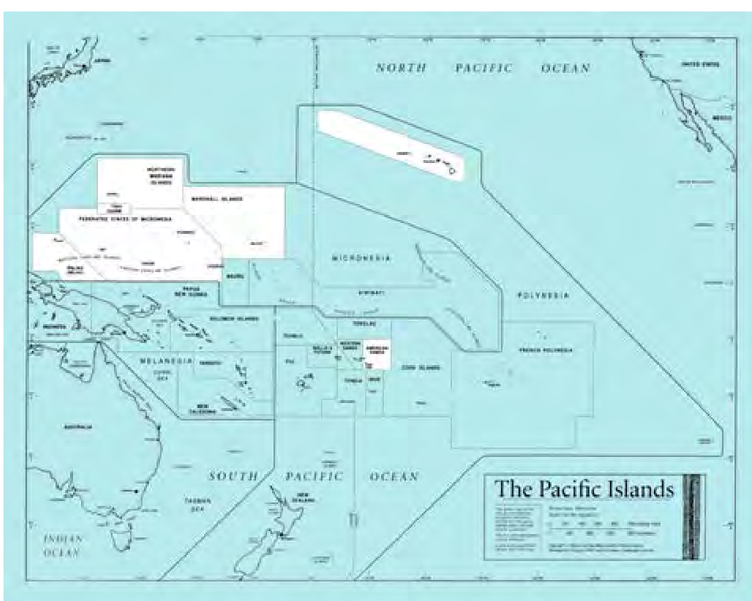
Introduction

There are too many islands in the Pacific to investigate future climate impacts on all of them in this case study. We will instead spend the remainder of the case study focusing on future climate impacts on the island of Oahu, which is part of the state of Hawaii. Oahu is not necessarily representative of small, low-lying Pacific Islands such as atolls. It is a relatively large island compared to most Pacific Islands, has a large population near 1 million, and a bustling economy. However, it is useful to examine closely because much is known about its geology, geography, weather, and economy. All this aids in projecting how future climate change with impact Oahu and thus can be useful in determining what impacts might occur to other islands.

Oahu Characteristics

The nearest continental land mass is over 3,864 kilometers (2,400 miles) away making Hawaii one of the world's most remote group of islands (Figure 16). Hawaii's climate is also one of the most diverse on the planet. Of all the major 11 different biomes on Earth, only tundra is not found in Hawaii. The surrounding tropical ocean supplies moisture to the air year round. This supply of moisture acts likes a thermostat and keeps seasonal temperature variations to a minimum. The warmest months are August thru September and the coolest months are January thru February. The islands are usually bathed in northeasterly trade winds due to a semi-permanent atmospheric high pressure cell that is situated northeast of the islands.

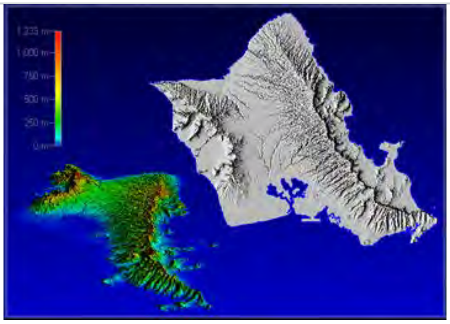
Figure 16. Pacific Island Map.



The elevation of Hawaii's mountains and ridges significantly influences the local weather and climate. In Hawaii, rainfall amount and distribution closely follow the topographic contours of the islands. Rainfall is greatest at ridges and windward areas (northeast slope of ridges and mountains) and is least in leeward lowlands (see below orographic rainfall description). Mt. Waialeale on the island of Kauai is one of the wettest places on Earth receiving 1016 centimeters (400 inches) of rain per year. Elevated windward sides of the islands can receive more than 508 centimeters (200 inches) per year, and leeward areas can receive as little as 38 centimeters (15 inches) per year. The leeward areas have mostly dry warm months and receive most of their rainfall accumulation during the winter storms. The windward regions tend to show smaller seasonal variations because persistent trade wind generated showers govern their rainfall accumulation. El Niño conditions usually disrupt these patterns resulting in drought conditions for the entire state and more frequent hurricanes and tropical storms.

Described by Mark Twain as "the loveliest fleet of islands that lies anchored in any ocean", Hawaii is comprised of 221 kilometers (137 miles) of islands encompassing a land area of 16,686 square kilometers (6,442.6 square miles). There are 8 major Hawaiian Islands: Kauai, Oahu, Lanai, Molokai, Maui, Niihau, Kahoolawe, and Hawaii (sometimes referred to as the "Big Island of Hawaii"). The islands were discovered by Polynesian explorers between the 3rd and 7th century AD and later by the British captain James Cook in 1778. Hawaii became the 50th state in the U.S. union in 1959. Honolulu, the capital city, is located on the island of Oahu. The state resident population in 2000 was a little over 1.2 million with 876,156 residing on the island of Oahu and a yearly population growth at 0.9%. The gross state product in 2000 was 39.1 billion U.S. dollars and the annual per capita income (in 1999) was $27,533. Age breakdown for Hawaii in 2000: Under 5 years old (6.5%); 5-19 years old (20.6%); 20-44 years old (36.8%); 45-64 years old (22.9%); 65+ years old (13.3%). The median age is 36.2 years old.

Chapter 5 - B2. Oahu Overview - Pearl Harbor Water Shed



Introduction

There are too many islands in the Pacific to investigate future climate impacts on all of them in this case study. We will instead spend the remainder of the case study focusing on future climate impacts on the island of Oahu, which is part of the state of Hawaii. Oahu is not necessarily representative of small, low-lying Pacific Islands such as atolls. It is a relatively large island compared to most Pacific Islands, has a large population near 1 million, and a bustling economy. However, it is useful to examine closely because much is known about its geology, geography, weather, and economy. All this aids in projecting how future climate change with impact Oahu and thus can be useful in determining what impacts might occur to other islands.

Oahu Characteristics

Discussion of the implications of climate change on water resources in Hawaii will focus on the island of Oahu, specifically the Pearl Harbor basin (Figure 33). The basin and associated aquifer underlie part of Honolulu's intensively developed urban area. In addition, there are extensively irrigated former sugar-cane, irrigated and non-irrigated pineapple, and upland pastures and forests. The basin's climate is extremely varied with rainfall ranging from 500 to 6000 millimeters (19.7 to 236 inches) per year over a distance of only 25 kilometers (16 miles) (Figure 34). The maximum elevation of Oahu is 1231 meters (4,040 feet) at Kalaa peak.

Figure 33. Oahu Island and the Pearl Harbor basin study area, which is the grey hatched area. Subdivisions or blocks are 1 square kilometer grid cells.

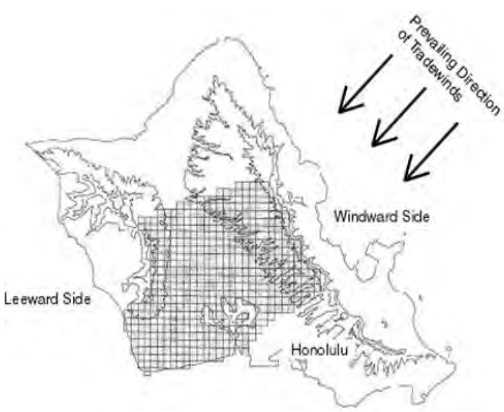
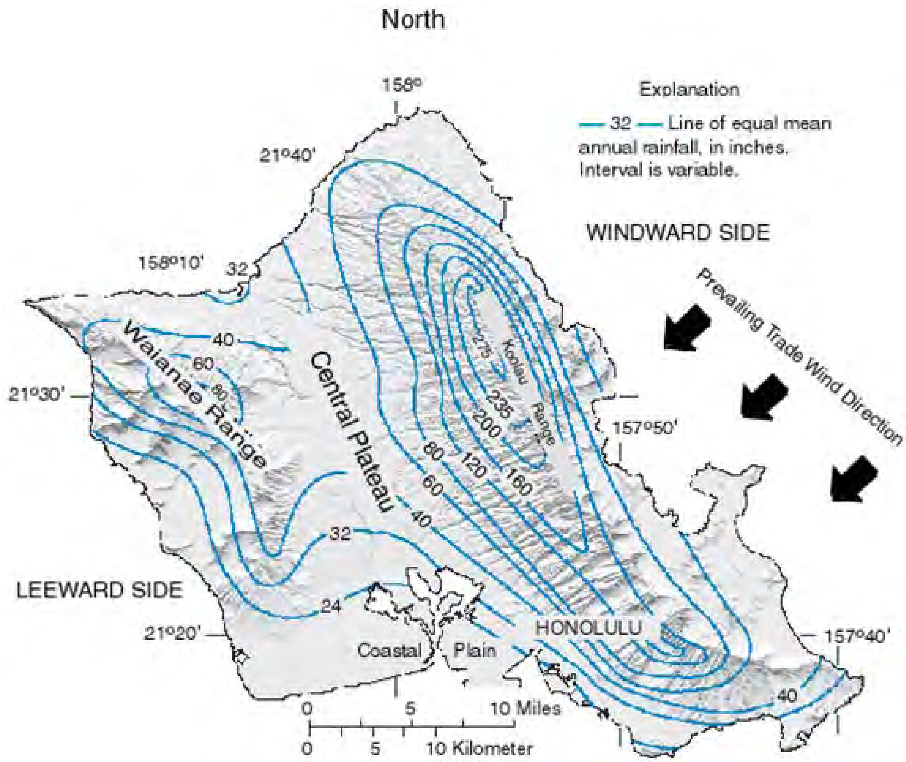
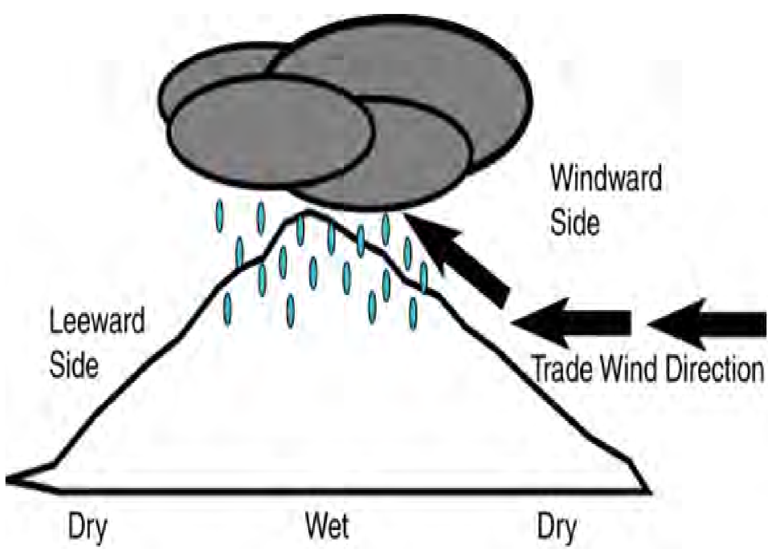


Figure 34. Median annual rainfall pattern of Oahu, Hawaii. Rainfall isopleths (n blue) are measured in inches per year. For example, the highest average rainfall for the Waianae Range is 80 inches per year.



Orographic processes are responsible for this wide range in rainfall (Figure 35). In addition, these orographic processes lead to wide spatial differences in cloudiness, solar radiation, and evaporation within the basin. The Pearl Harbor region is mainly dependent upon underground sources for its water requirements. Groundwater supplies Oahu with 92% of its water use. The development and use of the groundwater system have reached the point to where the sustainability of current and future water usage rates is in doubt.

Figure 35. Orographic rainfall. As air is forced upward over the mountain, it cools, causing water vapor to condense and fall out as rain.



Self Check 5B1 and 5B2

Click above to begin self check for 5B1 and 5B2.

Chapter 5 - C. Oahu: Temperature

Introduction

Temperature and rainfall will both be impacted by future climate change. The climate models, although continually being improved, have reached a stage where they are able to incorporate many processes that impact climate change. The projections we've seen so far suggest that the islands of Hawaii will be impacted by future climate change. Even though these regional and global climate models are quite sophisticated, are not able to take into account smaller scale processes that are important in determining the impact of changing climate to island such as Oahu.

Temperature Effect on Hawaii's Climate

The temperature projections from the Hadley HADCM2 model show that the surface temperature in Hawaii will increase for both short and long-term simulations. Over the short-term (years 2025-2034), sea surface temperatures (Figure 17) will increase between 0.5 to 1.3^{o} C for December, January, and February and 2.0 to 3.0^{o} C for the long-term (years 2090-2099). For the months of June, July, and August, the short-term temperature increase is between 1.0 to 1.6^{o} C and the long-term increase is from 2.3 to 3.3^{o} C (Figure 17).

As a comparison, we'll look at future projections of temperature from two other global climate models (Figure 29). These two models (labeled A2 and B2; Figure 29) project increases in mean surface temperature of 2.3 to 2.6^{o} C and 1.6 to 2.0^{o} C, respectively, for years 2071-2100. The differences between these two models and their projections primarily stem from the fact that model A2 generally has greater increases of greenhouse gases and thus more positive radiative forcing (warming). However, all three models (Hadley HADCM2, A2, and B2) are in general agreement that the tropical Pacific will warm in the next century and that the warming will likely occur over the entire year and not just during the summer months.

Figure 17. Projected changes in skin temperature (sea surface temperature over ocean and surface–air temperature over land) difference for the short-term results (the model's 2025-2034 average minus the 1961-1990 base period average) and the long-term results (2090-2099 average minus the 1961-1990 base period) for the seasons December-January-February and June-July-August, in ^{o} C.

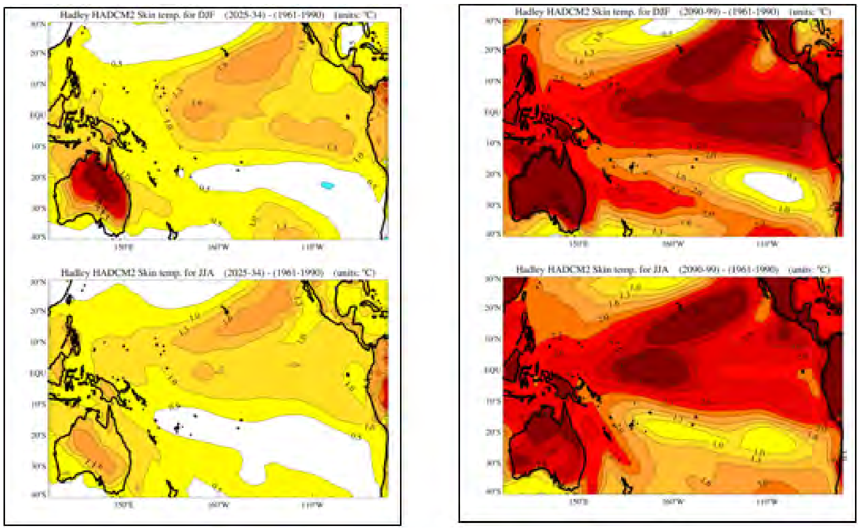
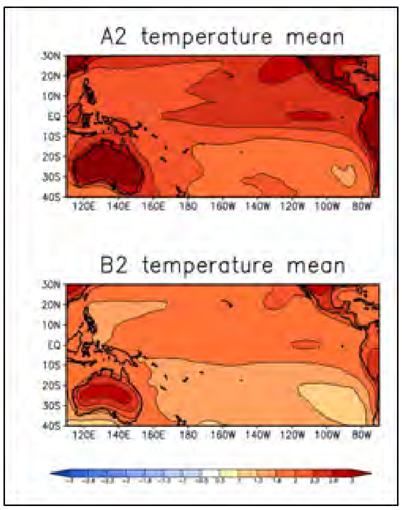


Figure 29. Mean surface air temperature change from the IPCC SRES A2 scenario, 2071-2100 minus 1961-1990, and mean surface air temperature change for SRES B2 scenario; units in ^{o} C.



Overall, the model projections suggest that Hawaii will have elevated temperatures (at least in the summer months of June, July, and August) in the near- (2025-2034) and long- (2090-2099) term. These projections are counter to some historic evidence that warmer periods in Hawaii may not have had elevated precipitation, but instead experienced lower rainfall and increased evaporation which would lead to a decrease in the amount of available water. On the basis of soil distribution, researchers have concluded that higher rainfall was associated with colder, and not warmer, past climates. Additionally, studies of sediments and their distribution in Hawaii suggest that higher trade wind velocities – therefore elevated orographic processes and rainfall – accompanied colder temperatures in the past.

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Chapter 5 - C2. Oahu: Rainfall

Introduction

Temperature and rainfall will both be impacted by future climate change. The climate models, although continually being improved, have reached a stage where they are able to incorporate many processes that impact climate change. The projections we've seen so far suggest that the islands of Hawaii will be impacted by future climate change. Even though these regional and global climate models are quite sophisticated, are not able to take into account smaller scale processes that are important in determining the impact of changing climate to island such as Oahu.

Rainfall Effect on Hawaii's Climate

The rainfall projections from the Hadley HADCM2 model show that rainfall in the vicinity of Hawaii will increase for both short and long-term simulations during the summer months. Over the short-term (years 2025-2034), rainfall (Figure 18) will increase between 1.0 to 2.0 millimeters (0.04 to 0.08 inches) per day for June, July, and August and 3.0 to 4.0 millimeters (0.12 to 0.16 inches) per day for the same months over long-term (years 2090-2099). The rainfall projections for December, January, and February for both short- and long-term show that there will be no change in precipitation during the winter, although in the long-term projections an area of reduced precipitation (0.5 millimeters or 0.020 inches per day) lies just the west of the islands (Figure 18). Except for an area southwest of the Hawaiian Islands in model A2, the A2 and B2 models project no change in the mean precipitation for the area around Hawaii from 2071-2100 (Figure 30). It is worthwhile to note that the A2 and B2 models look at year-long averages whereas the Hadley HADCM2 looks at both winter (December, January, and February) and summer (June, July, and August) month averages. So the Hadley HADCM2 model does not average out the effects of winter and summer, which are important to Hawaii.

*Figure 18. Projected changes in total precipitation change for 2025-2034 and 2090-2099 in units of millimeters per day*10 (centimeters per day).*

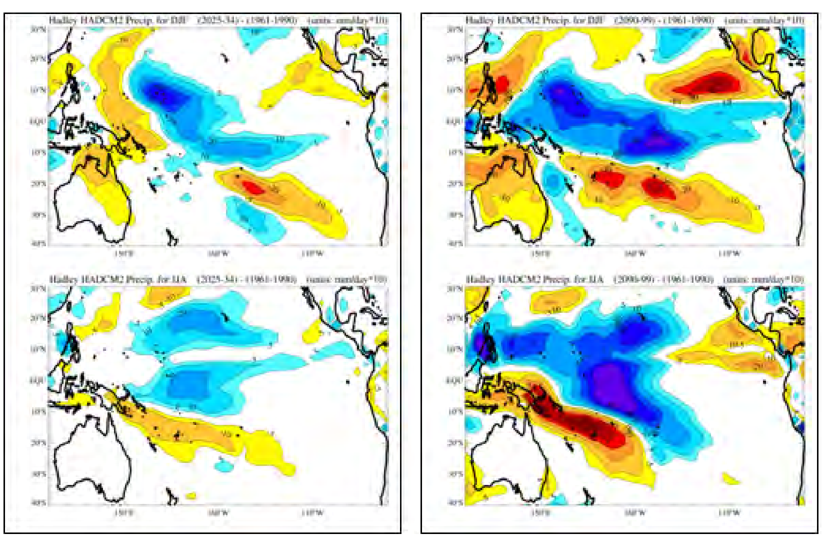
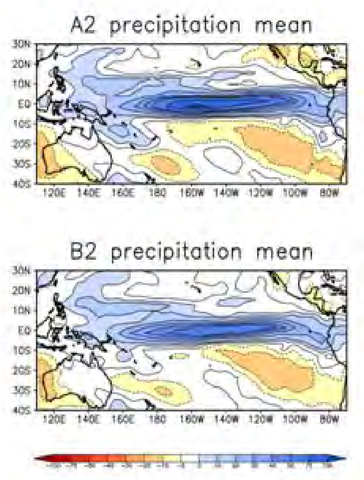


Figure 30. Mean percentage change in precipitation from the multimodel ensemble for the SRES A2 2071-2100 and

mean percentage change in precipitation for SRES B2 scenario. Both scenarios are relative to mean air surface temperatures of 1961-1990.



Overall, the model projections suggest that Hawaii will have elevated precipitation (at least in the summer months of June, July, and August) in the near- (2025-2034) and long- (2090-2099) term. These projections are counter to some historic evidence that warmer periods in Hawaii may not have had elevated precipitation, but instead experienced lower rainfall and increased evaporation which would lead to a decrease in the amount of available water. On the basis of soil distribution, researchers have concluded that higher rainfall was associated with colder, and not warmer, past climates. Additionally, studies of sediments and their distribution in Hawaii suggest that higher trade wind velocities – therefore elevated orographic processes and rainfall – accompanied colder temperatures in the past.

One problem with the larger regional (e.g., the Hadley HADCM2) or global climate models is the relatively course spatial scale resolution of these models. The large scale of these models prohibits them from resolving finer scale processes. Some of these processes impact the hydrology of islands where orography is important, and thus the magnitude and spatial distribution of rainfall and evaporation. Using a hydrologic model, researchers project that a temperature rise of 3^{o} C will result in a 10% increase in evaporation in the Pearl Harbor basin, and even if this change is accompanied by an increase of 10% in precipitation, there still may be a significant shortfall of water at the present water usage level. A 3^{o} C temperature increase is within the range of the long-term (Figure 17) sea surface temperature increase for both winter (December, January, and February) and summer (June, July, and August) months. There is a corresponding projected increase of 3.0 to 4.0 millimeters (0.12 to 0.16 inches) per day for the long-term in precipitation for the summer months (Figure 18).

Contrary to the Hadley HADCM2 model projections, the A2 and B2 models both do not show increased annual mean precipitation from year 2071 to 2100 for Hawaii (Figure 30). For the Pearl Harbor basin, a 10% increase in the yearly precipitation over the precipitation range of the basin (500 to 6000 millimeters or 19.7 to 236 inches per year) would correspond to an increase of 50 to 600 millimeters (2.0 to 24 inches additional rainfall per year). The Hadley HADCM2 summer long-term rainfall projections of 3.0 to 4.0 millimeters (0.12 to 0.16 inches) per day (Figure 18) would correspond to an increase of rainfall by 274 to 365 millimeters (10.8 to 14.2 inches) for those 3 months during the long-term (2090-2099). Note that this increase is only over 3 summer months and not the entire year. It is unclear whether there would be increased rainfall for the remaining 9 months, but for the long-term winter month projections (December, January, February in Figure 18), there is no projected increase in precipitation. It is possible that the increased rainfall in the summer months (274 to 365 millimeters or 10.8 to 14.2 inches) over the long-term will not balance the increased evaporation over the entire year caused by the elevated temperature (3^{o} C) leading to non-sustainability in the water resource for the island of Oahu.

Self Check for 5C1 and 5C2

Click here to begin self check for 5C1 and 5C2.

Chapter 5 - D1. El Niño and Storms

Introduction

Regional and global climate models investigate broad scale changes in climate. These broad scale changes can also influence destructive phenomenon such as El Niño, La Niña, and hurricanes. Changes in climate might make these events more likely or stronger when they occur.

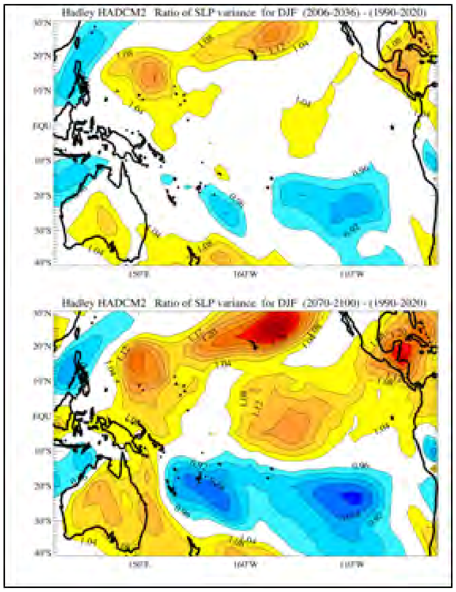
Big Impacts: Hurricanes and El Niño

Although some historical evidence suggests that rainfall increases during cooler times, and thus decreases during warmer times, alteration of the El Niño Southern Oscillation and storm variability by climate change could offset the reduction in trade wind, orographic driven precipitation. The general future increase in sea surface temperatures along the equatorial Central and Eastern Pacific projected by the Hadley HADCM2 and other models - A2 and B2 - we have looked at (Figure 17 in Chapter 4A and Figure 29 in Chapter 5C) suggests a greater tendency for El Niño-like conditions. It is uncertain whether future increases in ocean temperatures might change the character of the El Niño Southern Oscillation so that El Niños appear more or less frequently.

Increased tropical and equatorial sea surface temperatures however could lead to increased hurricane activity and the possibility of large-scale damage to property and resources. Hurricane Iniki made landfall on the island of Kauai, Hawaii, in September 1992 causing 7 deaths, 1.8 billion dollars in damage, and $260 million in Federal Emergency Management Act disaster relief costs. This is in spite that Iniki landed on the 4th most populous island in the state (Island populations from largest to smallest: Oahu > Big Island of Hawaii > Maui > Kauai). Had Iniki landed on Oahu, and specifically Honolulu and Waikiki, the cost and level of destruction would have been significantly greater not only to the island itself, but the entire state's economy.

The sea level pressure projections (Figure 24) for December, January, and February suggest that the level of storminess will increase around Hawaii during the winter months. This increased storminess and associated precipitation during the winter months (also when evaporation is lowest due to cooler temperatures) could offset the loss of water from increased evaporation due to higher average yearly temperatures predicted by the regional climate models. The issues brought up (see previous section *C. Temperature and Rainfall*) with the inability of the relatively course regional scale precipitation models to resolve the smaller scale processes (e.g. orographic) that impact the hydrology of islands are also relevant to the impact of increased storminess and resultant rainfall to the islands of Oahu.

Figure 24. The ratio of sea level pressure variance for December-January-February for the period 2006-2036 compared to 1990-2020 and the period 2070-2100 compared to 1990-2020. Higher ratios (>1 in yellow and orange) indicate more storminess in the future periods.


Hadley HADCM2 Ratio of SLP variance for DJF (2006-2036) - (1990-2020)
Hadley HADCM2 Ratio of SLP variance for DJF (2070-2100) - (1990-2020)

Chapter 5 - D2. La Niña

Introduction

Regional and global climate models investigate broad scale changes in climate. These broad scale changes can also influence destructive phenomenon such as El Niño, La Niña, and hurricanes. Changes in climate might make these events more likely or stronger when they occur.

Impacts of La Niña

The NOAA Climate Prediction Center announced in January 2006 the official return of La Niña. Oceanic sea surface temperatures have met the operational definition of La Niña for the November through January period. La Niña is the periodic cooling of ocean waters in the east-central equatorial Pacific, which can impact the typical alignment of weather patterns around the globe. NOAA predicts this La Niña event will likely remain into late spring, and possibly into summer.

"In mid-January 2006 the atmosphere over the eastern North Pacific and western U.S. began to exhibit typical La Niña characteristics in response to the cooling in the tropical central Pacific Ocean," said Vice Admiral Conrad C. Lautenbacher, undersecretary of commerce for oceans and atmosphere and NOAA administrator. He continued to say, "This pattern will favor continued drought in parts of the South and Southwest from Arizona to Arkansas and Louisiana, and above normal precipitation in the Northwest and the Tennessee Valley area."

Internationally, La Niña impacts during the Northern Hemisphere winter typically include enhanced rainfall across Indonesia and northern Australia, as well as in the Amazon Basin and in southeastern Africa and below-average rainfall across the eastern half of the equatorial Pacific and eastern equatorial Africa. Typically, La Niña events favor increased Atlantic hurricane activity.

La Niña events are operationally defined using the Oceanic Niño Index (ONI), which is the three-month running-mean values of sea surface temperature departures from average in the region of the central Pacific (bounded by 5^{o} N to 5^{o} S, 120 to 170^{o} W). NOAA defines La Niña as the condition whereby the ONI is less than or equal to -0.5 degrees C. This definition was adopted by the U.S. and 25 other countries in North and Central America and the Caribbean in April 2005. La Niña events recur approximately every three to five years. The last La Niña occurred in 2000-2001 and was a relatively weak event compared to the 1998-2000 event. NOAA continually releases 90 day outlook updates on El Niño/La Niña conditions and also its Atlantic and Pacific hurricane season outlooks.

Self Check 5D1 and 5D2

Click here to begin self check for 5D1 and 5D2.

Chapter 5 - E1. Sea Level: Honolulu and Waikiki, Oahu

Introduction

Using global climate models, it is possible to project how future increases in atmospheric greenhouse gas concentrations will impact sea surface temperatures. It is much more difficult to predict how the ocean's temperature will vary below the sea surface because this has to do with global ocean circulation. With global warming, sea level will rise due to two reasons: (1) melting of glacier and ice sheets that adds water to the ocean, and (2) local heating and subsequent expansion of water due to temperature rise. With rising sea level, the effects of storms will be greater. Rising sea level can also impact island groundwater resources by intruding on the groundwater table.

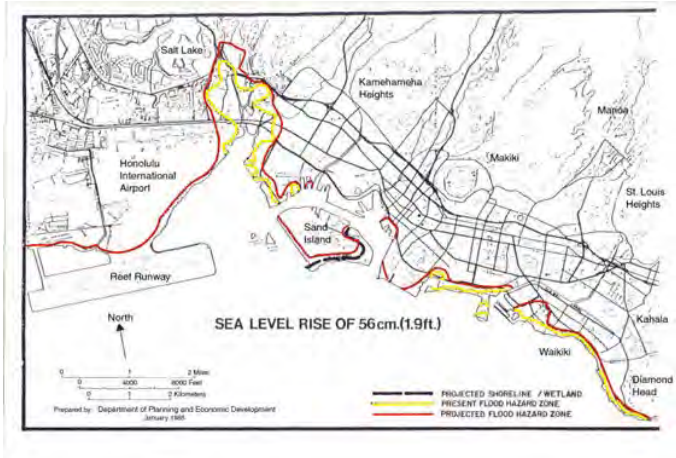
Sea Level and Pacific Islands

The projected sea level rise from the Pacific Islands Regional Assessment Group report (Figure 26) for the Hawaiian Islands during the period 2020-2040 (relative to 1980-2000) is 10.0 to 12.5 centimeters (3.94 to 4.92 inches) and for the period 2080-2099 (relative to 1980-2000) is between 35.0 and 37.5 centimeters (13.8 to 14.8 inches). In 1985, the State of Hawaii Coastal Zone Management Program and the Hawaii Institute of Geophysics, in response to Senate Resolution 137, compiled the report *Effects on Hawaii of a worldwide rise in sea level induced by the "Greenhouse Effect"*. The impetus, in part, for Senate Resolution 137 was due to wide ranging and thus controversial estimates from various studies on the projected range (70 centimeters to 600 centimeters or 28 to 236 inches) of sea level rise for the next century. The report's purpose was to determine the significance of the range of Environmental Protection Agency predictions for sea level rise by 2100. These predictions were categorized as (a) lowest conceivable (0.57 meters or 1.9 feet), (c) lowest likely (1.5 meters or 4.8 feet), (c) highest likely (2.2 meters to 7.1 feet), and (d) highest conceivable (3.4 meters or 11.3 feet). It should be noted that presently most of projections of future sea level rise made in the 1980's, in light of more recent estimates, are considered overestimates.

The report scenarios focused on rise of sea level impacts to Honolulu's shoreline since this coastal city is both the state's major population center and the transportation hub that the state economy depends on. The "lowest conceivable" Environmental Protection Agency estimate of sea level rise (0.57 meters or 1.9 feet) for 2100 is greater than the Pacific Islands Regional Assessment Group report projected sea level rise for 2080-2099 (0.350 to 0.375 meters or 1.15 to 1.23 feet; Figure 26), so it is difficult to extrapolate the report's conclusions of this scenario to the Pacific Islands Regional Assessment Group projections. Figure 36 is a map of how a sea level rise of 0.57 meters (1.9 feet) would change Honolulu's projected shoreline and flood hazard zone compared to the contemporary shoreline and flood hazard zone. In this scenario, only parts of Sand Island are inundated by sea level rise. However, Honolulu International Airport's reef runway and greater areas of Waikiki are both projected as flood hazard zones with this elevation in sea level. Again, it is important to recognize that these projections and subsequent impacts were determined using the best estimates of the early 1980's, which is 25 years ago.

The economic and social impacts of changing climate on the Hawaiian Islands are intimately tied to changes in rainfall and sea level. Given that the state's economy is heavily dependent upon the tourism industry (as of 2003, 26% of the state's economy is from tourism), any damage to the reef runway, which is used for landing and takeoffs of long-range heavy jets, and Waikiki could severely stress the state's economy. Waikiki, one square mile of the total area of Honolulu, is associated with supporting 11% of the state's civilian jobs, 12% of the state and local tax revenues, and is responsible for $3.6 billion or 46% of statewide tourism's total contribution to the 2002 Gross State Product.

Figure 36. Projected impact to Honolulu shoreline of sea level rise of 56 centimeters (1.9 feet).


Salt Lake
Kamehameha Heights
Manoa
Makiki
Honolulu International Airport
St. Louis Heights
Sand Island
Reef Runway
North
SEA LEVEL RISE OF 56cm.(1.9ft.)
Kahala
Waikiki
Diamond Head
0 1 2 Miles
0 4000 8000 Feet
0 1 2 Kilometers
Prepared by: Department of Planning and Economic Development
PROJECTED SHORELINE / WETLAND
PRESENT FLOOD HAZARD ZONE
PROJECTED FLOOD HAZARD ZONE

Chapter 5 - E2. Sea Level: Kailua, Oahu

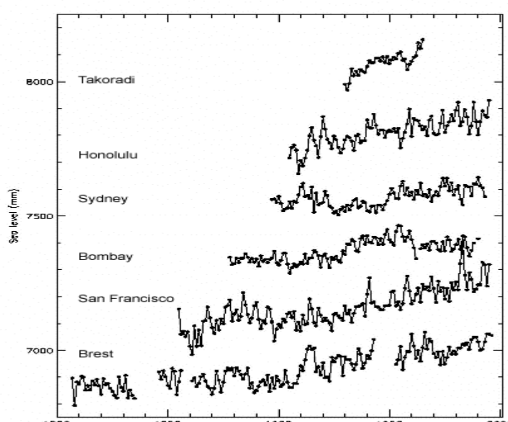
Introduction

Using global climate models, it is possible to project how future increases in atmospheric greenhouse gas concentrations will impact sea surface temperatures. It is much more difficult to predict how the ocean's temperature will vary below the sea surface because this has to do with global ocean circulation. With global warming, sea level will rise due to two reasons: (1) melting of glacier and ice sheets that adds water to the ocean, and (2) local heating and subsequent expansion of water due to temperature rise. With rising sea level, the effects of storms will be greater. Rising sea level can also impact island groundwater resources by intruding on the groundwater table.

Kailua, Oahu

In another study on Oahu, the effects of a 1 meter (3.3 feet) sea level rise were studied on shoreline migration and groundwater for the town of Kailua (population 43,780) located on the eastern coast of Oahu. The study anticipates that a 1 meter (3.3 feet) rise in sea level will not have a detrimental impact on Kailua's freshwater lens, although Kailua does not obtain drinking water from this source. Even if sea level rise would not be a detriment to local groundwater resources, it would cause the water table to rise and result in an increased opportunity for coastal flooding. Oahu's freshwater lens rides on top of underlying, denser saltwater. As sea level rises, as it may around Oahu and the globe (Figure 37), so will the level of the underlying saltwater. This would result in bringing the freshwater lens, or height of the water table, closer to the land surface. With the freshwater lens closer to the land surface, this would promote flooding during heavy rain events because there would be less ground to soak up excess rain (see below). Furthermore, tidal action can exacerbate the baseline rise in sea level over short time periods by elevating an already raised sea level due to global warming and climate change.

Figure 37. Sea level change measured by tide gauges.



Climate and Water Resource Case Study

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Chapter 5 - E3. Sea Level: Storms and Oahu

Introduction

Using global climate models, it is possible to project how future increases in atmospheric greenhouse gas concentrations will impact sea surface temperatures. It is much more difficult to predict how the ocean's temperature will vary below the sea surface because this has to do with global ocean circulation. With global warming, sea level will rise due to two reasons: (1) melting of glacier and ice sheets that adds water to the ocean, and (2) local heating and subsequent expansion of water due to temperature rise. With rising sea level, the effects of storms will be greater. Rising sea level can also impact island groundwater resources by intruding on the groundwater table.

Sea Level, Storms, and Oahu

Some evidence of how sea level rise, sometimes in conjunction with high tide periods, can impact Oahu may have been provided between November, 2003 to March, 2004. During this interval, termed the “ho'oilo” or wet season in Hawaiian, the Hawaiian Islands were repeatedly hit with heavy storm activity that was severe enough to spawn very rare occurrences of waterspouts and tornados. Over this interval, the island of Oahu and the remaining Hawaiian Islands received extensive intense rainfall (Table 3).

Table 3. Oahu rainfall station totals (in inches) from November 2003 through March 2004 for the Wilson Tunnel, Honolulu International Airport, and Aloha Tower (see Figure 38 for rainfall gauge locations). The percentage of the monthly rainfall total compared to the normal monthly rainfall is given in parentheses. Source: National Weather Service, Honolulu Forecast office.

Month	Wilson Tunnel	Honolulu Int. Airport	Aloha Tower[1]
Nov. 2003	19.67 (193%)	0.57 (25%)	1.60 (64%)
Dec. 2003	27.58 (251%)	4.81 (166%)	5.04 (136%)
Jan. 2004	19.78 (171%)	6.88 (255%)	7.98 (205%)
Feb. 2004	22.90 (260%)	9.47 (395%)	4.40 (183%)
Mar. 2004	19.02 (165%)	0.56 (29%)2	1.62 (54%)

[1] Aloha Tower is close to Mapunapuna; [2] by the end of March 2004, Honolulu International Airport had received within an inch of its yearly average of total rainfall.

Some examples of rainfall totals received were: (1) November 29th-30th, 2003, Oahu received up to 29.1 centimeters (11.47 inches) in 24 hours (Wilson Tunnel, Oahu), (2) December 7th and 8th, parts of Oahu received over 28 centimeters (11 inches) of rain, (3) on February 27th, Oahu received almost 20 centimeters (8 inches) in a 24 hr period. These storms resulted in extensive flooding, especially in certain Honolulu industrial areas (e.g. Mapunapuna). The flooding was a function of a variety of factors such as saturated soil, clogged drainage, and high tide. Because the storm events lasted many times longer than a day, the interval of their precipitation and resultant runoff occurred over enough time to encompass the daily high tide. The high tide (over 0.6 meters or 2 feet at times; Table 4) imposed on the long-term sea level rise trend (Figure 37) resulted in the flooding of the island drainage system to the ocean – i.e., runoff water can not drain to the ocean because the elevated sea level floods the drainage system. This backup due to elevated sea level increased the opportunity for flooding, especially given that the ground was already saturated and therefore unable to absorb more rainwater.

Figure 38. Rainfall gauge locations on Oahu.

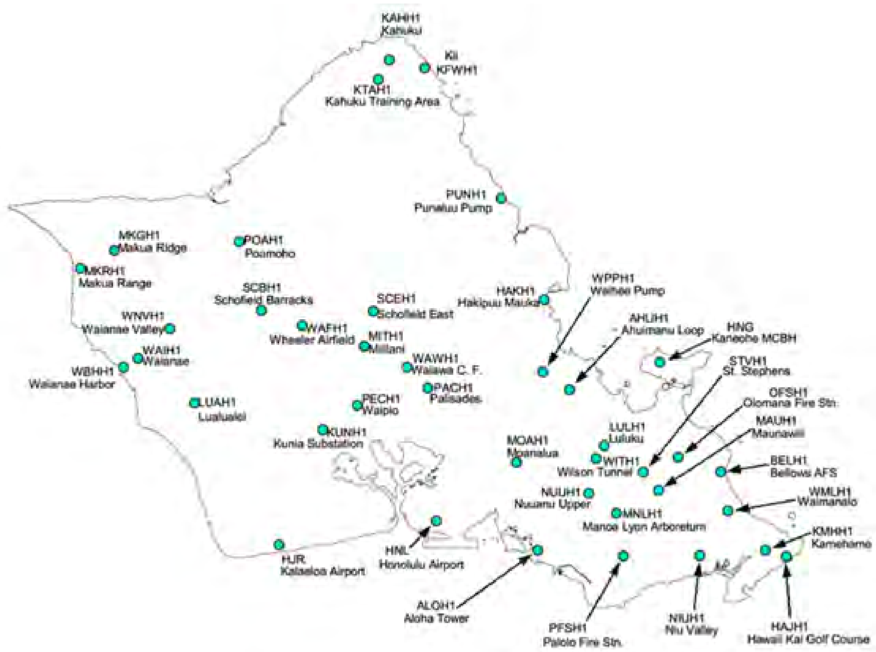

Table 4. Maximum high tide on major storm days for Honolulu (www.almanac.com).

Storm Date	Elevation (feet)
Nov. 29th –30th, 2003	2.08
Dec. 7th – 8th, 2003	2.18
Dec. 28th, 2003	1.92
Feb. 27th, 2004	1.56

Although the storms of late 2003 – early 2004 did not cause any significant damage to Waikiki, they did cause considerable damage elsewhere in Honolulu. Mapunapuna, an industrial section of Honolulu, was flooded several times during this period of time. Parts of Mapunapuna were under as much as several feet of water and mud resulting in significant damage to many businesses. During high tide, even without heavy rainfall, the ocean can back up onto streets in Mapunapuna through the drainage system. Sinking soil in the area has also put some areas below sea level

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further exacerbating the situation. Damage alone from the December 7 to 8 storm induced by flooding in Mapunapuna was estimated at $20 million.

Sea level change due to global warming has already been attributed to relocation for some Pacific Islanders. In 2002, rising sea levels in Vanuatu have forced the relocation of an entire village. This has been described as the first case in the world of the formal displacement of an entire human population due to global warming. More than 100 residents of Tegua Island had to abandon their settlement for higher ground after major flooding made their village uninhabitable. This could be just the beginning of a trend in the region. There are now some 2000 people on the Carteret Islands off Papua New Guinea planning to move to Bougainville Island because of similar flooding problems.

Read more about the situation in Vanuatu here.

Self Check 5E

Click here to begin self check for 5E.

Chapter 5 - F. Ocean Resources: Corals

Introduction

In addition to impacts on the island land biota, global climate change can also impact island-associated marine biota. Coral reefs are important components of the marine ecosystem that typically surround tropical Pacific Islands. Corals are great indicators of changes in environmental conditions. They are very sensitive to changes the level, temperature, and chemistry of sea water. Coral reefs provide a framework and home to many different species. These species not only form an important component of the marine ecosystem, but many are used by island inhabitants for example for food. In addition, coral reefs attract visitors and thus play a big role in many Pacific Island economies.

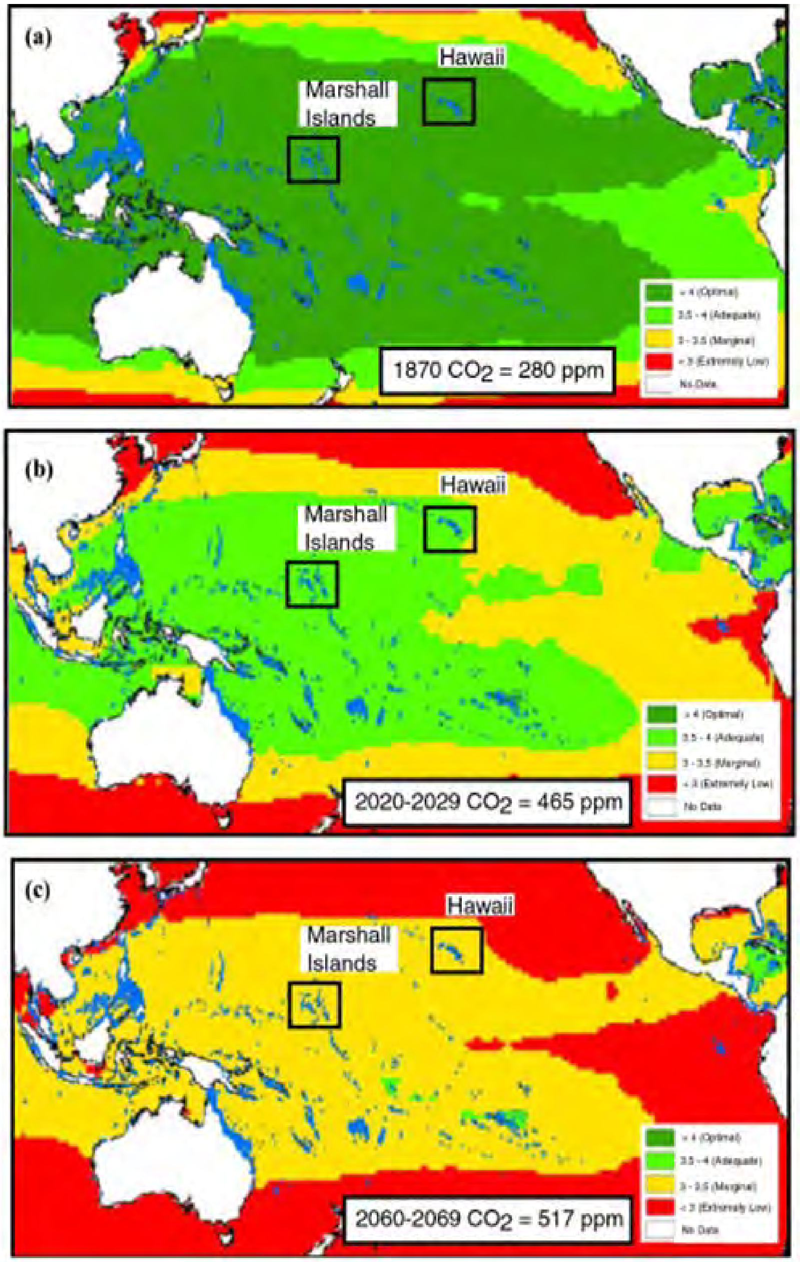
Coral Reefs

Factors associated with global change, such as elevated atmospheric carbon dioxide levels, can reduce the growth rate of corals. Increased atmospheric carbon dioxide concentrations would lead to increased dissolution of carbon dioxide into seawater, which in turn would decrease surface ocean pH (acidify the surface ocean). By lowering surface ocean pH, some investigators believe that the ability of corals to grow would be retarded and in some cases the corals might begin to dissolve. Reducing coral growth rates would further aggravate the effects of elevated sea-surface temperatures on the ability of coral reefs to keep up with sea level rise and subsequently protect shorelines from storm surge and wave action.

Click here to read an in-depth report on ocean acidification.

Below are results of a study on the impact that the rise in future atmospheric carbon dioxide levels until 2069 will have on the aragonite saturation state (click here for description of staturation state) of seawater in the Pacific Ocean basin. Aragonite ($CaCO_3$), made of calcium (Ca) and carbonate ions (CO_3), is the mineral which coral polyps precipitate to form their skeleton and thus reef structure. The saturation state of the ocean water with respect to aragonite indicates whether aragonite will precipitate or will dissolve. Among other things, the aragonite saturation state is a function of the amount of dissolved carbon dioxide in the water and temperature of the water. Figure 25 shows the negative impacts of future projected atmospheric carbon dioxide levels on aragonite saturation state in the Pacific Ocean basin. Generally speaking, from present day to 2069, the area of optimal and adequate saturation states contracts from high to low latitudes and from the ocean basin margins toward the center of the basin. By the year 2069, there is almost a complete absence of adequate areas of aragonite saturation state in the Pacific Basin. The reefs of Hawaii produce an estimated total annual economic benefit of $363 million dollars that future changes in surface ocean aragonite saturation state could negatively impact.

Figure 25. Pacific Basin aragonite (a form of the mineral calcium carbonate, $CaCO_3$, which serves as the physical structure that reef building organisms use to construct coral reefs) saturation state: (a) Calculated preindustrial (1870) values; Atmospheric carbon dioxide = 280 parts per million; (b) Projected values for 2020-2029; Atmospheric carbon dioxide = 465 parts per million; (c) Projected values for 2060-2069; Atmospheric carbon dioxide = 517 parts per million.



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Chapter 5 - G. Water Resources

Introduction

The most valuable natural resource for islands is fresh water. Without fresh water, vegetation and animals can not survive. Small islands, such as atolls, have very small water tables (the body of groundwater that can be used for fresh water) and are extremely susceptible to even short-term variation in sea level rise and precipitation rates. Large islands, such as Oahu, have greater groundwater resources primarily because their mountains can cause orographic rainfall, which is a consistent source of rainfall. However, large islands like Oahu have other pressures, such as population, that will exacerbate water resource problems associated with climate change and sea level rise.

Implications of Climate Change for Hawaii's Water Resources

How exactly climate change will impact Oahu's groundwater supply by changing precipitation and evaporation rates is difficult to determine. Recent studies noted that a temperature rise of 3 ^{o}C would result in a 10% increase in evaporation in Oahu's Pearl Harbor basin. Even an accompanying precipitation rate increase of 10% would be too little to sustain the groundwater reservoir at present water usage levels. It is important to note again that predicting how future climate change will impact island weather-related processes (e.g., orographic patterns) is currently difficult because the present climate models' spatial scale resolution is too course (course means large) to model successfully how these smaller-scale weather-related processes will be impacted by climate change. However, it is likely that as population continues to grow on Oahu, the groundwater supply will be taxed more and more, especially if climate change further makes the problem worse.

The economic and social impacts of changing climate on the Hawaiian Islands are intimately tied to changes in rainfall and sea level. Given that the state's economy is heavily dependent upon the tourism industry (as of 2003, 26% of the state's economy), any water shortage or restrictions imposed on the 100,000 or so visitors at any one time in Waikiki could severely stress the state's economy. Waikiki, one square mile of the total area of Honolulu, is associated with supporting 11% of the state's civilian jobs, 12% of the state and local tax revenues, and is responsible for $3.6 billion or 46% of statewide tourism's total contribution to the 2002 Gross State Product.

In 2002 and 2003, several government and local organization did ground-water-level surveys in the Pearl Harbor area of Oahu, Hawaii. On October 31, 2002, water levels at 24 wells (wells are holes dug in the ground to see where the water table level is at) were measured during a two and a half hour time period (9:00 a.m. to 11:30 a.m.). On May 15, 2003, water levels at 23 wells were measured between 9:00 a.m. and 11:30 a.m. Organizations and agencies participating included the U.S. Geological Survey, the Honolulu Board of Water Supply, the Hawaii Commission on Water Resource Management, the U.S. Air Force (through their consultant, URS Corporation), and the U.S. Navy.

Water levels measured on October 31, 2002 in the Pearl Harbor area ranged from 13.6 to 20.4 feet above the average sea level. Water levels measured on May 15, 2003 in the Pearl Harbor area ranged from 13.1 to 19.7 feet above the average sea level. In general, measured water levels were lowest near the southeastern and southwestern parts of the Pearl Harbor area and were highest in the inland, northern part of the area. The water-level measurements of October 31, 2002 and May 15, 2003 shared a total of 21 well sites in common. At each of these common sites, the change in water level can be determined. For three wells in the western part of the Pearl Harbor area, water levels changed by 0.1 foot or less. For the remaining 18 common sites, water levels measured on May 15, 2003 were about 0.4 to 1.6 feet lower than water levels measured on October 31, 2002. With fresh water use on Oahu already exceeding sustainable use by some estimates, the drop in ground water levels in the Pearl Habor basin is troubling.

Figure. October 31, 2002, Pearl Harbor area water level survey.

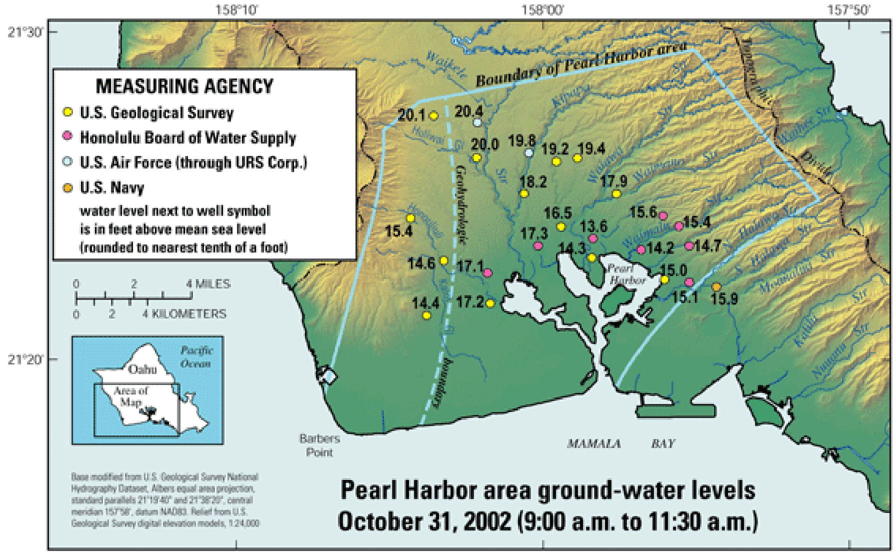
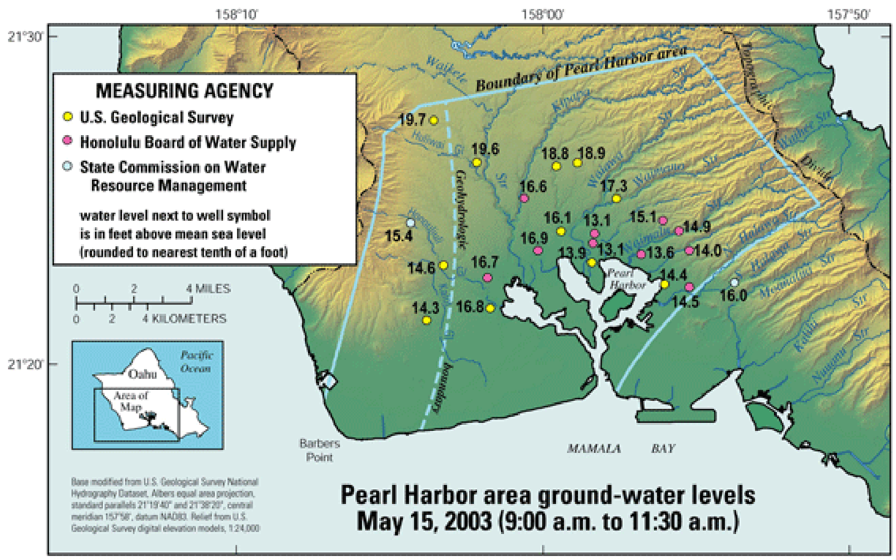


Figure. May 15, 2003, Pearl Harbor area water level survey.



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Chapter 6 - Conclusions

Conclusions

Coures Reference Links

- NASA Climate Center
- NOAA Climate Site
- NOAA El Niño Site
- NOAA Paleoclimate Site
- NOAA Climate/Weather Site
- Intergovernmental Panel on Climate Change (IPCC)

Final thoughts

This concludes the course on climate changes and impacts to Pacific Islands in general and more specifically Hawaii. You have studied the best future estimates of climate change from the most current global and regional climate models. You have also studied what these estimates of climate change might mean for Pacific Island resources. What are your thoughts on these estimates and potential impacts? If the future projections for the next 100 years are correct, are you worried about their potential impacts? Do you feel that there is anything that can be done to minimize the impacts of climate change on Pacifc Islands? If so, what do you think can be done and are these actions at an individual, local, regional, or global level? Are individuals like you and I responsible to help and therefore need to take action? Hopefully, this course has made you think about questions like these and also taught you some of the science that is important to understanding the climate change issue.

