CLIMATE CHANGE

From the *Technology and Environmental Decision-Making* Series

This 2016 version of the *Climate Change* module was originally published in 2003 by the Advanced Technology Environmental and Energy Center (ATEEC). The module, part of the series *Technology and Environmental Decision-Making: A critical-thinking approach to 7 environmental challenges*, was initially developed by ATEEC and the Laboratory for Energy and Environment at the Massachusetts Institute of Technology, and funded by the National Science Foundation. The ATEEC project team has updated this version of the module and gratefully acknowledges the past and present contributions, assistance, and thoughtful critiques of this material provided by authors, content experts, and reviewers. These contributors do not, however, necessarily approve, disapprove, or endorse these modules. Any errors in the modules are the responsibility of ATEEC.

Author: Michael Beck, ATEEC
Editor: Glo Hanne, ATEEC
Content Expert: Dr. Jeffrey I. Steinfeld, Massachusetts Institute of Technology
Content Reviewer: Vince Maraventano, Executive Director, MA Interfaith Power & Light, Inc.

This project was supported, in part, by the Advanced Technological Education Program at the National Science Foundation under Grant No. DUE #1204958. The information provided in this instructional material does not necessarily represent NSF policy.

Cover image: Tigvariak Island, Alaska North Slope. Credit: Rear Admiral Harley D. Nygren, NOAA Corps (ret.)

Additional copies of this module can be downloaded at ATEEC's website: www.ateec.org.

Climate Change

Credit: Heather Seyfang, MIT

Contents

Introduction

A subject both complex and controversial, climate change is a problem of global proportions. A Web search engine will return well over one million results for a query about "global climate change." In spite of—or perhaps because of—this wealth of information, how people view and interpret climate change concepts varies greatly. Learning the subject well enough to understand the various perspectives on climate change is a significant challenge. However, developing this understanding is key, as climate change may be the most critical challenge facing our world today. Decisions made today will have far-reaching, long-standing effects.

This module provides a multi-faceted context for understanding the issues surrounding climate change. It summarizes some of the readily available basic information, presents multiple perspectives on global climate change research and policy, and provides classroom activities that place climate change issues in a context accessible to students. The distinctive contributions of this module to the current body of instructional resources on global climate change include:

- A unique combination of perspectives, skills, and tools to help individuals critically evaluate climate change data and controversy;
- An integration of basic scientific concepts with potential solutions involving behavioral and technological change; and
- The inclusion of the perspectives of researchers at the Massachusetts Institute of Technology (MIT) and elsewhere working on the frontier of climate change research.

> "The global and holistic nature of the climate change threat, which affects all nations and requires continued progress on technology, policy, behavioral shifts, and beyond, makes it society's grandest challenge of the present day, possibly of all time."
>
> Report of the MIT Climate Change Conversation Committee (MIT C4), June 2015

The topic of climate change makes headlines on a seemingly daily basis. New information is released from a wide variety of sources. Compiling this information and distilling it to age-appropriate material can be a daunting task. Addressing those information needs, this module opens with a presentation of basic concepts about climate change and then offers some context for understanding those concepts and their impact on society. The final section offers potential solutions to the climate change problem through individual and social behavior and technological changes. The concluding section, Aids to Understanding, includes resources and additional activities for each section.

The main sections of the module are described briefly below.

- The Scientific Basis covers basic science principles—including the carbon cycle and the earth's radiation balance—needed to understand climate change and the uncertainties surrounding climate change.
- What Do We Know and How Do We Know It? investigates how the science involved in climate change is evaluated and who performs the evaluations. It also looks at the shifts in perceptions and understanding in recent years, the range of views based on what appears to be the same knowledge base, and an approach for making sense of this complex global issue.
- Climate Change and Its Potential Impact on Society examines how climate change might affect individuals and their jobs, communities, businesses, industries, and technology. Local and regional implications are considered, as well as global equity issues, such as how the costs and effects of climate change—both beneficial and harmful—are distributed.
- What We Can Do focuses on responses to the climate change problem. What actions can be taken—from increasing energy efficiency to adapting modes of transportation, from the actions of a group to those of the individual—that will help humans adapt to or reduce climate change?

The Scientific Basis

A huge amount of data is now available on climate trends; the effect that climate change is having on weather conditions, ecosystems, and the built environment; and forecasts of future trends and Earth system responses. Although many of the basic science principles are now well established, there still exists a level of debate among some scientists, policymakers, the media, and the public. Some of these disagreements have become highly polarized and politicized, impeding progress on finding solutions. This section summarizes the basic science principles of climate change and the associated uncertainties. We will also examine the participants in the climate change debate and possible motivations for their actions.

Basic Science Principles

Defining Climate

Climate is defined on a much longer time scale than weather (which is typically discussed in terms of 1–2 weeks). Often described by statistics such as temperature, precipitation, wind, and humidity, climate can be defined as the "average of weather over time and space."[1] According to Richard C. J. Somerville, climate modeler with the Scripps Institution of Oceanography, "We've begun to think of climate as not simply the average state of the atmosphere, but the average and measures of the variability of the atmosphere and other aspects that interact with it."[2] Several factors, described as climate forcings, influence climate and climate change.

"Climate lasts all the time and weather only a few days."

Mark Twain, "*English as She is Taught*"

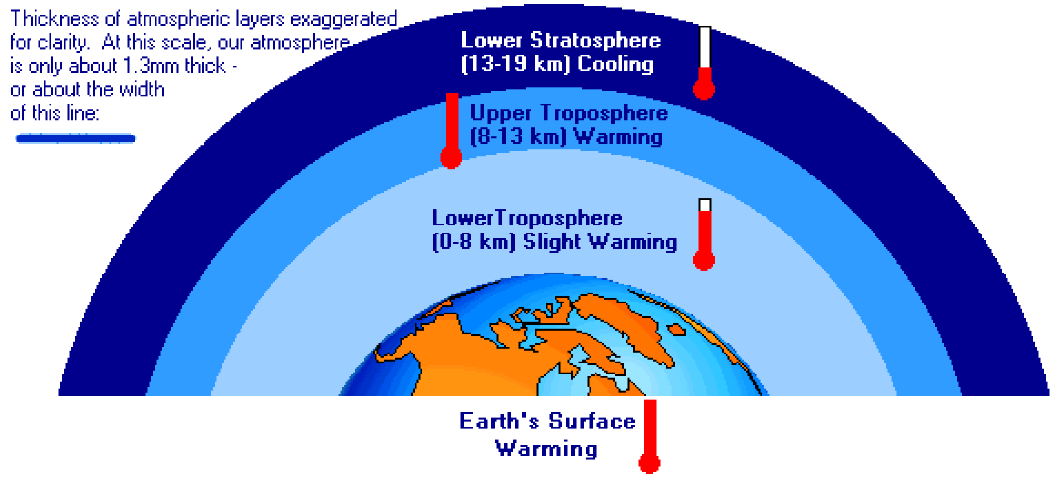
Climate forcings are "A measure of the influence of a particular factor on the net change in the earth's energy balance."[3] The energy balance of the planet Earth reacts to these forcings, causing a change in the climate state. A volcanic eruption is an example of a natural forcing. When a volcano erupts, it throws fine particles into the air. These particles reflect sunlight to space, reducing the solar energy delivered to the earth's surface.[4]

Five greenhouse gases (GHGs) are from both natural and human sources: water vapor (H_2O), ozone (O_3), carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4).

Three trace GHGs are from human sources: chlorofluorocarbons (CFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6).

Particulate materials, such as black soot, can also contribute to radiative forcing in the atmosphere.

Figure 2. Earth's Atmospheric Layers and Temperature Variations



Credit: science.NASA.gov

One type of climate forcing is called the greenhouse effect. Greenhouse gases (GHGs) in the atmosphere absorb thermal radiation emitted from the earth's surface. Most of the GHGs occur naturally. However, humans also contribute to greenhouse forcings, mostly through the burning of fossil fuels.[5]

The greenhouse effect stores some of the sun's energy in the earth's atmosphere. This process can be loosely compared to a greenhouse. Radiation from the sun passes through the atmosphere, just as it would enter a glass greenhouse filled with plants. The plants emit thermal radiation, but the glass acts as a blanket and keeps part of that radiation in the greenhouse, which stays warm. For the earth, the GHGs serve nearly the same function as the glass does for the greenhouse.[6] The natural greenhouse effect, first recognized and explained by Jean-Baptiste Fourier and Svante August Arrhenius, maintains the earth's average temperature at 15 degrees C, rather than at -6 degrees C. Because of this difference, we can comfortably live on this planet. Otherwise, few plants would grow well, and life on Earth would have developed very differently.

Jean-Baptiste Fourier

A sun worshipper, Jean-Baptiste Joseph Fourier in the early 1820s wondered "how Earth stays warm enough to support the diverse range of flora and fauna inhabiting its surface." Later criticized as a speculative work, Fourier's "General Remarks on the Temperature of the Terrestrial Globe and Planetary Spaces" described a "bell jar hypothesis." He compared the atmosphere above the earth to a bell jar where the black "dome" captured and re-radiated the Sun's warmth back to Earth. He believed that a "green-house effect" made it possible for life on Earth to flourish because without this re-heating, the planet would be too cold for life forms.[7]

Svante August Arrhenius

"Is the mean temperature of the ground in any way influenced by the presence of the heat-absorbing gases in the atmosphere?" Svante August Arrhenius spent a year on thousands of calculations, the most "tedious" of his life, from which he constructed a series of tables. These tables predicted a warming trend due to two gases—water vapor and CO_2. Interestingly enough, Arrhenius' manual calculations agree quite well with the most recent model projections carried out using supercomputers. Arrhemius used the term hothouse, later called the greenhouse effect. The trend for him seemed a positive one because he said it will "allow all our descendants [. . .] to live under a warmer sky and in a less harsh environment than we were granted."[8]

The recent increase in the greenhouse effect is a human-made forcing. Humans have released GHGs over and above natural emissions. Anthropogenic activities, including burning fossil fuels, have released enough CO_2 to contribute 74 percent of the enhanced greenhouse effect. Other gases are involved, such as methane (CH_4) contributing about 19 percent, and nitrous oxide (N_2O) contributing about 7 percent.[9] The additional CO_2 traps thermal radiation and changes the radiation balance. The earth's temperature shifts higher to regain equilibrium.

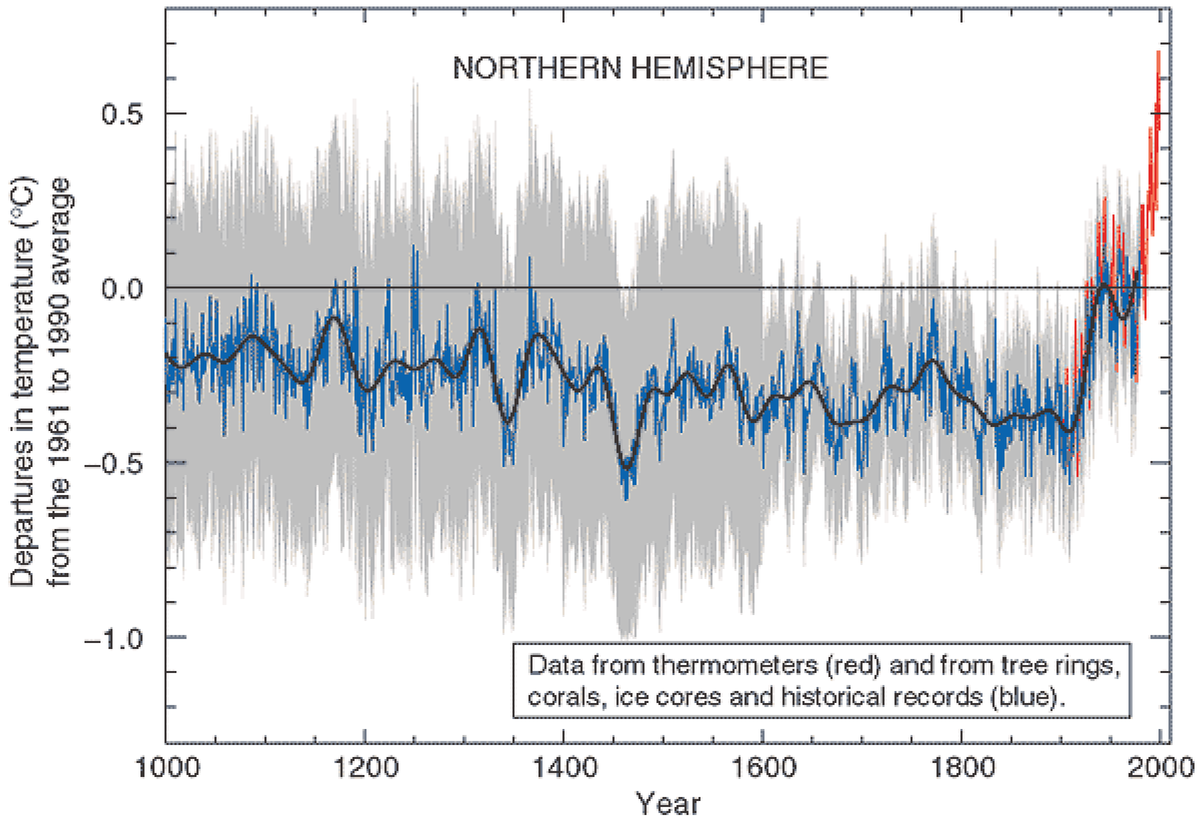
Recent Observations Confirm Increased Temperatures

1. **Warming over the past century is higher than in the previous 1,000 years.** NOAA (National Oceanic and Atmospheric Administration) uses paleoclimatology to study the last few thousand years. This is the best dated and best sampled part of the past climatic record. This area of study can help establish the range of natural climatic variability in the time before global human influence.[10]
2. **Natural variables cannot account for recent observed warming.** According to the U.S. Global Research Program, "Over the last five decades, natural factors (solar forcing and volcanoes) alone would actually have led to a slight cooling."[11]

For more information, visit the NOAA Paleoclimatology and Climate Change website at http://www.ngdc.noaa.gov/paleo/paleo.html and https://www.ncdc.noaa.gov/climate-information.

A particularly striking demonstration of temperature trends is provided by the temperature reconstructions by Prof. Michael Mann and associates, now at Pennsylvania State University. Using direct temperature measurements with thermometers (available only since the late 1800s) and proxy measurements using tree rings, coral growth, ice cores, boreholes, and historical records, Mann et al. estimated global average surface temperatures for the past 1,000 years as shown in Figure 3. The striking feature is that average temperatures declined slowly until around 1900. At that point, which coincides with a rapid increase in the use of fossil fuels such as coal and oil, the slope changes abruptly in both magnitude and sign. The trend has continued through the beginning of the present century, so that average temperatures are now approximately 1º C above its long-term, baseline value. The shape of the 1,000-year temperature record suggested the descriptive term "hockey stick curve" by which it is known today.

Figure 3. "Hockey Stick" Temperature Variations



Credit: IPCC

Multiproxy reconstruction of Northern Hemishphere surface temperature variations over the past millennium (blue), along with 50-year average (black), a measure of the statistical uncertainty associated with the reconstruction (gray), and instrumental surface temperature data for the last 150 years (red), based on work by Mann et al. (1999). This figure has sometimes been referred to as the "hockey stick." For more information, see Climate Change 2001: Working Group I: The Scientific Basis.

Radiation Balance and Radiative Forcing

> *"The basic principle of global warming can be understood by considering the radiation energy from the sun, which warms the earth's surface, and the thermal radiation from the earth and the atmosphere, which is radiated out to space. On average these two radiation streams must balance. If the balance is disturbed (for instance by an increase in atmospheric carbon dioxide) it can be restored by an increase in the earth's surface temperature."*
>
> ***J. Houghton[12]***

What comes in must go out. When solar energy is radiated from the sun to the earth, the outgoing radiation from the earth must create a radiation balance. The earth's surface temperature determines the amount of radiation emitted from its surface. As shown by the Stefan Boltzmann equation, the higher the surface temperature (T) of an object, such as Earth, the more energy (F) the object emits. The Stefan Boltzmann constant in the equation is represented by σ (sigma). Sigma, in this case, is equal to 5.67×10^{-8} $WM^{-2}K^{-4}$ (watts per meter squared per degree Kelvin). This equation shows that a small change in the surface temperature will result in a large change in the amount of energy emitted.

As shown by the Stefan Boltzmann equation, the higher the surface temperature of an object, such as Earth or the sun, the more energy the object emits. The equation is F=σT4.

Read more at http://www.meteor.iastate.edu/gccourse/influ/images/radiation.

The formula for converting degrees Centigrade to degrees Fahrenheit is:

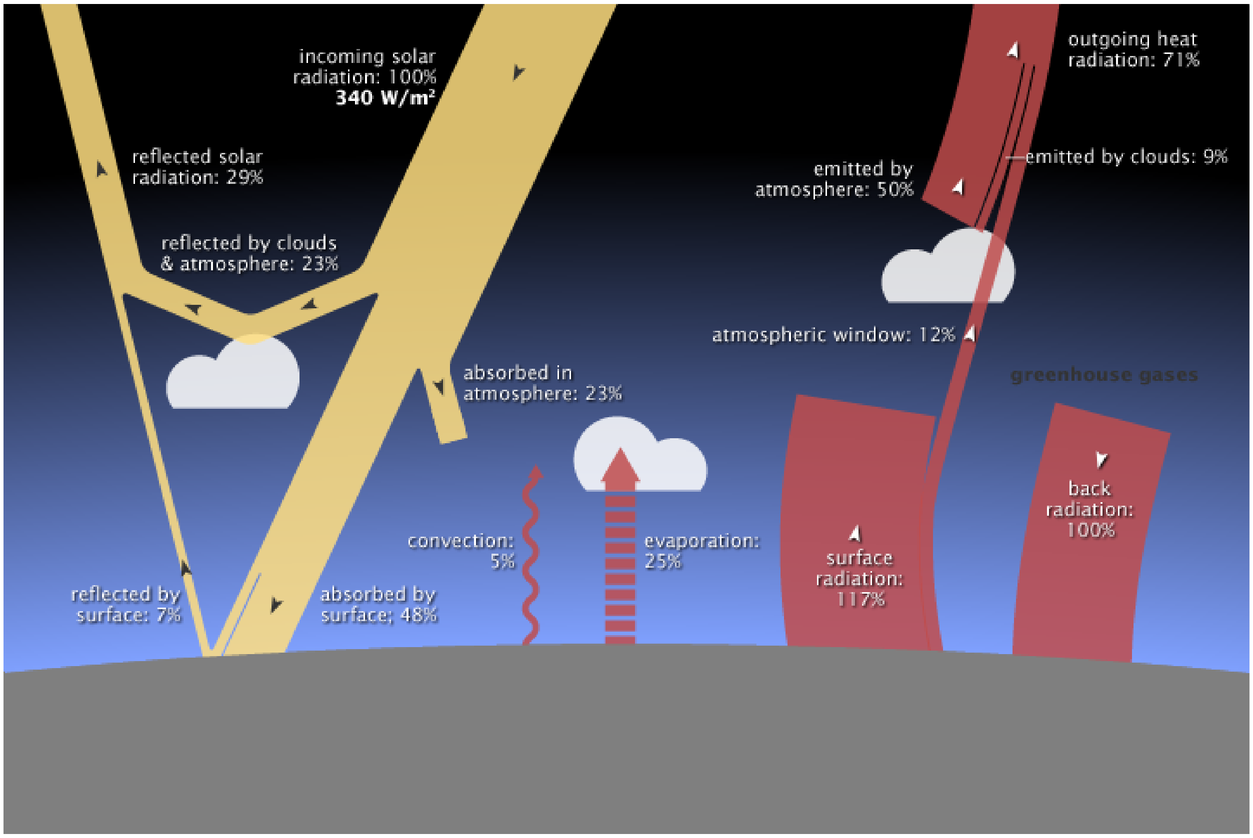
$T_f = (9/5 * T_c) + 32$

When the earth emits just enough infrared radiation to balance incoming solar radiation, its surface temperature should be -6 degrees C (based on a lack of cloud cover). Yet the average of temperatures around the earth is about 15 degrees C warmer.[13] What creates this difference in temperature of 21 degrees? What is the effect of the radiation balance on the planet Earth?

Radiative forcing is a change in average net radiation at the top of the troposphere. This occurs because of a change in the concentration of a greenhouse gas or because of some other change in the overall climate system.[14] This forcing is tied to the potential for variations in weather and ultimately a change in the climate. If more energy is re-radiated back to Earth because of the greenhouse effect, Earth's average temperatures will be higher and weather will be more erratic.

The NASA website offers data and activities about Earth's radiation budget at http://missionscience.nasa.gov/ems/13_radiationbudget.html.

Figure 1. Movement and Balance of Radiation in the Atmosphere



Credit: NASA

On average, 340 watts per square meter of solar energy arrives at the top of the atmosphere. Earth returns an equal amount of energy back to space by reflecting some incoming light and radiating heat (thermal infrared energy). Most solar energy is absorbed at the surface, while most heat is radiated back to space by the atmosphere. For more information, see the NASA Earth Observatory, "[The Natural Greenhouse Effect](#)."

Temperature and Radiation Flux

The temperature of the earth influences the flow of energy radiated back into space, as described by the ***Stefan Boltzmann equation***. If the earth's temperature is warmer, the flow of energy upward is greater.

The earth's atmospheric temperature responds to changes. If the radiation imbalance is positive (more solar radiation absorbed by the surface), the earth's surface becomes warmer. If it is negative, the forcing cools the surface of the earth. Extraterrestrial factors in radiative forcing might include the position of the earth with respect to the sun. Terrestrial factors that influence climate include the chemical and physical variations in the oceans, movement of land, changes in the makeup of the atmosphere, and the reflection of incoming energy by the earth and its atmosphere. The net amount of energy reflected from the earth and its atmosphere is called "planetary albedo" and quantifies the amount of radiation from the sun that is reflected back into space.

If planetary albedo increases, the atmospheric temperature decreases because less radiation is available to heat the planet as the planet reflects more of the sun's rays. The composition of the earth influences albedo from the amount of cloud cover to what covers the earth's surfaces such as snow, ice, and vegetation.[15] Increasing planetary albedo is an example of negative radiative forcing—the decrease of atmospheric temperature due to less radiation absorbed by the atmosphere. For an image of planetary albedo, see NASA's Earth Observatory website.[16]

Increasing the amount of GHGs is an example of positive radiative forcing. The atmosphere's composition has quite an impact on how much energy actually radiates back to space. The GHGs, such as water vapor and CO_2, absorb some of the sun's radiative energy, increasing the atmospheric temperature to 15 degrees C due to more radiation being absorbed by the atmosphere. One result is that life is sustained on Earth. Since the Industrial Age began, anthropogenic activities have increased GHG concentrations substantially. The CO_2 concentration in the atmosphere has increased from 280 parts per million (ppm) 1,000 years ago to 400 ppm today.[17] The atmosphere's CO_2 reservoir, always present, has increased substantially.

Reservoirs and Fluxes

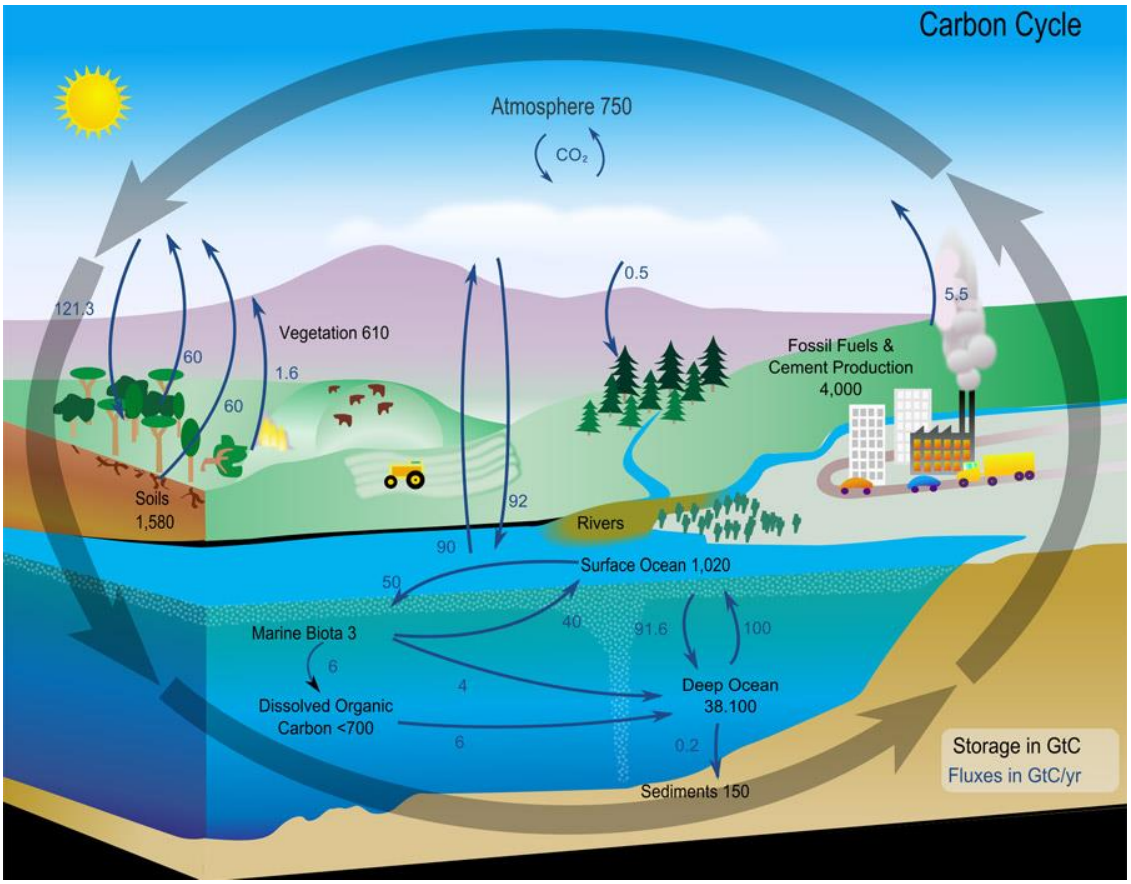
> *"Surveys show most Americans believe global warming is real. But many advocate delaying action until there is more evidence that warming is harmful. The "stock and flow" structure of the climate, however, means "wait and see" policies guarantee further warming. Atmospheric CO_2 concentration is now higher than any time in the last 750,000 years, and growing faster than any time in the past 20,000 years. The high concentration of CO_2 and other GHGs generates significant radiative forcing that contributes to warming. To reduce radiative forcing and the human contribution to warming, GHG concentrations must fall. To reduce GHG concentrations, emissions must fall below the rate at which GHGs are removed from the atmosphere."*
>
> ***J.D. Sterman and L.B. Sweeney*** [18]

Another basic science principle useful to understanding climate change dynamics is the idea of reservoirs and fluxes. A reservoir is an amount of material contained in one unit. A flux is the amount of material transferred from one reservoir to another per unit of time.

Where carbon is stored, how it is stored, and the amount that can be stored are essential to our understanding of climate change. The reservoirs of carbon include the atmosphere, oceans, soil, and all living things. Fossil fuels are also carbon reservoirs.

Sterman and Sweeney's reference to "stocks and flows," another way of referring to reservoirs and fluxes, draws on terminology often used to describe economic and energy systems. It is also useful for understanding the climate system and the concept of radiative forcing.[19] A reservoir can be compared to the balance in a bank account, with fluxes similar to deposits and withdrawals on that account. In discussions on climate change, reservoirs are also referred to as sinks, usually referring to reservoirs in which the constituents of GHGs could be stored for long periods of time with few emissions to the atmosphere.

Figure 4. The Earth's Carbon Reservoirs and Fluxes



Credit: NASA

Carbon reservoirs are found in the earth, biosphere, ocean, and atmosphere and annual exchanges of carbon dioxide between these. The units of stored carbon are thousand millions of tons (trillions of kilograms) or gigatons (Gt), and of the fluxes, Gt/year. An additional 5,000 to 10,000 Gt carbon also exists in the form of buried coal, oil, and gas, although no one is really sure what the exact amount may be.

Carbon Cycle

> *"Understanding of the earth's carbon cycle is an urgent societal need as well as a challenging intellectual problem. The impacts of human-caused changes on the global carbon cycle will be felt for hundreds to thousands of years. Direct observations of carbon stocks and flows, process-based understanding, data synthesis, and careful modeling are needed to determine how the carbon cycle is being modified, what the consequences are of these modifications, and how best to mitigate and adapt to changes in the carbon cycle and climate. The importance of the carbon cycle is accentuated by its complex interplay with other geochemical cycles (such as nitrogen and water), its critical role in economic and other human systems, and the global scale of its interactions."*
>
> ***Carbon Cycle Science Working Group***[20]

Carbon, mainly in the form of carbon dioxide, moves in and out of the atmosphere and other reservoirs. These movements of carbon are the fluxes, or flows, which create the carbon cycle, and can happen on timescales from one year to centuries. About one fifth of the total amount of carbon in the atmosphere is cycled in and out each year.[21]

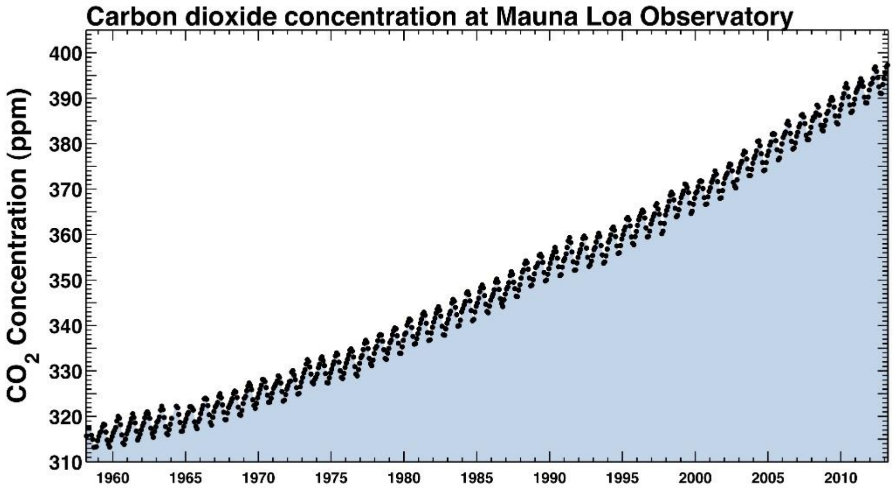
Where carbon is stored, how it is stored, and the amount that can be stored are essential to our understanding of climate change. The reservoirs of land and ocean carbon are much larger than the amount of carbon in the atmosphere. Even small changes in either land or ocean reservoirs can be important since they might cause a significant change in the amount of carbon in the atmosphere. Also, since so many different processes contribute to the flux of carbon dioxide in the atmosphere, the amount of time it takes for atmospheric CO_2 to return to equilibrium in the carbon cycle varies.[22] This makes predicting CO_2 levels in the atmosphere difficult.

> For more information on Keeling and his work, see https://scripps.ucsd.edu/programs/keelingcurve/.

> Activities that use the Keeling Curve to illustrate how data help detect patterns are available at http://egsc.usgs.gov/isb//pubs/teachers-packets/globalchange/globalhtml/guide.html.

Before the Industrial Revolution of the mid 1700s, the exchanges between the reservoirs were nearly constant. According to the measurements from ice cores going back several thousand years, the measurement of carbon dioxide stayed within 10 ppm of a mean value of about 280 parts per million by volume (ppmv).[23] Since 1750, the balance has been disturbed. In the late 1950s, Charles David Keeling from the University of California, decided to measure carbon dioxide in the atmosphere. Initially alone and later with help, he kept a record of atmospheric carbon dioxide measurements for nearly sixty years. The results of his work are well known and often referred to and shown as the Keeling Curve.

Figure 5. Keeling Curve Graph



Credit: Scripps Institution of Oceanography, UC San Diego

Carbon dioxide concentrations at Mauna Loa Observatory ("Keeling Curve").

Credit: NOAA, Climate Monitoring and Diagnostics Laboratory

Measurements of atmospheric carbon dioxide taken from this observatory on Mauna Loa in Hawaii (1959–present) show a yearly increase of 1.5 ppmv. This increase adds almost 3.3 thousand million tons, or gigatons (GT), to the carbon dioxide reservoir in the atmosphere every year.

Balancing carbon storage and carbon dioxide release is essential to maintaining an environment fit for the life of most organisms. During photosynthesis, plants act as carbon sinks by taking in carbon dioxide, then using the carbon for growth and releasing the oxygen back into the atmosphere. The process of respiration, in which carbon release occurs when plants and animals breathe, die, and decay, is offset by photosynthesis.[24] Plants normally use more carbon dioxide in the photosynthetic process than they release when they respire.[25] When forest ecosystems, which are net carbon sinks, are deforested, they release some or all of their carbon. (Forest fires and decay of forest plant material release CH_4 and CO_2.) Both of these processes happen in the ocean as well as on the land.

When drinking a soda pop, we experience carbon dioxide dissolving into and coming back out of water. The way the ocean works in the carbon cycle is a bit more complicated than a bottle of soda. Short-term exchanges of carbon dioxide occur at the surface layers of the ocean, especially as waves break. The concentration of carbon dioxide dissolved in the surface waters and the concentration in the air above the surface must be in a state of equilibrium. If the atmospheric concentration changes by 10 percent, the concentration in the water solution changes by only 1 percent. [26]

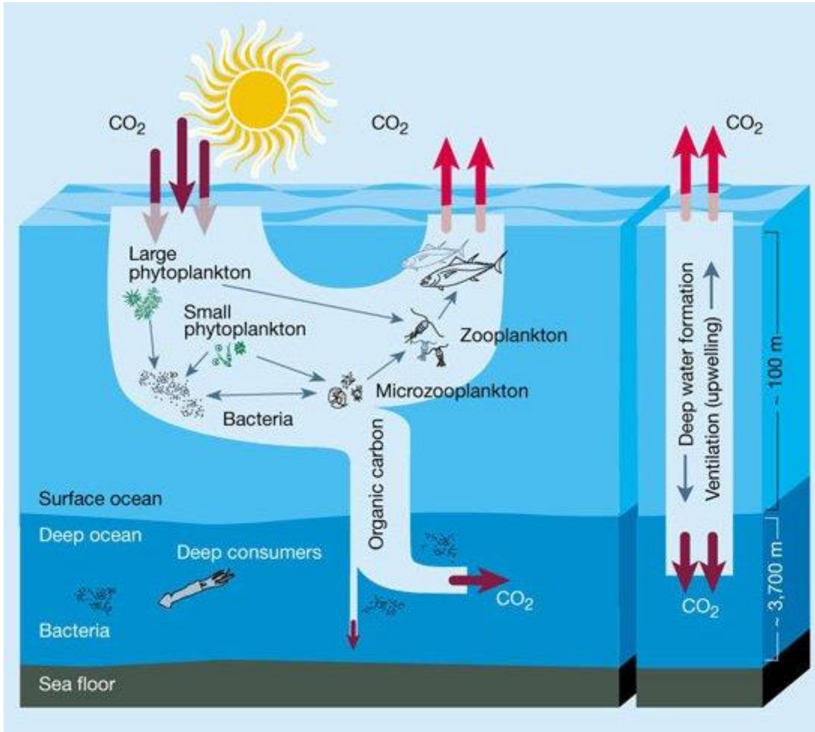
Two GHG sources: the car emits CO_2 while running and the cow emits CH_4 while digesting food. Credit: Heather Seyfang, MIT

In the lower part of the ocean (below the top hundred meters), the surface water mixes slowly with the deeper water. The transfer of CO_2 to deeper ocean water takes several hundred to a thousand years.[27] The oceans, therefore, only provide a temporary carbon sink in the short-term exchanges near their surface. While the oceans serve as a large reservoir for carbon (holding approximately 40,000 Gt), the slow rate of absorption limits the rate at which this reservoir responds to rapid changes in atmospheric carbon levels.

Another feature of ocean dynamics also plays a role in the carbon cycle. The ocean is filled with life forms, the majority of which are zooplankton and phytoplankton. Phytoplankton carries out photosynthesis, which removes CO_2 from the water. The phytoplankton are consumed by zooplankton and other aquatic animals. Most plankton have a short lifecycle. When they die and sink to the lower levels of the ocean, the carbon they contain sinks with them. One organism in particular, extensively studied by Penny (Sallie) Chisholm at MIT, is *Prochlorococcus*. This is the smallest and most abundant photosynthetic microbe in the ocean, and is responsible for the bulk of photosynthetic activity.[28]

The process of plankton removing CO_2 from the ocean via photosynthesis is called the biological pump. The biological pump has a net effect of moving carbon from the surface to lower levels of the ocean. In the spring, the upper levels of the ocean have a spring bloom of plankton, especially in temperate and high latitude zones of the ocean. The plankton eventually sink to the lower levels, and their movement is the pump. They take carbon from the surface to the depths, where it is lost to the carbon cycle for a long time. As the amount of carbon in the surface waters is reduced, more carbon dioxide from the atmosphere can be drawn down in order to restore the surface equilibrium. [29]

Figure 6. Biological Pump



Credit: Sallie W. Chisholm,
"Oceanography: Stirring Times in the Southern Ocean,"
Nature 407: 685–687. Reprinted by permission

The biological pump illustrates one way in which CO_2 is delivered to the ocean for storage in the deep.

Connection Between Carbon Flux and Energy

"Modern industrial society is driven by energy [. . .] It's possible to imagine driving those systems with energy that's not producing so much carbon [. . . .] It's possible to imagine living at the level that we're living—with less energy [. . . .] But it's not possible to live the life we do, moving around the way we move around, without a substantial use of energy. And the cheapest way to do that is with fossil fuels. So that the way we live is going to generate CO_2 until we devise some other system to do it."

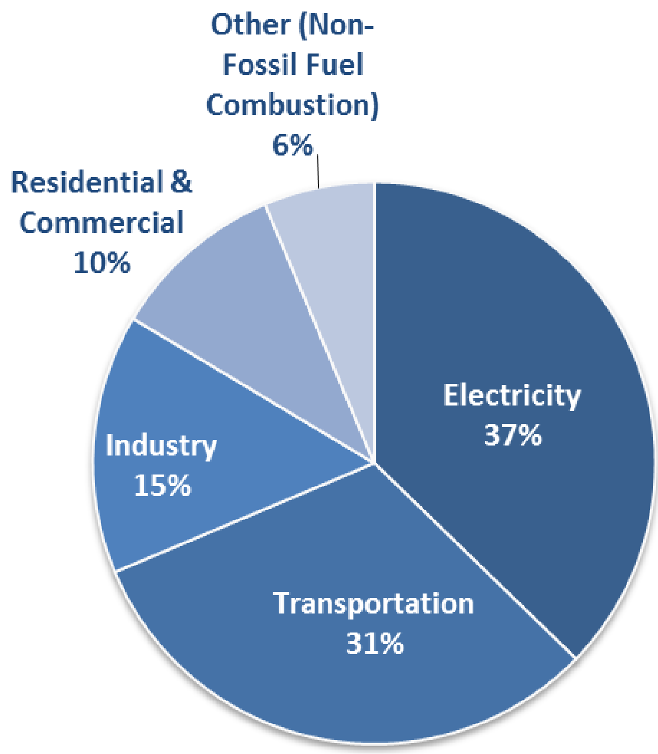
Henry (Jake) Jacoby[30]

What accounts for the net flow of carbon into the atmosphere from many of Earth's reservoirs? The amount of net flow is about 4 Gt (6.75 Gt from fossil fuels, 2.25 Gt to sinks).[31] The answer might be found by looking at energy-related activities, which accounted for almost all U.S. CO_2 emissions from 1990–2015. (See Figure 7.)

Fossil fuel sources accounted for 82 percent of the energy consumed in the U.S.[32] The remaining 18 percent of U.S. fuel sources comes from nuclear (about 8 percent) and renewable energy sources (about 10 percent) such as hydropower, biomass, wind, and solar. Although there will be some growth in these renewables, overall renewables plus nuclear are expected to remain roughly constant as a share of the U.S. energy production through 2040.[33]

Trends emerge from looking at the end-user data for energy consumption. Industrial CO_2 emissions from direct fossil fuel combustion and from the generation of electricity make up 37 percent of U.S. emissions from fossil fuels, transportation activities follow closely with 31 percent (almost all from petroleum products), industry accounts for 15 percent, and residential and commercial users are responsible for 10 percent. As our need for energy rises, so do our CO_2 emissions—if we rely on fossil fuel combustion. [34]

Figure 7. U.S. Carbon Dioxide Emissions by Source



Credit: U.S. EPA Overview of GHGs

Emissions from fossil fuel combustion for various end users (1995–1999).

Water Cycle

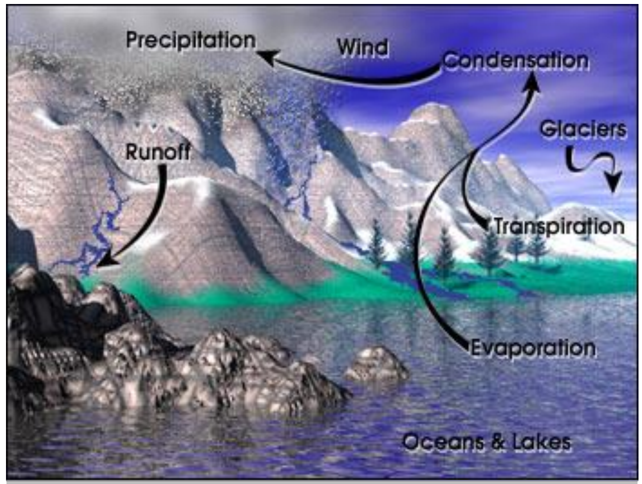
A crucial part of the earth's natural system is the water or "hydrologic" cycle. The cycle describes the journey of water molecules from the earth's surface to the atmosphere and back again. This vast system, powered by the sun's energy, constantly exchanges moisture between the oceans, the atmosphere, and the land.[35]

For more about the hydrologic cycle, see the "Water Pollution—Point Souce" module.

Two key issues when studying the water cycle and climate change are:

- Water vapor is a GHG. As the temperature changes, the amount of vapor and clouds affect radiation flow and albedo. The direction and size of this effect are uncertain, although most think it is a positive feedback increasing the greenhouse effect.
- Climate change affects the hydrologic cycle as to how much and where precipitation occurs.[36]

Most of the moisture in our atmosphere—90 percent—results from evaporation of oceans, seas, lakes, rivers, and streams. The other 10 percent comes from evaporation of water from pores in plants foliage. This process is called transpiration. A small amount of moisture comes from sublimation, when ice or snow (a solid) changes to a gas.[37]



The hydrologic cycle.
Credit: Hailey King, NASA Goddard Space Flight Center

The hydrologic cycle has five steps:

1. Liquid and solid water evaporate from the ocean and land, becoming water vapor in the atmosphere.
2. Water vapor is transported through the atmosphere by winds.
3. Water vapor condenses into cloud droplets and crystals.
4. Cloud particles aggregate by coalescence and accretion into larger liquid and solid drops that fall as precipitation to the surface.
5. Continental rivers, aquifers, and ocean currents transport the water through land and ocean reservoirs.[38]

Climate change may greatly affect the global water cycle. According to the Intergovernmental Panel on Climate Change AR5 Synthesis Report, "Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, and in global mean sea level rise; and it is extremely likely to have been the dominant cause of the observed warming since the mid-20th century." [39]

The potential effects of climate change on the water cycle are many. Increased atmospheric temperatures increase evaporation. The effect of increased evaporation leads to changes in precipitation patterns. These changes can contribute to more erratic and extreme weather events. Increased temperatures lead to glacial melting that increase sea level, even to the point of inundating coastal areas. An increase in the temperature of the ocean diminishes its capacity to absorb CO_2. Warmer ocean temperatures also affect how circulation occurs. (For details on how climate change might affect the water cycle and other natural systems, go to Climate Change and Its Potential Impact on Society.)

"Amongst the highest priorities in Earth science and environmental policy issues confronting society are the potential changes in the Earth's water cycle due to climate change."

Read more at NASA's Earth Observatory website at http://earthobservatory.nasa.gov/Features/Water/water_cycle_2000.pdf.

The Uncertainties of Climate Change Science

"Due to the nature of science, not every detail is ever totally settled or completely certain. Nor has every pertinent question yet been answered."

R.J. Cicerone and Sir Paul Nurse[40]

"The Nature of Science [is that] we never quite know for sure."

Greg Craven[41]

The complexity of climate makes it difficult to make absolute predictions of how much temperatures will rise and the consequences of a warmer earth. Much of the debate around climate has focused on, and sometimes exaggerated, the uncertainty of current conclusions on climate change. It is important to remember that uncertainty is an integral part of all science. Every scientific result involves a certain degree of uncertainty, and scientists have developed systems to accurately quantify their results. To evaluate the scientific result, one must examine the magnitude of the uncertainty, and make a judgment of the result's accuracy.

This section provides an overview of how the scientific community describes the uncertainties of climate change research. Later sections will examine how others view the uncertainties of climate change, and how evaluation of uncertainty is judged in society's decision about taking action to prevent and reduce climate change.

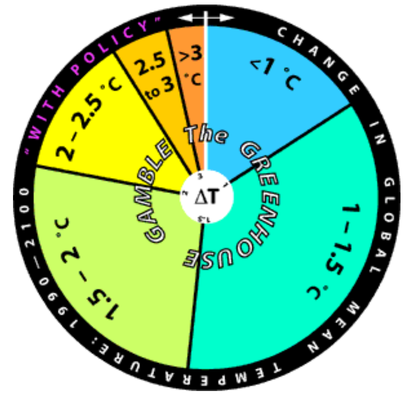
Some key sources of uncertainty in climate change science include:

- *Which factors contribute to climate change and how do they contribute?* These include clouds, natural cycles of CO_2, CH_4, N_2O and other GHGs, aerosols (natural and anthropogenic), solar output, and ocean circulation.[42]

  Clouds, for instance, play different roles depending on the time of day. During daytime hours, clouds reflect solar radiation back into space, which has a cooling effect. However, during the night, clouds trap the heat radiated from the earth. The causes of long-term changes in nighttime humidity and cloud cover are not yet completely understood. What is the cumulative effect of both of these cloud functions? Do they cancel each other out, or is one more dominant?

  Scientists are also still learning about the details of the natural cycles of the GHGs. Many sources of CO_2 and CH_4 are known, but their removal by sinks such as oceans and the biosphere, and at what rate, have not been established in detail. The rate of CO_2 removal is a function of ocean circulation, which can be very slow. Ocean sequestration of CO_2 is difficult to observe since the time scales of deep ocean circulation may be hundreds of years.

The Greenhouse Gamble



MIT's Joint Program on the Science and Policy of Climate Change has created two wheels to illustrate the uncertainty of global warming. The wheels depict the possible range of outcomes of global warming and the probability of each outcome, based on the Program's research and analysis. One wheel shows possible scenarios when no action is taken. The other (above) presents possible scenarios when a certain action is taken. How does human action potentially alter the global climate? What is the uncertainty presented here?

The global warming wheels may be found and spun at http://globalchange.mit.edu/focus-areas/uncertainty/gamble.

- *How will the climate change (globally and locally)?* An important question is how climate will be affected, not just at the global scale, but in specific regions. For example, observations have established that Arctic regions have been warming twice as fast as the global average. Which regions will face drought and desertification? Which regions will experience improved growing seasons? Will there be more extreme rainfalls that cause flooding, and who will be affected by it most? The continuing improvement in the speed and capacity of supercomputers is making it possible to run model calculations at increasingly fine regional resolution, but many of these questions are still unsettled.

Cryosphere is the name for the parts of the earth where water exists in its solid state (ice, snow, and permafrost). An important part of the global climate system, the cryosphere, is affected by and affects temperature, solar radiation, and precipitation. For more information, go to http://www.climate-cryosphere.org/.

- *What will be the effects of that change, both on human society and the environment?* The ecosystem is as complex as the climate system. We do not have a complete picture of how the ecosystem and its components will react to changes in the climate. Which species will adapt? Which will become extinct? How will we have to adapt our societies to deal with the new climate? What is the range of possibilities? On the extreme side, will there be huge numbers of environmental refugees as land floods worldwide and the middle latitudes become too hot to be livable? In the middle range, will the U.S. agriculture industry be severely damaged by changes in the growing seasons for corn and wheat? Or will it merely mean buying more summer clothes and rain gear instead of sweaters and winter coats?
- *Will humans, given our knowledge, react (or not) to prevent or offset the predicted climate change?* Given our current knowledge, will we choose to take action, such as switching to entirely renewable energy sources, to prevent possible extreme events that could result from climate change? Will we look on the challenges of mitigation as opportunities to be energy efficient and to develop new technologies to help us? The human factor contributes to the uncertainty in predicting climate change. We are capable of using our knowledge to change our behavior to prevent further damage to the climate system. We are also capable of deciding that the evidence does not warrant a change in behavior, especially if it could be costly. These are the two extremes that must be taken into account when trying to model future climate change. It is still uncertain which way on the continuum society will choose to move.

Characteristics of global climate change models are summarized in a chart developed by the U.S. Global Change Research Program:

http://nca2014.globalchange.gov/report/appendices/climate-science-supplement.

Decisions must be made in spite of the uncertainty surrounding climate change. While scientists work to better comprehend the climate system, governments and individuals must decide whether or not to take action. Ideally, these solutions should be based on what scientists know and the predictive models generated from this knowledge. Too often, however, special interests and extreme views have dominated the debate.

Modeling

The models used by the Intergovernmental Panel on Climate Change (IPCC)[43] and various governments and agencies are based on mathematical equations that represent the interrelationships between the factors being considered. For example, climate modelers come up with an equation to represent how clouds deflect solar radiation back into space. This equation is then incorporated into a model made up of hundreds of thousands of other equations that represent other components of climate. Computer models are only as accurate as the equation formulations and as comprehensive as the computer capacity allows. The last several decades have resulted in vast improvements; however, both the equations and computers require constant improvements and expansion.[44]

Global climate change models help research and predict what might happen in response to the many variables involved with the process. They should take into account changes in the:

- Atmosphere (circulation, turbulence, chemical composition, particulates, etc.)
- Ocean (circulation, salinity, exchange of gases with the atmosphere, etc.)
- Cryosphere (seasonal and annual variations, etc.)
- Biosphere (changes in water bodies and biomass, etc.)
- Interactions of all of these components.[45]

In addition, economic and social aspects can affect each of those components. For example, growing economies use more resources and emit more pollution. Deforestation and increasing CO_2 emissions over the last 100 years are examples of how society is affecting the structure of the biosphere and atmosphere. How can we accurately model such a large and complex system?

Due to the inherent uncertainties, it is extremely important to validate model results. Several methods, none individually sufficient, can be used together to show evidence of a model's validity. The methods include: [47]

1. Simulation of the current climate. Check the model's ability to replicate today's climate, though this may not adequately test how well the model can predict changes over very long periods of time.

Two Approaches to Modeling Changes in Technology[46]

Why do model results differ even though they use the same information? Modelers analyze and incorporate the information in different ways, which can lead to different results.

Bottom-up models are based on a few specific technologies. They look at how a set of innovative technologies would change the world's current situation, often with respect to emissions reduction or energy conservation. These engineering-based models usually conclude that action to slow climate change will be inexpensive to society.

Top-down models begin with the relationship between the economy and the environment. The rate of technological change is determined by the assumed rate of increases in energy efficiency (not related to the cost of energy). This rate is usually based on historical data of increasing efficiency.

2. Sensitivity analysis of the model's components. Evaluate how crucial model outputs (i.e. sea level, rainfall, and temperature changes) are affected by the uncertainty in the submodels, such as atmospheric chemistry, climate, and economic factors.[48]
3. Duplication of the greenhouse effect. Check the model's ability to replicate the thermal energy flows of the greenhouse effect within 10 percent of the actual flow. This has already been established.
4. Reproduction of climate history. Check whether the model simulates the climate from ancient history.

The Earth System Research Laboratory scrutinizes oceanic and atmospheric observations to improve the ability to predict climate. The lab provides interactive analysis and climate plotting pages on their website at http://www.esrl.noaa.gov/psd/csi/.

Since climate models are not perfect, in part due to an incomplete understanding of the physical principles involved and of the past climate forcing. Simulations may have errors.[49] Because of these errors, climate models can project a substantial range in global temperature range predictions. However, models are unanimous in their prediction of climate warming due to the effects of GHGs. [50]

Analysis

"Unfortunately, the global change experiments now underway are not merely academic exercises in the microchips of supercomputers, but are being performed on the laboratory that we and all other living things share—Earth."

Kevin E. Trenberth, National Center for Atmospheric Research [51]

Collecting great quantities of data is not enough to provide an understanding of climate change. The data must be analyzed to gain an understanding of how components are interconnected and what the observed changes mean to the climate system as a whole. Natural and social scientists perform analysis of climate observations and data; it is not uncommon for different groups to reach different conclusions from the same information. Climate prediction entails determining future behavior for both the climate and humans based on past and present behavior. Natural scientists and social scientists must work together and extrapolate on the basis of the data collected. Given the uncertainty in climate change and the range of assumptions analysts must make, some of the suggested climate impacts are robust predictions, and others are not.

Climate sensitivity is an important thing to understand because it provides an expectation for the level of warming in response to the amount of heat-trapping gases.[52] It is defined as "a metric used to characterize the response of the global climate system to a given forcing."[53] Climate studies have mainly explored how sensitive model projections are to different parameters. This sensitivity is determined by repeating a numerical simulation with the parameter in question set to a nominal, low, and high value, etc., and noting how much the model reacts to the change in value.[54] The IPCC has used the sensitivity analysis approach, as has MIT with its Integrated Global Systems Model in which researchers examined the uncertainty effects from greenhouse gas emissions, climate sensitivity, and heat and carbon uptake by the deep oceans.[55]

An example of using models to reduce uncertainties in climate change data is the method for constraining uncertainty properties "by comparing the modeled response to anthropogenic forcings over the 1961–1995 period against climate observations of this period."

Read more in MIT's "Constraining Uncertainties in Climate Models Using Climate Change Detection Techniques."

As a result of numerous simulations using different models and state-of-the-art technology supercomputers, climate sensitivity has been constrained to a fairly consistent distribution of possible values. Very low sensitivities (1º C or less for doubled CO_2), would mean that global warming is, in fact, not something to worry about; but the probability of such a low value is less than 0.05 (1 chance in 20). The most likely range for climate sensitivity is 1.5º to 4.5º C.[56] And there is a 10 percent probability that climate sensitivity is greater than 5º C, possibly as high as 10º C.[57] For reference, the global average temperature increase for the 40 percent increase in atmospheric CO_2 which has already occurred is nearly 1º C. The climate science community has stated that in order to avoid serious and irreversible damage to the earth's climate system, the increase must be held to less than 2º C by appropriate policies and actions. The choice of such policies and actions then becomes an exercise in risk assessment, where, as Kevin Trenberth noted in the quote above, what is at risk is the earth.

Summary

By studying reservoirs, fluxes and the carbon cycle, scientists learn how carbon moves in and out of the atmosphere. Of the 6 to 6.5 Gt of carbon released annually by burning fossil fuels and changing land use patterns, about half is added to the atmosphere each year.[58] Clearly, some of the carbon is being removed and deposited in carbon sinks such as oceans and biomass. The degree to which CO_2 is taken out of the atmosphere by natural processes is one of the most important aspects of climate change.

Aids to Understanding provides resources and activities.

What Do We Know and How Do We Know It?

> *"... professional societies make up the greatest collection of experts on the planet, with massive reputations on the line, easy-to-check track records, and the least amount of bias you can expect from a group made of fallible humans. That's why in my opinion professional societies are the most credible sources—because when it comes to finding out what science knows, I can't come up with anything that would rank higher. Lord knows these groups aren't perfect. But they are simply as good as it gets."*
>
> ***G. Craven,***
> ***"What's the Worst that could Happen"***

Scientific uncertainty and complexity means that data collected regarding climate change may be open to interpretation. Uncertainty is an integral part of science and should be taken into account in making decisions, but the presence of uncertainty does not disqualify the result. This section explores who is responsible for evaluating and interpreting that data and looks at some of the varying viewpoints on the issue of climate change.

The Major Actors

In view of the complexity and uncertainty referred to above, carrying out an assessment of available data and communicating the results to policymakers and the general public is a crucial task. Who has the responsibility for evaluating the science surrounding climate change? Which source is the most reliable and least biased? In this section, we consider four major sources of authoritative analysis: the Intergovernmental Panel on Climate Change (IPCC), the American Association for the Advancement of Science (AAAS), the National Academy of Sciences (NAS), and the Vatican. All of these groups have recently issued statements on climate change.

Intergovernmental Panel on Climate Change

In 1988, the IPCC was created when the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) decided that a scientific panel was needed to "assess the state of existing knowledge about the climate system and climate change; the environmental, economic, and social impacts of climate change; and possible response strategies." The IPCC released its First Assessment Report (FAR) in 1990. Approved after careful review by hundreds of leading scientists and experts, the report confirmed the scientific basis for climate change.[59] It should be emphasized that the IPCC does not carry out original research on the climate, nor does it offer policy recommendations. Instead, the scientific panels review all available published reports on the science and present the most likely findings, typically with associated likelihoods of their being correct. The IPCC also presents policy options and scenarios along with likely outcomes as a basis for making policy decisions.

The IPCC has continued to issue assessment reports at regular intervals. The Fifth Assessment Report (AR.5) appeared in 2014. Each report consists of three major parts plus a Synthesis Report. Each of the technical parts includes a "Summary for Policymakers" which presents the major findings but omits the complete technical details found in the full report. Some of the key findings presented in the AR.5 will be discussed in the section "How have understanding and perceptions changed over the last decade?"

- Part 1: The Physical Science Basis. Each assessment report accumulates additional data from new studies of current and paleoclimates, shares improved analysis of data sets with more rigorous evaluation of their quality, and offers comparisons among data from different sources. Recent reports have included estimates of the confidence attached to each finding, such as "more likely than not," "very likely," or "virtually certain."
- Part 2: Impacts, Adaptation, and Vulnerability. All regions are likely to experience some adverse effects of climate change. Small island states and low-lying coastal areas are among the most vulnerable because of increases in sea level and storms, and because they have limited capabilities to adapt. Polar regions will experience climate change impacts significantly as sea-ice is reduced and permafrost is altered. International cooperation and coordination is needed to assess impacts; build capacity; and train for monitoring, assessment, and data gathering.[60]
- Part 3: Mitigation of Climate Change. Because climate change is global, long-term (up to several centuries), and involves complex interactions among several processes (climatic, environmental, economic, political, institutional, social, and technological), a response to climate change requires making decisions which demand taking risks while being uncertain about the possibility of causing irreversible changes. This part of the report address gaps in knowledge and describes the many challenges of mitigation.[61]
- Synthesis Report. In addition to the three technical sections, the IPCC prepared a Synthesis Report (SYR) which summarized the findings of the three technical parts. Since this is typically the most widely read and cited of each assessment report, it is subject to unusually detailed review and editing. The AR.5 SYR is the best entry point for the inexperienced reader.

All IPCC documents and reports are available at www.ipcc.ch.

American Association for the Advancement of Science (AAAS)

The AAAS, founded over 150 years ago by a group of scientists and inventors including Thomas Edison, has over 140,000 members representing all branches of science, technology, engineering, and mathematics (STEM). AAAS' main activity has been publishing *Science* magazine and convening meetings and conferences. However, in recent years AAAS has issued reports and statements on key STEM issues. In 2014, AAAS issued a white paper entitled "What We Know: The Reality, Risks, and Response to Climate Change." The document affirms three statements on which there is virtually total agreement in the climate science community:

- Climate change is happening here and now.

- We are at risk of pushing our climate system toward abrupt, unpredictable, and potentially irreversible changes with highly damaging impacts.
- The sooner we act, the lower the risk and cost. And there is much that can be done.[62]

Other professional societies, such as the American Chemical Society and the American Geophysical Union, have also issued statements on climate change which are in general agreement with the AAAS position.

National Academy of Sciences

NAS was established by congressional charter in 1863. Together with the National Academy of Engineering and the Institute of Medicine, it makes up the National Academies of the United States. NAS members are selected by nomination and approval of the current membership. They are considered to represent the elite of the American scientific community.

The National Academies' working arm, the National Research Council (NRC), prepares study reports on a wide range of STEM-related issues. The NRC has issued a number of reports relating to climate change, including a massive multi-part report entitled "America's Climate Choices." Recently, the NAS issued a joint statement with the Royal Society of Great Britain, "Climate Change: Evidence and Causes." This statement corroborates the IPCC and AAAS findings, among which are:

- GHGs affect the earth's energy balance and climate.[63]
- Human activities have added GHGs to the atmosphere.[64]
- Climate records show a warming trend.[65]
- Many complex processes shape our climate.[66]
- [Nevertheless] human activities are changing the climate.[67]

NRC reports can be searched and downloaded from the NAS website at www.nas.edu.

The Vatican

In June 2015, Pope Francis issued a wide-ranging encyclical letter ("Laudato si'") on the topic of the environment, sustainability, and social justice.[68] The Vatican does not carry out original scientific research (except in astronomy at the Vatican Observatory), so statements in the encyclical letter concerning climate change are based on the consensus views of the scientific community, including the Vatican's own Pontifical Academy of Sciences.

> *"The climate is a common good, belonging to all and meant for all. At the global level, it is a complex system linked to many of the essential conditions for human life. A very solid scientific consensus indicates that we are presently witnessing a disturbing warming of the climatic system. In recent decades the warming has been accompanied by a constant rise in the sea level and, it would appear, by an increase in extreme weather events, even if a scientifically determinable cause cannot be assigned to each particular phenomenon. Humanity is called to recognize the need for changes of lifestyle, production, and consumption, in order to combat this warming or at least the human causes which produce or aggravate it … a number of scientific studies indicate that most global warming in recent decades is due to the great concentration of greenhouse gases (carbon dioxide, methane, nitrogen oxides, and others) released mainly as a result of human activity. Concentrated in the atmosphere, these gases do not allow the warmth of the sun's rays reflected by the earth to be dispersed in space. The problem is aggravated by a model of development based on the intensive use of fossil fuels, which is at the heart of the worldwide energy system."*
>
> ***Pope Francis***
> ***Laudato si*** [69]

How Have Understanding and Perceptions Changed Over the Last Decade?

The terminology used by the IPCC defines probability estimates. For example, "more likely than not" means there is a 50:50 chance that human activity may in fact *not* be affecting the climate. "Extremely likely" means that the null hypothesis, which is that our activity does not affect the climate, has only 1 chance out of 100 ($p = 0.01$) of being true—that is, the odds are 100 to 1 that humans are causing climate change, with possibly catastrophic consequences.

Over time, an increasing amount of data on the earth's climate has been observed, validated, and archived. Increasingly detailed model simulations have been carried out using new generations of supercomputers. The results have been critically examined by a large number of experts. All of this has advanced our understanding and reduced the level of uncertainty associated with climate change observations and forecasts. In this section, we highlight two particular areas in which our understanding of the climate system has progressed.

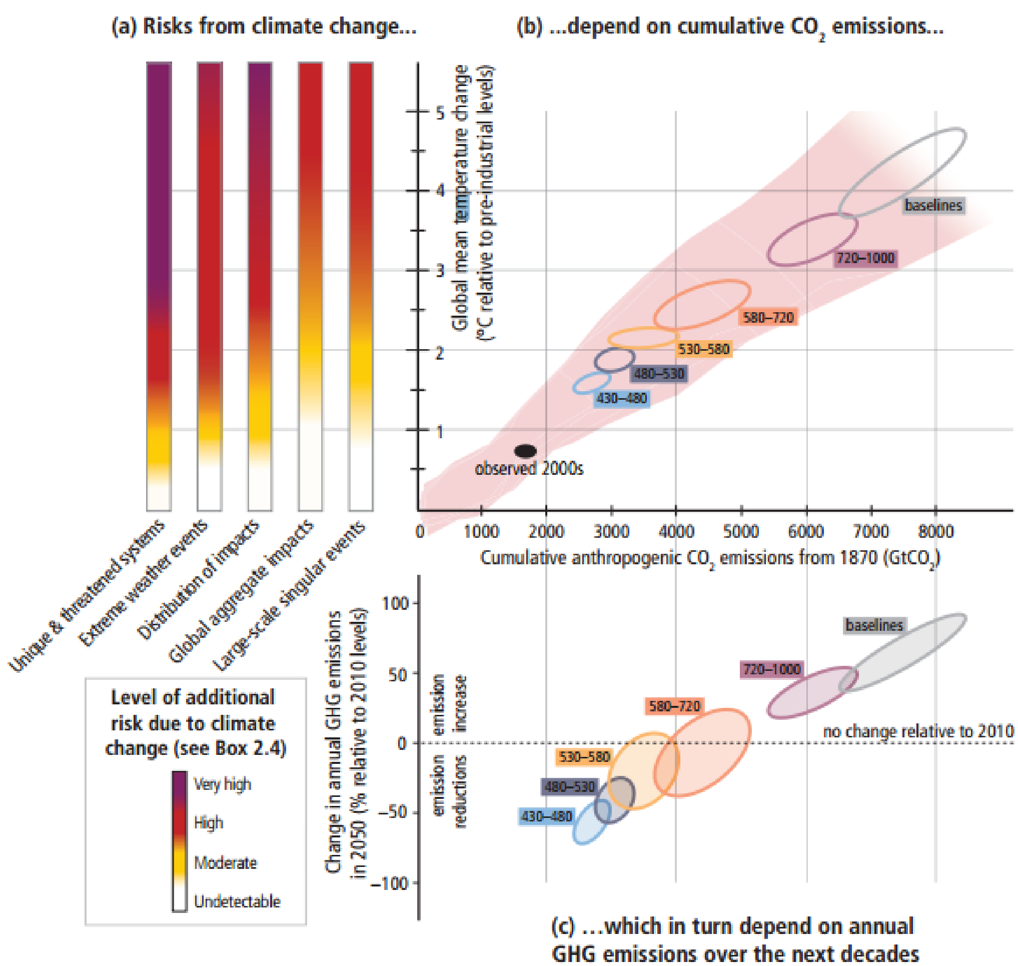
In its First Assessment Report (FAR, 1990), the IPCC stated that the balance of evidence suggested that human activity was affecting the earth's climate patterns—a rather vague and indefinite statement. Successive reports have been increasingly definite on this point:

- "more likely than not" that observed warming is caused, at least in part, by human activity (Second Assessment Report, SAR 1995)
- "likely" (Third Assessment Report, TAR 2001)
- "very likely" (Fourth Assessment Report, AR.4 2007)
- "extremely likely" (Fifth Assessment Report, AR.5 2014)[70]

There are a couple of important lessons from this series of statements. First, the steady accumulation of data and analysis has only strengthened the hypothesis that the climate is changing and that we are, at least in part, causing these changes. There is no credible evidence to the contrary. Second, the probability estimates now presented in the IPCC assessment reports allow us to make realistic risk assessments. Most people, when confronted with solid evidence that the confidence level is 95% that their actions are leading to a damaging or catastrophic outcome, will choose to change their actions in order to avoid such an outcome.

Another very important insight is that the risks from climate change depend on cumulative carbon dioxide (CO_2) emissions, which in turn depend on annual greenhouse gas (GHG) emissions over the next decades. This is shown in the figure below, taken from the IPCC Fifth Assessment Report Synthesis Report Summary for Policymakers.

Figure 8. Cumulative Temperature Risk



Credit: IPCC

Relationship between risks from climate change, temperature change, cumulative CO_2 emissions and changes in annual GHG emissions by 2050.

According to Panel (b) of Figure 8, cumulative CO_2 emissions to date are approximately 1,800 Gt CO_2. A portion of these emissions has accumulated in the atmosphere to give the present 400 ppm CO_2 concentration. This has increased the average temperature to around 0.8 º C. Climate change effects which have already been observed at this level of warming include extreme weather events and ecosystem impacts (Panel (a)).

Refer to section on "Reservoirs and Fluxes" for an explanation of how the addition and removal rates of GHGs to the atmosphere affects their concentrations over time.

Let's look at the consequences of several "scenarios" for future GHG emissions. Suppose all GHG emissions were turned down to zero right now (100 percent emission reduction)—an extremely unlikely, in fact unattainable scenario. As discussed in "Reservoirs and Fluxes," this does not mean that atmospheric CO_2 levels would return to the "pre-industrial" level of 285 ppm right away. CO_2 levels would slowly decline over many decades or centuries because of the slow removal rates. Global average temperatures would stop rising, and may decrease at the same slow rate.

If emissions were to be "frozen" at today's levels ("no change relative to 2010" in panel (c)), CO_2 levels would continue to rise to 580–720 parts per million (ppm), which would result in a temperature increase of 2º to 3.5º (panel (b)). This would in turn bring about increased risk of all adverse climate change effects (panel (a)). The regions labeled "baseline" in panels (b) and (c) are the "business-as-usual" scenario, in which energy demand and production continues to rise at their current rates, with most energy generation from fossil fuels. The result would be cumulative total anthropogenic CO_2 emissions of ca. 8,000 gigatonnes (Gt), atmospheric CO_2 levels in excess of 1000 ppm, projected total mean temperature rise of 4º to 5º C, and high to very high increased risks of catastrophic climate related effects—a scenario which is deemed unacceptable by most scientists, governments, and citizens' groups.

In fact, a consensus has developed that the global average temperature rise should be limited to no more than 2º C. As panels (b) and (c) show, in order to have a reasonable chance of achieving this, no more than an additional 1,000 Gt or so can be emitted to the atmosphere, which means that emissions need to be cut by 50 percent from current levels.[71] This is the basis for policy proposals for reducing emissions by 30 percent to as much as 80 percent by the middle of this century.[72]

There is one further hypothetical scenario which is worth examining, namely if all remaining coal, oil, and natural gas reserves were to be burned for energy production. No one really knows just how much carbon in the form of these fossil fuels is still in the ground, but we can make an educated guess of 10,000 Gt. If only half of this total is actually recoverable, that would be 5,000 Gt of carbon oxidized to CO_2: a total additional emission of 18,000 Gt of CO_2, multiplying by 44/12. This is off the charts in Figure 8, but a conceivable outcome would be atmospheric CO_2 levels of 2,000–3,000 ppm and a global average temperature increase in the neighborhood of 18º to 20º C—conditions which have not existed on Earth since the age of dinosaurs.

Recognizing the significance of cumulative emissions has several important implications. The first is geopolitical: although developing countries such as China may be the largest GHG emitters right now, their cumulative emissions are still small relative to developed economies such as the US or the EU.[73] In international negotiations they argue, with some justification, that they should be allowed to continue to use fossil fuels as their economies develop to parity with rich countries. The second issue is financial. As discussed below in the section on "Impacts on Business and Industry," restrictions on total carbon emissions will severely affect the industries that extract and make use of fossil fuels.

The Range of Views: Activists vs. Deniers

The growing body of knowledge about climate change, and the uncertainties associated with some of the data, have led to a wide range of interpretations and viewpoints. Is climate change an imminent threat to human society? Or will global warming have much less impact on society than many claim, and even benefit those living in colder regions? Is global warming just a hoax? And why have so many authoritative and influential organizations issued statements emphasizing the risks from climate change and the need for action?

Many of the recent statements on climate change stem from the increasing polarization of the climate change discussion, to the point at which views are determined as much or more by politics and ideology as by scientific research and analysis. The IPCC, the AAAS, the National Academies, and other organizations such as the Union of Concerned Scientists (UCS; www.ucsusa.org) present science-based assessments of climate change, some of which were described above in "The Major Actors."

Activist groups accept the scientific consensus about anthropogenic climate change and its consequences wholeheartedly, and promote steps to limit or even eliminate GHG emissions which are deemed responsible. Some of the more active groups are:

- "350.org" (www.350.org), so named from the 350 ppm atmospheric CO_2 level at which it is believed little or no climate related damages will occur. Since atmospheric CO_2 is already at the 400 ppm level, continuing to rise, and hundreds to thousands of years are required for CO_2 to be removed (see "Reservoirs and Fluxes"), this is more of a slogan than a practical, attainable goal. Nevertheless, 350.org's activities have been effective in raising public awareness of climate issues. They make effective use of civil disobedience tactics, such as marches and sit-ins, to get their message across.
- Interfaith Power & Light (http://www.interfaithpowerandlight.org/) is a national organization that is active in 40 states. Their goals are to:
    - Provide practical assistance to faith communities to decrease GHG emissions and energy costs at houses of worship, which are often the least efficient components of the building stock.
    - Educate people on why climate change is an environmental justice issue, and therefore should be a priority to faith communities.
    - Increase awareness of public policies addressing climate change, and advocate for these policies within the limits on charitable non-profit organizations.

> *"Disinformation and misinformation are rampant in the climate arena and have strongly contributed to the gap between public perceptions and professional assessment of the looming threats … The fossil fuel industry and many well funded political organizations have been sowing seeds of doubt about the science of climate change for years … The scientific consensus that climate change is real and anthropogenic is as conclusive as the link between smoking and lung cancer. And yet, largely due to disinformation campaigns funded by prominent fossil fuel companies, much of the American public still believes there to be controversy about this fact."*
>
> ***MIT C4 Report (June 2015)***

At the other end of the spectrum is an assortment of organizations that claim to be climate science "skeptics" but who are more accurately described as deniers of climate science. These groups seek to block regulations which would limit GHG emissions or promote renewable energy at the local, regional, or national level; support political candidates who pledge to block any and all climate regulations, especially in the U.S. Congress; and fund media campaigns casting doubt on climate science. In some extreme cases, they encourage attacks on individual climate scientists and challenge their activities in court, as was the case with Prof. Michael Mann and the "hockey stick" curve.[74] The principal tools that are used are *misinformation,* which is presenting flawed or inaccurate statements as established scientific facts; and *disinformation,* which involves denying or casting doubt on well-founded scientific facts. Among the disinformation tactics these groups employ is choosing a name for themselves, such as American Legislative Exchange Council ("ALEC") or Americans for Prosperity, which sounds innocuous or even progressive, but completely conceals their climate science denial agenda.

In their book "Merchants of Doubt" (Bloomsbury, 2010) now made into a documentary movie (Sony Pictures Classics, 2014), Prof. Naomi Oreskes and Erik Conway show in detail how the climate denial movement has made use of the same techniques employed by the tobacco industry for years, blocking government action on climate by disseminating inaccurate information, recruiting "experts" from a small cadre of climate change skeptics, and recruiting political opposition to any kind of government controls. Indeed, it seems that many of the scientists, consultants, and fund raising professionals who opposed the anti-smoking campaigns are now engaged in similar campaigns to block action addressing climate change.[75]

In a speech at Georgetown University in June 2013 outlining his climate and energy policy, President Barack Obama, trying to highlight the urgency of quick action, quipped, "We don't have time for a meeting of the Flat Earth Society." Daniel Shenton, the President of the Flat Earth Society, responded, "The Flat Earth Society doesn't have an 'official' position on climate change. Personally … I believe the evidence available does support the position that climate change is at least partially influenced by human industrialization. So if President Obama wants to reference people that actively deny anthropogenic climate change, he'd probably be better served by citing groups like the American Enterprise Institute rather than the Flat Earth Society."

Business Insider, June 25, 2013

The amount of data, views, claims, counter-claims, and opinions available on the subject of climate change is vast and continually expanding. As individual citizens, how can we determine which views to take seriously because they reflect current, accurate data and solid reasoning? How do we keep up with the research articles, news, and overwhelming amounts of information available on global climate change? One might think that the vast amount of information sources on the Internet makes this goal more attainable. In reality, however, there are several serious difficulties associated with using the Internet. First, the sheer quantity and exponential growth of information makes it impossible for one person to access and carefully review everything that is available online. Second, the information that is presented has, in many cases, not been subject to independent review and fact checking, and the sources are often not clearly identified as to sponsorship or affiliation.

Here are some suggestions:

- Keep an open mind, access a wide variety of sources, and consider different viewpoints that reflect careful reasoning and accurate data.
- Read frequently on the subject because new data are presented daily.
- Consider where your sources obtain their data. Greg Craven, in his book "What's the Worst that Could Happen? A Rational Response to the Climate Change Debate," outlines a series of steps for ranking sources from more credible to less credible, and places specific statements and assertions regarding climate change on this "credibility spectrum."

Try this role-playing activity from the Center for Learning Technology in Urban Schools:

"Becoming Advisors to Individual Nations and Assembling Country Profiles" http://www.lessonplanet.com/teachers/assigning-roles-becoming-advisors-to-individual-nations-and-assembling-country-profiles.

When it comes to climate change, constant appraisal and reappraisal is essential to help validate perceptions. Just as climate scientists continue to fine-tune their models and observations, each of us should fine-tune what we believe to be true.

Aids to Understanding provides resources and activities.

Climate Change and Its Potential Impact on Society

> *"By the time we see that climate change is really bad, your ability to fix it is extremely limited... The carbon gets up there, but the heating effect is delayed. And then the effect of that heat on the species and ecosystem is delayed. That means that even when you turn virtuous, things are actually going to get worse for quite a while."*
>
> ***Bill Gates***

The impacts of climate change on natural and social systems define the scope and urgency of the issue. Thanks to the ever-increasing coverage and sensitivity of satellite and ground-based measurements, and the increasing speed and power of computer systems to assimilate these measurements and forecast future trends, we are getting a clearer idea of what these impacts are now and are likely to be in the future.

This section considers various regions and segments of the world's ecosystems, nations, and cultures to explore the potential effects on each of them—natural systems, built systems, jobs and individual lifestyles, communities, business, industry, technology, and global equity. (If there are damages, who should pay?) Looking at each of these aspects should help make what is happening seem more concrete, or real.

Overviews and Sources

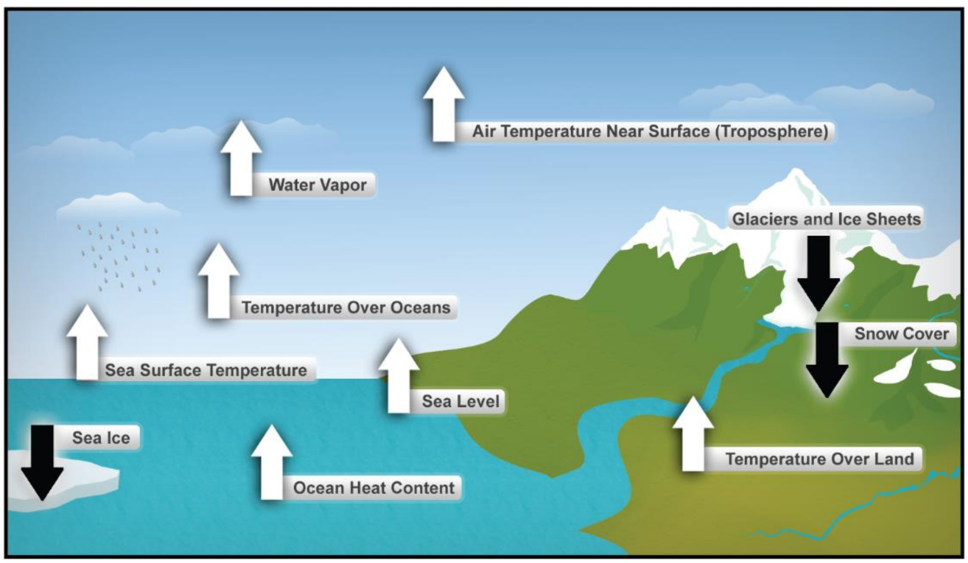
Each IPCC Assessment Report includes the Working Group II (WG2) report ("Impacts, Adaptation, and Vulnerability"). This section summarizes the present and projected impacts of climate change. Box SPM2 Table 1 in the Summary for Policymakers of the AR.5 WG2[76] report describes detailed risks by regions and sectors, along with options for risk reduction and adaptation. Some of the key impacts include:

- Stress on water resources as a result of changing precipitation patterns in Africa and Latin America
- Riverine and coastal flooding in Europe, Asia, Australasia, and North America
- Wildfire-induced losses in North America
- Reduced crop productivity in many regions
- Increased risk of heat-related human mortality during heat waves
- Unprecedented risks to ecosystems and indigenous peoples in polar regions, since these regions are warming twice as fast as the global average
- Complete loss of low-lying small island territories as a result of rising sea levels and storm surges

The IPCC document does suggest some positive effects of climate change, such as modest reductions in cold-weather illnesses and mortality, and shifts in food production to less favorable growing regions. But they conclude that "the magnitude and severity of negative impacts are projected to increasingly outweigh positive impacts … By [the end of the present century] the combination of high temperature and humidity in some areas for parts of the year is projected to compromise normal human activities, including growing food or working outdoors."[77]

The US Global Change Research Program issues a *National Climate Assessment* (NCA) report prepared by a team of more than 300 climate experts; guided by a 60-member Federal Advisory Committee; and extensively reviewed by the public, independent experts, federal agencies, and a panel of the National Academy of Sciences (http://nca2014.globalchange.gov/). As shown in Figure 9 below, the NCA highlights these "Ten Indicators of a Warming World":

Figure 9. Ten Indicators of a Warming World



Credit: NOAA

These are just some of the indicators measured globally over many decades that show that the earth's climate is warming. White arrows indicate increasing trends, and black arrows indicate decreasing trends. All the indicators expected to increase in a warming world are, in fact, increasing, and all those expected to decrease in a warming world are decreasing. [78]

A number of these indicators are explained in more detail below.

Additional sources of information include the annual "State of the Climate Report" from the National Oceanic and Atmospheric Administration (NOAA).[79]

The Union of Concerned Scientists also publishes science based reports on various aspects of climate change, including region-specific projections. The descriptive material is often combined with advocacy for policies and strategies to mitigate climate change risks (www.climatechoices.org).

Global Temperatures

To date, the measured global average temperature has risen by a little less than 1º C (1.8º F) over its "pre-industrial" value. As shown earlier in Figure 6, the projected future temperature increase depends on total cumulative GHG accumulation in the atmosphere, which in turn depends on annual GHG emission rates over the coming decades.

1º C may not seem to be very much at all—after all, day-to-day temperature variations are often much larger than this. However, as the analysis by Hansen et al. in "Perception of Climate Change"[80] demonstrates in Figure 10, the issue involves much more than a small degree of warming. Hansen aggregated surface temperature data for sixty years, starting in 1951, for the 3-month period of June through August over a (250 km x 250 km) grid of the earth's surface and plotted the results by decades. Naturally, there is a lot of variation year-to-year and place-to-place, reflecting the variability of weather patterns.

For the 1950s, 1960s, and 1970s, the distributions are essentially the same, so Hansen plotted the data as a Normal Distribution and used this as a baseline. The observed distribution moved to higher temperatures and broadened out in the 1980s. This trend became more pronounced in the 1990s and 2000s. The data are not complete for the current decade, but the trend seems to be continuing. 2014 was among the ten warmest years on record; NOAA reported that July 2015 was the hottest single month in the instrumental temperature record. January to July 2015 was the hottest six-month period ever recorded since systematic temperature measurements began in the late 1880s.

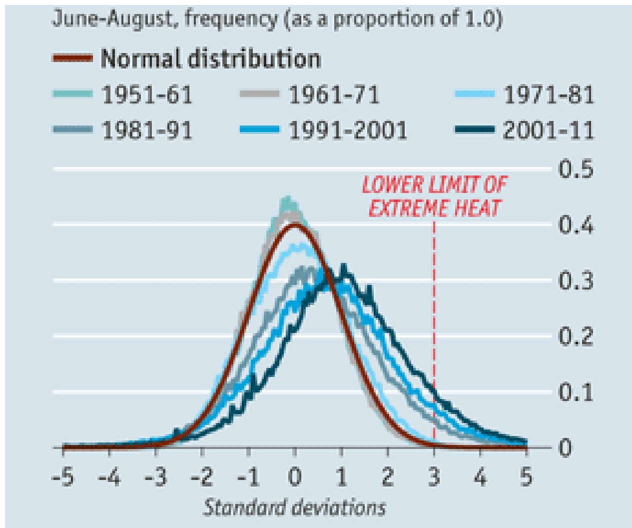
On January 20, 2016, CNN published an article by Brandon Miller stating that NOAA and NASA had proclaimed 2015 as the warmest year recorded on Earth since 1880 when recordkeeping began. This is significant in and of itself, but it is also important to note the margin. According to Miller, “Its margin of victory was startling—it lapped the field, with the average temperature across the

Normal Distribution is a function that represents the distribution of many random variables as a symmetrical bell-shaped graph.

For further explanation of normal distribution, please see https://www.mathsisfun.com/data/standard-normal-distribution.html.

entire planet 1.62˚F (0.90˚C) above the 20th century average, more than 20 percent higher than the previous highest departure from average."[81]

Figure 10. Deviant Behavior



Credit: Goddard Institute for Space Studies

Temperature deviations from reference value (average 1951–1980) in 250km-wide cells around the earth's surface.

The significance of this analysis lies in the extreme values of the distribution (the "fat tails"). As the figure shows, unusually cold periods can still occur during global warming, but the number of extreme heat events increases enormously over the baseline. What was a heat wave occurring once in 100 years now occurs every 10 or 12 years. In any given year, approximately 12 percent of the earth's surface is experiencing an extreme heat wave. During the summer of 2015, 47,000 people went to the hospital during unusually hot days in Japan, and more than 1,000 people died in India and Pakistan during heat waves. It is also important to remember that the warming is not uniform across the globe. The Arctic is warming at about twice the rate of the major continents, leading to loss of sea ice and major impacts on arctic ecosystems and indigenous communities.[82]

The Effects of Climate Change on Natural Systems

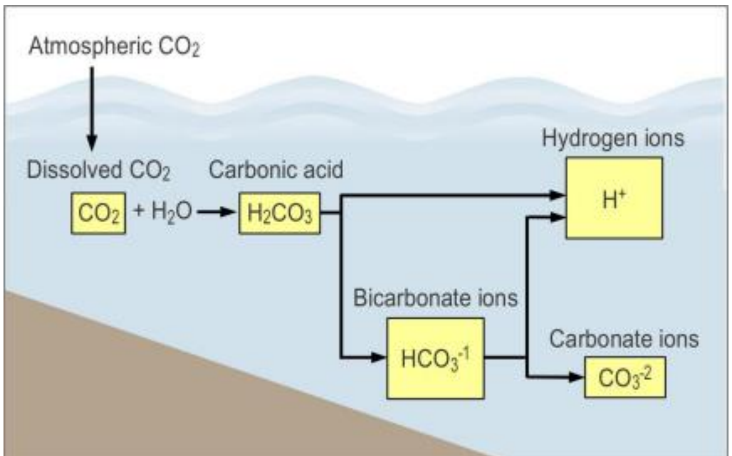
This section identifies and describes a number of major factors that affect natural and human systems: hydrology and water resources; agriculture and food security; terrestrial and freshwater ecosystems; coastal zones and marine ecosystems; human health; human settlements, energy, and industry; and insurance and other financial services.

The Oceans

Oceans form an important part of the climate system. When the water temperatures vary, the fish population may increase or decrease, which affects any societies dependent on fish for food. Temperature effects on plankton populations—the base of marine food chains—have been observed. Many coastal regions will experience flooding if the sea level rises due to climate changes. Coasts will erode, wetlands may disappear, seawater may alter sources of freshwater near a coast, and coastal communities may be destroyed.[83] Increased ocean temperatures for the past 30 years have already started a process that is bleaching coral. Future warming trends may continue to stress coral reefs and may result in a higher incidence of marine diseases.[84]

Ocean acidification

In addition to storing heat, oceans have absorbed approximately 30 percent of the excess carbon dioxide in the atmosphere. When CO_2 dissolves in sea water, a series of chemical reactions takes place:



Information and activities about ocean acidification can be found at http://dataintheclassroom.noaa.gov/Documents/Ocean%20Acidification%20Teacher%20Guide.pdf
Credit: NOAA

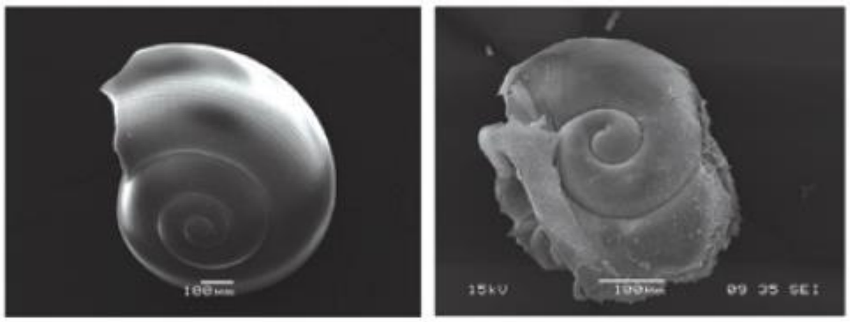
"Climate dice", describing the chance of unusually warm or cool seasons, have become more and more "loaded" (biased) in the past 30 years, coincident with rapid global warming. The distribution of seasonal mean temperature anomalies has increased. The climate dice concept was suggested in conjunction with climate simulations made in the 1980s as a way to describe the variability of local temperatures, with the implication that the public should recognize the existence of global warming once the dice became sufficiently "loaded." Temperatures reached a level such that four of the six sides of the climate dice were red (i.e. hot) in the first decade of the 21st century.

Read more at http://www.pnas.org/content/109/37/E2415.abstract.

The overall result of adding excess CO_2 to sea water is an increase in hydrogen ion concentration ($[H^+]$), which translates to an increase in the water's acidity as measured by its pH. Since pre-industrial times, ocean pH has decreased from 8.2 to 8.06; and since pH is a logarithmic scale, this corresponds to a ca. 26 percent increase in the acidity level.

This change is significant, even alarming, on several counts. Many marine organisms including reef corals, mollusks (clams, oysters, abalone), echinoderms such as urchins and starfish, zooplankton such as *Pteropoda*, and diatoms require carbonate ion ($CO_3^{=}$) to construct their shells and skeletons. One might think that more CO_2 means more carbonate. In fact, solving the set of equations above shows that added CO_2 results in decreased carbonate, with a corresponding increase in bicarbonate ion, as acidity increases. Since these organisms cannot build hard shells out of bicarbonate, their growth is slowed or even stopped. In extreme cases, shells start to dissolve in acidic sea water[85] as shown in Figure 11.

Figure 11. Shells Dissolve in Ocean Water



Credit: Bednaršek et al.

Pteropods, or "sea butterflies," are eaten by a variety of marine species ranging from tiny krill to salmon to whales. The photos show what happens to a pteropod's shell in seawater that is too acidic. On the left is a shell from a live pteropod from a region in the Southern Ocean where acidity is not too high. The shell on the right is from a pteropod in a region where the water is more acidic.

This is important because the plankton are the base of the marine food chain which culminates in fish, marine mammals, and humans. The fish and other macrobiota are also affected: increased acidity has been found to change sensory, reproductive, and other behavioral responses in a variety of species.[86] Phytoplankton also respond to changes in acidity, with dramatic effects on population distributions. Phytoplankton such as *Prochlorococcus* are a key component of the food chain, as well as generating much of the oxygen which we breathe.[87] Scientists at the Monterey Bay Aquarium have said that ocean acidification, on the scale and at the rate at which it is currently occurring, is the most critical challenge to Earth's ecosystems since the massive extinctions of earlier geological eras.[88]

In addition to the biogeochemical effects of ocean acidification, the phenomenon should also lead to a major shift in public attitudes. Some climate skeptics have argued that Earth systems are too immense and too resilient to be affected by human activities. The large changes observed in carbonate and acid concentrations throughout the ocean's vastness effectively puts paid to this notion, and reminds us that humans bear a special responsibility for the well-being of our planetary home.

Sea Level Rise

The rise in sea level which has already occurred has had major destructive impacts, e.g. high-water storm events and the disappearance of territory of small low-lying island states such as

Kiribati and the Maldive Islands. Between 1901 and 2010, mean sea level rose 0.2 meters, or about 8 inches.[89] This is a result of ocean warming (water expands as its temperature increases) and melting land-based ice masses (mountain glaciers, Greenland and Antarctic ice sheets). Melting sea ice, which is floating in water, does not lead to sea level rise. If global temperatures continue to increase as predicted, forecasts of future sea level rise range from 0.3 to 1 meter or more.[90] Sea level rise is one of the "unknown knowns." It is certain to occur, but its magnitude depends on the behavior of large land-based ice sheets which are not well understood. Loss of one or both of the polar ice sheets (which would lead to expanding water volume) would raise sea levels by several meters or even several tens of meters. The exact amount is uncertain. Since more than a billion people now live in coastal areas (i.e. within one meter of the high tide mark) this would have catastrophic consequences. There would be huge property losses and mass migration of "climate refugees," resulting in economic upheaval and security challenges.

In 2014, several high-temperature records were broken in Europe, a spectacular heat wave struck Australia, and the American Midwest experienced bitter-cold temperatures. In 2015, California entered a fourth year of exceptional drought, another heat wave invaded Western Europe with temperatures of more than 40ºC (104ºF) in some regions of Germany, and Montreal experienced one of its coldest winters on record. Such extremes have devastating consequences on societies and infrastructures.

Read more in F. Massonnet's "Communicating Climate Complexity."

Extreme Weather Events

Increased atmospheric temperatures can also lead to extreme weather events, which are meteorological phenomena having unusually powerful force. According to MIT Professor Kerry Emanuel, the atmosphere functions as a vast heat engine, working to reduce the temperature difference between its hot and cold regions.[91] By the laws of Thermodynamics, the greater this difference, the more work can be extracted from the "engine." In the case of the atmosphere, the work takes the form of air motion, or wind, which is dissipated by blowing down stationary objects such as trees and buildings. Since the temperature difference between the earth's surface and the stratosphere increases with global warming, atmospheric phenomena such as cyclones and hurricanes produce stronger and longer-lasting wind fields, and therefore more damage.[92] This is a significant problem for people who have settled in storm-prone regions, resulting in increasing storm damage and loss of life.

Another important physical principle is the Clausius-Clapeyron Equation, which states that vapor pressure of a liquid (such as water vapor) is higher in warm air than in cold air. When the vapor condenses as rain or snow, the

Clausius-Clapeyron Equation

Warm air is able to hold more water vapor than cool air.

$$\left(\frac{dp}{dT}\right)_{coexist} = \left(\frac{\Delta \overline{H}}{T \Delta \overline{V}}\right)_{Q1 \rightarrow \beta}$$

The atmosphere's ability to hold water vapor increases by 4 percent for every 0.6º C rise in temperature.

precipitation can be much larger than average, leading to floods or "Snowmageddon" events.

Extreme weather events seem to be occurring more regularly and with greater severity, both in the U.S. and worldwide.

- **Severe storms**. As noted above, climate change can lead to stronger, more frequent, and/or longer-lasting storm events. Example: Hurricane Katrina hit New Orleans, Louisiana on August 29, 2005, resulting in 1,833 fatalities, $108 billion in property damage, and hundreds of thousands of environmental refugees from New Orleans, many of who have not yet returned. In October 2013, Hurricane Sandy made landfall in the New York/New Jersey coastal metropolitan area. Although this storm was not as powerful as Katrina, today's higher sea level and larger storm surges poured sea water into much of lower Manhattan's underground infrastructure, including rail and vehicular tunnels, the NYC subway system, and electrical substations, shutting down the city and causing billions of dollars of property damage.
- **Wildfires**. Hotter and drier weather, continuing extreme drought, and earlier (or meager) snow melt mean that wildfires in the Western U.S. start earlier in the spring, last later into the fall, and burn more acreage.[93] Example: Firefighting crews and emergency management agencies in California and Washington have described the 2015 fire season as the most costly in terms of forest acreage and burned structures, and the most demanding of resources that they have ever experienced. Again, it must be kept in mind that more and more people have been building in fire-prone areas.[94]
- **Very Heavy Precipitation**. Throughout most of the U.S., rain and snowfall have been occurring as very heavy events. This leads to runoff that exceeds the capacity of storm drains, levees, and drainage channels, causing flood events and accelerated erosion.[95] Similar events have taken place in river basins in Pakistan, Thailand, parts of Europe, and other regions.

The governor of South Carolina characterized the rains that flooded the state in early October 2015 as a "thousand-year event." Read more about it at http://www.cnn.com/2015/10/04/us/east-coast-rain-flood/index.html.

Climate scientists are quick to remind us that specific individual weather events cannot simply be blamed on climate change, but the overall pattern most likely is one of its signatures. A team from the UK Meteorological Office has offered the following analogy.

Weather on Steroids

"One analogy of the effects of climate change on extreme weather is with a baseball player (or cricketer) who starts taking steroids and afterwards hits on average 20% more home runs (or sixes) in a season than he did before. For any one of his home runs (or sixes) during the years that the player was taking steroids, you would not know for sure whether it was caused by steroids or not. But you might be able to attribute his increased number to the steroids … all other things being equal, steroid use has increased the probability of that particular occurrence by 20%. [That is] the job of attribution assessment in climate change."

T.C. Peterson, P.A. Stott, and S. Herring[96]

The Effects of Climate Change on Social Systems

In the previous sections, we have considered the effects of climate change on a range of Earth systems. We now turn our attention to how these impact the basic structures of society: water resources, agriculture, human health, human settlements, and national security.

Hydrology and Water Resources

Water problems can result from too much or too little water. Urban flooding is an example of the first scenario. As noted above, the magnitude and frequency of floods has been increasing in recent years, very likely as one of the results of climate change.

"Water scarcity already affects every continent. Around 1.2 billion people, or almost one-fifth of the world's population, live in areas of physical scarcity, and 500 million people are approaching this situation. Another 1.6 billion people, or almost one quarter of the world's population, face economic water shortage (where countries lack the necessary infrastructure to take water from rivers and aquifers)." Read more at http://www.un.org/waterforlifedecade/scarcity.shtml.

Approximately one-fourth of the global population currently live in water-stressed countries. A striking example is the extreme drought being experienced in California, which has resulted in severe water shortages and forest fires. Researchers at the University of California Santa Cruz (UCSC) have produced a detailed picture of the changes to California's climate that may occur in the next 50 to 100 years. Lisa Sloan, an associate professor of Earth sciences at UCSC, and her coauthors predicted in 2004 that the loss of Arctic ice due to climate change would dry out California. In 2014, Sloan said "I think the actual situation in the next few decades could be even more dire that our study suggested."[97]

Water consumption means the use of water with no return flow. With little water in streams and rivers—not even enough to satisfy current water rights and claims—climate change could cause more competition for water supplies, decreased water quality in areas with slow flow of water, poor ground water quantity and quality, more risk of flooding in the winter and early spring, less risk of flooding later in the spring, and increased water shortages in summer.[98]

Approximately 70 percent of freshwater is used in agriculture.[99] The agriculture industry uses the most water and pays the least for it. Since U.S. agriculture is an essential resource for much of the world's food consumption, simply restricting water use or raising water rates is not easily implemented.

Agriculture and Food Security

In the U.S., agricultural productivity has increased by nearly 1.5 percent annually from 1948–2011.[100] Climate change may have a positive impact on some crops in the U.S. because of the longer growing season and the fertilization effect. Crops vary in how they respond to increased CO_2, but overall photosynthesis is enhanced with more carbon to assimilate which improves crop yields. This fertilization effect is very likely to be overwhelmed, though, by extended heat waves, water stress during droughts, and increased numbers and kinds of crop pests that flourish at higher temperatures.

Agricultural technologists are working on areas of concern in anticipation of continued increases in CO_2 concentrations, which may increase crop yields as well as alter the amount of and need for irrigation water. There may also be an increased need for fertilizers to continue the increase in carbon production, changes in surface water quality, and an increased use of pesticides or other ways to prevent damage from pests.[101] These demands put increasing stress on the surrounding environment.

> "Climate disruptions to agricultural production have increased in the past 40 years and are projected to increase over the next 25 years. By mid-century and beyond, these impacts will be increasingly negative on most crops and livestock."
>
> Find more information about the effects of climte change on agriculture in *Climate Change Impacts on the United States*.

Agriculture is always affected when weather is erratic. Changes in precipitation type (rain, snow, or hail), timing, frequency, and intensity, along with changes in wind (windstorms, hurricanes, and tornadoes) may have significant impacts. Intense precipitation can also lead to soil erosion and leaching of animal wastes, pesticides, fertilizers, and other chemicals into surface and ground water.[102]

Freshwater and Terrestrial Ecosystems

Changes in climate and land use frequently interact, sometimes to the harm of many species that are already threatened. One of the biggest problems is disruption of habitat. More species may become rare, if not extinct.[103] Some human activities that may be affected are recreation—such as sport hunting and wildlife viewing—and the cultural and religious practices of indigenous people.[104]

Because of changes in the climate, southern and northern boundaries of fish distributions may move poleward, cold- and cool-water fish may lose habitat, and warm-water fish may gain habitat.[105] Inland water areas are often smaller bodies of water located near human activities. When lake and river ice is reduced, species can decrease or become extinct, just as when their habitat is destroyed from anthropogenic activities. Many species of fish are at risk as a result.[106] Any species finely attuned to temperature and/or weather may have its life cycle disrupted, making survival much more difficult. These changes will also affect many ecosystems already under stress from pollution, species loss, invasive species, or habitat loss. Species with specific habitat needs that are unable to migrate will be especially threatened.

Communities may lose their natural resources, native species of fish, recreational opportunities, and food sources. On the other hand, they may gain new crops and new seasonal recreations.

Terrestrial ecosystems are one of the major sinks for atmospheric carbon. The boreal (Northern) forests, in particular, store more carbon than any other land ecosystem.[107] Boreal forests are threatened by three consequences of climate change:

- Increasingly hot and dry summers cause water stress. The trees respond by constricting the stomata (pores) in their needles (leaves) to conserve water, which restricts the intake of carbon dioxide and slows photosynthesis. This effectively negates the hypothesized "CO_2 fertilization" effect.[108]
- Higher temperatures and extended drought accelerate forest fires. The warmer atmosphere also produces favorable conditions for "dry lightning," which is ground-to-air lightning, that can ignite fires without much rain to quench the fire. The fire seasons in Canada's Northwest Territories in 2014 and in the U.S. West (California through Washington) in 2015 were among the worst experienced.[109]
- Warming also favors the insect pests "that are exploding across the boreal forest." For example, the mountain pine beetle has spread from its original localization in British Columbia eastward through Alberta and is poised to go all the way to Newfoundland.[110]

Recreational opportunities may change with climate change. For example, the Kenai Peninsula with its dying trees is only a few hours' drive from Anchorage, which draws many tourists. If fire consumes the forest and harms the animal population, that attraction will be lost. If the climate is substantially warmer, people may shift to mountain hiking and higher elevation activities. In the winter, downhill skiing may be negatively affected by less snowpack and a reduced number of cold days. Changing fish stocks will have an impact on fishing as a recreational activity.[111]

Between wood products and recreation activities, forests and their uses will likely be affected by climate variations. “Climate change is increasing the vulnerability of many forests to ecosystem changes and tree mortality through fire, insect infestations, drought, and disease outbreaks,” according to the U.S. Global Change Research Program’s National Assessment Report.[112] Salvaging dead and dying timber and replanting species that work in the new climate are two ways to adapt to climate variations.[113] However, care must be given that non-indigenous species are not introduced into the native ecosystems that may harm already struggling species.

Both for freshwater and terrestrial ecosystems, adaptive changes related to climate variations seem to be occurring, but the results will lag behind the changes in climate for decades or centuries, or may result in irreparable harm to unique ecosystems.[114]

> *"Local and state governments in the Northeast have been leaders and incubators in utilizing legal and regulatory opportunities to foster climate change policies. [. . .] Massachusetts became the first state to officially incorporate climate change impacts into its environmental review procedures by adopting legislation that directs agencies to consider reasonably foreseeable climate change impacts, including additional greenhouse gas emissions, and effects, such as predicted sea level rise.*
>
> *In addition, Maine, Massachusetts, and Rhode Island have each adopted some form of rolling easement to ensure that wetlands or dunes migrate inland as sea level rises and reduce the risk of loss of life and property."*
>
> ***"Climate Change Impacts on the United States"***
> ***May 2014***

Coastal Zones and Marine Ecosystems

Evaluating what will happen to resources from the sea and along coasts is uncertain, varying from area to area. Will the systems adapt to the changes? If they do, will the adaptations accommodate human needs, especially as connected with the marine fisheries industry? Will adaptation result in a less diverse ecosystem? The potential consequences of climate change are only now starting to be considered in coastal management. As an example of this, coastal management programs in Maine, Rhode Island, South Carolina, and Massachusetts have begun to use "rolling assessment" policies to ensure that wetlands and beaches can migrate inland as sea level rises.[115] On the other hand, some jurisdictions have explicitly prohibited use of the term "climate change" in planning documents.[116]

Perhaps the most troublesome uncertainty is associated with climate modelers' projections that global warming will increase sea level between 1 to 4 feet in the 21st century. This increase would have the most impact on regions with current erosion problems as already described.[117] Three coastal adaptation strategies have been identified: protect, accommodate, and retreat.[118] These strategies incorporate soft protection measures,[119] managed retreat, and enhanced resilience of biophysical and socioeconomic systems, including the use of flood insurance to spread financial risk.[120]

Human Health and the Effects of Climate Change on Natural and Human Systems

> *"Until mid-century, projected climate change will impact human health mainly by exacerbating health problems that already exist. Throughout the 21st century, climate change is expected to lead to increases in ill-health in many regions and especially in developing countries with low income …"*
>
> ***IPCC AR.5 Synthesis Report***

Climate change has the potential to have a great impact on human health around the world. Developing countries may have more health-related challenges in the face of climate change than do the developed countries, but how changes will affect various populations in the U.S. differ according to demographic characteristics. According to the U.S. National Climate Assessment Report, "Certain groups of people are more vulnerable to the range of climate change related health impacts, including the elderly, children, the poor, and the sick."[121]

- Economically challenged (poor) people often live in urban areas and cannot afford air-conditioning. Polluted air and extreme heat will affect people living in these conditions more than those who have access to air conditioning.
- Another population at risk is the elderly (65 years and older), which is growing quickly. By 2050, the U.S. Census Bureau projects that there will be 83.7 million elderly people, almost double the estimated population of 43.1 million in 2012.[122]
- Children younger than five years old are also at risk, in part because 20 percent of this population lives in poverty conditions. Children may have less access to medical care, and environmental factors might affect children more due to their physiological variability and dependence on others.
- People who suffer from compromised immune systems may be more susceptible to pathogens that would normally be rendered inactive by ultraviolet light.[123]

According to the U.S. Global Change Research Program's National Climate Assessment from 2014, five issues exist for the effects of climate change on human health: heat-related illnesses and deaths; health effects related to extreme weather events (floods and storms); air pollution-related health effects; water- and food-borne diseases; and insect-, tick-, and rodent-borne diseases.[124]

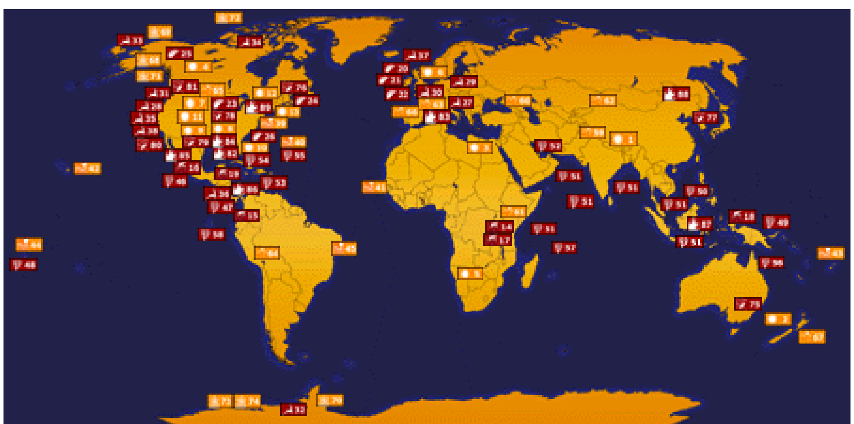
If these possibilities occur, health care costs will increase as a result. If certain areas of the world become uninhabitable due to climate change, relocation will be a major issue. In addition to refugees, there could be populations wanting to move from uncomfortable climates and areas with extreme weather events. A major influx of population could threaten the health of the native population.

Global Warming: Early Warning Signs is a science-based world map placing the local and regional consequences of global climate change in two broad categories: direct indicators (fingerprints) and events that are likely to become more frequent and widespread with continued warming (harbingers). The map, produced as a collaborative project by several environmental organizations, has been peer-reviewed by scientists. The Union of Concerned Scientists produced a curriculum guide geared for students and teachers in grades 9–12 with individual activities adaptable to different grade levels.

The map can be found at http://www.climatehotmap.org/.

Heat-Related Illnesses and Deaths

In 1995, a heat wave in Chicago lasted five days. Temperatures rose to between 93 and 104 degrees F and caused 733 deaths.[125] Whether or not this excessive heat was associated with climate change, it serves as an example of the damage caused by extreme temperatures. In urban areas, temperatures can be even higher and last longer because of the physical structures and cement that retain heat. What can be done to help? People need to adapt to the energy and health demands of longer heat waves by staying hydrated and using air-conditioning if at all possible. The development of community-wide heat emergency plans, improved heat warning systems, and better heat-related illness management plans are also possible adaptive strategies.[126]



Link to a clickable version of this climate change events map at http://www.climatehotmap.org/. It illustrates the local consequences of global warming, which includes extreme weather events.

Credit: Union of Concerned Scientists and World Resources Institute

Health Effects Related to Extreme Weather Events

If climate change causes more extreme weather events, how might we be affected? Some of the possible scenarios include heavy precipitation events and higher frequency of tornadoes and hurricanes. According to the National Weather Service, over the ten-year period of 2005–2014, 638 people per year were killed in weather-related deaths.[127]

Floods are the "second deadliest of all weather-related hazards in the U.S."[128] With the possibility of coastal flooding increasing, these health effects are of great concern.

Air Pollution-Related Health Effects and Water-and Food-borne Diseases

Weather and air pollution can work together to create extremely unhealthy climate conditions. Climate change may work differently in each region, depending on other variables such as topography, to create a concentration of air pollution. Anthropogenic causes of emissions that accumulate and do not disperse due to a temperature inversion have set the scene for air disasters since the mid-1800s and the Industrial Age. If the climate is warming and is less predictable, air quality is affected, especially in populous areas like Los Angeles and Mexico City. Warmer temperatures may spike the demand for electricity for increased use of air conditioning. This in turn can create more emissions. Higher surface temperatures can also contribute to the formation of ground-level ozone due to the chemical reaction of the sun on the contents of these emissions, thus creating a vicious cycle.

The health effects of these exposures to air pollutants are many—reduced lung function, sensitized lung tissues, chest pain, coughing, pulmonary congestion, altered defense systems of the body, cancer, etc. The young (under 5 years) and the elderly (65 years and older) are especially at risk. While there is much uncertainty as to what the future holds for health risks, particularly related to air quality concerns, the important thing is to be aware of these risks and the preventive and mitigative measures to be taken. [129]

"In the U.S., food-borne diseases are estimated to cause 48 million cases of illness, with 128,000 hospitalizations and 3,000 deaths per year."

Centers for Disease Control and Prevention[130]

Climate-induced changes in precipitation, temperature, humidity, salinity, and wind "will affect distribution of food- and water-borne diseases as well as food trade and distribution." [131]

Insect-, Tick-, and Rodent-Borne Diseases

Changes in the prevalence of insect, tick, and rodent diseases may also be affected by climate change. Many of the communicable diseases, like malaria and yellow fever, were once common in the U.S. before the use of antibiotics, vaccines, and water sewage sanitation. The occurrence of these diseases has been reduced through improvements in where and how people live, in control of vectors, and in public health systems and practices. However, humans can still contract these diseases from insects or ticks (as with Lyme disease and West Nile virus) or by contact with infected animals or their body fluids (as with hantaviruses). Weather variables affect the spread of these diseases. For example, warmer weather may allow vectors more reproductive cycles in a year and assure their survival over the winter months. Wetter weather increases the population of water-dependent vectors, like mosquitoes. Although the U.S. has reduced the occurrence of dengue and malaria (and other diseases), the continued presence of diseases in tropical and semi-tropical countries spread more easily due to today's worldwide travel patterns.[132]

Some agencies are taking a proactive approach to vector control. Orange County has a Web page set up to provide information, request service, and receive alerts. For more information see http://www.ocvcd.org/.

Security Threats

The IPCC AR.5 WG2 (2014) report identified several national security issues arising from climate change:

- Climate change over the 21st century is projected to increase the displacement of people. Displacement risk increases when populations that lack the resources for planned migration experience higher exposure to extreme weather events or losses of food and water resources, particularly in developing countries with low income. The flow of political and economic refugees that caused such turmoil in Europe in the summer of 2015 would likely be dwarfed by floods of "environmental refugees."
- Climate change can indirectly increase risks of violent conflicts in the form of civil war and inter-group violence by amplifying well-known drivers of such conflicts such as poverty and economic shocks.
- The impacts of climate change on the critical infrastructure and territorial integrity of many states can impact national security policies and strategies.

Accordingly, the military and intelligence agencies in many countries are incorporating climate change into their forward planning, even in the absence of policy decisions by the central government.[133]

Energy for Human Settlements

How does climate affect where humans live? Settlements located near rivers and coasts are at risk, but even in urban settlements, storm drains and water supplies can be affected by heavy rains and increased intensity of thunderstorms, hurricanes, etc. City planners need to take all of these factors into consideration to avoid potential costly and dangerous impacts. As much as possible, humans need to plan for these situations and adapt to possible changes in their environment. [134]

Throughout the 21st century, climate-change impacts are projected to slow down economic growth, make poverty reduction more difficult, further erode food security, and prolong existing and create new poverty traps.[135] According to the IPCC, "Climate change is projected to reduce energy demand for heating and increase energy demand for cooling in the residential and commercial sectors."[136]

The Advanced Technology Environmental Education Center (ATEEC), a National Science Foundation Center of Excellence, held a forum (2014) to validate/update the results from a 2008 workshop that defined the environmental technology field, its occupational categories, its job titles, and the functions for each category. Participants came from industry, education, business, and government. The document is available at http://ateec.org/defining-environmental-tech-report/.

Jobs Needed in a Changing Climate

Depending on area of residence, people could be affected by climate change in any number of ways. This section examines how climate change might affect job opportunities, especially in the environmental and energy technology fields. What is environmental technology, and what are some of the jobs tied to climate change?

> *" Environmental Technology is a career field that applies the principles of math, science, technology, engineering, communication, economics, and law to ensure the health and safety of the worker and community, and protection of the environment. This career field encompasses the management and conservation of natural resources, regulatory compliance, and sustainability"* [137]
>
> ***ATEEC***
> ***"Defining Environmental Technology"***

The newest occupational category identified in ATEEC's *Defining Environmental Technology* is the "Sustainability" category. "Climate Change Adaptation Specialist" and "Climate Change Mitigation Specialist" have both been identified as existing jobs, and the category also includes several other jobs pertaining to the sustainable job market.[138]

The energy technician career field is one "that applies knowledge, skills, and abilities, to perform scientific, technical, communication, and regulatory tasks."[139] For example, an energy auditor conducts audits of buildings and process systems.

The most recent data from the Bureau of Labor Statistics found 3.4 million green jobs in the U.S. of the end of 2011.[140] The following list breaks down the employment numbers by energy source:[141]

- Biogas: 20,000 jobs (2014)
- Biomass: 152,000 jobs (2012–2013)
- Fuel Cells: 10,845 jobs (2011)
- Geothermal: 35,000 jobs (2014)
- Hydropower: 200,000 to 300,000 jobs (2014)
- Renewable Fuels: 852,056 jobs (2014)
- Solar: 143,000 jobs (2013)
- Waste to Energy: 5,350 jobs (2014)
- Wave and Ocean Power: 371 jobs (2010)
- Wind: 50,500 jobs (2013)

Climate Change's Impact on Business and Industry

Many different businesses will be affected in a variety of ways by climate change. The extent to which a business is affected will depend on the location of its resources and facilities, as well as on the type of business. Businesses that are not tied to a particular place, such as some telecommunications firms, might have an easier time making any necessary moves from threatened areas. However, severe weather and flooding might affect above- and underground cable and phone lines that are the infrastructure of the communications system, as occurred in New York City during Hurricane Sandy.

> "This [WWF] study shows that a responsible approach to energy policy can help us meet the challenge of climate change while still benefiting the economy and creating new jobs."
>
> Brooks Yeager, vice president of Global Threats for World Wildlife Fund
>
> The WWF study is based on research and analysis conducted by the Tellus Institute for WWF. Data are from the U.S. Department of Energy, Energy Information Administration's Annual Energy Outlook for 2001, and the Bureau of Labor Statistics' Economic and Employment Projections. Read more at http://www.worldwildlife.org/news/headline.cfm?newsid=303.

As noted earlier in the discussion of cumulative CO_2 emission budgets, anticipated limits on total allowable emissions mean that a significant portion of fossil fuel reserves will become "unburnable carbon" and have to remain in the ground. Since a major part of the assets of fossil fuel corporations is the total reserve of coal, oil, and/or gas which can be recovered and sold in the future, this has a severe impact on their business model. If the use of these fuels is restricted, the reserves become "stranded assets," which will not contribute to the companies' future revenues or profits. Estimates vary, but anywhere from one-third to one-half of fossil fuel reserves would become “unburnable carbon.” This would decrease the value of the companies’ balance sheets, and their share prices would be expected to fall accordingly. Some financial advisors have recommended diversifying away from fossil fuel investments. These financial arguments lend strength to the growing call for divestment from such investments, especially on the part of public trusts such as pension funds, foundation reserves, or university endowments.[142]

Energy companies seem to be taking this into account in planning their business strategies, at least in their public statements. Investment strategies are also recognizing this issue. "In April [2013] Citi Research … concluded that investors who strongly believe in ‘unburnable carbon’ would find it productive to actively tilt their portfolios (i.e. sell fossil-fuel firms)."[143] In fact, 2,000 individuals and 400 organizations have already committed to stop investing in firms that produce fossil fuels. The market capitalization of America's four largest coal companies has fallen to $1.2 billion from $22 billion during the past four years and some three dozen American coal firms have gone bankrupt since 2012.[144]

The Center for Climate and Energy Solutions includes representatives from 37 major companies who see the need to act and are taking “concrete steps to protect the climate.” The companies are mostly Fortune 500 firms, such as General Electric, Entergy, Shell, Alcoa, and Bank of America. Read more at http://www.c2es.org/.

Another type of business that is being especially affected is the insurance and financial industry. Private and public institutions that offer insurance and financing for industries could be profoundly harmed when assets are damaged by climate changes and extreme weather events. Many in the insurance industry are taking notice of this, as “weather-related losses increased nearly fourfold in the U.S. since 1980.”[145]

Extreme weather events cost money, a trend exhibited in recent decades. According to the National Oceanic and Atmospheric Administration, “The U.S. has sustained 188 weather and climate disasters since 1980 where overall damages/costs reached or exceeded $1 billion ... The total cost of these 188 events exceeds $1 trillion.”[146]

Global Equity Issues

> *" What constitutes a fair response to climate change is the main question underlying many of the unresolved issues in the climate change debate. It is behind the questions of the level of commitment by industrialized countries, the type of participation to be undertaken by developing countries, the structure of the various trading mechanisms, and the nature and magnitude of financial obligations. What has been missing from the debate, however, are consensus principles that define equity in the context of this issue."* [147]
>
> ***Eileen Claussen***
> ***former President, Pew Center on Global Climate Change***
> ***[now Center for Climate and Energy Solutions]***

> *"[A] true ecological approach always becomes a social approach; it must integrate questions of justice in debates on the environment, so as to hear both the cry of the earth and the cry of the poor."* [148]
>
> ***Pope Francis***

Predicted impacts of future climate change differ from one country to another and from one culture to another, especially as based on economic circumstances and the ability to mitigate them. Who will pay for climate change mitigation in Bangladesh, for example, as well as in other developing countries? Issues of global equity are especially relevant because of the global and disparate effects of climate change. A serious question of equity arises in light of the fact that while the 50 least developed countries contribute less than one percent of the global carbon emissions, they bear the burden of over 99 percent of deaths from weather-related disasters and over 90 percent of the total economic losses. For a more in-depth study of the equity issues of climate change, please see the Global Humanitarian Forum report "The Anatomy of a Silent Crisis."

The IPCC, as a part of its *Climate Change 2014* report, produced a chapter on sustainable development and equity, noting "the relevance of ethical frameworks and equitable burden sharing in assessing climate responses." The chapter identifies issues in equity, and offers a passage on "equity and burden sharing in the context of international cooperation on climate."[149]

The uncertainty of the specific effects of climate change has an impact on communities and their sources of livelihood—their businesses and industry. From the personal—"me and my job"—to the overall job outlook for a city, a country, and a world, will climate change create new jobs, change existing jobs, or cause jobs to disappear? This uncertainty can also be applied to the future of technology and its applications. How can technologies be used to mitigate the effects of climate change? The global picture should encompass more than one people or culture, more than one country, more than one business or industry, and more than one viewpoint. This picture should include a world equitably dealing with the effects of climate change.

Aids to Understanding provides resources and activities.

What We Can Do

"Understanding the global climate system, determining how our activities may be influencing it, and taking responsible actions to protect it for future generations, may be among the greatest challenges that humanity has ever faced."

Jeffrey I. Steinfeld
Professor of Chemistry Emeritus, MIT[150]

"The Precautionary Principle says that unless you are sure that you are not causing a serious problem, don't do it, or at least moderate your behavior."

Michael B. McElroy, Gilbert Butler Professor of Environmental Studies

Because of the uncertainty about what impacts will result from human-induced climate change around the globe, determining a course of action is difficult. In spite of this complexity and uncertainty, it is important to consider the costs of acting and the risks of not acting.

The following strategies endorsed by major scientific and professional societies, including the American Geophysical Union (AGU) and the American Chemical Society (ACS), represent two courses of action: obtain more detailed and accurate information to reduce scientific uncertainty; and develop science and technology options for rapid response should climate conditions change quickly.

The AGU adopted the following climate change position statement in 1998, stating, "AGU believes that the present level of scientific uncertainty does not justify inaction in the mitigation of human-induced climate change and/or the adaptation to it." [151]

The current (2013–2016) ACS public policy statement on climate change states, "… climate change is real, largely attributable to emissions from human activities, and potentially a very serious problem."[152]

The ACS policy statement offers a set of linked recommendations to:

- Maintain and expand research programs on Earth systems, particularly on climate.
- Develop subsidies, tax, regulatory, and other incentives to reduce GHG emissions.
- Invest in technologies to mitigate climate change through energy conservation, energy. sources not based on fossil fuels, and carbon sequestration.
- Develop appropriate adaptation strategies that meet the needs of their communities.
- Support and encourage climate change education and communication.[153]

Many of these will be considered in more detail in this section.

"In order to protect the environment, the precautionary approach shall be widely applied by states according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."[154]

The Rio Declaration from the 1992 United Nations Conference on Environment and Development

This approach to policymaking, known as the Precautionary Principle, interprets scientific research with a different standard of uncertainty for the purpose of making environmental policy. If there is a risk of harm to humans or the environment, the Precautionary Principle states that regulation should be implemented even if scientific proof of the problem is not firmly established. In the current U.S. policy environment, proof of harm usually must be shown before a process or pollutant is regulated. Besides climate change, genetically modified foods and use of hormones and pesticides in food production are also issues that are causing government agencies to consider the Precautionary Principle. Sometimes laws are precautionary by nature. The Pollution Prevention Act of 1990 reflects a base of precaution, with its emphasis on preventative measures.

For a more in-depth look at the factors involved in making policy related to the environment, see the "Environmental Decision-Making" module.

Three critical areas help delineate how society and individuals can make a positive response to climate change. One preventive strategy is to change behaviors in ways that reduce GHG emissions. A second strategy is to use possible technological solutions to help change energy sources from those that produce carbon dioxide (CO_2) to those that do not. A third strategy is to identify ways to mitigate CO_2 emissions after they are produced but before they reach the atmosphere. The following sections discuss these three possible courses of action.

Business and Energy

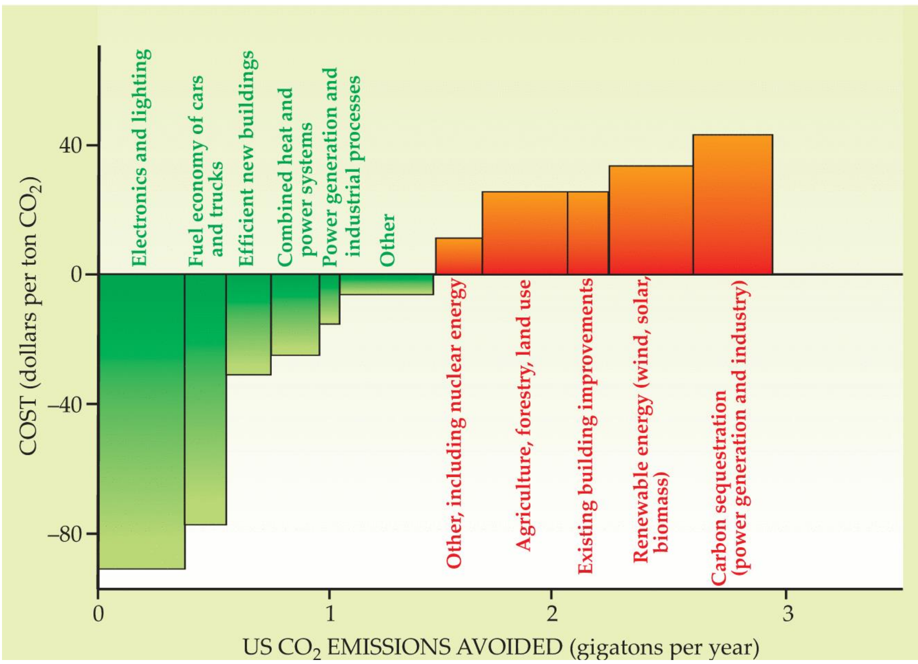
"Companies with a history of climate-related activity are trying to shift their strategies from a focus on risk management and bottom-line protection to instead emphasize business opportunities and top-line enhancements. Firms that incorporate climate change into their core business strategies will be in the best position to take advantage of emerging opportunities and gain competitive advantage in a changing market environment. Sustainable climate strategies cannot be an add-on to business as usual; they must be integrated with a company's core business activities."

Andrew Hoffman[155]

Companies vary in their approach to the energy issue—from long-term research with little immediate action to short-term reduction of GHGs and research into using renewable technologies in the future. [156]

The goal of most companies is to maximize profits by increasing revenue and reducing costs. McKinsey, a global business consultancy, has developed the chart shown below which displays the estimated cost of emission avoidance strategies with the likely amount of CO_2 emissions thus avoided.[157]

Figure 12. Estimated Cost of Emission Avoidance Strategies



Credit: McKinsey and Company

The green bars on the left are negative costs, that is, strategies such as energy efficient lighting or improved vehicle fuel economy which reduce overall costs as well as reducing emissions. The red bars on the right represent increased net costs. If a "carbon cost" of around $30 per tonne of CO_2 is imposed, then all strategies with the possible exception of carbon sequestration become negative costs.

The aggregate total of avoided emissions, if all strategies were implemented, would be 2.5 to 3 gigatonnes (Gt) CO_2 per year.[158] This is about half of the current U.S. emission rate of 5.5 Gt per year. That is a 50 percent reduction in emissions as called for by climate scientists and policy advocates. Since much of this reduction could be accomplished and costs reduced at the same time, it is not surprising that many companies have announced plans to cut emissions.

The World Resources Institute recommends a climate change action plan for business[159] based on a collaboration of industrial leaders and environmental groups:

- Set ambitious targets: This means setting an emissions-reduction target in line with what the science says is necessary to limit warming to below 2 degrees C (3.6 degrees F) and prevent the worst impacts of climate change.
- Embed mechanisms for change: Set an internal price for carbon to spur innovation, drive efficiency, and prepare companies to be competitive in a carbon-constrained world.
- Speak with a consistent voice: Commit to a responsible approach to policy engagement so actions and words—as well as those of the trade organizations that represent companies—are complementary.
- Create demand: As a user of energy, create the demand for renewables that will further accelerate the market for this critical resource.

Business and industry is represented by several organizations in terms of climate change. The Business Environmental Leadership Council, part of the Center for Climate and Energy Solutions, clearly states its beliefs and its participating industries and businesses:[160]

- We accept the scientific consensus that climate change is occurring and that the impacts are already being felt. Delaying action will increase both the risks and the costs.
- Businesses can and should incorporate responses to climate change into their core corporate strategies by taking concrete steps in the U.S. and abroad to establish and meet GHG emission reduction targets, and/or invest in low and zero GHG products, practices and technologies.
- The U.S. should significantly reduce its GHG emissions through economy-wide, mandatory approaches, which may vary by economic sector and include a flexible, market-based program. Complementary policies may also be necessary for sectors such as buildings, electricity generation, forestry, agriculture, and transportation that will help drive innovation and ease the transition to a low-carbon economy.
- Climate change is a global challenge that ultimately requires a global solution. An international climate framework must establish fair, effective, and binding commitments for all developed and major developing economies.

Business and Technology

Ironically, the technologies that enabled this production of goods and services have often used fossil fuels, causing the release of carbon to the atmosphere. Technology has helped, at least in part, to cause climate change. Yet it is now being looked at to address climate change and its impacts.

How will technological advances help mitigate climate change and its effects? One conclusion drawn in the “Energy for Change: Creating Climate Solutions” report is that “no single technological silver bullet will be sufficient. The ultimate success of a climate change strategy—at both national and international levels—will hinge on the innovation and commercialization over time of a broad spectrum of technologies that can compete in a carbon-constrained world."[161] Technology might not always be the knight in shining armor galloping to a timely rescue. Technology develops over a period of time and undergoes trial and error in its application.

The relationship between the time it takes to develop the technology and have it in place to mitigate climate change's effects is not clearly understood. The Institute of International System Analysis (IIASA) of Austria found it took anywhere from 50 years to 100 years for a form of energy to increase its share of global energy production from 1 percent to 50 percent.[162] Changing from the use of one energy form (fossil fuel) to another form of energy like hydro or nuclear takes time. Understanding the whole picture is important—not just the technologies needed but their relationship to the economy and society overall—in responding to environmental problems. What the different levels of government can do in addressing climate change forms an important part of the total picture.

International Action

Read the five agreements resulting from the 1992 Earth Summit in Rio de Janeiro, Brazil at http://www.un.org/geninfo/bp/envirp2.html.

In 1992 in Rio de Janeiro, Brazil, representatives of the world's governments met at the 1992 Earth Summit and produced two international agreements, two statements of principles, and a major action agenda on worldwide sustainable development. One of the major international conventions negotiated in Rio was the *United Nations Framework Convention on Climate Change (UNFCCC)*. Its goal for developed countries was to return GHG emissions to 1990 levels by 2000 and to take the lead in reducing emissions. The Conference of the Parties (COP), the working committee of the Climate Change Convention, now carries on with what began at the Earth Summit. COP has annual conferences to implement UNFCCC principles.[163]

The Kyoto Protocol, approved at the Third COP in Kyoto in 1997, proposed mandated GHG emissions reduction to be signed and ratified. In retrospect, the Kyoto Protocol turned out to be ineffective in limiting GHG emissions for a number of reasons:[164]

- Although the U.S. representative to COP-3 signed the agreement, it was never ratified by Congress and therefore never had the force of law in the U.S., which was the world's largest GHG emitter at the time.
- Developing countries were specifically exempted from the Protocol. China and India are now the world's #1 and #3 GHG emitters, respectively.
- No penalties were specified for non-compliance, so some signatories withdrew their participation when there was a change of government.

- The negotiated emissions reductions were not sufficient to limit global warming to a "manageable" level. In fact, global carbon emissions were 58 percent *higher* in 2012 than they were in 1990.

The World Resources Institute provides an excellent interactive map of the emission reductions pledged at COP-21. The map can be found at http://cait.wri.org/indc/#/map.

The plan agreed to at the COP-21 in Paris in December 2015 calls for every UN member nation to establish and enforce its own GHG emission reductions. This provides the flexibility that is demanded by economies at various stages of development. According to a recent analysis by the UN Environment Programme, in order to limit global temperature rise to 2º C, the world will have to reach carbon neutrality between 2055 and 2070. This would require carbon emissions to equal uptake by carbon sinks and offsets, so that no more carbon dioxide is added to the atmosphere.

In support of COP-21, bilateral agreements are being implemented, such as the one between the U.S. and China announced in November 2014 (China and U.S. are currently the #1 and #2 CO_2 emitters, although China's per capita emissions are still much less than those in the U.S.) The terms of this agreement require the U.S. to cut its level of carbon emission to 26 to 28 percent of those in 2005 by the year 2025.[165] China's emissions would increase, albeit more slowly, up to 2030 and decrease thereafter. China also committed to get 20 percent of its energy from zero-carbon-emission sources by that year.[166] During a White House summit in September 2015, President Xi Jinping announced that China would begin to implement a nationwide cap-and-trade policy starting in 2017.[167]

“What we need is an agreement that’s ambitious—because that’s what the scale of the challenge demands. We need an inclusive agreement—because every country has to play its part. And we need an agreement that’s flexible—because different nations have different needs. And if we can come together and get this right, we can define a sustainable future for your generation.”

President Barack Obama, addressing Georgetown University.

Read the entire address at https://www.whitehouse.gov/the-press-office/2013/06/25/remarks-president-climate-change).

National and State Government

Despite numerous attempts, no legislative action on climate change and GHG emission reductions has ever been approved by the U.S. Congress. In order to take action on climate change, in June 2013 President Barack Obama laid out a series of steps that could be acted on through executive orders not requiring Congressional approval.[168]

The plan includes a number of policies and regulations designed to lower emissions. Its centerpiece is the Clean Power Plan (CPP) which is intended to reduce CO_2 emissions from power plants 30 percent below 2005 levels by 2030. In 2009, power plants emitted 2.15 Gt of CO_2, equivalent to 41 percent of U.S. emissions from fossil fuel combustion and over 30 percent of total GHG emissions.[169]

By authority of the Clean Air Act [U.S.C. § 7411(b)], as interpreted by the U.S. Supreme Court [Massachusetts v. U.S. EPA, 2005] the U.S. EPA has the prerogative, and therefore the obligation, to regulate GHG emissions as an endangerment to public health. In September 2013, the U.S. EPA issued Section 111(b) standards for new source power plants, which limits emissions to 1,000 to 1,100 lbs of CO_2 per Megawatt-hour (MW-hour) generated.[170] Natural gas-fired power plants already operate below this limit, with emissions in the range of 700 to 800 lbs CO_2 per MW-hour. However, the best of current coal-fired plants generate 1,600 to 1,800 lbs CO_2 per MW-hour generated. Therefore, new natural gas-fired power plants could comply without changing anything since they are already below the limit. Emissions from new coal-powered plants would have to be at least 40 percent below today's most advanced designs, for example, by the installation of carbon capture and storage technology. Section 111(d) standards for existing power plants, announced more recently, are similar but allow individual states considerable flexibility in meeting the standard.[171] In addition to enforcing emission standards at power plants, states could invest in renewables, improve energy efficiency, and establish regional cap-and-trade programs. This is seen as a hybrid system that makes optimal use of market mechanisms. The overall impact of these regulations is that *coal would no longer be a viable option for electricity generation in the U.S.*

State governments have also been dealing with the issues of climate change. Twenty nine states have implemented GHG emission standards for electricity generation (Renewable Portfolio Standards).[172] Others, including California, have imposed fleet average emission limits for mobile sources, which has spurred the introduction of electric and hydrogen fuel-cell vehicles.

Nine states have joined with the Canadian Maritime Provinces in a Regional Greenhouse Gas Initiative (RGGI)[173], a cap-and-trade system in which total emission limits are set for large emitters. Those that are not able to attain the limits can purchase extra CO_2 allowances from those that have succeeded in doing so. Over time, successive reductions in the emissions cap drive increased efficiency and introduced new, low-carbon technology. Significant emissions reductions have already been achieved, largely through replacing coal-fired power plants with efficient natural gas plants.

Local Government—Laboratories of Democracy

> *"Successfully reaching the deep emissions reduction goals called for by scientists will require action at all levels of society. Local governments are uniquely situated to implement measures at the community level that impact everyone's ability to reduce their emissions in cost-effective ways."*
>
> ***Yale School of Forestry and Environmental Studies***[174]

For a series of municipal climate change solutions, see "Solution Stories" from the Climate Solutions website at http://www.climatesolutions.org/stories.

Cities and towns can be instrumental in promoting climate solutions. The U.S. EPA's State and Local Climate and Energy Program provides a comprehensive system of actions to help municipalities save money and energy; clean the air; and reduce congestion, GHGs, and urban sprawl.[175] Some of those actions include:

- Identifying and documenting cost-effective policies and initiatives that address climate change, including those that promote renewable energy, energy efficiency, and related clean technologies.
- Measuring and evaluating the environmental, economic, and public health benefits of climate change and clean energy initiatives.
- Offering tools, guidance, and outreach support for assessing the options and benefits of actions to reduce GHG emissions.
- Fostering peer exchange opportunities for state and local officials to share information on best practices and lessons learned about innovative policies and programs.

Read more about SEEC at http://icleiusa.org/programs/emissions-management/seec/.

One example of a local-level reduction in GHG emissions is underway in California. The International Council of Local Environmental Initiatives (ICLEI) has developed its Statewide Energy Efficiency Collaborative (SEEC) to provide "no-cost resources to support the climate and energy initiatives of California local governments."[176] SEEC is built on the ICLEI's "Five Milestones of Emissions Management,"[177] which are:

- Inventory GHG Emissions
- Establish Reduction Target
- Develop Climate Action Plan
- Implement Policies and Measures
- Monitor and Verify Results

These U.S. EPA and ICLEI resources point to a larger need for state and local government to take the initiative and act as the "front lines" in attacking the GHG emissions problem.

Individuals

"Never doubt that a small group of committed individuals can change the world—indeed it's the only thing that ever has."

Margaret Mead

Climate change is a global problem. What difference can individuals make with such an enormous challenge? The average U.S. resident contributes approximately 22 tons (20 metric tonnes) of carbon dioxide emissions per year to the global system.[178] This is far larger than the average for the rest of the world, as shown in the "carbon footprint" graphic in Figure 13.

Check your contribution to the world's carbon budget at http://www3.epa.gov/carbon-footprint-calculator/.

Figure 13. Average Carbon Footprint

Credit: Patrick Gillooly and Prof. Timothy Gutowski, MIT

To take corrective action, start by looking at the various places you go and what you do to determine areas of your life where you can take "smart actions." Two key areas on which to focus are the home environment where carbon emissions are created by activities including heating, lighting, and electricity use; and modes of transportation where carbon emissions are produced by different forms of mobility.

The World Business Council for Sustainable Development has launched a program called Mobility 2.0, a three-year project that "aims to accelerate progress towards delivering universal access to safe and low-impact mobility for both goods and people" in order to "demonstrate that concrete solutions can be enacted that will make a difference to the sustainable mobility of a city and inspire others to follow and implement the solution on a more global scale."

Read more about Mobility 2.0 at http://www.wbcsd.org/work-program/sector-projects/mobility.aspx.

Home Environment

The U.S. EPA global warming website provides tips for protecting the climate, reducing air pollution, and saving money inside the home, at school, in the office, and on the road. These steps are small and are easily managed on an individual level.[179]

At home, you can purchase products with the U.S. EPA ENERGY STAR® label. These products "can reduce greenhouse gas emissions by about 130,000 pounds and save you $11,000 on energy bills" over their lifetimes.[180] For example, replacing the five most frequently used light bulbs in the house with ENERGY STAR® qualified products will generate 75 percent less heat and use 75 percent less energy.[181] Other options include insulating your home and tuning up or replacing your furnace with an energy-efficient one. The same sort of measures can be taken with your water use. Home is an excellent place to work on your carbon diet.

Transportation

Most people rely on various modes of transportation every day to travel from home to work and other destinations, depending on their needs and wants. Every time we fly to a meeting or a vacation destination, we contribute to the world's carbon budget. When we drive to work or to shop, we again contribute to the carbon budget of the earth.

Gas Mileage Tips

Driving more efficiently
Keeping your car in shape
Planning and combining trips
Choosing a more efficient vehicle

U.S. Department of Energy http://www.fueleconomy.gov/feg/drive.shtml.

Rethinking how we organize trips could make our use of autos more energy efficient. A site called Planning and Combining Trips[182] provides excellent recommendations about:

- Combining errands in one trip to avoid multiple short trips “taken from a cold start,” which uses twice as much fuel.
- Staggering work hours to avoid rush hour traffic (in which cars idle and consume more gas).
- Working from home if possible (flexiplace).
- Carpooling and sharing rides.
- Using public transportation.

Consider using public transportation systems whenever possible. The American Public Transportation Association’s website has a tool called “Public Transportation Near You” that provides links to public transportation agencies, organized by state and county. [183]

For those who rely on automobiles for transportation, these ideas may help reduce carbon emissions while driving:[184]

- Research and compare vehicles when you shop for a new one. The U.S. DOE’s Fuel Economy website allows you to select a year, make, and model to compare annual fuel cost, GHG emissions, and the U.S. EPA air pollution score.
- Follow some gas mileage tips.
- Investigate gasoline prices.

Another creative alternative is to explore the world of personal transportation. If you like to bicycle for exercise and recreation, try biking to work. Of course, the length and nature of your destination are factors to keep in mind. Whatever personal transportation you choose, you are helping reduce your carbon diet.

An excellent source for all aspects of energy technology is the textbook "Sustainable Energy: Choosing Among Options" by J.W. Tester, E.M. Drake, M.J. Driscoll, M.W. Golay, and W.A. Peters (MIT Press, Cambridge Mass., 2005). The course material on which the textbook is based is freely available at MIT OpenCourseWare: http://ocw.mit.edu/courses/find-by-topic/#cat=energy

Another good source is "Sustainable Energy—without the hot air" by D.J.C. MacKay (UIT, Cambridge UK, 2008). The complete book is available for free download at www.withouthotair.com.

Developing Energy Technology

Energy Efficiency

U.S. EPA ENERGY STAR Program

"ENERGY STAR was introduced by the U.S. EPA in 1992 as a voluntary labeling program designed to identify and promote energy-efficient products, in order to reduce CO_2 emissions. The U.S. EPA partnered with the U.S. Department of Energy in 1996 to promote the ENERGY STAR label, with each agency taking responsibility for particular product categories. ENERGY STAR has expanded to cover new homes, most of the buildings sector, residential heating and cooling equipment, major appliances, office equipment, lighting, consumer electronics, etc."

The ENERGY STAR program provides benchmarking tools for companies to determine energy use and ways to become more efficient, to improve building design, and to use energy efficient products (recommended by ENERGY STAR and identified by the logo). Similar information is available to make personal energy use more efficient.

energy LEARN MORE AT energystar.gov

Alternative Energy Solutions

"[With regard to electricity] we need to shift the supply mix—not necessarily to wean ourselves entirely from fossil fuels [. . .] but to place ever-increasing emphasis on the lowest carbon fossil fuel (natural gas) while increasing our reliance on renewables."

Eileen Claussen[185]

Electricity in the U.S. comes primarily from burning fossil fuels (coal, natural gas, and oil).[186] Not only are these sources limited in supply, but they also emit GHGs as well as other pollutants as they burn. Several alternative sources produce clean energy—solar, wind, biomass, geothermal, and hydropower. Fuel cells may use clean sources or fossil fuels much more efficiently. Nuclear energy does not produce GHGs, but it is controversial because of other waste products and security risks. Creative solutions and wise decisions are required to meet the needs of urban and rural areas alike.

Solar

Use of solar energy is one means of reducing GHG emissions. Sunlight can be used in several ways to produce usable energy—photovoltaic cells, solar thermal power stations, solar space heating, and solar water heating.

Over 40,000 ExaJoules (40,000 x 10^{18} J, or 38,000 Quads) of solar energy hit the U.S. each year, which is around 400 times the total primary energy from all sources that we use each year. Why then don't we meet all our energy needs from solar energy? There are several reasons:[187]

- Solar energy is *intermittent*—the sun is filtered by clouds, and doesn't shine at all during the night.
- Solar energy tends to be most abundant in regions where local demand is low, such as deserts.
- There are intrinsic thermodynamic limits to the efficiency with which sunlight can be converted into useful energy such as electricity, heat, or motion.
- Although sunlight is a "free good," the initial capital cost of a solar energy installation is large. These costs are steadily decreasing as the technology becomes more widespread.

"Since the discovery of fire, humans have used captured energy, for example, from wood. The Industrial Revolution used various forms of captured energy, including water wheels, windmills, and biomass fuels. In the year 2013, 97.4 quads (each quad is equivalent to 1 quadrillion BTU) of energy were consumed in the U.S. Renewable energy provided 9 quads—4.5 from biomass, 2.5 from hydroelectric generation, 0.2 from geothermal sources, 0.3 from solar energy, and 1.6 from wind turbines. The remaining 88 quads came from coal, oil, gas, and nuclear power."

Read more in *The Economist's* "Let there be light."

A small scale solar PV unit.
Credit: Warren Gretz/NREL

Solar Photovoltaic

Photovoltaic (PV) cells are solid-state semiconductor devices that absorb light and generate an electric current. The phenomenon was first discovered in the 18th century. It was explained by Einstein in 1905. Practical PV cells were developed at Bell Labs in 1950 initially for space applications.[188] Most commercial devices are fabricated from silicon, which has a solar-to-electricity conversion efficiency between 8 and 12 percent. New materials and designs can achieve efficiencies of 30 percent or more, but these are very costly. PV installations can be large-scale, feeding power into the electrical grid, or placed on the roofs of homes or businesses to provide electricity for individual buildings.

The main limitations on solar PV generation are:

1. The obvious fact that the sun doesn't shine all the time. This means that efficient high-capacity energy storage is needed to provide power at night or on heavily overcast days, and a backup energy source is also required. For an individual home, this can simply be a connection to the commercial power grid; for the grid itself, gas turbine generators are the preferred backup supply.
2. The best locations for solar energy collection often are sparsely populated, such as deserts or tropical regions. An efficient and flexible electrical grid ("smart grid") is needed to carry the power generated to areas of high demand, such as cities. An advantage is that solar PV generators can be deployed in remote locations off the grid, such as villages in India, to charge batteries and mobile phones and provide efficient LED lighting in villagers' homes. Even in developed countries, solar powered highway signs are much easier to deploy than locating and connecting to power lines.

If an individual customer is able to generate more electric power than he or she needs, a *net metering program* allows them to sell the excess power back to the utility to which they are connected and receive a credit on their electricity bill.

Read more about net metering at http://www.seia.org/policy/distributed-solar/net-metering.

Concentrated Solar Thermal Power Stations

A large-scale strategy for using solar energy that does not rely on PV cells is Concentrated Solar Power (CSP). In a CSP installation, sunlight is collected by a large array of heliostats or mirrors and focused on a receiver (a "power tower"). Temperatures of hundreds of degrees C can be generated in the power tower, which heats or boils a working fluid such as molten salt or steam. The fluid drives a conventional turbine to generate electricity which is then fed into transmission lines.[189] Up to several hundred megawatt electrical (MW_e) can be generated with good efficiency. An additional advantage is that energy can be stored in the hot working fluid. CSP installations have been built in California, Arizona, and Spain. There are proposals for a huge CSP installation in the Sahara Desert ("Desertec") with electricity so generated transmitted to Europe via cables under the Mediterranean Sea.

Solar Collector Systems—Active and Passive

If fans or pumps are required to move the heated air or water, the heater is called an active solar heater. If the heated air or water from the collector moves to another part of the house naturally without fans or pumps, then the heater is called a passive solar heater.

Read more from the U.S. Department of Economic Development website at https://energy.mo.gov/energy/solar/solar-overview.

Solar Space and Water Heating

Solar space heating uses solar collectors to trap heat from the sun's rays. Most solar collectors are boxes, frames, or rooms that contain clear covers that let in solar energy; dark surfaces inside, called absorber plates, that soak up heat; insulation materials to prevent heat from escaping; and vents or pipes that carry the heated air or liquid from inside the collector to where it can be used. Heated by the collector, the air is carried by vents, ducts, and fans to another part of the building. [190]

Solar water heaters use the thermal energy from the sun to heat water, which is an intensive electricity user—up to 25 percent of a household's energy use is devoted to heating water.[191] Using a solar water heater can reduce the need for traditional fuels.[192] When a collector is used to heat water, then pipes, tubes, and pumps move the water from the collector to the water heating equipment.

Wind Power

Sailing ships and windmills have used moving air—wind—for thousands of years. Today windmills are quite technologically advanced. Small units typically generating tens of kilowatt electrical (kW_e) can be placed on rooftops to power individual buildings. The largest wind turbines can generate 5 MW_e or more. These are often grouped together in wind farms which are sited in locations having strong and persistent wind fields, such as mountain passes or offshore on the continental shelf. Wind power is currently providing 4.4 percent of electricity in the U.S. and is growing rapidly in importance.[193]

Public Service of Colorado Ponnequin Wind Farm. Credit: Warren Gretz/NREL

Among the reasons for the strong presence of wind power in the energy mix is its low cost, averaging 5¢ per kWh,[194] which is comparable to the cost of natural gas electricity and less than that of coal. Land around turbines can be used for other purposes, such as agriculture and grazing, and often provides a good rental income to the land owners. Wind turbine technology is well-established, and installations can (in principle) be set up in a relatively short time.

Some problems with wind power are similar to those of solar: intermittency (the wind is not blowing all the time) and variable input. This means that large-scale energy storage is needed when excess power is being generated, and standby capacity is needed for other times when the wind is insufficient to power the grid. Also, the best wind sites (open prairies, offshore) tend to be located away from population centers so that a robust transmission system is required. Indeed, on windy days coinciding with times of low energy use, more power can be generated than is being drawn from the grid. Since electricity must be used as it is being generated, to avoid damaging the grid and causing power shutdowns, the power must either be stored or dispatched to other consumers.

An additional issue affecting wind power is a strong "NIMBY"("Not in My Back Yard") attitude among some residents, where the Back Yard may be ridge lines or ocean views. This has resulted in permitting and construction delays at some locations. Nevertheless, the economic and ecological advantages of wind power mean that it will continue to make a growing contribution to energy production.

For an account of some of the issues relating to installing an offshore wind farm see http://www.capewind.org/.

Biomass

Defined as energy coming from organic substances, biomass uses the sun's energy stored in plants. Plants carry out photosynthesis, using chlorophyll to convert the energy from the sun's rays into energy stored in the plants themselves. Several methods can be used to convert biomass energy into energy we can use:[195]

Algae is used to produce biomass energy.
Credit: Warren Gretz/NREL.

1. **Burning**: Direct burning is the most straightforward way to produce energy. Humans have burned wood to warm themselves, cook their food, and make tools for thousands of years. The energy coming from burning biomass is in the form of heat, which can be used to power turbines to create electricity. Biomass combustion releases carbon dioxide, but it is claimed to be "carbon neutral" since the carbon had previously been withdrawn from the atmosphere. However, that is sometimes debated.[196]
2. **Fermentation to alcohol**: With this method the starch in the organic matter is changed to sugar by heating. The sugar is fermented to produce ethanol, which is distilled and blended into automotive fuel. In addition to reducing petroleum use, the ethanol meets the oxygen content mandate imposed by the U.S. EPA for regions with air quality non-compliance. Several life cycle analyses (LCA) of corn ethanol have shown that the GHG emission from growing the crop, processing it, and land use changes overwhelm the GHG emission savings from substitution by ethanol. In addition, using a food crop such as corn for fuel production tends to drive up the cost of food. For these reasons, research is going on to find ways of producing cellulosic ethanol from plant wastes such as corn stover, grasses, or fast-growing trees such as poplar. Ethanol derived from sugar processing waste in Brazil provides, on balance, a net reduction in GHG emissions, and most cars sold in Brazil are "flex-fuel" models which are able to use a large proportion of ethanol as fuel.[197]

Life cycle analysis (LCA) is the systematic approach of looking at a product's complete life cycle, from raw materials to final disposal of the product. It offers a "cradle to grave" look at a product or process, considering environmental aspects and potential impacts. Read more about LCAs at http://www.istc.illinois.edu/info/library_docs/tr/tr40.pdf.

3. **Anaerobic Digestion**: In the presence of methanotrophic bacteria and the absence of oxygen, organic materials break down and release methane. If the methane is captured instead of released to the atmosphere, it can be used as fuel, especially in small scale applications such as gas cooking or gaslight illumination where commercial fuel or electric power is unavailable or expensive. Anaerobic digestion is a particularly cost effective strategy for turning waste materials into usable energy sources.[198]
4. **Pyrolysis**: This process, practiced for millennia, involves the heating of wood or agricultural waste to 1,000 degrees Fahrenheit in the absence of oxygen. This produces charcoal, an amorphous form of carbon, which can be used as a fuel for cooking and heating.[199] This process does not release carbon dioxide, but it does require significant energy—most likely from fossil fuels—to heat the biomass to the high temperatures required. Harvesting or scavenging trees and bush plants to make charcoal has led to deforestation in many low income regions such as Haiti.[200]

For examples of biomass processes, see http://www.epa.gov/rhc/biomass-heating-and-cooling-technologies.

Geothermal

Energy coming from the heat (thermal) of the earth (geo) is another resource for heat and power. Located between the earth's core and its surface, this thermal energy can be transformed into heat and electricity.[201] Humans have used the energy derived from heat below the earth's surface for thousands of years. For example, Paleo-Indians used hot springs for cooking and bathing in more than 10,000 years ago.[202] The Japanese have made use of hot springs in volcanic areas for their traditional hot baths (*onsen*).[203] Iceland gets more than half of its energy from geothermal sources.[204]

Japan has provided geothermal hot pools near Nagano for the exclusive use of Japanese snow monkeys (*nihon-zaru).* Credit: Koji Sasahara

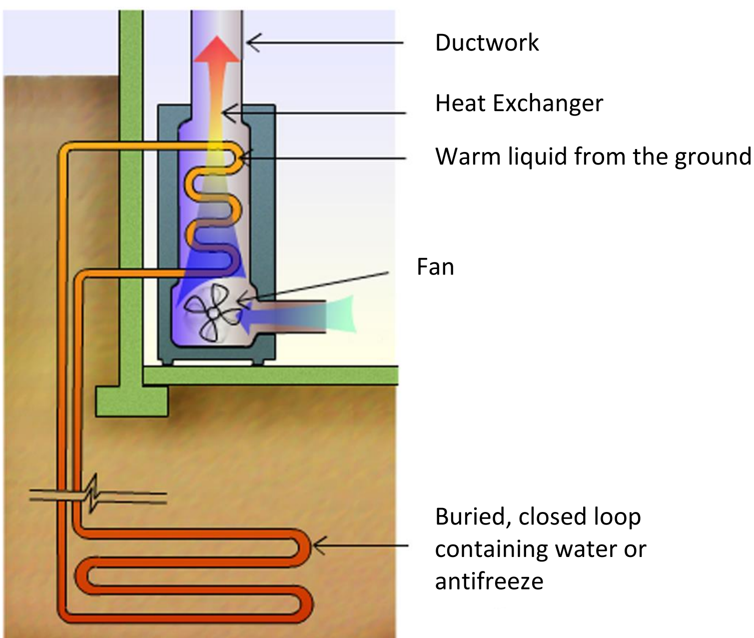
Geothermal energy is "clean (emits little or no greenhouse gases), reliable (average system availability of 95 percent), and domestically available."[205]

Three technology categories for converting geothermal energy include geothermal heat pumps, direct-use applications, and power plants.

- **Geothermal heat pump systems** consist of pipes placed in the ground near the surface, a heat exchanger, and ductwork in the building to be heated. When it is cold, heat from the ground goes through the exchanger to heat the building. When the temperatures are warm, hot air in the building is removed by the exchanger to the ground. The heat removed in the summer is a “no-cost energy” that can be used to heat water.

- **Direct-use applications** require the presence of hot water near the earth’s surface. In the U.S. most of these reserves of hot water can be found in the western states, Alaska, and Hawaii. The hot water is piped directly into a building to heat it, grow plants in greenhouses, melt snow, etc. If the pipe is networked, whole communities can be heated.
- **Power plants** can generate electricity from geothermal reservoirs. The hot water from the reservoirs drives the turbines that drive the electrical generators. Power plants that run with geothermal energy can generate electricity 90 percent of the available time as compared with coal (75 percent) and nuclear (65 percent).[206]

This two-story, 3,000-square-foot house has a verified average electric bill of $60 per month. It uses GeoExchange heating and cooling capacity: 5-ton, two-speed. Credit: Geothermal Heat Pump Consortium (GHPC); NREL



Schematic of Geothermal Process
Credit: California Energy Commission

Read about the environmental and economic impacts of geothermal energy at http://energy.gov/science-innovation/energy-sources/renewable-energy/geothermal.

Air Source Heat Pump

An air source heat pump is an efficient source of both heating and cooling where it is impractical or not permitted to drill deep wells to tap into the earth's thermal reservoir. An air source heat pump functions somewhat like an inside-out refrigerator: to cool an indoor space, a compressor unit sends heat to the outside air and the cool air from the expansion cycle is blown into the room. For heating, the compressor is reversed and the outside air is cooled while warm air is blown into the space to be heated. Since the heat is taken from the ambient air and electricity is needed only to run the compressor and convector units, the electrical efficiency can be 3 or 4 coefficients of performance (COP). Air source heat pumps are widely used in Japan and are starting to have a presence in the U.S.[207]

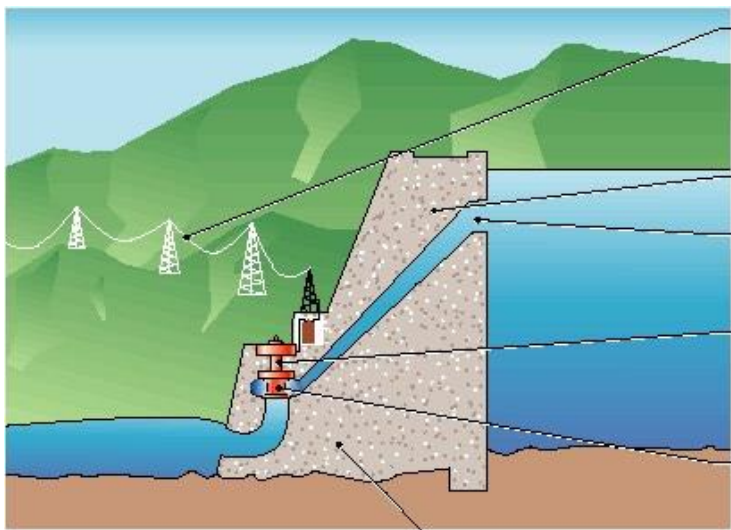
Mitsubishi PKFY air source heat pump compressors installed at the Boston Synagogue, Boston, MA. By switching from district steam heating to this system, the synagogue reduced its carbon emissions by 70 percent and its utility bills by 57 percent.

For further details, see http://mipandl.org/success_stories/BostonSynagogue.pdf.

Hydropower

Water in motion possesses tremendous energy. That energy might be destructive—as with floods—or constructive, if captured and harnessed. Water power has been in use in Europe since Roman and medieval times. Historically in the U.S. water wheels were used to help grind grains and operate sawmills.[208] Today the dams and turbines that evolved from these water wheels provide 7 percent of the U.S. electric generating capacity. [209]

Figure 14. Hydropower Facility



Credit: U.S. DOE Hydropower Program

Read more about hydropower at the U.S. Department of Energy's Hydropower Program website at http://energy.gov/eere/water/water-power-program.

Hydropower plants generate electricity from the kinetic energy resulting from water as it falls. The turbines and generators, which change the water's energy to electricity, are placed in or near dams, or use pipelines, which carry the pressured water below the dam to the powerhouse.

Hydropower is renewable (but subject to drought), non-polluting, and reasonably cost-efficient. One limitation on further development of hydroelectric power is that many of the best hydropower sites in the U.S. have already been dammed and used for electricity generation.[210] Potential environmental impacts altered river flow, water quality degradation, mortality of fish that pass through hydroelectric turbines, blockage of upstream fish migration, and flooding of terrestrial ecosystems by new impoundments. The design and operation of hydropower projects can mitigate these impacts, although controversy persists regarding the effectiveness of these measures. Some hydroelectric dams have been removed to allow rivers and their associated ecosystems to restore themselves.[211]

Nuclear Power

Since the large scale implementation of nuclear fission in the 1940s, attempts have been made to use nuclear power to provide society's energy needs. There are two possible approaches to doing this:

1. Splitting of atomic nuclei, or **nuclear fission**. Uranium atoms have heavy nuclei, created long ago when a large star exploded.[212] An uncontrolled branching chain reaction of splitting nuclei can release enough energy for an atomic bomb; a controlled steady-state reaction provides usable nuclear energy.
2. Merging of hydrogen nuclei to form a helium nucleus, or **nuclear fusion**. The fusion process also releases nuclear energy, as used in the hydrogen (thermonuclear) bomb. So far it has not been possible to use controlled nuclear fusion reactions to generate electricity. The major difficulty is that the hydrogen fuel must be heated to tens of millions of degrees in order to get the nuclei to combine in a fusion reaction.

In the fission process, the released nuclear energy heats a fluid coolant, which in turn drives a turbine to generate electricity. In 2014, 19.4 percent of US electricity generation (8.5 percent of total primary energy use) came from nuclear power.[213] However, the leftover products of the fission reactions are highly radioactive and must be stored for thousands of years. This is one reason that research is continuing on controlled nuclear fusion, in which heavy water—water formed with hydrogen containing one or two extra neutrons—would be the fuel. Only 0.02 percent of natural hydrogen is deuterium (hydrogen-2), so that an enrichment process is required. Tritium (hydrogen-3) is an artificial radioisotope, which is produced by neutron irradiation of lithium in a nuclear (fission) reactor. To date, it has not been possible to produce hydrogen densities and temperatures sufficiently high enough to yield a net production of energy. A major current effort to harness nuclear fusion is the multi-billion-dollar ITER facility in France, although smaller scale experiments continue.[214]

Credit: Evergy.gov

Carbon Sequestration

"Carbon sequestration in terrestrial ecosystems can be defined as the net removal of CO_2 from the atmosphere into long-lived pools of carbon. The pools can be living, aboveground biomass (e.g., trees); products with a long, useful life created from biomass (e.g., lumber); living biomass in soils (e.g., roots and microorganisms); or recalcitrant organic and inorganic carbon in soils and deeper subsurface environments. It is important to emphasize that increasing photosynthetic carbon fixation alone is not enough. This carbon must be fixed into long-lived pools. Otherwise, one may be simply altering the size of fluxes in the carbon cycle, not increasing carbon sequestration."

Read more at the U.S. DOE's Carbon Sequestration in Terrestrial Ecosystems (CSITE) website at http://csite.esd.ornl.gov/.

For a list of sequestration links, see MIT's Laboratory for Energy and the Environment website at https://sequestration.mit.edu/.

Under normal operating conditions, nuclear energy has a low immediate impact on health and the environment. The problems that have led to public opposition to nuclear power include what to do with accumulating stores of radioactive spent fuel assemblies and the possibility of catastrophic radiation release. In 1986, an unauthorized experiment with one of the reactors at the Chernobyl power station led to an explosion which delivered radioactive fallout to the Ukraine and large parts of Eastern Europe and Scandinavia. In March 2011, a massive earthquake off Japan's northeast coast led to an unanticipated large tsunami which incapacitated cooling water systems at the Fukushima Dai-ichi nuclear power station, producing meltdowns in three of the reactors. The environs of Fukushima were heavily contaminated, and radioactive water escaped into the ground and the nearby ocean. One result of this event was that several countries terminated operation of their nuclear reactors, with the further result that the energy demand was made up by increased burning of fossil fuels.[215]

Mitigative Action

Renewable energy can be costly, and nuclear energy is looked upon with caution, if accepted at all. Strategies for reducing the amount of CO_2 emitted to the atmosphere include carbon capture and storage (CCS, CO_2 sequestration) and policy instruments such as cap-and-trade or carbon taxes. Geoengineering, an extremely controversial mitigating action, has been mooted as a last ditch measure to limit climate change.

CO_2 Capture and Storage

One possible strategy for limiting the amount of CO_2 entering the atmosphere is to remove it from effluent streams as it is formed, using a reversible chemical or physical absorber. The captured CO_2 would then be injected into a storage reservoir, such as underground rock formations or deep ocean water. CO_2 can also be pumped with pressure into depleted oil and gas wells to enhance recovery of these resources.[216] Deployment of CCS at new or existing power plants would in principle allow coal to continue to be used as a fuel. However, a substantial amount of the energy generated must be used (15 to 30 percent) to transport the gases, regenerate the absorber, etc. This means that less of the output is available for sale to customers, and the price per KWh would have to be increased accordingly. Pilot CCS projects have been built with government subsidies, but this technology is still not widely deployed.[217]

An example of the use of CO_2 ocean sequestration is taking place in the Sleipner field in the North Sea and hence is called the Sleipner CO_2 Injection Project (shown below). This project produces large amounts of natural gas in the North Sea. This gas contains 9 percent CO_2. To meet export specifications, the CO_2 level has to be lowered by 2.5 percent. The extraction amounts must be at least one million tons of CO_2 per year. If emitted to the atmosphere, this CO_2 would increase Norway's CO_2 emissions by nearly 3 percent. In October 1996 with the beginning of natural gas production, Statoil, the company that runs this project, decided to adopt a saline aquifer storage strategy.

There are also proposals for removing CO_2 that has already been emitted from the atmosphere. The captured CO_2 might then be used to manufacture organic chemicals or even fuels.[218] Such processes require a large energy input, and also suffer from an entropic disadvantage since CO_2 makes up only 0.04 percent of the atmosphere.

The Sleipner CO_2 Injection Project in the North Sea.
Credit: IEA Greenhouse Gas R&D Program and Statoil

Policy Instruments

Economists, scientists, and policy analysts uniformly agree that the most effective way to reduce CO_2 emissions is to impose a price on fuel producers and users for using carbon-based fuels which release CO_2 when they are burned. Two strategies for establishing and imposing a carbon price are emissions trading (cap-and-trade) and a tax on carbon. Both strategies take advantage of market mechanisms to maximize the efficiency of the emission reductions.

Cap-and-Trade
In cap-and-trade, a limit on emissions is established. Industries that can operate below this cap are allowed to sell their excess emission permits to those that are unwilling or unable to reduce their emissions, thereby establishing a market price for the permits. Since there is an economic advantage to reducing emissions via technology and/or increased efficiency, and an economic cost to continuing to emit, the result should achieve the desired reduction.[219] A cap-and-trade regime was successful in reducing sulfur emissions, as mandated by the Clean Air Act of 1970.[220] Large reductions were achieved at a cost considerably less than had originally been predicted.

A cap-and-trade system for CO_2 would be applied to large emitters such as power generation; iron and steel production; chemical manufacturing; and makers of building materials, cement, paper, and fertilizer. Such a scheme was implemented in Europe (Emission Trading System, ETS) in an attempt to meet emission reduction goals under the Kyoto Protocol, which the EU had ratified. However, the initial caps were set so high that the permit price was driven to very low values, so that many emitters found it less costly to purchase the permits than to invest in emissions reduction technology. In 2015, the People's Republic of China announced that it was implementing a national cap-and-trade system. The U.S. has so far failed to introduce such a system nationwide, although several regional groupings of states and Canadian provinces have done so.[221]

A Tax on Carbon
Many economists and policy analysts believe that a straightforward tax on carbon is more efficient than a cap-and-trade system. The amount of tax would depend on the quantity of CO_2 emitted, and would be levied on all fossil fuels, either at the point of sale (gasoline at the pump) or at the point of use (electricity purchased from a utility). Proposed tax amounts vary widely, but a typical value is \$30 to \$40 per tonne of CO_2. Thus a U.S. citizen responsible for 20 tonnes of CO_2 annually would be liable for a carbon tax of \$600–\$800 per year.[222]

To make such a tax more palatable, it is usually framed as a revenue-neutral "fee-and-rebate" scheme. The government revenues from the tax would be offset by corresponding reductions in the income tax and sales tax (VAT) rates. Thus a person using little or no fossil fuel for their daily activity would benefit twice, first from paying a low carbon tax and then from reduced income and sales taxes. However, the suggestion of any new or additional taxes is so widely disliked that very few jurisdictions have imposed one. The Canadian Province of British Columbia is one of the few that has done so, and it has been successful both in reducing the Province's carbon emissions and generating revenue for investment in renewable energy.[223]

Geoengineering

Efforts are underway in many quarters to limit greenhouse gas emissions to a level where the effects are manageable, even if they may be unavoidable. If, however, unmanageable effects cannot be avoided, then a "last ditch" strategy has been receiving some attention. This strategy is "geoengineering:" modifying the earth's physical behavior to forestall the worst effects of global warming and climate change. The most widely discussed form of geoengineering involves injecting large quantities of sulfur dioxide into the stratosphere from high altitude aircraft. The sulfur would form sulfate particles which reflect visible radiation, and thus effectively increase the earth's albedo. This would reduce the radiative forcing from sunlight, and therefore offset some portion of the warming effect of GHGs. This occurs during massive volcanic eruptions, when a temporary cooling effect is observed. Sulfate particles have a relatively short atmospheric lifetime, so injecting perhaps 20 million tons of SO_2 into the atmosphere every year would have to be an ongoing activity.

Such proposals are highly controversial. There is the question of unintended consequences (Murphy's Law). What would be the effect of reduced surface insolation on rainfall patterns or crop yields? Since deploying the aircraft is well within the capability of many state actors, how can this be controlled or subjected to international agreement? Would this deflect attention and resources from the real long-term solution, which is reducing total GHG emissions? Sulfur injection does nothing to reduce ongoing ocean acidification which, as we have seen, is a serious problem in and of itself. The current view is that "more research is needed," but we are not ready to deploy geoengineering at the scale required for significant mitigation.[224]

Aids to Understanding provides resources and activities.

"Everyone knows what must be done about climate change, but no one is doing anything about it. More than two decades of speeches and summitry have failed to thin out emissions of greenhouse gases … a quarter of all the carbon dioxide ever pumped into the air by humans was put there in the decade between 2000 and 2010. It will hang around for centuries, meaning that the future is sure to be hotter, even if all greenhouse gas emissions cease overnight. The official ambition of limiting the global temperature rise to 2ºC looks increasingly like a bad joke."

The Economist
(23 November 2013)

Summary

"… [A] true 'right of the environment' does exist, for two reasons. First, because we human beings are part of the environment. We live in communion with it, since the environment itself entails ethical limits which human activity must acknowledge and respect. [Humans …] can only survive and develop if the ecological environment is favorable. Any harm done to the environment, therefore, is harm done to humanity. Second, because every creature, particularly a living creature, has an intrinsic value, in its existence, its life, its beauty, and its interdependence with other creatures."

Pope Francis

"… where in the nine circles [of hell] would Dante place all of us who are borrowing against this Earth in the name of economic growth, accumulating an environmental debt by burning fossil fuels, the consequences of which will be left for our children and grandchildren to bear? Let's act now, to save the next generations from the consequences of the beyond-two-degree inferno."

Marcia McNutt
Editor-in-Chief of Science magazine
and President-designate of the
National Academy of Science

"On many past occasions MIT has played a key role in dealing with national challenges such as World War II. We call upon the Institute once again to rise to confront what may prove to be the greatest threat to current and future generations."

MIT
C4 Report

These statements, coming from a widely diverse set of authoritative sources, underscore the scale and scope of the climate change issue. The MIT C4 report characterizes climate change as an existential threat to humanity, on the scale of the Second World War (1939–1945). Dr. McNutt, representing a solid scientific viewpoint, uses literary and theological allusions to highlight the responsibility that humans have for protecting all of Earth's support systems. And Pope Francis reminds us of the urgency of taking action, and our moral obligation to do so.

Because of the remaining uncertainties about what impacts will result from human-induced climate change around the globe and the time scale of future consequences, humans have found it very hard to determine a personal course of action and to understand the paths taken by decision-makers. Misinformation and disinformation injected into the debate do not make it any easier. In spite of these complexities and uncertainties, we must weigh the cost of acting against the risks of not acting.

To use an analogy, if the earth is a bathtub being filled with carbon dioxide (mostly resulting from anthropogenic sources), will we be able to slow down the flow enough to contain the effects to today's levels? Can we rely on technology to come up with affordable alternative energy sources to allow us to continue our lifestyles? Or will we need to adapt to new ways of living more conservatively in terms of energy use? In this century of complexity, what sources should we trust? What courses of action will take into account the needs of people around the world, both now and into the future?

Ultimately it seems clear there is no "silver bullet" or a "knight in shining armor" galloping to the rescue. Global climate change has too many stakeholders possessing differing viewpoints and priorities to rely solely on technology to solve the challenges. We must determine a course of action, based in great part on where responsible science steers us, yet taking other economic and social factors into account. To be sure, we should all continue to follow new developments in the area of climate change and let that knowledge inform our beliefs and our behavior. But the evidence has become so compelling, and the consequences of not addressing climate change so dire, that as students, teachers, energy consumers, and responsible citizens, we should all act to protect the earth's climate and its systems which make our life here possible.

> "If you want a magic bullet, I don't have one—I don't think anybody does."
>
> Steven C. Wofsy, Professor of Atmospheric and Environmental Sciences, Harvard University

Aids to Understanding

The Scientific Basis

Resources

The following resources provide further information on **basic scientific principles**:

- Molina, Mario J. “Climate Change: Science, Policy, and Communication.” Compton Lectures. Massachusetts Institute of Technology. 11 May, 2015. Lecture.
- J.H. Seinfeld and S.N. Pandis, “Atmospheric Chemistry and Physics” New York: Wiley (1998). Chapter 21 covers Atmospheric Chemistry and Climate.
- U.S. Environmental Protection Agency, Office of Atmospheric Programs. “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2013.” Washington DC, US EPA. Report #EPA 430-R-15-004.

Read more about **radiation balance** in the following sources:

- Houghton, J. *Global Warming: The Complete Briefing*. 5th Edition. Cambridge, UK: Cambridge University Press, 2015. This is a great source for a basic understanding of basic science and mechanisms involved in climate change and the various greenhouse gases and the carbon cycle.
- NASA’s “Mission: Science” website has a page dedicated to explaining Earth’s radiation budget.[225]

The **carbon cycle** is explained in more detail in:

- The Earth System Research Laboratory, part of the National Oceanic & Atmospheric Administration, has a website that provides a great deal of information about carbon cycle science.
- Archer, David. “The Global Carbon Cycle.” Princeton University Press. 2010.

Explore the **water cycle** in the following sources:

- Arnell, N. W. “Global Water Cycle.” ELS. 2005.
- The Earth Observatory Website provides new satellite imagery and scientific information about Earth, with a focus on climate and environmental change. Materials published on the site are available for re-publication or re-use, except where copyright is indicated.[226]
- Del Genio, A. D. “The Dust Settles on Water Vapor Feedback.” *Science* 296(5568): 665–666. 2002.
- Wanucha, Genevieve. “An Ocean’s Perspective on the Changing Water Cycle.” *Oceans at MIT.* 27 September, 2012.
- U.S. Geological Survey’s The Water Cycle Web page contains basic information and a helpful visual representation of the water cycle.[227]

The following resources provide a **general background** of climate change science:

- Hamburg, S. P., et. al. “Common Questions About Climate Change.” United National Environment Program/World Meteorological Organization Pamphlet. Nairobi, Kenya.
- Intergovernmental Panel on Climate Change. Fifth Assessment Report AR5 provides a clear and up-to-date view of the current state of scientific knowledge relevant to climate change. It consists of three Working Group (WG) reports and a Synthesis Report (SYR).[228]
- Mann, M. E. “Dire Predictions: Understanding Climate Change.” London: DK. 2015.
- Molina, Mario J. “Climate Change: Science, Policy, and Communication.” Compton Lectures. Massachusetts Institute of Technology. 11 May, 2015. Lecture.
- Reck, R.A. (ed.) “Climate Change and Sustainable Development,” Yarnton, Oxon (UK) 2010. Forty contributions on a wide range of topics from participants in Oxford Round Table on Climate Change and SD with review questions provided.

The following resources illustrate the **general uncertainties** of climate change science:

- Changnon, S. A. “Midwestern Cloud, Sunshine and Temperature Trends since 1901: Possible Evidence of Jet Contrail Effects.” *Journal of Applied Meteorology* 20(5): 496–508. 1981.
- Craven, Greg. *What’s the Worst that Could Happen? A Rational Response to the Climate Change Debate.* New York: Perigee. 2009.
- Resutek, Audrey. “Pinpointing climate change uncertainty.” *MIT News.* 2014.[229]
- Travis, D. J., A.M. Carleton, and R.G. Lauritsen. “Climatology: Contrails Reduce Daily Temperature Range.” *Nature* 418: 601. 2002.

Climate modeling is one of the main tools scientists have for predicting the effect of human behavior on the planet. For more information about what climate models are and how they work, see:

- Environmental Protection Agency. “Climate Economic Modeling.” 2015.[230]
- Gillingham, Kenneth et al. “Modeling Uncertainty in Climate Change: A Multi-Model Comparison.” *National Bureau of Economic Research* No. 21637. October 2015.
- Schneider, S.H. “Chapter 1: Introduction to Climate Modeling.” in *Climate System Modeling*. K.E. Trenberth, ed. Cambridge University Press, 2010.
- Smith, T. M., T.R. Karl, and R.W. Reynolds. “How Accurate Are Climate Simulations?” *Science* 296(5567): 483–484. 2002.
- Webster, M. et al. “Uncertainty Analysis of Climate Change and Policy Response.” Report No. 95. December 2002.
- World Meteorological Organization. “Climate Models.” Retrieved 21 January 2016.[231]
- Center for Climate and Energy Solutions. “Economic Modeling for Climate Policy.”[232]

Activities

Activity: NOAA Activities

NOAA—the National Oceanic and Atmospheric Administration (NOAA) features climate change activities on varied topics. Level is high school but adaptable for junior college.[233] Topics include El Niño and La Niña and the dance of the ocean and atmosphere; climate data, predictions, and variability; paleoclimatology and the role of weather past in today's weather predictions; and global positioning and climate.

Activity: Educator Resources

U.S. Global Climate Change Research Program—(USGCRP)/USGC Research Office (USGCRIO)—Excellent resource with links to a variety of climate change lesson plans, all from trusted sources.[234] This website contains Resources for Educators that apply to the following topics:[235]

- Teaching Climate Using the National Climate Assessment
- The Climate Literacy Framework
- The Energy Literacy Framework
- Wildlife and Wildlands Toolkit
- Climate Literacy and Energy Awareness Network (CLEAN)
- Climate Change Education Videos from the National Park Service

Activity: Climate Hot Map

Climatehotmap.org—Geared for high school but adaptable for junior college. Excellent material from Union of Concerned Scientists. It uses a map to help the student visualize global climate change and early warning signs around the world. The pedagogy behind the activities reflects the use of the principles of CTL (Contextual Teaching and Learning). The material is cross-disciplinary and emphasizes problem solving. It is also tied to standards, especially important for high school.[236]

Activity: Climate Change Library

The CAN Europe library has more than 3,000 documents on climate change and is regularly updated. This is a resource that might spark an idea for an activity.[237]

Activity: Lesson Plan Resource

Climate Change Live—This website provides lesson plans for grades K–12, and also includes resources for students, webcasts, and other multimedia. An excellent resource.[238]

Activity: Earth Data

Destination: Earth—Datasets and images from NASA about what is happening on Earth.[239] Also from NASA, Earth's Radiation Budget—Data and suggested activities to use the data.[240]

Activity: Climate Change Glossary

Climate Change: A Glossary of Terms from IPIECA (International Petroleum Industry Environmental Conservation Association).[241]

Activity: Data and Graphics

Vital Climate Graphics includes observed trends and potential impacts. Excellent source of data and graphics for activities from the United Nations Environment Program.[242]

Activity: Tropical Rainfall Mission

Investigating the Climate System: NASA's Tropical Rainfall Measuring Mission—link to climate change data, resources, and activities for educators about energy, precipitation, winds, and clouds. Problem-based, cross-disciplinary activities that are adaptable for junior college.[243]

What Do We Know and How Do We Know it?

Resources

The following resources provide a **general background** of climate change knowledge:

- American Association for the Advancement of Science. "What We Know: The Reality, Risks, and Response to Climate Change." 2014.[244]
- Craven, G. "What's the Worst that Could Happen? A rational response to the climate change debate." New York: Perigee/Penguin (2009). A clear and accessible treatment of climate change issues featuring a logical process for evaluating source credibility. "It very clearly and concisely covers all of the important points not only about the climate change situation … but also how we think and decide about important issues." (Kim Stanley Robinson)
- Emanuel, Kerry. *What We Know About Climate Change.* 2nd Ed. Cambridge, MA: The MIT Press. 2012.
- Edmonds, J., Roop, J.M., and M.J. Scott. "Technology and the Economics of Climate Change Policy." Pew Center on Global Climate Change. Washington, DC. September 2000.[245]
- Intergovernmental Panel on Climate Change. "Summary for Policy Makers" in *IPCC Working Group II: Fifth Assessment Report on Climate Change*. Cambridge UK: Intergovernmental Panel on Climate Change, 2014. (An excellent way to grasp the full report without all the reading.)
- Jacoby, H. D., R.G. Prinn, and R. Schmalensee. "Needed: A Realistic Strategy for Global Warming." July 1997. Available online at the MIT Joint Program on the Science and Policy of Global Change (MJPSPGC) Report #21.[246]
- National Academy of Sciences. *Climate Change: Evidence and Causes.* February 2014.[247]

These websites explain and expand on climate change **benchmark development**:

- Burck, Jan, Franziska Marten, Christoph BalsReiner. "The Climate Change Performance Index: Results 2015." Bonn, Germany: Germanwatch. December 2014. [248]
- Ernst and Young. "Climate change reporting and benchmarking." Home page. 2016.[249]
- National Physical Laboratory. "TRUTHS (Traceable Radiometry Underpinning Terrestrial- and Helio- Studies)." The TRUTHS program is a "satellite mission to support climate adaptation by establishing a space based climate and calibration observing system facilitating improved confidence in climate change forecasts." One of NPL's goals is to assist in developing and measuring climate change benchmarks.[250]

These resources provide information about the **observation** of climate change:

- National Research Council. *Climate Change Science: An Analysis of Some Key Questions*. Washington, DC: National Academy Press. 2001.[251]
- USGCRP. "Observed Change" from "Our Changing Climate" website. This website is a great resource for understanding the impact of climate change.[252]
- World Meteorological Organization. "Climate Observation Networks and Systems." The WMO provides general information for climate observation as well as links for further information. This is a great resource for digging a little deeper into the observational science.[253]

Politics have been an important factor in studying climate change from the earliest studies. The following resources provide more information:

- Childress, Sarah. "Timeline: The Politics of Climate Change." A collaboration between Frontline and PBS, this resource lists the major political events of climate change in a helpful timeline format.[254]
- E. Conway and N. Oreskes. "Merchants of Doubt." Bloomsbury (2010). A scathing indictment of professional climate change deniers. Also available on DVD from Sony Pictures Classics and Interfaith Power & Light.
- Giddens, Anthony. "The politics of Climate Change." Malden, MA: Polity Press (2009).
- Mann, M.E. "The Hockey Stick and the Climate Wars." New York: Columbia University Press (2012).
  Activities

Activity: Merchants of Doubt

Read the book and/or watch the video, then discuss the following questions:

1. Where should one's loyalty to paid interests end and respect for the truth begin?
2. What did you think of the way climate change deniers talked about their work? Do you think they believe what they are saying?
3. Should there be consequences for companies that knowingly spread disinformation and intentionally support climate science deniers who undermine efforts to address climate change? What should those consequences be?

4. Should TV news programs screen “experts” more carefully? Do you think some journalists believe the denial, or do they simply want to create controversy to drive up ratings?
5. What are some ways to cope with people who are in denial of climate change and refuse to engage in honest conversation?
6. Do you think that our response to climate change means less prosperity and abundance or more? What role will our support of clean energy play?
7. Do you now feel more equipped to recognize and call out climate change deniers? What talking points can you develop so you’re prepared?
8. What actions might we take as individuals or together when we spot climate change deniers?

Activity: Gulf Coast Region

Confronting Climate Change in the Gulf Coast Region—Guide created especially for teachers and educators in science education grades 9 to 12. Easily adaptable for junior college. Guide helps transform climate change from an abstract concept to a real phenomenon with tangible effects on peoples’ lives. It includes ten activities that are backed by sound science and meet state-specific science education criteria for grades 9 to 12. The materials highlight the real-life impacts of climate change on students’ home states and their environments and emphasize practical solutions to mitigate potential harm and adapt to possible changes.[255]

Activity: United Nations Youth

Youth and Climate Change. This provides information about how young people are involved in the fight against climate change impact.[256]

Activity: NASA Multimedia Activities

Global Climate Change—Provides both teacher and student materials, uses an interactive, multimedia approach, and is cross-disciplinary in nature. It covers a gamut of issues from what we know to finding solutions.[257]

Activity: Global Change Lesson Plans

U.S. Geological Survey Learning Web—Well organized with lots of links to resources, lesson plans, and activities. Lesson plans for Global Change are spread throughout.[258]

Activity: UK Consortium Activities

Environmental Change Network (ECN)—A multi-agency program sponsored by a consortium of fourteen United Kingdom government departments and agencies.[259]

- Weather Tutorials with links for students and teachers
- Climate Change tutorial

Climate Change and Its Potential Impact on Society

Resources

Technology may provide answers for climate change problems. For more information see:

- Center for Climate and Energy Solutions. "Climate Change 101: Technological Solutions." C2ES is the succeeding organization to the Pew Center on Global Climate Change. This report is an updated version of a report from the Pew Center.[260]

These resources observe and explain **global temperature**:

- Gray, N.F. *Facing Up to Global Warming.* Switzerland: Springer International Publishing. 2015.
- NASA's "Global Temperature" map is an interactive tool to look at how the temperature of the earth has changed since the advent of temperature recording in 1884.[261]
- NOAA's "Climate Change: Global Temperature" interactive graph that charts temperature over time. This graph is updated regularly.[262]

For a broad view of how climate change affects **society** please see:

- Backlund, Peter, et al. *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States.* U.S. Climate Change Science Program Synthesis and Assessment Product 4.3. 2008.
- The EPA's "a student's guide to global climate change" website has a section entitled "Effects on People and the Environment" that exposes students to how climate change will affect agriculture, energy, water supplies, health, and the ecosystem. It also contains helpful links for further information.[263]
- G. Wagner and M.L. Weitzman, "Climate Shock: The Economic Consequences of a Hotter Planet" Princeton: University Press (2015).
- NASA provides a "Climate Time Machine," which is a "series of visualizations shows how some of Earth's key climate indicators are changing over time."[264]
- NOAA's "Societal Impacts" Web page provides an overview of the impacts climate change will have on human society, and also provides helpful links to further explore the various ways in which humans will feel the effects.[265]

Activities

Activity: Computer Simulation

C-ROADS is an award-winning computer simulation that helps people understand the long-term climate impacts of policy scenarios to reduce greenhouse gas emissions. It allows for the rapid summation of national greenhouse gas reduction pledges in order to show the long-term impact on our climate. Extensive materials and documentation are available.[266]

Activity: Gulf Coast Region

Confronting Climate Change in the Gulf Coast Region—Guide created especially for teachers and educators in science education grades 9 to12. Easily adaptable for junior college. Guide helps transform climate change from an abstract concept to a real phenomenon with tangible effects on peoples' lives. It includes ten activities that are backed by sound science and meet state-specific science education criteria for grades 9 to 12. The materials highlight the real-life impacts of climate change on students' home states and their environments and emphasize practical solutions to mitigate potential harm and adapt to possible changes.[267]

Activity: Climate Change Hot Map

Climatehotmap.org—Geared for high school but adaptable for junior college. Excellent material from Union of Concerned Scientists. It uses a map to help the student visualize global climate change and early warning signs around the world. The pedagogy behind the activities reflects the use of the principles of CTL (Contextual Teaching and Learning). The material is cross-disciplinary and emphasizes problem solving. It is also tied to standards, especially important for high school.[268]

Activity: Interactive Activites

Choose Climate—Interactive programs on climate change.[269] These activities could be used with any of the sections of this module. Samples include:

- Java Climate Model: Dynamic graphical model linking science and policy from emissions to impacts.
- Flying off to a Warmer Climate: Click on the map to calculate the greenhouse warming effect of any flight.
- Climate Engineering: A critical review of global-scale technical fixes for climate change

Activity: NOVA Online

Well done resource with teacher activities and printable lesson plans to use NOVA's broadcast "Warnings from the Ice."[270]

Activity: Earth Systems

Ohio State University Earth Systems Education Program—This site provides sample activities and lists many additional resources.[271]

Activity: Earthguide

Earthguide—Links to teaching tools, science content, data, diagrams, maps, etc. from UC San Diego and the California Space Institute at Scripps Institution of Oceanography. Great resource with activities and data.[272]

What We Can Do

Resources

For more information on **climate change mitigation**, see:

- The Massachusetts Institute of Technology Provides specific examples of carbon sequestration on their carbon capture and sequestration website.
- J.W. Tester, E.M. Drake, M.J. Driscoll, M.W. Golay, and W.A. Peters. "Sustainable Energy: Choosing Among Options." Cambridge, MA: MIT Press (2005). A definitive book on energy technology.
- D.J.C.MacKay. "Sustainable Energy—without the hot air." Cambridge UK: UIT (2009). Available free online at www.withouthotair.com.
- G.P. Shultz and R.C. Armstrong. "Game Changers: energy on the move." Hoover Institution Press Publication No. 656. Stanford, CA (2014). Five chapters on new and emerging energy technologies including Natural Gas from Shales, Solar Photovoltaics, Grid-Scale Electricity Storage, Electric Cars, and LED Lighting. A handy guide to what energy technicians will need to know for their future careers.

Climate change solutions will have a significant **impact on business and industry**. The following resources discuss this impact from a variety of perspectives:

- The Center for Climate and Energy Solutions (formerly the Pew Center on Global Climate Change) focuses on the relationship between the environment and the economy. Promotes responsible business management perspectives.[273]
- M. Berners-Lee and D. Clark. "The Burning Question." Vancouver: Greystone Books (2013).
- Wagner, G. and M.L. Weitzman. "Climate Shock: The Economic Consequences of a Hotter Planet." Princeton: University Press (2015).
- Worland, Justin. "Why Big Business Is Taking Climate Change Seriously." *Time.* 23 September 2015.

Climate change solutions will have to come from multiple levels. For information on **international solutions**, please see:

- The United Nations COP21 news room provides information about the international climate change talks that took place in Paris during November and December 2015.[274]
- New York Times. "The Road to a Paris Climate Deal." This Web page offers several articles leading up to, during, and in the aftermath of the COP21 conference.[275]
- The World Resources Institute created an excellent interactive map that contains all of the climate change goals submitted by each country at the COP21 conference.

Climate change solutions will have to come from multiple levels. For information on **what individuals can do**, please see:

- Cicerone, R. J. "Human Forcing of Climate Change: Easing Up on the Gas Pedal." Proceedings of the National Academy of Sciences of the United States of America 97(19): 10304–10306. 2000.

Climate change solutions will have to come from multiple levels. For possible **local government solutions**, please see:

- See the U.S. EPA's "Local Climate and Energy Program" and develop your own creative solutions on the municipal level.[276] This is an in-depth resource for exploring what communities can and are doing at the local level about climate change.
- Department of Ecology, Washington State. "Climate Change Education Resources" provides a number of helpful links, activities, information, and resources that are useful in and of themselves, but also paint a picture of action at the state level.[277]
- The White House website released a fact sheet entitled "Building community resilience by strengthening America's natural resources and supporting green infrastructure" in 2014.[278]
- Stevens, Caleb, Robert Winterbottom, Katie Reytar and Jenny Springer. "Securing Rights, Combating Climate Change: How Strengthening Community Forest Rights Mitigates Climate Change." From July 2014, this report from the World Resources Institute is an "analysis of the growing body of evidence linking community forest rights with healthier forests and lower carbon dioxide (CO2) emissions from deforestation and forest degradation." [279]

Activities

Activities: Carbon Footprint Calculators

The UNFCCC sponsors a website, "Climate Neutral Now" which includes a carbon footprint calculator and suggests strategies for emission reductions and certified carbon offsets.[280]

U.S. EPA's Personal Carbon Footprint Calculator.[281] "Use this online calculator to obtain a rough estimate of your household's greenhouse gas emissions. Then move on to the next section of the calculator to explore actions you can take to lower your emissions while reducing your energy and waste disposal costs. For each action you choose to take, the calculator displays the amount of emissions you could avoid and how that amount relates to your total emissions." Other calculators include:

- American Forest Carbon Calculator[282]
- Carbon Diet[283]
- The CO2 Calculator[284]

Activity: Educator Toolkits

U.S. EPA Climate Change—Educator Links provides several resources, including an Online Greenhouse Gas Calculator; case studies; materials to help inform the public and to use with students; and a search function designed to help the educator to find lesson plans, videos, books, and toolkits. Extensive and rich resource.[285]

Activity: Canadian Global Warming Site

Government of Canada Climate Change website—Canadian version of the U.S. EPA Global Warming site. Choose "Resources for Teachers." Geared mostly for high school, but adaptable for junior college.[286]

Activity: Classroom Resources and Lesson Plans

Learning for a Sustainable Future (LSF). LSF Classroom Resources and Lesson Plans—Well-organized table shows climate change activities for grades 9 to 12. Adaptable for undergraduate. Knowledge, skills, and values are listed.[287]

Activity: World Resources Institute

Sustainable Cities: From a Vision to Reality. Have students vision what they could do to help create a sustainable community. Then share the vision with others online.[288]

Activity: ClimateWatch documentaries

ClimateWatch—Series of audio documentaries and public service messages about Earth's atmosphere, climate change and global warming, and success stories. Five CD set available to university, community, public and commercial radio stations, and to educational and academic users. Very attractive and user friendly.[289]

Endnotes

[1] National Oceanic and Atmospheric Administration. "What is the difference between weather and climate?" Retrieved 22 October 2015. <http://oceanservice.noaa.gov/facts/weather_climate.html>.

[2] Summerville, Richard. Interview on *Nova and Frontline's* "What's Up With the Weather?" *NOVA and Frontline.* PBS and WGBH. 2000. Retrieved 5 November 2015. <http://www.pbs.org/wgbh/warming/debate/somerville.html>.

[3] Environmental Protection Agency. "Glossary of Climate Change Terms." Retrieved October 22, 2015. <http://www3.epa.gov/climatechange/glossary.html#R>.

[4] NRC. *Climate Change Science: An Analysis of Some Key Questions*. p. 6. <http://books.nap.edu/books/0309075742/html/R1.html>.

[5] ---.

[6] Houghton. p. 20.

[7] Christianson, Gale. *Greenhouse: The 200-Year Story of Global Warming.* New York: Walker & Company, 1999.

[8] ---.

[9] Houghton. p. 18.

[10] National Oceanic and Atmospheric Administration. "What is Paleoclimatology?" Retrieved 23 October 2015. <http://www.ngdc.noaa.gov/paleo/primer.html>.

[11] U.S. Global Change Research Program. *Climate Change Impacts on the United States.* May 2014. p. 23. Retrieved 25 October 2015. <http://s3.amazonaws.com/nca2014/low/NCA3_Climate_Change_Impacts_in_the_United%20States_LowRes.pdf?download=1>.

[12] Houghton, J. *Global Warming: The Complete Briefing.* Fifth Ed. Cambridge, UK: Cambridge University Press, 2015. p. 15.

[13] ---. p. 15.

[14] ---. p. 33.

[15] Steinfeld, J. I. R. "Global Climate Change: Information Pamphlet." American Chemical Society. 1999.

[16] NASA Earth Observatory. "Measuring Earth's Albedo." Retrieved 9 December 2015. <http://earthobservatory.nasa.gov/IOTD/view.php?id=84499>.

[17] USGCRP. *Climate Change Impacts on the United States.* May 2014. p. 740. Retrieved 11 November 2015. <http://s3.amazonaws.com/nca2014/low/NCA3_Climate_Change_Impacts_in_the_United%20States_LowRes.pdf?download=1>.

[18] Sterman, J.D. and L.B. Sweeney. "Understanding public complacency about climate Change." 2007. p. 1. Retrieved 25 October 2015. <http://www.climateaccess.org/sites/default/files/Sterman_Understanding%20Public%20Complacency.pdf>

[19] ---. 3

[20] Carbon Cycle Science Working Group. "A U.S. Carbon Cycle Science Plan." 2011. Retrieved 10 December 2015. <http://carboncyclescience.us/sites/default/files/documents/USCarbonCycleSciencePlan-2011.pdf>. Vii.

[21] Houghton. p. 33.

[22] ---. p. 34.

[23] ---. p. 34.

[24] ---. p. 33.

[25] Environment Canada. A Primer on Climate Change. Retrieved 23 October 2015. <http://www.ec.gc.ca/climate/primer/sec-4.htm>.

[26] Houghton. p. 37.

[27] ---. p. 27.

[28] Joint Genome Institute. "Prochlorococcus marinus MIT 9313." Retrieved 4 December 2015. <http://genome.jgi.doe.gov/prom9/prom9.home.html>.

[29] Houghton p. 42.

[30] Jacoby, Henry. Interview on PBS.org Retrieved 10 December 2015. <http://www.pbs.org/wgbh/warming/debate/jacoby.html>.

[31] Houghton. p. 36.

[32] U.S. EPA. "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990- 2013." April 2015. Retrieved 5 November 2015. <http://www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2015-Main-Text.pdf>. 2-11.

[33] U.S. Department of Energy, Energy Information Administration. "Annual Energy Outlook 2015." 14 April 2015. Retrieved 11 October 2015. <http://www.eia.gov/forecasts/aeo/section_energyconsump.cfm>.

[34] U.S. EPA. "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990- 2000." <http://www3.epa.gov/climatechange/Downloads/ghgemissions/02CR.pdf>.

[35] NASA Earth Observatory. "The Water Cycle: A Multi-Phased Journey." Retrieved 20 October 2015. <http://earthobservatory.nasa.gov/Features/Water/page2.php>.

[36] ---.

[37] ---.

[38] U.S. Geological Survey. "Summary of the Water Cycle." Retrieved 11 December 2015. <http://water.usgs.gov/edu/watercyclesummary.html>.

[39] Intergovernmental Panel on Climate Change. "AR5 Synthesis Report - Climate Change 2014" 2014. Retrieved 11 December 2015. <http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full.pdf>. p. 47.

[40] Cicerone, Ralph, and Sir Paul Nurse. "Climate Change: Evidence and Causes." 27 February 2014. Retrieved 20 February 2016. <http://nas-sites.org/americasclimatechoices/events/a-discussion-on-climate-change-evidence-and-causes/>.

[41] Craven, Greg. *What's the Worst that Could Happen?* USA: TarcherPerigee, 2009.

[42] Houghton. p.239.

[43] IPCC. Home page. Retrieved 10 December 2015. <http://www.ipcc.ch/>.

[44] NRC. *Climate Change Science: An Analysis of Some Key Questions.* 2001. p. 15. <http://books.nap.edu/books/0309075742/html/R1.html>.

[45] Schneider, S.H. "Chapter 1: Introduction to Climate Modeling." *Climate System Modeling.* K.E. Trenberth, ed. Cambridge, UK: Cambridge University Press, 2010.

[46] McGuiffe, Kendall and Ann Henderson-Sellers. *The Climate Modeling Primer.* Fourth Edition. Hoboken, USA: Wiley-Blackwell, 2014.

[47] Schneider, S.H .---.

[48] Prinn, Ronald G. "Development and application of Earth system models." *Proceedings of the National Academy of Sciences of the United States.* Retrieved 11 December 2015. <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3586611/>.

[49] IPCC. "Climate Change 2007: Working Group I: The Physical Science Basis" 2007. Retrieved 11 December 2015. <https://www.ipcc.ch/publications_and_data/ar4/wg1/en/faq-8-1.html>

[50] ---.

[51] Trenberth, Kevin E. *Climate System Modeling*. Cambridge, UK: Cambridge University Press, 2010. p. 26.

[52] USGCRP. *Climate Change Impacts on the United States.* May 2014. p. 753. Retrieved 25 October 2015. <http://s3.amazonaws.com/nca2014/low/NCA3_Climate_Change_Impacts_in_the_United%20States_LowRes.pdf?download=1>.

[53] IPCC. "8.6.1 Introduction" from "Climate Change 2007: Working Group I: The Physical Science Basis" 2007. Retrieved 11 December 2015. <https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch8s8-6.html>.

[54] MIT Joint Program on the Science and Policy of Global Change. "The MIT Integrated Global System Model (IGSM) Version 2: Model Description and Baseline Evaluation." July 2005. Retrieved 11 December 2015. <http://web.mit.edu/globalchange/www/MITJPSPGC_Rpt124.pdf>. p. 3.

[55] ---. p. 3.

[56] Wagner, G. and M.L. Weitzman. *Climate Shock: The Economic Consequences of a Hotter Planet.* Princeton University Press, 2015. p. 13.

[57] ---. p. 14.

[58] Houghton. p. 34.

[59] IPCC. “Climate Change: The IPCC Scientific Assessment.” 1990. Retrieved 5 March 2016. <https://www.ipcc.ch/publications_and_data/publications_ipcc_first_assessment_1990_wg1.shtml ttp://www.un.org/ecosocdev/geninfo/sustdev/climate.htm>.
[60] IPCC. “Climate Change 2014: Impacts, Adaptation, and Variability” in “AR5 Summary for Policymakers.” Retrieved 5 November 2015. <https://ipcc-wg2.gov/AR5/images/uploads/IPCC_WG2AR5_SPM_Approved.pdf>.
[61] IPCC. “Climate Change 2014: Mitigation” in “AR5: Summary for Policymakers.” 2014. Retrieved 20 November 2015. <http://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_summary-for-policymakers.pdf>.
[62] American Association for the Advancement of Science. “The Reality, Risks, and Response to Climate Change.” Retrieved 10 December 2015. <http://whatweknow.aaas.org/get-the-facts/>.
[63] National Academy of Sciences. *Climate Change: Evidence and Causes.* p.2. 27 February 2014. Retrieved 18 December 2015. <http://nas-sites.org/americasclimatechoices/events/a-discussion-on-climate-change-evidence-and-causes/>.
[64] ---. p. 5.
[65] ---. p. 3.
[66] ---. p. B6.
[67] ---. p. B7.
[68] Pope Francis. “Laudato si'.” 24 May 2015. Retrieved 10 October 2015. <http://w2.vatican.va/content/francesco/en/encyclicals/documents/papa-francesco_20150524_enciclica-laudato-si.html>.
[69] ---.
[70] Wagner, G. and M.L. Weitzman. p. 49.
[71] Edenhofer, Ottmar. “King Coal and the queen of subsidies.” *Science*. 349. 18 September 2015. p. 1286.
[72] “It’s getting hotter.” *The Economist.* 3 October 2015. Retrieved 11 November 2015. <http://www.economist.com/news/international/21669885-climate-talks-paris-later-year-negotiators-should-ponder-damage-already>.
[73] World Resources Institute. “CAIT - Country Greenhouse Gas Emissions Data.” Retrieved 21 December 2015. <http://www.wri.org/resources/data-sets/cait-country-greenhouse-gas-emissions-data>.
[74] Goldenberg, Suzanne. “The inside story on climate scientists under siege.” *The Guardian.* 17 February 2012. Retrieved 15 December 2015. <http://www.theguardian.com/environment/2012/feb/17/michael-mann-climate-war>.
[75] Oreskes, Naomi and Erik Conway. “Merchants of Doubt.” Bloomsbury, 2010. p. 185.
[76] IPCC. “Report of Working Group II.” in “AR5 Summary for Policymakers.” p. 7. <https://ipcc-wg2.gov/AR5/images/uploads/WG2AR5_SPM_FINAL.pdf>.
[77] ---. p. 20.
[78] USGCRP. *Climate Change Impacts on the United States.* May 2014. p. 793. Retrieved 25 October 2015. <http://s3.amazonaws.com/nca2014/low/NCA3_Climate_Change_Impacts_in_the_United%20States_LowRes.pdf?download=1>.
[79] USGCRP. *Climate Change Impacts on the United States.* May 2014. Retrieved 5 November 2015. <http://s3.amazonaws.com/nca2014/low/NCA3_Climate_Change_Impacts_in_the_United%20States_LowRes.pdf?download=1>.
[80] Hansen et al. Perception of Climate Change", Proc. US National Academy of Sciences, 29 March 2012. Retrieved 25 October 2015. <http://www.pnas.org/content/109/37/E2415.full>.
[81] Miller, Brandon. “2015 is warmest year on record, NOAA and NASA say.” *CNN.* 20 January, 2016. Retrieved 28 January, 2016. <http://www.cnn.com/2016/01/20/us/noaa-2015-warmest-year/index.html>.
[82] Kintisch, Eli. “Boom & Bust in the Great White North.” *Science.* 349. 7 August 2015. p. 579.
[83] IPCC. “Report of Working Group II.” in “IPCC AR5: Climate Change 2015.” Retrieved 10 October 2015. p. 7. <https://www.ipcc.ch/pdf/assessment-report/ar5/wg2/ar5_wgII_spm_en.pdf>.
[84] ---. p. 12.
[85] USGCRP. *Climate Change Impacts on the United States.* May 2014. p. 561. Retrieved 5 November 2015. <http://s3.amazonaws.com/nca2014/low/NCA3_Climate_Change_Impacts_in_the_United%20States_LowRes.pdf?download=1>.

[86] Chu, Jennifer. “Ocean acidification may cause dramatic changes to phytoplankton.” *MIT News.* 20 July, 2015. Retrieved 10 November 2015. <http://news.mit.edu/2015/ocean-acidification-phytoplankton-0720>.

[87] ---.

[88] Public Broadcasting System. “The invisible ocean threat that ripples through the food chain.” *PBS News Hour.* 31 August 2015. Retrieved 10 October 2015. <http://www.pbs.org/newshour/bb/invisible-ocean-threat-ripples-food-chain/>.

[89] Intergovernmental Panel on Climate Change. “AR5 Synthesis Report - Climate Change 2014” 2014. Retrieved 11 December 2015. <http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full.pdf>. p. 4.

[90] ---.p.11.

[91] Annenberg Learner. “Interview with Kerry Emanuel.” Retrieved 5 December 2015. <https://www.learner.org/courses/envsci/scientist/transcripts/emanuel.html>.

[92] ---.

[93] USGCRP. *Climate Change Impacts on the United States.* May 2014. p. 178. Retrieved 5 November 2015. <http://s3.amazonaws.com/nca2014/low/NCA3_Climate_Change_Impacts_in_the_United%20States_LowRes.pdf?download=1>.

[94] Roman, Jesse. “The Year in Wildfire.” *NFPA Journal.* 2 November 2015. Retrieved 22 December 2015. <http://www.nfpa.org/newsandpublications/nfpa-journal/2015/november-december-2015/features/the-year-in-wildfire>.

[95] USGCRP. *Climate Change Impacts on the United States.* May 2014. p. 9. Retrieved 5 November 2015. <http://s3.amazonaws.com/nca2014/low/NCA3_Climate_Change_Impacts_in_the_United%20States_LowRes.pdf?download=1>.

[96] T.C. Peterson, P.A. Stott, and S. Herring. "Explaining Extreme Climate Events of 2011 from a Climate Perspective." *Bulletin of the American Meteorological Society*. July 2012.

[97] Romm, Joe. “Climatologist Who Predicted California Drought 10 Years Ago Says It May Soon Be ‘Even More Dire’” *Climate Progress.* 7 March 2014. Retrieved 10 October 2015. <http://thinkprogress.org/climate/2014/03/07/3370481/california-drought/>.

[98] USGCRP. *Climate Change Impacts on the United States.* May 2014. p. 16. Retrieved 5 November 2015. <http://s3.amazonaws.com/nca2014/low/NCA3_Climate_Change_Impacts_in_the_United%20States_LowRes.pdf?download=1>.

[99] Pacific Institute. “Issues We Work on: Water, Food, and Agriculture.” Retrieved 10 October 2015. <http://pacinst.org/issues/water-food-and-agriculture/>.

[100] USDA. “Agricultural Productivity Growth in the United States: 1948-2011.” Retrieved 5 September 2015. <http://www.ers.usda.gov/amber-waves/2014-januaryfebruary/agricultural-productivity-growth-in-the-united-states-1948-2011.aspx#.VnmEh_krIdU>.

[101] USGCRP. *Climate Change Impacts on the United States.* May 2014. p. 161. Retrieved 5 November 2015. <http://s3.amazonaws.com/nca2014/low/NCA3_Climate_Change_Impacts_in_the_United%20States_LowRes.pdf?download=1>.

[102] ---. p. 197

[103] IPCC. “Report of Working Group II.” in “IPCC AR5: Climate Change 2015.” Retrieved 10 October 2015. p. 4. <https://ipcc-wg2.gov/AR5/images/uploads/WG2AR5_SPM_FINAL.pdf>.

[104] ---. p. 26

[105] ---. p. 34.

[106] ---. p. 30.

[107] Gauthier, S. et al. “Boreal forest health and global change.” *Science.* 349. 21 August 2015. Retrieved 10 November 2015. p. 819. <http://www.sciencemag.org/content/349/6250/819.full>.

[108] ---. p. 822.

[109] ---.

[110] ---. p. 820.

[111] USGCRP. *Climate Change Impacts on the United States.* May 2014. p. 899. Retrieved 16 November 2015. <http://s3.amazonaws.com/nca2014/low/NCA3_Climate_Change_Impacts_in_the_United%20States_LowRes.pdf?download=1>.

[112] ---. p. 177

[113] ---. p. 202

[114] IPCC. “Synthesis Report Summary for Policymakers.” *Climate Change 2014.* p. 18. Retrieved 5 November 2015. <https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf>.

[115] USGCRP. *Climate Change Impacts on the United States.* May 2014. p. 382. Retrieved 20 November 2015. <http://s3.amazonaws.com/nca2014/low/NCA3_Climate_Change_Impacts_in_the_United%20States_LowRes.pdf?download=1>.

[116] Korten, Tristram. “In Florida, officials ban term 'climate change'.” *Miami Herald.* 8 March 2015. Retrieved 10 November 2015. <http://www.miamiherald.com/news/state/florida/article12983720.html>.

[117] USGCRP. *Climate Change Impacts on the United States.* May 2014. p. 21. Retrieved 20 November 2015. <http://s3.amazonaws.com/nca2014/low/NCA3_Climate_Change_Impacts_in_the_United%20States_LowRes.pdf?download=1>.

[118] United Nations Environment Programme. *Technologies for Climate Change Adaptation.”* November 2010. p. 12. Retrieved 12 December 2015. <http://www.unep.org/pdf/TNAhandbook_CoastalErosionFlooding.pdf>.

[119] ---. p. 21

[120] ---. p. 37

[121] USGCRP. *Climate Change Impacts on the United States.* May 2014. p. 12. Retrieved 20 November 2015. <http://s3.amazonaws.com/nca2014/low/NCA3_Climate_Change_Impacts_in_the_United%20States_LowRes.pdf?download=1>.

[122] Ortman, Jennifer et al. “An Aging Nation: The Older Population in the United States.” May 2014. p. 1. Retrieved 15 January 2016. <http://www.census.gov/prod/2014pubs/p25-1140.pdf>.

[123] USGCRP. *Climate Change Impacts on the United States.* May 2014. p. 197-198. Retrieved 20 November 2015. <http://s3.amazonaws.com/nca2014/low/NCA3_Climate_Change_Impacts_in_the_United%20States_LowRes.pdf?download=1>.

[124] USGCRP. “Human Health.” *National Climate Assessment.* May 2014. Retrieved 20 February 2016. <http://nca2014.globalchange.gov/report/sectors/human-health>.

[125] Schreuder, Cindy. “The 1995 Chicago heat wave.” *Chicago Tribune.* 14 July 2015. Retrieved 3 July 2016. <http://www.chicagotribune.com/news/nationworld/politics/chi-chicagodays-1995heat-story-story.html>.

[126] USGCRP. *Climate Change Impacts on the United States.* May 2014. p. 288. Retrieved 20 November 2015. <http://s3.amazonaws.com/nca2014/low/NCA3_Climate_Change_Impacts_in_the_United%20States_LowRes.pdf?download=1>.

[127] National Weather Service. “Summary of Natural Hazard Statistics for 2014 in the United States.” 10 June 2015. p. 3. Retrieved 10 November 2015. <http://www.nws.noaa.gov/om/hazstats/sum14.pdf>.

[128] USGCRP. *Climate Change Impacts on the United States.* May 2014. p. 252. Retrieved 20 November 2015. <http://s3.amazonaws.com/nca2014/low/NCA3_Climate_Change_Impacts_in_the_United%20States_LowRes.pdf?download=1>.

[129] U.S. EPA. “Air Pollution: Current and Future Challenges.” Retrieved 10 November 2015. <http://www.epa.gov/clean-air-act-overview/air-pollution-current-and-future-challenges>.

[130] Centers for Disease Control and Prevention. “Estimates of Foodborne Illness in the United States.” Retrieved 10 October 2015. <http://www.cdc.gov/foodborneburden/>.

[131] USGCRP. *Climate Change Impacts on the United States.* May 2014. p. 162-163. Retrieved 20 November 2015. <http://s3.amazonaws.com/nca2014/low/NCA3_Climate_Change_Impacts_in_the_United%20States_LowRes.pdf?download=1>.

[132] ---. p. 225.

[133] IPCC. “Summary for Policy Makers.” *Climate Change 2014.* p. 20. Retrieved 20 October 2015. <http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/ar5_wgII_spm_en.pdf>.

[134] ---. p. 18.

[135] ---. p. 20.

[136] ---. p.19.

[137] Advanced Technology Environmental Education Center (ATEEC). *Defining Environmental Technology*. 2014. p. 9. Retrieved 4 December 2015. <http://ateec.org/wp-content/uploads/2014/10/DefiningEnvironmentalTechnologyReport_08082014.pdf>.

[138] ---. p 24.

[139] ---. *Defining Energy Technology and Services*. 2008. Retrieved 4 December 2015. <http://ateec.org/wp-content/uploads/2011/09/DefiningEnergyTechServReport_1.pdf>.

[140] Small, Laura. "Fact Sheet: Renewable Energy Job Numbers." 7 January 2015. Retrieved 12 December 2015. <http://www.renewableenergyworld.com/articles/2015/01/fact-sheet-renewable-energy-job-numbers.html>.

[141] ---.

[142] Berners-Lee, M. and D. Clark. *The Burning Question*. Greystone Books. 2013. p. 173.

[143] The Economist. "Unburnable fuel." 4 May 2013. Retrieved 10 October 2015. <http://www.economist.com/news/business/21577097-either-governments-are-not-serious-about-climate-change-or-fossil-fuel-firms-are>.

[144] ---. "Black moods." 6 June 2015. Retrieved 25 November 2015. <http://www.economist.com/news/business/21653622-coals-woes-are-spreading-it-still-has-its-fans-black-moods>.

[145] National Association of Insurance Commissioners. "Climate Change and Risk Assessment." 23 December 2015. Retrieved 10 January 2016. <http://www.naic.org/cipr_topics/topic_climate_risk_disclosure.htm>.

[146] National Oceanic and Atmospheric Administration. "Billion-Dollar Weather and Climate Disasters: Overview." Retrieved 10 January 2016. <https://www.ncdc.noaa.gov/billions/ >.

[147] Claussen, Eileen. <http://www.c2es.org/publications/equity-global-climate-change-complex-elements-global-fairness>.

[148] Pope Francis. "Laudato si'." 24 May 2015. Retrieved 10 October 2015. <http://w2.vatican.va/content/francesco/en/encyclicals/documents/papa-francesco_20150524_enciclica-laudato-si.html>.

[149] IPCC. "Sustainable Development and Equity." *Climate Change 2014.* Retrieved 20 October 2015. <http://www.ipcc.ch/report/ar5/wg3/>.

[150] Steinfeld, Jeffrey I. "Climate Change and Energy Options: Decision Making in the Midst of Uncertainty." Presentation at "Fuel Science in the Year 2000—Where Do We Stand, Where Do We Go From Here?" American Chemical Society, Division of Fuel Chemistry Conference, San Francisco, 2000. Available on-line at <https://web.anl.gov/PCS/acsfuel/preprint%20archive/Files/45_1_SAN%20FRANCISCO_03-00_0139.pdf>.

[151] American Geophysical Union. "Climate Change and Greenhouse Gases." December 2002. Retrieved 9 October 2015. <https://www.aip.org/fyi/1999/text-agu-position-statement-climate-change>.

[152] American Chemical Society. "ACS Position Statement." Retrieved 10 January 2016. <http://www.acs.org/content/acs/en/policy/publicpolicies/promote/globalclimatechange.html>.

[153] ---.

[154] United Nations. "Agenda 21." 1992. Retrieved 9 October 2015. <http://www.un.org/documents/ga/conf151/aconf15126-1annex1.htm>.

[155] Hoffman, Andrew J. "Getting Ahead of the Curve: Corporations that Address Climate Change." Retrieved 10 January 2016. <http://www.c2es.org/docUploads/PEW_CorpStrategies.pdf>.

[156] ---.

[157] Sneider, Roel and Sally M. Benson. "Education for the global energy challenge." *Physics Today.* Retrieved 15 January 2016. <http://scitation.aip.org/content/aip/magazine/physicstoday/article/61/7/10.1063/1.2963011>.

[158] McKinsey & Company. "Reducing the U.S. Greenhouse Gas Emissions: How Much at What Cost?" 2007. p. xi. Retrieved 12 December 2015. <http://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/reducing-us-greenhouse-gas-emissions>.

[159] World Resources Institute. "Business and Climate Action: The Times They Are A-Changin'" 2 December 2015. Retrieved 9 January 2016. <http://www.wri.org/blog/2015/12/business-and-climate-action-times-they-are-changin>.

[160] C2ES. "Business Environmental Leadership Council." Retrieved 9 January 2016. <http://www.c2es.org/business/belc>.

[161] ---. p. 45.

[162] Grubler, Arnulf. *Energy Technology Innovation.* p. 46. Cambridge University Press, 2013. Print.

[163] UN. “First steps to a safer future: Introducing the United Nations Framework Convention on Climate Change.” Retrieved 11 January 2016. <http://unfccc.int/essential_background/convention/items/6036.php>.
[164] Mistrick, Janine. “Kyoto Protocol: Good Intentions, Failed Legislation?” Retrieved 11 January 2016. <https://sites.psu.edu/mistrickblog/2013/02/21/kyoto-protocol-good-intentions-failed-legislation/>.
[165] WRI. “CAIT Climate Data Explorer.” Retrieved 15 January 2016.” <http://cait.wri.org/indc/#/map>.
[166] ---.
[167] Davis, Julie Hirschfield and Coral Davenport. “China to Announce Cap-and-Trade Program to Limit Emissions.” *The New York Times.* 24 September 2015. Retrieved 5 January 2016. <http://www.nytimes.com/2015/09/25/world/asia/xi-jinping-china-president-obama-summit.html?_r=0>.
[168] Obama, Barack. “The President’s Climate Action Plan.” June 2013. Retrieved 11 January 2016. <https://www.whitehouse.gov/sites/default/files/image/president27sclimateactionplan.pdf>.
[169] ---. p. 9.
[170] U.S. EPA. “What EPA is Doing.” *Clean Power Plan.* Retrieved 5 January 2016. <http://www.epa.gov/cleanpowerplan/what-epa-doing>.
[171] ---.
[172] Durkay, Jocelyn. “State Renewable Portfolio Standards and Goals.” *National Conference of State Legislatures.* 15 January 2016. Retrieved 21 January 2016. <http://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx>.
[173] Regional Greenhouse Gas Initiative. “RGGI, Inc.” Retrieved 16 January 2016. <http://www.rggi.org/rggi>.
[174] Yale School of Forestry and Environmental Studies. “Citizen’s Guide to Taking Action on Climate Change.” Retrieved 9 January 2016. <http://environment.yale.edu/climate-communication/article/citizens-guide-to-taking-action-on-climate-change>.
[175] U.S. EPA. “State and Local Climate and Energy Program.” Retrieved 9 December 2015. <http://www3.epa.gov/statelocalclimate/>.
[176] International Council of Local Environmental Initiatives. “Statewide Energy Efficiency Collaborative.” Retrieved 10 January 2016. <http://icleiusa.org/programs/emissions-management/seec/>.
[177] ---. “Five Milestones of Emissions Management.” Retrieved 10 January 2016. <http://icleiusa.org/programs/emissions-management/5-milestones/>.
[178] Walser, Maggie L. “Carbon footprint.” *The Encyclopedia of Earth.* 14 July 2010. Retrieved 12 December 2015. <http://www.eoearth.org/view/article/150926/>.
[179] U.S. EPA. “What You Can Do.” Retrieved 15 January 2016. <http://www3.epa.gov/climatechange/wycd/>.
[180] ---. “What You Can Do: At Home.” Retrieved 15 January 2016. <http://www3.epa.gov/climatechange/wycd/home.html>.
[181] ---.
[182] U.S. DOE. “Planning and Combining Trips.” Retrieved 9 December 2015. <http://www.fueleconomy.gov/feg/planning.shtml>.
[183] American Public Transportation Association. “Public Transportation Near You.” Retrieved 9 January 2016. <http://www.apta.com/Pages/default.aspx>.
[184] U.S. DOE. Fuel Economy Home page. Retrieved 9 January 2016. <http://www.fueleconomy.gov/>.
[185] Claussen, Eileen. “Technology and Climate Change: Sparking a New Industrial Revolution.” American Institute of Chemical Engineers, New Orleans, LA. 10 March 2002. Retrieved 9 December 2015. <http://www.c2es.org/newsroom/speeches/technology-and-climate-change-sparking-new-industrial-revolution>.
[186] U.S. EPA. “Sources of Greenhouse Gas Emissions.” Retrieved 9 January 2016. <http://www3.epa.gov/climatechange/ghgemissions/sources.html>.
[187] Energy Informative. “Solar Energy Pros and Cons.” Retrieved 21 January 2016. <http://energyinformative.org/solar-energy-pros-and-cons/>.
[188] NREL. “Solar Photovoltaic Technology Basics.” Retrieved 10 December 2015. <http://www.nrel.gov/learning/re_photovoltaics.html>.
[189] NREL. “Concentrating Solar Power Basics.” Retrieved 15 December 2015. <http://www.nrel.gov/learning/re_csp.html>.
[190] ---. “Solar Process Heat Basics.” Retrieved 15 December 2015. <http://www.nrel.gov/learning/re_solar_process.html>.

[191] U.S. EPA. “Electricity from Non-Hydroelectric Renewable Energy Sources: Solar.” Retrieved 9 March 2003. <http://www.epa.gov/cleanenergy/impacts/renew.htm#solar>.

[192] U.S. DOE.”Solar Buildings: Residential and Commercial Water Heating.” Retrieved 9 March 2003. <http://www.eren.doe.gov/solarbuildings/hotwater.html>.

[193] American Wind Energy Association. “Wind 101: the basics of wind energy.” Retrieved 10 December 2015. <http://www.awea.org/Resources/Content.aspx?ItemNumber=900&navItemNumber=587>.

[194] ---. “The Cost of Wind Energy in the U.S.” Retrieved 10 December 2015. <http://www.awea.org/Resources/Content.aspx?ItemNumber=5547>.

[195] U.S. EPA “Biomass Energy.” *A Student’s Guide to Global Climate Change.* Retrieved 11 January 2016. <http://www3.epa.gov/climatechange/kids/solutions/technologies/biomass.html>.

[196] Bracmort, Kelsi. “Is Biopower Carbon Neutral?” Congressional Research Service. Retrieved 10 December 2015. <https://www.fas.org/sgp/crs/misc/R41603.pdf>.

[197] Shikida, Pery Francisco Assis. “The Economics of Ethanol Production in Brazil: A Path Dependence Approach.” p. 2. *University of Wisconsin Urban and Regional Planning.* Retrieved 20 December 2015. <http://urpl.wisc.edu/sites/urpl.wisc.edu/files/research/lectures/10Pery.pdf>.

[198] California Energy Commission. “Anaerobic Digestion.” Retrieved 20 November 2015. <http://www.energy.ca.gov/biomass/anaerobic.html>.

[199] Extension. “Fast Pyrolysis Efficiently Turns Biomass into Renewable Fuels.” 14 April 2015. Retrieved 11 December 2015. <http://articles.extension.org/pages/72722/fast-pyrolysis-efficiently-turns-biomass-into-renewable-fuels>.

[200] USAID. “Environment.” Retrieved 10 January 2016. <https://www.usaid.gov/haiti/environment>.

[201] U.S. DOE. “Geothermal Energy Basics.” Retrieved 9 October 2015. <http://energy.gov/eere/geothermal/geothermal-basics>.

[202] U.S. EPA. “Electricity from Non-Hydroelectric Renewable Energy Sources: Geothermal.” Retrieved 9 March 2003. <http://www.epa.gov/cleanenergy/impacts/renew.htm#geothermal>.

[203] Armstrong, David. “No monkeys like snow monkeys: Soak up Japan's hot-tubbing wildlife.” *SF Gate.* 2 March 2008. Retrieved 10 November 2015. <http://www.sfgate.com/travel/article/No-monkeys-like-snow-monkeys-Soak-up-Japan-s-3292583.php>.

[204] Zolfagharifard, Ellie. “The LAVA-fuelled power station: Iceland is harnessing energy directly from molten magma for the first time.” *Daily Mail.* 5 February 2015. Retrieved 30 October 2015. <http://www.dailymail.co.uk/sciencetech/article-2552418/The-LAVA-fuelled-power-station-Iceland-harnessing-energy-directly-molten-magma-time.html>.

[205] U.S. DOE. “Geothermal Energy Basics.” Retrieved 9 October 2015. <http://energy.gov/eere/geothermal/geothermal-basics>.

[206] ---.

[207] MacKay, David JC. “Sustainable Energy—without the hot air.” 2009. Retrieved 10 January 2016. <http://www.withouthotair.com/c21/page_144.shtml>.

[208] Idaho National Engineering and Environmental Laboratory. “Hydropower’s Historical Progression.” Retrieved 9 October 2015. <http://hydropower.inel.gov/hydrofacts/historical_progression.shtml>.

[209] ---.

[210] U.S. DOE, Office of Energy Efficiency and Renewable Energy. “Hydropower Basics.” Retrieved 10 January 2016. <http://energy.gov/eere/water/hydropower-basics>.

[211] Union of Concerned Scientists. “Environmental Impacts of Hydroelectric Power.” Retrieved 10 November 2015. <http://www.ucsusa.org/clean_energy/our-energy-choices/renewable-energy/environmental-impacts-hydroelectric-power.html#.VqJsnyorIdU>.

[212] Few, Arthur A. *Energy Use by Humans.* Boulder, CO: University Corporation for Atmospheric Research, 1998. p. 8.

[213] U.S. DOE, NREL. “2014 Renewable Energy Data Book.” pp. 7, 10. Retrieved 10 January 2016. <http://www.nrel.gov/docs/fy16osti/64720.pdf>.

[214] Clery, Daniel. “Dark horse scores a fusion coup.” *Science.* 28 August 2015. Retrieved 11 January 2015. <http://science.sciencemag.org/content/349/6251/912.full>.

[215] World Nuclear Association. “Nuclear Power in Germany.” 30 November 2015. Retrieved 20 December 2015. <http://www.world-nuclear.org/info/Country-Profiles/Countries-G-N/Germany/>.

[216] Carbon Capture and Storage association. “What is CCS?” Retrieved 20 January 2016. <http://www.ccsassociation.org/what-is-ccs/>.
[217] Talbot, David. “Carbon Sequestration: Too Little, Too Late?” *MIT Technology Review.* <http://www.technologyreview.com/news/531531/carbon-sequestration-too-little-too-late/>.
[218] Service, Robert F. “Tailpipe to Tank.” *Science.* 11 September 2015. Retrieved 15 January 2016. <http://science.sciencemag.org/content/349/6253/1158>.
[219] Wagner, Gernot, and Martin L. Weitzman. *Climate Shock: The Economic Consequences of a Hotter Planet.* pp. 24–26. 2013. Princeton University Press. Print.
[220] ---. p. 20
[221] Mufson, Steven. “With cap and trade plan, China adopts emissions policy that couldn’t get through U.S. Congress.” *The Washington Post.* 28 September, 2015. Retrieved 11 December 2015. <https://www.washingtonpost.com/news/energy-environment/wp/2015/09/28/with-cap-and-trade-plan-china-adopts-emissions-policy-that-couldnt-get-through-u-s-congress/>.
[222] C2ES. “Options and Considerations for a Federal Carbon Tax.” Retrieved 22 January 2016. <http://www.c2es.org/publications/options-considerations-federal-carbon-tax>.
[223] Foulis, Patrick. “British Columbia’s carbon tax: The evidence mounts.” *The Economist.* 31 July 2014, Retrieved 17 January 2016. <http://www.economist.com/blogs/americasview/2014/07/british-columbias-carbon-tax>.
[224] Goldenberg, Suzanne. “Scientists urge global 'wake-up call' to deal with climate change.” *The Guardian.* 10 February 2015. Retrieved 6 January 2016. <http://www.theguardian.com/environment/2015/feb/10/geoengineering-should-not-be-used-as-a-climate-fix-yet-says-us-science-academy>.
[225] NASA. “Mission: Science.” Retrieved 9 December 2015. <http://missionscience.nasa.gov/ems/13_radiationbudget.html>.
[226] NASA, Earth Observatory. Home page. Retrieved 9 December 2015. <http://earthobservatory.nasa.gov/>.
[227] USGS. “The Water Cycle.” Retrieved 15 December 2015. <http://water.usgs.gov/edu/watercycle.html>.
[228] IPCC. “Fifth Assessment Report.” *Climate Change 2014.* 2014. Retrieved 10 November 2015. <http://www.ipcc.ch/report/ar5/index.shtml>.
[229] Resutek, Audrey. “Pinpointing climate change uncertainty.” *MIT News.* Retrieved 20 January 2016. <http://news.mit.edu/2014/pinpointing-climate-change-uncertainty>.
[230] U.S. EPA. “Climate Economic Modeling.” 2015. Retrieved 21 January 2016. <http://www3.epa.gov/climatechange/EPAactivities/economics/modeling.html>.
[231] WMO. “Climate Models.” Retrieved 21 January 2016. <https://www.wmo.int/pages/themes/climate/climate_models.php>.
[232] C2ES. “Economic Modeling for Climate Policy.” 2016. Retrieved 19 January 2016. <http://www.c2es.org/economics/modeling>.
[233] NOAA. “Education Resources: Climate.” Retrieved 9 December 2016. <http://www.education.noaa.gov/Climate/>.
[234] U.S. Global Climate Change Research Program. Home page. Retrieved 9 March 2003. <http://www.globalchange.gov/>.
[235] ---. “Resources for Educators.” Retrieved 9 December 2015. <http://www.globalchange.gov/browse/educators>.
[236] Union of Concerned Scientists. “Climate Hot Map.” Retrieved 9 January 2016. <http://www.climatehotmap.org/curriculum/index.html>.
[237] Climate Action Network (CAN) Europe. “Library Catalogue.” Retrieved 9 January 2016. <http://www.caneurope.org/library/library.htm>.
[238] Climate Change Live. Home Page. Retrieved 20 January 2016. <http://www.climatechangelive.org/index.php?pid=180/>.
[239] NASA. “Earth.” Retrieved 9 January 2016. <http://science.nasa.gov/earth-science/>.
[240] ---. “Earth’s Radiation Budget.” Retrieved 9 January 2016. <http://missionscience.nasa.gov/ems/13_radiationbudget.html>.

[241] International Petroleum Industry Environmental Conservation Association. “Climate Change: A Glossary of Terms.” 5th edition. October 2012. Retrieved 9 December 2015. <http://www.dsi.gov.tr/docs/iklim-degisikligi/glossary.pdf?sfvrsn=2>.

[242] UNEP. “Vital Climate Graphics.” Retrieved 9 January 2016. <http://www.grida.no/climate/vital/>**.**

[243] NASA. “Investigating the Climate System: Tropical Rainfall Measuring Mission.” Retrieved 9 January 2016. <http://trmm.gsfc.nasa.gov/>.

[244] American Association for the Advancement of Science. “The Reality, Risks, and Response to Climate Change.” Retrieved 10 December 2015. <http://whatweknow.aaas.org/get-the-facts/>.

[245] Edmonds, J., et al. “Technology and the Economics of Climate Change Policy.” Pew Center on Global Climate Change. Washington, DC. September 2000. Retrieved 9 January 2016. <http://www.c2es.org/publications/technology-economics-climate-change-policy>.

[246] Jacoby, H. D., R.G. Prinn, and R. Schmalensee. “Needed: A Realistic Strategy for Global Warming.” July 1997. Available online at the MIT Joint Program on the Science and Policy of Global Change (MJPSPGC). Retrieved 19 December 2015. <http://web.mit.edu/globalchange/www/rpt21.html>.

[247] National Academy of Sciences. *Climate Change: Evidence and Causes.* p.2. 27 February 2014. Retrieved 18 December 2015. <http://nas-sites.org/americasclimatechoices/events/a-discussion-on-climate-change-evidence-and-causes/>.

[248] Burck, Jan, Franziska Marten, Christoph BalsReiner. “The Climate Change Performance Index: Results 2015.” Bonn, Germany: Germanwatch. December 2014. Retrieved 20 January 2016. <https://germanwatch.org/en/download/10407.pdf>.

[249] Ernst and Young. “Climate change reporting and benchmarking.” Home page. 2016. Retrieved 25 January 2016. <http://www.ey.com/GL/en/Services/Specialty-Services/Climate-Change-and-Sustainability-Services/Action-amid-uncertainty---Climate-change-reporting-and-benchmarking>.

[250] National Physical Laboratory. “TRUTHS.” Home page. Retrieved 25 January 2016. <http://www.npl.co.uk/upload/pdf/truths_exec_summary.pdf>.

[251] NRC. *Climate Change Science: An Analysis of Some Key Questions.”* <http://books.nap.edu/books/0309075742/html/R1.html>.

[252] USGCRP. “Observed Change.” Retrieved 15 January 2016. <http://nca2014.globalchange.gov/report/our-changing-climate/observed-change>.

[253] WMO. “Climate Observation Networks and Systems.” Retrieved 25 January 2016. <http://www.wmo.int/pages/themes/climate/climate_observation_networks_systems.php>.

[254] Childress, Sarah. “Timeline: The Politics of Climate Change.” *Frontline/PBS.* 23 October 2012. Retrieved 15 January 2016. <http://www.pbs.org/wgbh/frontline/article/timeline-the-politics-of-climate-change/>.

[255] Union of Concerned Scientists. “Confronting Climate Change in the Gulf Coast Region.” Retrieved 9 December 2015. <http://www.ucsusa.org/sites/default/files/legacy/assets/documents/global_warming/gulfcoast.pdf>.

[256] UN Youth. “Youth and Climate Change.” Retrieved 9 January 2016. <http://www.un.org/esa/socdev/documents/youth/fact-sheets/youth-climatechange.pdf>.

[257] NASA. “Global Climate Change.” Retrieved 9 January 2016. <http://climate.nasa.gov/educationalActivities/>.

[258] U.S. Geological Survey. “Learning Web: Global Change Teacher’s Guide.” Retrieved 9 January 2016. <http://education.usgs.gov/>.

[259] Environmental Change Network. Home page. Retrieved 19 January 2016. <http://www.ecn.ac.uk/>.

[260] Center for Climate and Energy Solutions. “Climate Change 101: Technological Solutions.” Retrieved 28 January 2016. <http://www.c2es.org/docUploads/climate101-technology.pdf>.

[261] NASA. “Global Temperature.” Retrieved 28 January 2016. <http://climate.nasa.gov/vital-signs/global-temperature/>.

[262] NOAA. “Climate Change: Global Temperature.” Retrieved 20 January 2016. <https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature>.

[263] U.S. EPA. “Plants, Animals, and Ecosystems.” Retrieved 20 December 2015. <http://www3.epa.gov/climatechange/kids/impacts/effects/ecosystems.html>.

[264] NASA. “Climate Time Machine.” Retrieved 20 January 2016. <http://climate.nasa.gov/interactives/climate-time-machine>.

[265] NOAA. “Societal Impacts.” Retrieved 19 December 2015. <http://www.ncdc.noaa.gov/societal-impacts/>.

Section 2 – Scope.

a. **License grant**.

1. Subject to the terms and conditions of this Public License, the Licensor hereby grants You a worldwide, royalty-free, non-sublicensable, non-exclusive, irrevocable license to exercise the Licensed Rights in the Licensed Material to:
    A. reproduce and Share the Licensed Material, in whole or in part, for NonCommercial purposes only; and
    B. produce, reproduce, and Share Adapted Material for NonCommercial purposes only.
2. Exceptions and Limitations. For the avoidance of doubt, where Exceptions and Limitations apply to Your use, this Public License does not apply, and You do not need to comply with its terms and conditions.
3. Term. The term of this Public License is specified in Section 6(a).
4. Media and formats; technical modifications allowed. The Licensor authorizes You to exercise the Licensed Rights in all media and formats whether now known or hereafter created, and to make technical modifications necessary to do so. The Licensor waives and/or agrees not to assert any right or authority to forbid You from making technical modifications necessary to exercise the Licensed Rights, including technical modifications necessary to circumvent Effective Technological Measures. For purposes of this Public License, simply making modifications authorized by this Section 2(a)(4) never produces Adapted Material.
5. Downstream recipients.
    A. Offer from the Licensor – Licensed Material. Every recipient of the Licensed Material automatically receives an offer from the Licensor to exercise the Licensed Rights under the terms and conditions of this Public License.
    B. Additional offer from the Licensor – Adapted Material. Every recipient of Adapted Material from You automatically receives an offer from the Licensor to exercise the Licensed Rights in the Adapted Material under the conditions of the Adapter's License You apply.
    C. No downstream restrictions. You may not offer or impose any additional or different terms or conditions on, or apply any Effective Technological Measures to, the Licensed Material if doing so restricts exercise of the Licensed Rights by any recipient of the Licensed Material.
6. No endorsement. Nothing in this Public License constitutes or may be construed as permission to assert or imply that You are, or that Your use of the Licensed Material is, connected with, or sponsored, endorsed, or granted official status by, the Licensor or others designated to receive attribution as provided in Section 3(a)(1)(A)(i).

b. **Other rights**.

1. Moral rights, such as the right of integrity, are not licensed under this Public License, nor are publicity, privacy, and/or other similar personality rights; however, to the extent possible, the Licensor waives and/or agrees not to assert any such rights held by the Licensor to the limited extent necessary to allow You to exercise the Licensed Rights, but not otherwise.
2. Patent and trademark rights are not licensed under this Public License.
3. To the extent possible, the Licensor waives any right to collect royalties from You for the exercise of the Licensed Rights, whether directly or through a collecting society under any voluntary or waivable statutory or compulsory licensing scheme. In all other cases the Licensor expressly reserves any right to collect such royalties, including when the Licensed Material is used other than for NonCommercial purposes.

Section 3 – License Conditions.

Your exercise of the Licensed Rights is expressly made subject to the following conditions.

a. **Attribution**.

1. If You Share the Licensed Material (including in modified form), You must:
    A. retain the following if it is supplied by the Licensor with the Licensed Material:
        i. identification of the creator(s) of the Licensed Material and any others designated to receive

attribution, in any reasonable manner requested by the Licensor (including by pseudonym if designated);

    ii. a copyright notice;
    iii. a notice that refers to this Public License;
    iv. a notice that refers to the disclaimer of warranties;
    v. a URI or hyperlink to the Licensed Material to the extent reasonably practicable;

  B. indicate if You modified the Licensed Material and retain an indication of any previous modifications; and
  C. indicate the Licensed Material is licensed under this Public License, and include the text of, or the URI or hyperlink to, this Public License.

1. You may satisfy the conditions in Section 3(a)(1) in any reasonable manner based on the medium, means, and context in which You Share the Licensed Material. For example, it may be reasonable to satisfy the conditions by providing a URI or hyperlink to a resource that includes the required information.
2. If requested by the Licensor, You must remove any of the information required by Section 3(a)(1)(A)to the extent reasonably practicable.

a. **ShareAlike**.

In addition to the conditions in Section 3(a), if You Share Adapted Material You produce, the following conditions also apply.

1. The Adapter's License You apply must be a Creative Commons license with the same License Elements, this version or later, or a BY-NC-SA Compatible License.
2. You must include the text of, or the URI or hyperlink to, the Adapter's License You apply. You may satisfy this condition in any reasonable manner based on the medium, means, and context in which You Share Adapted Material.
3. You may not offer or impose any additional or different terms or conditions on, or apply any Effective Technological Measures to, Adapted Material that restrict exercise of the rights granted under the Adapter's License You apply.

Section 4 – Sui Generis Database Rights.

Where the Licensed Rights include Sui Generis Database Rights that apply to Your use of the Licensed Material:

a. for the avoidance of doubt, Section 2(a)(1) grants You the right to extract, reuse, reproduce, and Share all or a substantial portion of the contents of the database for NonCommercial purposes only;
b. if You include all or a substantial portion of the database contents in a database in which You have Sui Generis Database Rights, then the database in which You have Sui Generis Database Rights (but not its individual contents) is Adapted Material, including for purposes of Section 3(b); and
c. You must comply with the conditions in Section 3(a) if You Share all or a substantial portion of the contents of the database.

For the avoidance of doubt, this Section 4 supplements and does not replace Your obligations under this Public License where the Licensed Rights include other Copyright and Similar Rights.

Section 5 – Disclaimer of Warranties and Limitation of Liability.

a. **Unless otherwise separately undertaken by the Licensor, to the extent possible, the Licensor offers the Licensed Material as-is and as-available, and makes no representations or warranties of any kind concerning the Licensed Material, whether express, implied, statutory, or other. This includes, without limitation, warranties of title, merchantability, fitness for a particular purpose, non-infringement, absence of latent or other defects, accuracy, or the presence or absence of errors, whether or not known or discoverable. Where disclaimers of warranties are not allowed in full or in part, this disclaimer may not apply to You.**
b. **To the extent possible, in no event will the Licensor be liable to You on any legal theory (including, without limitation, negligence) or otherwise for any direct, special, indirect, incidental, consequential, punitive, exemplary, or other losses, costs, expenses, or damages arising out of this Public License or use of the Licensed Material, even if the Licensor has been advised of the possibility of such losses, costs, expenses, or damages. Where a limitation of liability is not allowed in full or in part, this**

limitation may not apply to You.

c. The disclaimer of warranties and limitation of liability provided above shall be interpreted in a manner that, to the extent possible, most closely approximates an absolute disclaimer and waiver of all liability.

Section 6 – Term and Termination.

a. This Public License applies for the term of the Copyright and Similar Rights licensed here. However, if You fail to comply with this Public License, then Your rights under this Public License terminate automatically.

b. Where Your right to use the Licensed Material has terminated under Section 6(a), it reinstates:
   1. automatically as of the date the violation is cured, provided it is cured within 30 days of Your discovery of the violation; or
   2. upon express reinstatement by the Licensor.

   For the avoidance of doubt, this Section 6(b) does not affect any right the Licensor may have to seek remedies for Your violations of this Public License.

c. For the avoidance of doubt, the Licensor may also offer the Licensed Material under separate terms or conditions or stop distributing the Licensed Material at any time; however, doing so will not terminate this Public License.

d. Sections 1, 5, 6, 7, and 8 survive termination of this Public License.

Section 7 – Other Terms and Conditions.

a. The Licensor shall not be bound by any additional or different terms or conditions communicated by You unless expressly agreed.

b. Any arrangements, understandings, or agreements regarding the Licensed Material not stated herein are separate from and independent of the terms and conditions of this Public License.

Section 8 – Interpretation.

a. For the avoidance of doubt, this Public License does not, and shall not be interpreted to, reduce, limit, restrict, or impose conditions on any use of the Licensed Material that could lawfully be made without permission under this Public License.

b. To the extent possible, if any provision of this Public License is deemed unenforceable, it shall be automatically reformed to the minimum extent necessary to make it enforceable. If the provision cannot be reformed, it shall be severed from this Public License without affecting the enforceability of the remaining terms and conditions.

c. No term or condition of this Public License will be waived and no failure to comply consented to unless expressly agreed to by the Licensor.

d. Nothing in this Public License constitutes or may be interpreted as a limitation upon, or waiver of, any privileges and immunities that apply to the Licensor or You, including from the legal processes of any jurisdiction or authority.

Creative Commons is not a party to its public licenses. Notwithstanding, Creative Commons may elect to apply one of its public licenses to material it publishes and in those instances will be considered the “Licensor.” The text of the Creative Commons public licenses is dedicated to the public domain under the CC0 Public Domain Dedication. Except for the limited purpose of indicating that material is shared under a Creative Commons public license or as otherwise permitted by the Creative Commons policies published at creativecommons.org/policies, Creative Commons does not authorize the use of the trademark “Creative Commons” or any other trademark or logo of Creative Commons without its prior written consent including, without limitation, in connection with any unauthorized modifications to any of its public licenses or any other arrangements, understandings, or agreements concerning use of licensed material. For the avoidance of doubt, this paragraph does not form part of the public licenses.

[266] Climate Interactive. “C_ROADS.” Retrieved 20 January 2016. <https://www.climateinteractive.org/tools/c-roads/ >.
[267] Union of Concerned Scientists. “Confronting Climate Change in the Gulf Coast Region.” Retrieved 9 December 2015. <http://www.ucsusa.org/sites/default/files/legacy/assets/documents/global_warming/gulfcoast.pdf>.
[268] Union of Concerned Scientists. “Climate Hot Map.” Retrieved 9 January 2016. <http://www.climatehotmap.org/>.
[269] Choose Climate. “JAVA Climate Model.” Retrieved 12 January 2016. <http://www.chooseclimate.org/>.
[270] PBS. “Warnings from the Ice: Teacher’s Guide.” *NOVA*. 21 April 1998. Retrieved 9 December 2015. <http://www.pbs.org/wgbh/nova/warnings/>.
[271] Ohio State University, Earth Systems Education Program. Home page. Retrieved 9 January 2016. <http://www.ag.ohio-state.edu/~earthsys/>.
[272] University of California, San Diego and Scripps Institute of Oceanography.. “Earthguide.” Retrieved 19 December 2015. <http://earthguide.ucsd.edu/>.
[273] Center for Climate and Energy Solutions. Home page. Retrieved 16 November 2015. <http://www.c2es.org/>.
[274] UN. “COP21 Paris Newsroom.” Retrieved 20 January 2016. <http://newsroom.unfccc.int/paris/>.
[275] New York Times. “The Road to a Paris Climate Deal.” Retrieved 20 January 2016. <http://www.nytimes.com/interactive/projects/cp/climate/2015-paris-climate-talks>.
[276] U.S. EPA. “Local Climate and Energy Program.” Retrieved 15 January 2016. <http://www3.epa.gov/statelocalclimate/local/>.
[277] Department of Ecology, Washington State. “Climate Change.” Retrieved 20 December 2015. <http://www.ecy.wa.gov/climatechange/climateEd_resources.htm>.
[278] Whitehouse.gov website. “FACT SHEET: Building community resilience by strengthening America’s natural resources and supporting green infrastructure.” Retrieved 22 January 2016. <https://www.whitehouse.gov/administration/eop/ceq/Press_Releases/October_8_2014>.
[279] Stevens, Caleb, et al. “Securing Rights, Combating Climate Change: How Strengthening Community Forest Rights Mitigates Climate Change.” *World Resources Institute* Web page. July 2014. Retrieved 15 December 2015. <http://www.wri.org/securingrights>.
[280] UNFCCC. “Climate Neutral Now.” Retrieved 15 December 2015. <http://climateneutralnow.org/SitePages/Home.aspx>.
[281] U.S. EPA. “Carbon Footprint Calculator.” Retrieved 9 January 2016. <https://www3.epa.gov/carbon-footprint-calculator/>.
[282] American Forests. “Climate Change Calculator.” Retrieved 11 November 2015. <https://www.americanforests.org/discover-forests/carbon-calculator/>.
[283] Meyer, Ron. “Your Carbon Diet.” PBS *NOVA* Online. Retrieved 20 January 2016. <http://www.pbs.org/wgbh/nova/warming/carbonpage.html>.
[284] Global Development Research Center. “The CO2 Calculator.” Retrieved 10 November 2015. <http://www.gdrc.org/uem/co2-cal/co2-calculator.html>.
[285] U.S. EPA. “Educator Links.” Retrieved 4 November 2015. <http://www3.epa.gov/climatechange/links.html>.
[286] Government of Canada Climate Change website. “Canada's Action on Climate Change.” Retrieved 19 January 2016. <http://www.climatechange.gc.ca/default.asp?lang=En&n=72f16a84-1 >.
[287] Learning for a Sustainable Future. “LSF Classroom Resources and Lesson Plans.” Retrieved 9 December 2015. <http://lsf-lst.ca/en/projects/teacher-resources/additional-resources>.
[288] World Resources Institute. “Sustainable Cities: From a Vision to Reality.” Retrieved 19 January 2016. <http://www.wri.org/blog/2014/02/sustainable-cities-vision-reality>.
[289] Climate Watch. “An Audio Series About Earth’s Atmosphere, Climate Change, and Global Warming.” Retrieved 12 January 2016. <http://www.climatewatch.net/>.