

Human-caused Global Warming and Climate Change: Understanding the Science

A Resource for Teachers, Students and Policy Makers



There Is No Planet B

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Understanding the Science***

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“I am only one, but I am one. I cannot do everything, but I can do something.
And I will not let what I cannot do interfere with what I can do.”

— Edward Everett Hale

Preface

I write this summary with a sense of humility as a nonscientist, standing on the shoulders of giants – the men and women of science who have done the research, understand the problem completely, and are worried about the consequences of unmitigated global warming. This Resource is my attempt to make this complex subject accessible to teachers, students, and policy-makers

You might be wondering how an assistant professor of education would decide to research and write about the science of global warming and climate change. Aside from the fact that this is a topic that everyone should become familiar with, I was actually just doing what teachers always do – respond to students’ questions. Students ask questions all the time about topics that are interesting to them. Some of those questions were about climate change and I had no information that I could confidently provide to them. For example, one student wanted to know *exactly* how carbon dioxide in the atmosphere warms the earth. Answering difficult questions has always been one of the most exciting aspects of teaching because it compels both teacher and student to expand their knowledge inventory.

It didn’t take long after beginning my research into global warming and climate change to realize that this subject was truly of paramount importance for everyone, but especially our students who must live in the world we are creating. After a decade of research, I decided to publish a summary of the science to provide other teachers with the objective, science-based information they need to design effective lessons on global warming and climate change. I have made every effort to keep the sections in this ‘teacher’s resource’ short and to the point, and I have included quotes from legitimate science sources as well as numerous graphics to help make the message clear. I believe it is imperative that the topic of global warming and climate change be taught at every grade level and in every subject area; the consequences of inaction will be horrific in terms of human suffering. Hopefully, teachers will use the information to design creative activities that help their students understand the problems posed by global warming and gain insights into possible solutions. This resource can also serve as a ‘student reading’ to provide the basic knowledge to junior high and high school students, college undergrads, and other interested parties. Policy makers should also find the content informative.

Most of the writing is mine but I have attempted to incorporate quotes from more “expert” sources whenever feasible and consistent with the overall objective of making the science understandable.

For those seeking a broader perspective written in language accessible to non-scientists, I recommend the book, *Earth: The Operators’ Manual*, by Richard Alley. The author is the Evan Pugh Professor of Geosciences at Penn State University and a member of the National Academy of Sciences. The book reads like a novel but provides virtually all relevant climate change information to make the reader well informed on the topic. It is an excellent resource.

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Introduction

Writing a summary such as this in language that is clear, concise, and accurate in language a non-scientist can understand is always a challenge, and it's especially challenging because the earth's climate system is extremely complex. But the science is clear, experimentally and theoretically verified, and compelling, and the consequences of unmitigated climate change so dire that any concerned inhabitant of earth should make the effort to understand what's going on with our planet.

Int.1 – Fossil Fuels, Greenhouse Gases and Global Warming

It is undeniably true that Earth, our home planet, is warming. The warming is rapid and global and virtually every climate scientist in the world agrees that this warming results from human activities, primarily the burning of fossil fuels. Since the combustion of fossil fuels plays such a prominent role, let's be sure we understand what we mean by the term "fossil fuels". The word "fossil" gives away the origin of these fuels. They are ancient. According to the U.S. Department of Energy:

*"Fossil energy sources, including **oil, coal and natural gas**, are non-renewable resources that formed when prehistoric plants and animals died and were gradually buried by layers of rock. Over millions of years, different types of fossil fuels formed -- depending on what combination of organic matter was present, how long it was buried and what temperature and pressure conditions existed as time passed."*

Importantly, fossil fuels are "non-renewable". In other words, the supply is finite, and when they're gone, they're gone. There is no process occurring today that will replenish these fuels.

Burning fossil fuels has provided us with a very comfortable standard of living, but it comes with a cost. The combustion of fossil fuels emits greenhouse gases that accumulate in the atmosphere. These greenhouse gases allow sunlight to penetrate the earth's atmosphere unimpeded and warm the earth's surface. The earth then reradiates this heat energy back to space at infrared wavelengths, but unlike incoming sunlight, these outgoing infrared wavelengths do not pass through the atmosphere unimpeded. Much like a blanket prevents the escape of heat from your body, greenhouse gases absorb the outgoing radiation, retaining the heat and further warming the earth.

The main greenhouse gases are water vapor, carbon dioxide, methane, ozone, nitrous oxide, and the manmade gases, chloroflourocarbons and hydroflourocarbons. Although greenhouse gases occur naturally, human activities have increased the atmospheric concentration of these gases causing global warming and climate change. Unless we eliminate all human emissions of greenhouse gases, the warming will continue.

How confident are climate scientists that human activities are causing greenhouse gases to accumulate in the atmosphere, warming the earth, and forcing earth's climate to change in ways that pose a serious problem for the earth and humanity? They're certain.

Int.2 – The Scientific Consensus

Virtually every organization of professional scientists in the world concurs with the position that our current global warming is the result of human activities. The following passage quotes the body of a letter written under the auspices of the American Association for the Advancement of Science (AAAS), *Letter to Congress* dated June 28, 2016.

“Dear Members of Congress,

We, as leaders of major scientific organizations, write to remind you of the consensus scientific view of climate change.

Observations throughout the world make it clear that climate change is occurring, and rigorous scientific research concludes that the greenhouse gases emitted by human activities are the primary driver. This conclusion is based on multiple independent lines of evidence and the vast body of peer-reviewed science.

There is strong evidence that ongoing climate change is having broad negative impacts on society, including the global economy, natural resources, and human health. For the United States, climate change impacts include greater threats of extreme weather events, sea level rise, and increased risk of regional water scarcity, heat waves, wildfires, and the disturbance of biological systems. The severity of climate change impacts is increasing and is expected to increase substantially in the coming decades.

To reduce the risk of the most severe impacts of climate change, greenhouse gas emissions must be substantially reduced. In addition, adaptation is necessary to address unavoidable consequences for human health and safety, food security, water availability, and national security, among others.

We, in the scientific community, are prepared to work with you on the scientific issues important to your deliberations as you seek to address the challenges of our changing climate.”

The letter is signed by the presidents of 31 American scientific organizations, and, since 2016 when the letter was written, the evidence has become far more compelling and worrisome.

But it's not just professional scientists in the United States who are deeply concerned. Virtually every organization of professional scientists in the world concurs. And the United States Government agrees. The Fourth National Climate Assessment, a congressionally mandated report written by 13 agencies of the United States Federal Government states that:

“it is extremely likely that human activities, especially emissions of greenhouse gases, are the dominant cause of the observed warming since the mid-20th century. For the warming over the last century, there is no convincing alternative explanation supported by the extent of the observational evidence.” (Vol. 1, “Climate Science Special Report”)

Int.3 – Corporate Hypocrisy on Global Warming

But aren't there scientists that do not believe in anthropogenic climate change? Yes, but they are very few and they are outliers, often funded by the fossil fuel industry or conservative "think tanks", that profit from the fossil fuel industry. This is the same fossil fuel industry that has known the truth about global warming for a long time.

In the August 1966 edition of the *Mining Congress Journal*, James Garvey, President of Bituminous Coal Research, states:

"There is evidence that the amount of carbon dioxide in the Earth's atmosphere is increasing rapidly as a result of the combustion of fossil fuels." Garvey continues, "If the future rate of increase continues as it is at the present, it has been predicted that, because the CO2 envelope reduces radiation, the temperature of the Earth's atmosphere will increase and that vast changes in the climates of the Earth will result."

This past October, Rex Tillerson, former CEO of ExxonMobil and Secretary of State under President Trump, testified under oath in a New York courtroom that the company knew for years that global warming was a significant threat.

"We knew, we knew it was a real issue," said Tillerson. "We knew it was a serious issue and we knew it was one that's going to be with us now, forevermore, and it's not something that was just suddenly going to disappear off of our concern list because it is going to be with us for certainly well beyond my lifetime."

ExxonMobil's internal documents confirm this. An internal report prepared by Exxon researcher, James Black in 1978 states:

"A doubling of carbon dioxide is estimated to be capable of increasing the average global temperature by from 1° to 3°C, with a 10°C rise predicted at the poles."

And there are many other internal reports from decades ago that corroborate exactly what the scientific community tells us about human-caused global warming and climate change. Despite their own reports, the fossil fuel industry continues to fund climate denialism producing propaganda intended to create doubt, obscure the truth and deceive the public.

The scientific process encourages presenting evidence that contradicts an established scientific position, but climate denialists offer no such evidence. Their challenges are baseless smokescreens, debunked by legitimate scientists, only to reappear again and again.

Here is one undeniable fact. If the fossil fuel industry and its contrarian scientists could disprove the scientific consensus, they would publish their rebuttal, win the Noble Prize and we would all be dancing in the streets. Don't hold your breath.

Chapter 1 – Historical Perspective on Global Warming

1.1 - The First Hint that Greenhouse Gases Warm the Earth

In the late 1800's, scientists measured the solar energy reaching the earth and calculated that the temperature of the earth should be minus 18^o Celsius (0^oF) – a frozen snowball. But actual measurements revealed the earth's temperature to be a relatively mild 15^oC (59^oF). The scientists concluded that this additional warming must result from trace amounts of greenhouse gases in the earth's atmosphere. This was not wild speculation. In 1859 John Tyndall had experimentally proved that carbon dioxide and other greenhouse gases absorb infrared radiation, producing a warming effect. Around the same time, chemists had discovered the formulas for the combustion of fossil fuels providing an understanding of mankind's role in the emissions of greenhouse gases. By the early 1900's physicists understood the basics of quantum theory – the physics explaining how subatomic particles interact with each other and with ordinary matter. This provided the basis for understanding how greenhouse gases absorb infrared radiation, causing the earth to warm.

By the mid 1900's, scientists were aware of the relationships affecting the earth's climate system. We now understand those relationships quite well. These relationships haven't changed since the 1800's, they have been experimentally and theoretically verified, and they form the foundation for understanding how and why the earth's climate is changing. Let me summarize in a brief paragraph the scientific knowledge as we understand it today. The proofs will be provided later.

We know that greenhouse gases absorb infrared radiation the earth emits to space, warming the planet. We know that human activities produce emissions of these greenhouse gases that accumulate in the atmosphere. This increase in the atmospheric concentration of greenhouse gases causes additional warming – global warming. We know that global warming forces the earth's climate system to adjust to the increased temperature, a phenomenon we call climate change. Finally, we know that extreme weather events, such as droughts, intense rainfall events, flooding, and tropical cyclones, are increasing in frequency and intensity due to global warming.

1.2 - Determinism and Climate Change

The Earth's Climate System Is Deterministic. Determinism, the notion that there is a cause for every effect, has two implications for climate science.

- First, significant changes to the earth's climate system always have a cause. The climate change might be slow, as in the recurring glacial-interglacial events (Milankovitch orbital variations), or the change can be rapid, as in the extinction of the dinosaurs (asteroid impact). Or, the climate can change at a relatively quick pace such as the current human-caused warming caused by increased emissions of greenhouse gases.
- Second, the current global warming of 1^oC (1.8^oF) since 1900 is a significant climate change event, hence there must be a cause. This temperature change doesn't seem like much but on a geological timescale, this increase in temperature of 1^oC in a hundred years, without a dramatic event such as an asteroid strike, is unprecedentedly rapid. We should be paying attention to changes this "rapid".

Chapter 2 – The Earth Is Warming

2.1 – Fact: The Warming Is Unprecedentedly Rapid

Professor Ed Hawkins, a climatologist at Reading University in the United Kingdom, has created a unique set of graphics called “Warming Stripes” to help us visualize the current global warming trends. His graphic below depicts the years “0 to Present” and clearly shows the rapid global warming that is occurring today as the darkening red spike at the far right that represents the present day. The warming is extremely rapid.

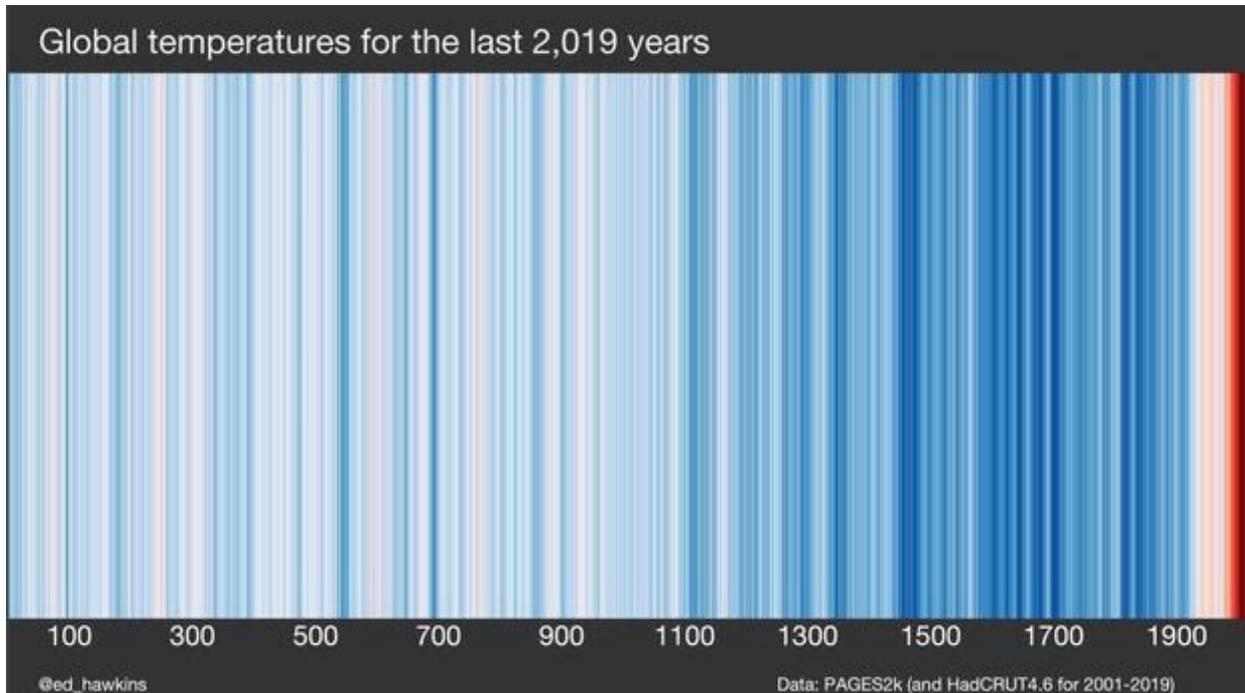
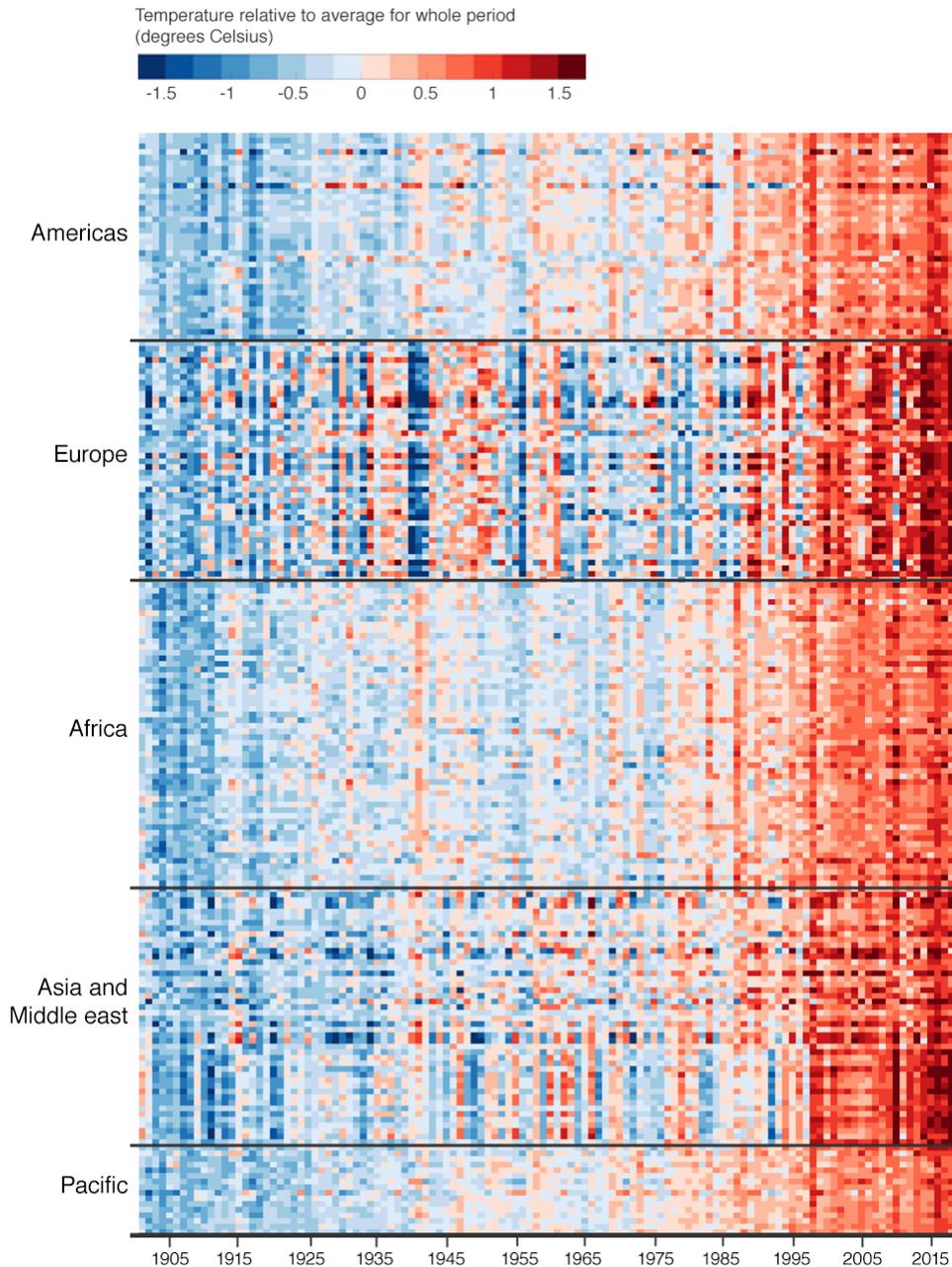


Figure 1 (Graphic courtesy of Reading University, credit Ed Hawkins, showyourstripes.info). Each line in this graphic represents a year, from 0 to 2019, with blue hues indicating temperatures below the 20th century average and red for years when temperatures were above that mark. Since reliable temperature data exists only from the 1800's, the data used to create the chart came from an international collaboration called “Past Global Changes 2K”. This group analyzed “proxy data” from tree rings, sediments, isotopic analyses, corals, stalactites, and marine foraminifera to approximate temperatures before the 1800's.

2.2 – Fact: The Warming Is Global

Another of the “Warming Stripes” series created by Professor Hawkins that demonstrates clearly that the current warming we are experiencing is not just some local or regional event but rather a strong global event. Each horizontal line represents a single country within the region.

Temperature changes around the world (1901-2018)



Source: Ed Hawkins/Reading University

BBC

Figure 2 (Graphic courtesy of Reading University, credit Ed Hawkins, showyourstripes.info). This graphic clearly shows the trend toward increasing temperatures for each world region. Each horizontal line represents one country in the region. The measured warming is clearly global.

Actual measurements by several different research groups establish that since 1880 the average temperature of the earth has risen by 1°C (1.8°F). In a commentary published in Nature Climate Change on February 25, 2019, scientists announced that a review of data from 40 years of satellite measurements of Earth’s temperature indicate that there is a 99.9999% probability that the increase in temperature is human-caused.

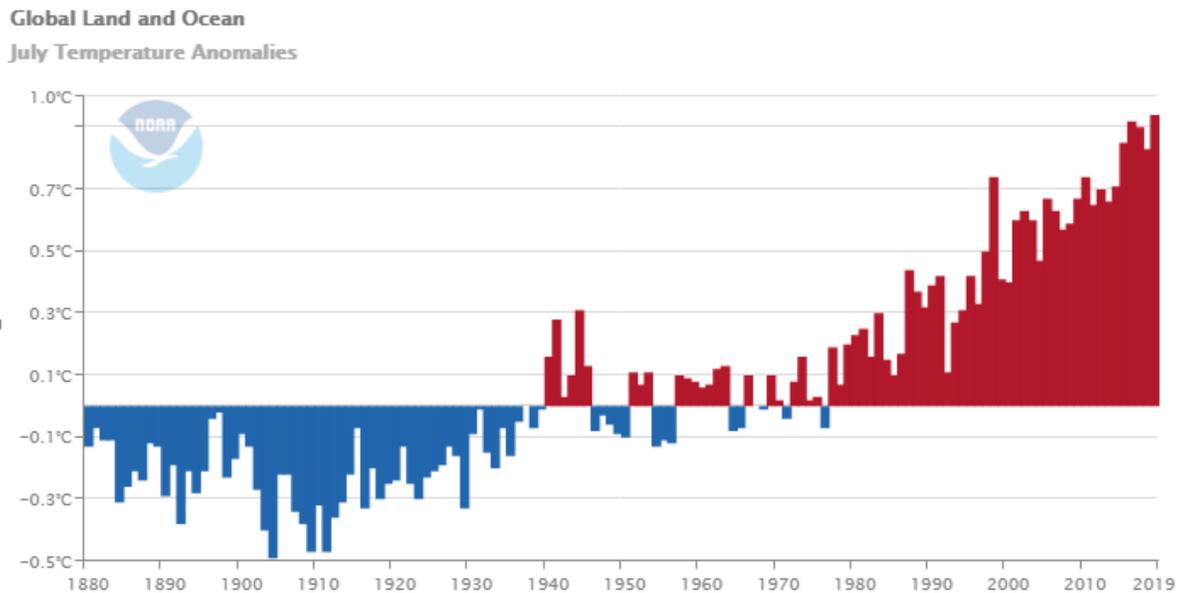


Figure 3 (Graphic courtesy of NOAA). This chart shows temperature anomalies from 1880 to 2019. Temperature anomalies are deviations from some baseline standard, such as the 20th century average temperature. Deviations above the baseline are warmer than average and those below the baseline are cooler than average. Temperature anomalies are often used because they clearly show any warming or cooling trend on a yearly basis. Note that both 1998 and 2016 were very warm years. Both years experienced a strong El Nino-Southern Oscillation (ENSO) event.

2.3 – Fact: The Measurements of Warming Are Reliable

Numerous different organizations worldwide provide the temperature datasets and all point to the same conclusion that the earth has warmed. These datasets include the following:

- NASA:GISSTEMP – NASA Goddard Institute for Space Studies
- NOAA:MLOST – NOAA Merged Land-Ocean Surface Temperature
- BEST – Berkeley Earth Surface Temperature
- Japan Meteorological Association
- HadCRUT – Combined sea surface temperature from the Hadley Centre of the UK Meteorological Office and land surface air temperatures from the Climatic Research Unit (CRU) of the University of East Anglia.
- Satellite temperature datasets (Earth System Science Center of the University of Alabama at Huntsville [UAH], Remote Sensing Systems [RSS], NASA Atmospheric Infrared Sounder [AIRS]).

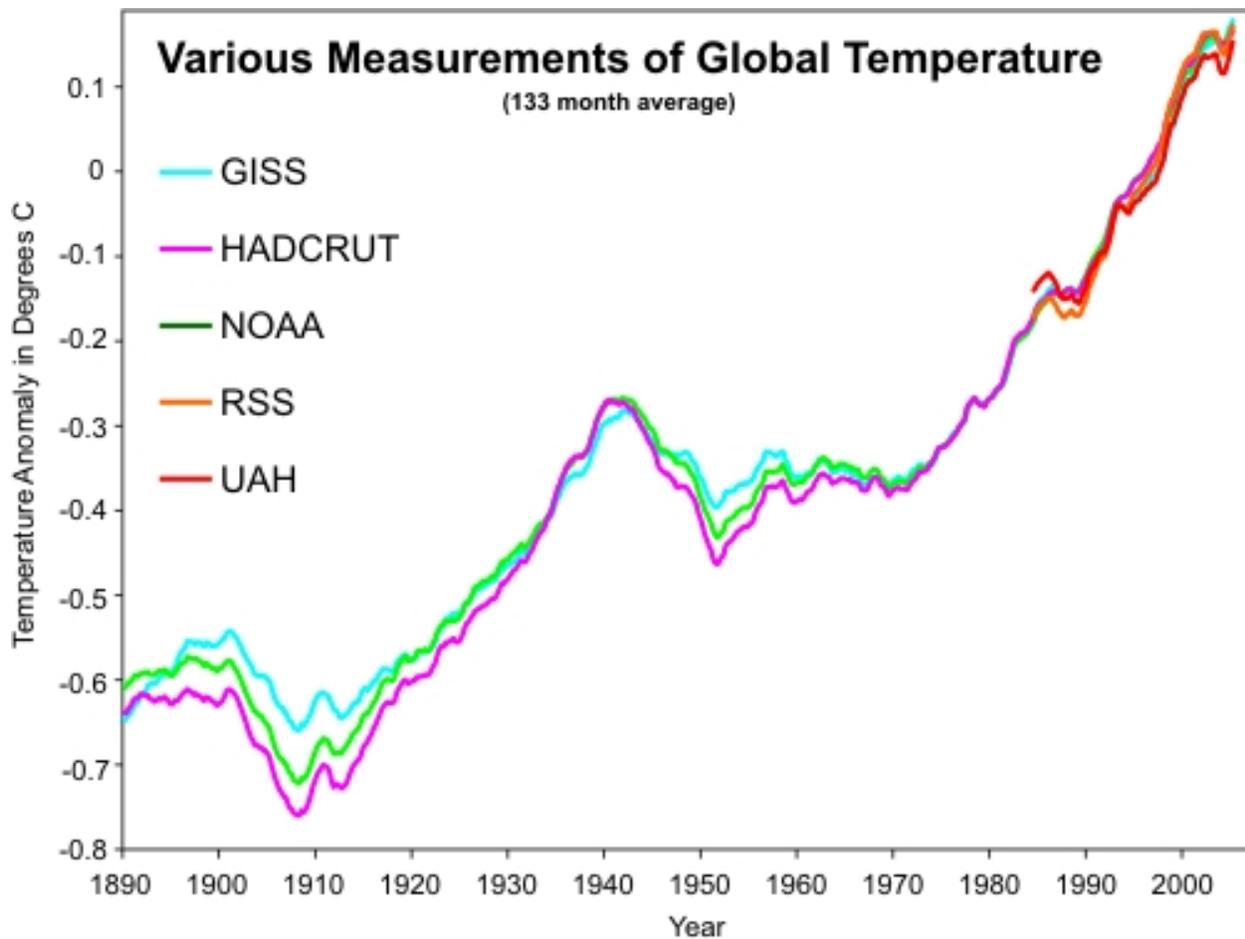


Figure 4 (Graphic courtesy of Skeptical Science). A composite of all the major global temperature records going back to 1890 (the satellite records only begin in the late 20th century). The datasets are the surface temperature measurements of NASA GISS, HadCRUT, and NOAA, plus the satellite measurements of lower atmosphere temperature by RSS and UAH. The datasets were compiled using the 1980-2010 average temperatures from each dataset. The data support the conclusion that the annual global temperature in 2019 was 1.1°C warmer than the average for 1850–1900, used to represent pre-industrial conditions. Additionally, since the 1980s, every decade has been warmer than the previous one, a trend expected to continue as the concentration of atmospheric greenhouse gases continues to increase. Other datasets, such as the independent Berkeley Earth and Japan Meteorological Agency agree with those listed above.

It's important to note that there are two ways different groups use to measure the earth's temperature: land and sea based thermometers and satellites. Thermometers are considered a bit more accurate since they are taking a direct measure of the heat content of the earth's surface and atmosphere. Satellite data is used to infer temperature indirectly by measuring microwave radiation emitted by oxygen molecules and then using computer models to analyze the data and determine temperature. Both measurements produce datasets that are consistent and complement each other proving the earth truly is warming.

2.4 – Fact: Earth’s Climate System Must Adjust to a Warming World

If the world is actually warming, and measurements show that it is, then we should expect to see the earth’s climate system adjust to this increasing temperature. Graphically, this would appear as the entire climate system shifting to a warmer world as shown in Figure 5.

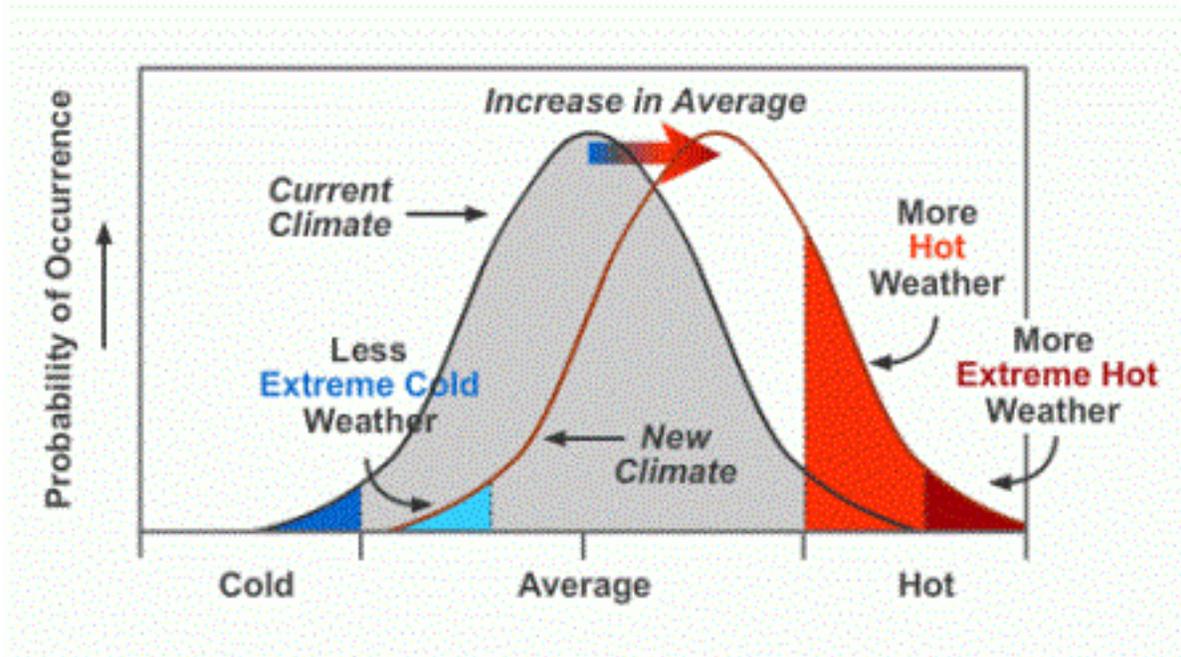


Figure 5 (Graphic courtesy of the EPA). As the graph indicates, warming temperatures shift all temperature-dependent elements of the climate system towards the warmer temperature ranges. In terms of weather, most regions will likely become hotter with more extreme hot weather events. Local variations in weather will, of course, continue to exist influenced by many factors independent of the general shift of the earth’s climate to a warmer world. Additionally, any elements of the climate that are influenced by temperature, such as droughts, will likely intensify.

A warming earth will affect many different elements of the climate system. For example, the rate of evaporation depends on temperature. Warmer temperatures increase evaporation causing heavier rainfall events. With heavier rainfall, flooding becomes more likely. As ocean temperatures rise, hurricanes are likely to become more intense since ocean heat drives tropical cyclones. If the earth is warming, we should see the effects of this warming in a variety of ways, and we do.

2.5 – How Earth Adjusts to a Warming World

Temperature measurements only tell part of the story. If the earth is actually warming, we should see visible, verifiable evidence of this warming – events we can see and measure that are expected if the planet is actually warming. In fact, observations of the natural world confirm that global warming is causing the earth’s climate system to adjust. The graphic depiction “Indicators of a Warming World” summarizes the observations.

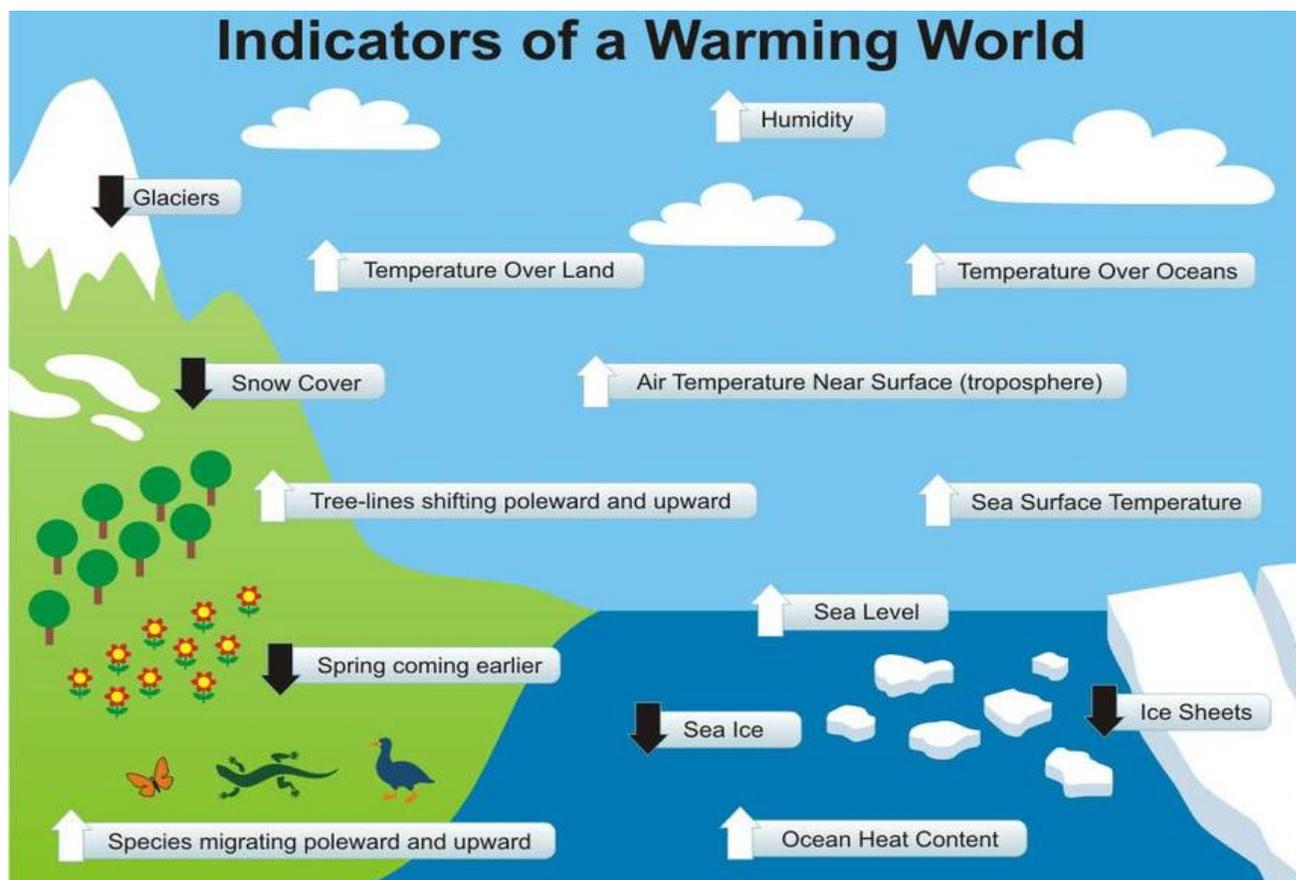


Figure 6 (Graphic courtesy of Skeptical Science). Each of these events was predicted to be an effect of global warming and observations confirm these predictions. If temperatures continue to increase, these effects will likely become magnified and create very serious problems for human societies worldwide.

2.6 – Observational Evidence Confirms Global Warming: The Effects of 1⁰ C (1.8⁰ F) Warming since 1880

One degree Celsius (1.8⁰F) warming doesn’t seem like a big deal but remember that the entire earth’s land, oceans and troposphere (lower atmosphere) have warmed by that amount. That’s a huge amount of mass that has absorbed enough energy to raise the average global temperature by that one degree Celsius. To put this in perspective, think about a child with a normal temperature of 98.6⁰F. If we add that 1.8⁰F of warming to the child’s temperature, the child has a temperature of 100.4⁰. Not life threatening but a fever to be sure. The problem with global warming is that there is no quick antibiotic fix. Unless we act, the temperature will continue warming and that *could* be life threatening.

The following symptoms are consequences of the 1^oC of global warming that we have already observed. Many climate effects are regional, but the general rule is this: Dry areas will become dryer, wet areas will become wetter, and rain events will become more intense.

- **Record setting temperatures!** A direct effect of the 1^oC increase in global mean temperature, the earth is experiencing consistently warmer record temperatures worldwide. June and July, 2019, were the warmest summer months since modern records have been kept (1880). July was also the warmest month ever recorded beating out July, 2016, which was a strong el Niño year. 2019 summer temperatures hit 115^oF in several countries of Europe and India saw 120^oF. Data show that for decades now, record high temperatures vastly outnumber record lows worldwide.
- **Heatwaves!** A heat wave is a prolonged period of extremely high temperatures for a particular region. Since what is considered a high temperature for any particular region varies, the term is “relative”. Like record setting high temperatures, heatwaves have become more common and more intense. Additionally, research and models suggest that as temperatures rise, heat waves will continue to become more frequent and more intense.
- **Droughts!** A drought is a prolonged period of abnormally low rainfall. Higher global temperatures cause an increase in evaporation. Increased evaporation combined with excessive temperatures and more frequent and intense heat waves have resulted in severe droughts in drought-prone areas of the world. Droughts lead to crop failure, famine and the displacement of thousands of people leading to worldwide refugee problems. Then there are **megadroughts** – prolonged periods of severe drought that last for months or years. These are so serious that historically they are known to have ended vibrant civilizations such as the Anasazi in the American Southwest. Remember the general rule: Dry areas will become dryer due to the increased evaporation caused by increasing temperatures.
- **Wildfires!** Another consequence of increased temperature, evaporation and drought is the drying of ground cover making wildfires more common and more intense. The 2018 wildfire season was one of the deadliest and most destructive on record with California enduring the most destructive wildfire season ever. 2019 saw the same situation in Australia. As worldwide temperatures increase, wildfires increase even in areas such as the Arctic that typically do not experience wildfires.
- **Heavy precipitation events!** Higher global average temperatures cause increased evaporation putting more water vapor into the atmosphere. Importantly, a warmer atmosphere holds more water vapor than a cooler atmosphere. As clouds containing water vapor rise, they cool and the increased amount of water vapor condenses and falls as relatively heavier, monsoon-like rainfall. Also, water vapor is a potent greenhouse gas and the additional amount of water vapor in the atmosphere is an amplifying feedback mechanism that enhances the “greenhouse effect”.
- **Flooding!** Because of the increased heavy precipitation events caused by increasing evaporation, extreme flooding events are occurring with increasing frequency and intensity. Monsoon-like heavy rainfall can overwhelm the natural and manmade channels and produce extreme flooding, which causes human suffering and places a financial burden on individual, state, and federal resources.

- **Sea Ice Melting!** As the earth warms, sea ice melts especially in the Arctic Ocean and Southern Ocean surrounding the continent of Antarctica. This does not cause sea levels to rise since sea ice is already “part of” the oceans. But the real problem involves the “Ice-Albedo” effect, an amplifying (warming) feedback. Sea ice reflects virtually all of the sunlight that strikes it. As sea ice melts, the darker ocean water absorbs almost all of that heat energy from sunlight causing additional warming.
- **Mountain Glaciers Melting!** Mountain glaciers virtually worldwide are melting and retreating as the earth warms and they are melting at an accelerating rate. Much of the meltwater eventually reaches the oceans, which accounts for about one-third of current sea level rise (about the same contribution as the melting Greenland ice sheet). Another problem is the effect the loss of mountain glaciers will have on the local communities that depend on melt water for their fresh water supply. In many of these regions there is simply no substitute and the local inhabitants will become refugees.
- **Polar Ice Sheets Melting!** The two largest ice sheets on the planet, the Greenland ice sheet and the Antarctic ice sheet, are both melting and losing mass. If the Greenland ice sheet melts entirely, the sea level will rise by 6 meters (about 20 feet) and the Antarctic ice sheet contains enough water to raise sea level by about 70 meters (about 230 feet). While a total meltdown is not likely, both ice sheets are losing mass at an accelerating rate. Currently, the Greenland ice sheet contributes about one-third of the rise in sea level and Antarctic ice sheet much less. These melt rates are accelerating and could become significantly higher if human emissions of GHGs continue to push the concentration of these gases higher. Most climate scientists believe the Greenland ice sheet is considerably more vulnerable and could reach a “tipping point” at global warming of 2⁰C. This is also more problematic because of the “Arctic Amplification”. Due to the local Ice-Albedo amplifying feedback that is currently occurring, the Arctic is warming twice as fast as the rest of the world. Recent research indicates that polar ice sheets are melting 6 times faster than the 1990’s.
- **Sea Level Rise!** According to NASA, over the last several decades, sea levels have risen at the fastest rate ever recorded and the rate is accelerating. Currently, sea levels are rising due to thermal expansion of the oceans (like most substances, water expands as it warms), land subsidence, slowing of ocean currents, the melting of mountain glaciers, and the melting of the polar ice sheets. If sea levels rise by 1 to 2 meters (about 3 to 6 feet) by 2100 as predicted, millions of people living in coastal regions will become refugees. And sea level rise varies considerably depending on other variables affecting specific coastal regions of the world. For example, the United States East Coast will experience greater than average sea level increase due to rebound land subsidence from the last glaciation and slowing of the Gulf Stream, allowing water to “pileup” along the coast. Worldwide, the threat of sea level rise and storm surge associated with storms will endanger over a billion people by 2100.
- **Desertification!** The definition of “desertification” is broader than the Sahara-like image most of us have. According the United Nations Convention to Combat Desertification (UNCCD), desertification means, “land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities.” Writing in Carbon Brief Explainers, August 6, 2019, Robert McSweeney states, “The combined impact of climate change, land mismanagement and unsustainable freshwater use has seen the world’s water-scarce regions increasingly degraded. This leaves their soils less able to support crops, livestock and wildlife... threatening the food

security and livelihoods of more than two-billion people.” While there are natural factors contributing to desertification, these problems are exacerbated by global warming as drylands become even dryer due to increased evaporation.

- **Tropical cyclones!** Tropical cyclones are fueled by sea surface temperatures, which is why they have traditionally been tropical events. As sea surface temperatures (SST) rise, climate scientists predict that these cyclones will increase in intensity and duration. The actual variables that cause these storms to form are complex and complicated, which makes the frequency of these extreme weather events difficult to predict. However, the increased sea surface temperature will definitely impact these storms once they form and the increased evaporation will cause more intense rainfall associated with these storms. Also, warming SSTs in middle latitudes enable tropical systems to maintain intensity as they move poleward.
- **Ocean acidification!** The oceans are currently absorbing between 25% and 50% of the carbon dioxide emitted by humans. The CO₂ dissolves in the salt water and forms carbonic acid, which “dissociates” into bicarbonate ions and hydrogen ions. The increased concentration of hydrogen ions lowers the pH causing the ocean to become more acidic. According to the Ocean Conservancy, ocean acidification has increased by 30% since the beginning of the Industrial Revolution and, “This rate of change surpasses all ocean chemistry changes in the past 50 million years. Living in an acidifying ocean is challenging for corals, oysters, lobsters and other shell-building animals.”
- **Species extinction!** Many scientists are suggesting the current geologic epoch, the Holocene epoch, should be renamed the “Anthropocene” because humans are having such an enormous impact on earth’s climate. One of the human impacts is named the “Sixth Mass Extinction” because so many species are unable to adapt to environmental changes humans have caused. Natural selection works by selecting those body forms best adapted to changing conditions and passing those genes on to the next generation. But for many species with slower reproductive rates that produce few offspring, this evolutionary process takes too much time to accomplish and, if they cannot adapt, they become extinct. The current pace of global warming is placing severe limits on the adaptive ability of many, many species.
- **Tropical climate zones expand poleward** – As the earth’s temperature rises, tropical ecosystems and species follow the warmth and expand poleward putting additional pressure on indigenous species. But the real problem for humans involves the increasing risk of tropical diseases invading subtropical regions, such as Florida and the American Southwest. Some of these tropical diseases are rare but deadly including Ebola hemorrhagic fever and Lassa fever and currently, there is no vaccine or cure for these diseases. These diseases are carried by insect vectors, such as mosquitoes, which cannot survive colder climates but as global warming expands their range, the diseases will follow into populous, more temperate regions.

As global mean temperature increases, all of these observed effects will likely increase in intensity and frequency. The IPCC issued a Special Report: Global Warming of 1.5⁰C (see page 19) has warned us that failing to stop global warming at 1.5⁰C will have drastic consequences for the earth’s climate system and all of earth’s species, including humans.

Chapter 3 – Climate Denialism: Could the Warming be Natural?

Scientists rely on objective evidence to reach their conclusions and all conclusions are conditional – tentatively accepted based on current evidence. Objectivity requires complete honesty and that means all explanations must be considered viable until they are disproved or rejected for lack of evidence. Of course, this means that scientists must consider natural explanations for the current global warming and climate change and they have. Scientists have evaluated and eliminated every known natural event that could cause the global warming we are measuring today. However, honesty requires that we address some of the most common claims for natural causes.

3.1 – Is the Current Global Warming just another Natural Event?

“The earth has warmed and cooled many times in the past, it’s just natural.”

Climate denialists have argued that because the earth has “naturally” warmed many times in the past, today’s warming must also be natural. While it is true that warming and cooling events have occurred in the past, those events always had a cause. Remember that the earth’s climate system might be very complex, but it is still deterministic – any significant change must have a cause. Without identifying a specific cause for the current warming, the argument that “it’s natural” immediately fails because it commits the logical fallacy of “jumping to conclusions”. Specifically, the premise, “the earth has warmed naturally in the past”, does not necessarily lead to the conclusion, “today’s warming must be natural.” Proving that link requires naming the natural cause and presenting convincing, objective evidence that proves the asserted natural cause is operating today. For example, the fact that some natural force, such as an increase in solar irradiance or large scale tectonic activity, caused warming hundreds of millions of years ago does not prove that it is operating today. This fallacy becomes obvious when we look at similar examples. For instance, “Humans have often died in the past from natural causes, therefore this man with a knife sticking out of his chest must have died of natural causes.”

In fact, over the earth’s long history there have been many *different* natural causes for warming and cooling events, including changes in solar output, asteroid strikes, mega-volcanic eruptions that released huge amounts of magma (and carbon dioxide), the Milankovitch orbital variations that caused the ice ages, and others. The one constant is this: There is always a cause for warming, cooling and a changing climate.

Now we can definitively add another cause for these warming events, human activities.

3.2 – Could the Sun Be Causing the Current Global Warming?

The sun is a magnetic variable star so its output does vary. Although solar irradiance varies the chart below shows that from 1880 to 2019 there is no correlation between solar activity and the current warming trend.

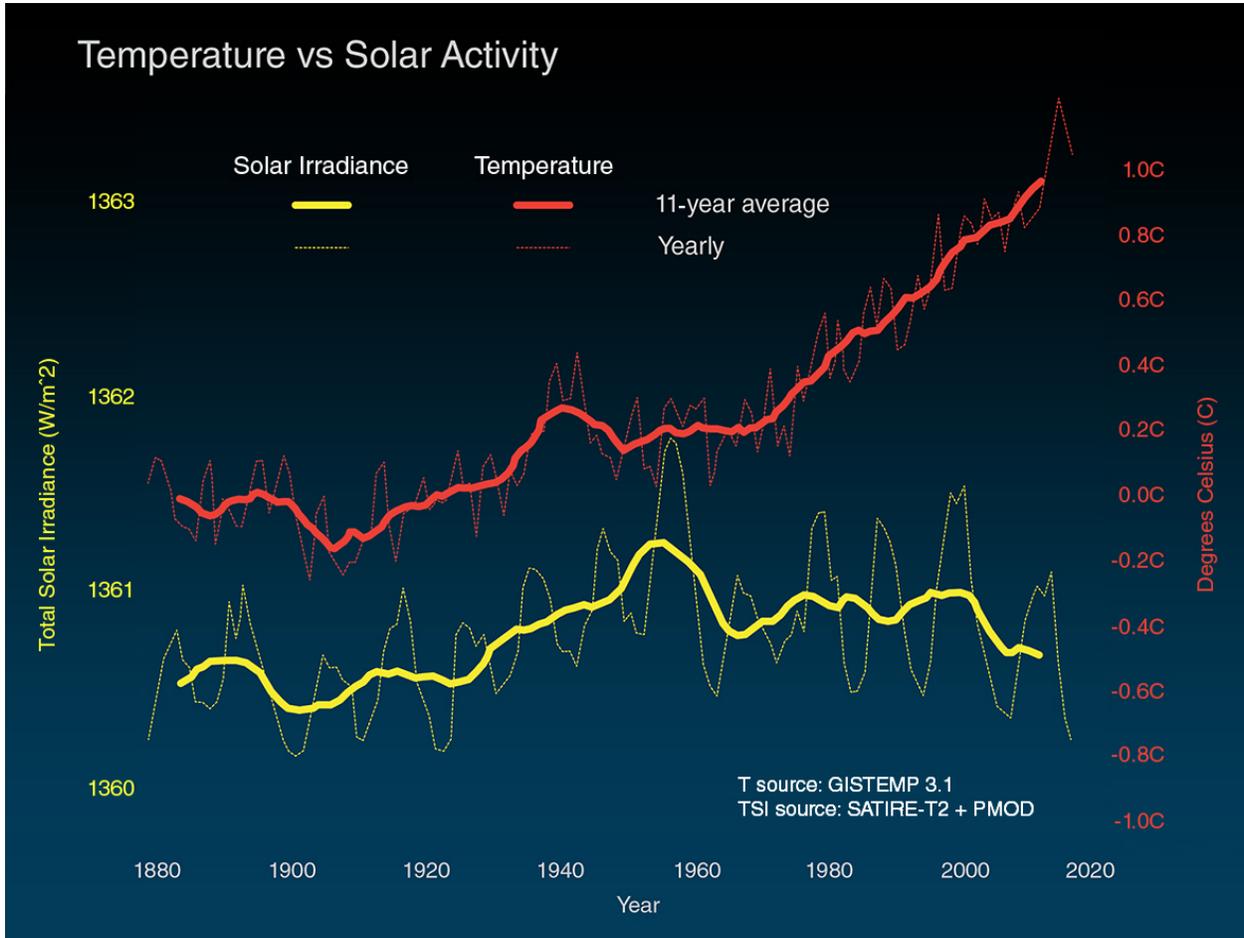


Figure 7 (Graphic and caption courtesy of NASA). “The above graph compares global surface temperature changes (red line) and the Sun’s energy received by the Earth (yellow line) in watts (units of energy) per square meter since 1880. The lighter/thinner lines show the yearly levels while the heavier/thicker lines show the 11-year average trends. Eleven-year averages are used to reduce the year-to-year natural noise in the data, making the underlying trends more obvious. The amount of solar energy received by the Earth has followed the Sun’s natural 11-year cycle (sunspot cycle, Ed.) of small ups and downs with no net increase since the 1950s. Over the same period, global temperature has risen markedly. It is therefore extremely unlikely that the Sun has caused the observed global temperature warming trend over the past half-century.”

According to NASA, Global Climate Change: “Is the Sun Causing Global Warming?”

“No. The Sun can influence the Earth’s climate, but it isn’t responsible for the warming trend we’ve seen over the past few decades. The Sun is a giver of life; it helps keep the planet warm enough for us to survive. We know subtle changes in the Earth’s orbit around the Sun are responsible for the comings and goings of the ice ages. But the warming we’ve seen over the last few decades is too rapid to be linked to changes in Earth’s orbit, and too large to be caused by solar activity.

One of the “smoking guns” that tells us the Sun is not causing global warming comes from looking at the amount of the Sun’s energy that hits the top of the atmosphere. Since 1978, scientists have been tracking this using sensors on satellites and what they tell us is that there has been no upward trend in the amount of the Sun’s energy reaching Earth.

A second smoking gun is that if the Sun were responsible for global warming, we would expect to see warming throughout all layers of the atmosphere, from the surface all the way up to the upper atmosphere (stratosphere). But what we actually see is warming at the surface and cooling in the stratosphere. This is consistent with the warming being caused by a build-up of heat-trapping gases near the surface of the Earth, and not by the Sun getting ‘hotter’.”

Furthermore, nights are warming faster than days and winter is warming faster than summer. Both of these observations are predicted by global warming theory resulting from heat being trapped in the atmosphere rather than increasing solar radiation, which would cause day and night and all seasons to warm evenly.

3.3 – Is the Current Global Warming a Result of Natural Variability?

Just as the earth has warmed and cooled before in the past, natural variability produces fluctuations in a wide variety of components of the climate system including temperature, rainfall, the extent of Arctic sea ice, and many others. Some of these fluctuations are known, such as the El Nino Southern Oscillation (ENSO). El Nino is the warm phase of the Southern Oscillation that can influence surface temperatures and weather patterns around the world. But these fluctuations tend to “even out” and the warm El Nino event alternates with the cooler phase called La Nina. The peaks and valleys in the graph below show the fluctuating nature of earth’s temperature from 1880 to 2018 but the *trend* is crystal clear, especially from 1960 to the present.

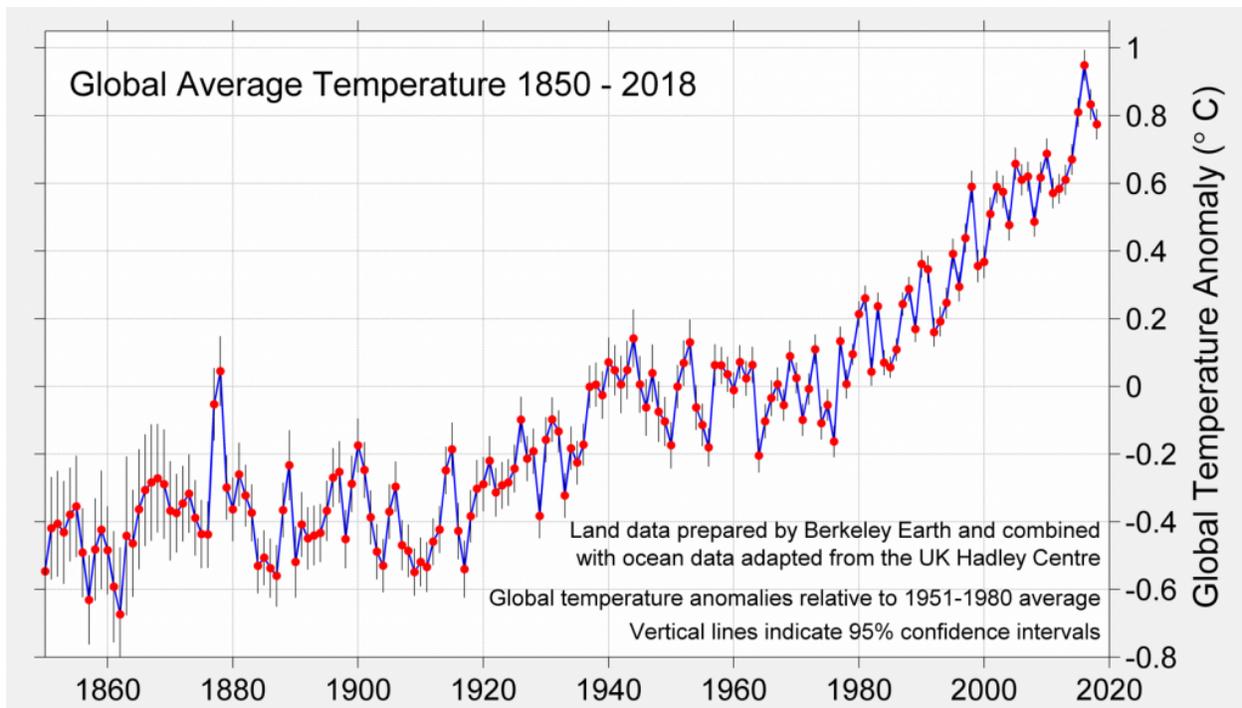


Figure 8 (Graphic courtesy of Berkeley Earth, “Global Temperature Report 2018”). The fluctuations in global temperature resulting from natural variability of the climate system are apparent in this graph as the dips and peaks but the trend of rising temperatures, especially since 1960, results from human-caused global warming.

To quote the Fourth National Climate Assessment produced by 13 federal agencies of the U.S. Government under the Trump administration (bold highlights are mine – Ed.):

*“Many lines of evidence demonstrate that human activities, especially emissions of greenhouse gases, are primarily responsible for the observed climate changes in the industrial era, especially over the last six decades... Over the last century, there are no alternative explanations supported by the evidence that are either credible or that can contribute more than marginally to the observed patterns. There is no convincing evidence that natural variability can account for the amount of and the pattern of global warming observed over the industrial era. Solar flux variations over the last six decades have been too small to explain the observed changes in climate. **There are no apparent natural cycles in the observational record that can explain the recent changes in climate. In addition, natural cycles within Earth’s climate system can only redistribute heat; they cannot be responsible for the observed increase in the overall heat content of the climate system.** Any explanations for the observed changes in climate must be grounded in understood physical mechanisms, appropriate in scale, and consistent in timing and direction with the long-term observed trends. Known human activities quite reasonably explain what has happened without the need for other factors. Internal variability and forcing factors other than human activities cannot explain what is happening, and there are no suggested factors, even speculative ones, that can explain the timing or magnitude and that would somehow cancel out the role of human factors.”*
(Chapter 1, Introduction 1.1)

3.4 – Conclusion: Climate Denialism Fails

Climate denialists have made many arguments suggesting that climate change is somehow “natural” but they provide no evidence to support that claim nor do they identify a specific natural cause. No reasonable person should accept a premise or hypothesis that offers no credible evidence to support it. In conclusion, we can make two observations:

The evidence for a “natural” cause of global warming is lacking. To this date, climate denialists have not identified any “natural” force that could be driving the current global warming nor have they produced any credible evidence to support that assertion. In fact, for decades, scientists have examined all “climate drivers”, both natural and manmade, and found no natural causes that could possibly explain the warming we are seeing today. The “burden of proof” has not been met. See also Chapter 15, Science and Uncertainty.

The evidence for anthropogenic global warming is compelling. On the other hand, the scientific evidence for anthropogenic global warming is compelling and it is the most persuasive kind of evidence science can offer – *convergent evidence*. This is evidence from various different scientific disciplines that support the same, single conclusion – that human activities are causing the current global warming. The evidence, grounded in established scientific theory, also proves that today’s global warming *is occurring at a pace much quicker than events from the past*. The fact that earth has warmed by 1⁰C in 100 years is pretty much unprecedented. This suggests two points:

1. Human activities that create an increase in the atmospheric concentration of greenhouse gases are surprisingly powerful at initiating climate change.
2. Since human emissions of greenhouse gases have caused the problem, humanity must act to address the problem by reducing these emissions. There is no natural force that can reverse global warming and climate change over any reasonable timescale. The earth’s thermostat, the long-term carbon cycle mentioned in Chapter 7, requires many millions of years to reduce atmospheric carbon dioxide, cooling the planet.

Chapter 4 – Climate Sensitivity

Very basically, climate sensitivity asks this question: If we double the atmospheric concentration of carbon dioxide, how much will the earth's temperature rise? Climate scientists know that current emissions of greenhouse gases will cause changes to the earth's climate system that will be bad. Climate sensitivity asks the questions, "How bad?" and "How soon?"

For perspective on the problem the Intergovernmental Panel on Climate Change (IPCC) released a "Special Report: Global Warming of 1.5⁰ C" in October 2018 warning us that overshooting 1.5⁰C and warming to 2.0⁰C would have dramatic consequences for the earth's climate. It will not be an easy journey. In an October 7, 2018 article in National Geographic entitled "Environment", Stephen Leahy, captures the essence of the monumental effort that will be required:

"The IPCC's Special Report lays out various pathways to stabilize global warming at 2.7 degrees Fahrenheit (1.5 degrees Celsius). These solutions all require unprecedented efforts to cut fossil-fuel use in half in less than 15 years and eliminate their use almost entirely in 30 years. This means no home, business, or industry heated by gas or oil; no vehicles powered by diesel or gasoline; all coal and gas power plants shuttered; the petrochemical industry converted wholesale to green chemistry; and heavy industry like steel and aluminum production either using carbon-free energy sources or employing technology to capture CO2 emissions and permanently store it."

Cutting the use of fossil fuels to "net zero emissions" is a critical first step. This will prevent any further increase in the atmospheric concentration of GHGs. Unfortunately, accurately assessing climate sensitivity is extremely difficult because it must attempt to predict the future efforts of the world's governments to effectively reduce emissions of GHGs. Additionally, scientists must try to predict amplifying (positive) feedbacks that intensify global warming, such as increasing emissions of GHGs from melting permafrost.

Regarding current estimates of climate sensitivity, an article in the January, 2020 edition of *Nature*, Comment Section entitled, "Emissions – The 'business as usual' story is misleading" provides an updated analysis of likely possible future outcomes for various potential emissions pathways. To quote from the conclusion of the article:

"Assessment of current policies suggests that the world is on course for around 3 °C of warming above pre-industrial levels by the end of the century — still a catastrophic outcome, but a long way from 5 °C (the "business as usual" estimate of the IPCC Fifth Report – Ed.)."

While the new estimate is far below earlier pessimistic predictions, it is still "catastrophic". If the earth's temperature increases by 3⁰C, sea levels will likely rise over 100 feet, wildfires will ravage large sections of the earth, droughts will cause widespread famine, floods and other extreme weather events will displace tens of millions, and prolonged heat waves will kill many tens of millions. And there will be additional horrors difficult to predict or even imagine. Total deaths will be counted in the hundreds of millions.

Figure 9 shows the newer projected emissions scenarios and outcomes that will likely appear in the IPCC Sixth Assessment Report.

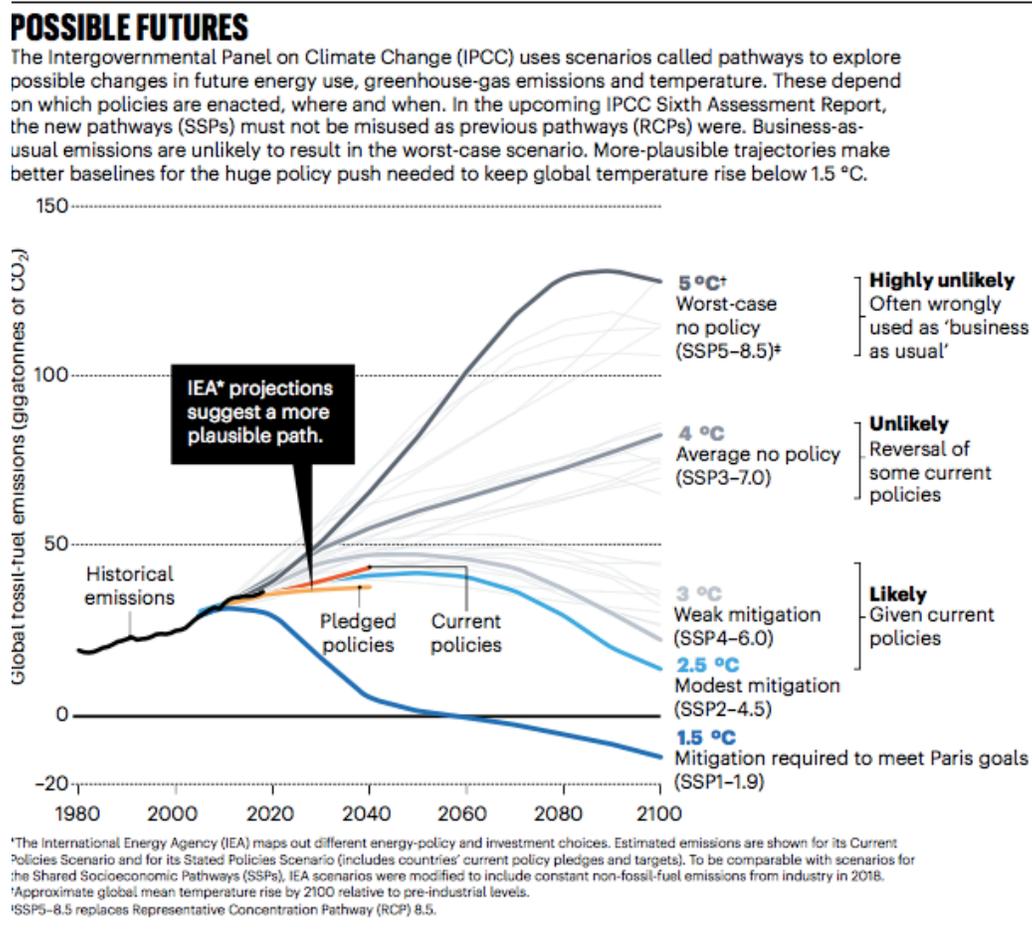


Figure 9 (Graphic courtesy of the International Energy Agency). It's important to remember the difference between greenhouse gas emissions and the concentration of atmospheric greenhouse gases. The article and graph represent a discussion of the various emissions policies that countries of the world might, or might not, implement. But any future global warming will be the result of the total, actual concentration of greenhouse gases and that is influenced by factors in addition to human emissions. For example, if climate feedbacks increase significantly, this will cause an increase in the concentration of GHGs beyond what is produced from human emissions and the situation could be far worse than even these dire predictions. But make no mistake about this fact, an increase of 3⁰C will result in devastating consequences for Planet Earth and its inhabitants.

Chapter 5 – Understanding the Basics of Global Warming: Heat and Heat Transfer

5.1 – Understanding “Heat”

According to the kinetic-molecular theory of heat, ordinary matter is made up of atoms and molecules that are in constant motion due to the energy they possess. The motion of these atoms and molecules depends on their phase of matter – gas, liquid, or solid. In a gas, the molecules are spread out and the motion of the molecules is more or less random with the molecules constantly colliding with each other. In a liquid, the molecules are in loose contact with each other and their energy of motion involves the molecules “sliding” around each other. Finally (ignoring plasmas), in a solid sample of matter, the molecules are locked into a fixed position and their energy exists as vibrational motion. What we call “heat” depends upon the speed of motion of the atoms and molecules. If the molecules of a sample of matter are forced to speed up, their heat energy (and temperature) increases and vice versa. “Temperature” is a measure of the average molecular motion in any sample of matter at a specific time.

5.2 – Understanding “Heat Transfer”: Conduction, Convection, and Radiative Transfer

Heat can be transferred in three basic ways, by conduction, convection, and radiation. Both conduction and convection require matter – molecules or atoms – to be in direct contact and heat transfers in the direction from warmer to cooler (always warmer to cooler). Radiative transfer does not require direct contact between the warmer and cooler objects.

Conduction. Conduction occurs when two objects of different temperature are in physical contact. Heat always moves from the warmer to the cooler object until both are at the same temperature – thermodynamic equilibrium. Conduction occurs when the faster moving molecules of the warmer object collide with the slower moving molecules of the cooler object. The faster (warmer) molecules transfer some of their energy of motion to the slower (cooler) molecules causing them to move more quickly, which means they are getting warmer. The process continues until all the molecules that are in contact are moving at the same rate, and are therefore at the same temperature. The system has reached thermodynamic equilibrium.

Convection. Convection occurs in liquids or gases when warmer areas rise relative to cooler areas and are replaced by cooler molecules. This occurs because warmer areas are composed of molecules moving more quickly and rapidly colliding with each other, driving them further apart in the process. This means these colliding areas are *less dense* (fewer molecules per unit area) so they “rise”. As they rise, they leave an “empty” area behind that is replaced by cooler, denser molecules. Convection is critically important to earth’s weather system; the rising air masses replaced by cooler air masses create winds as well as areas of lower and higher pressure, which dramatically affect local weather events.

Radiation. Radiation is a form of heat transfer that can be transmitted through empty space and it operates because electromagnetic radiation can interact with ordinary matter following the rules of physics. Very basically, all objects above absolute zero emit photons (radiation). Individual atoms and molecules can also emit photons when “excited”. The electrons of

“excited” atoms or molecules have “jumped” to a higher energy level but the “excited” state is unstable. Molecules emit a photon when they fall back into their stable “ground” state. The emitted energy, the photon, is actually electromagnetic radiation of a certain wave length and frequency. If the photon collides with a molecule of matter, it can be absorbed raising the energy level of the absorbing molecule. This transfer of energy forms the basis for the exchange of heat that warms earth, to be explained in greater detail shortly.

All three of these heat transfer processes are involved in understanding global warming and climate change. The basic processes are depicted in the diagram below.

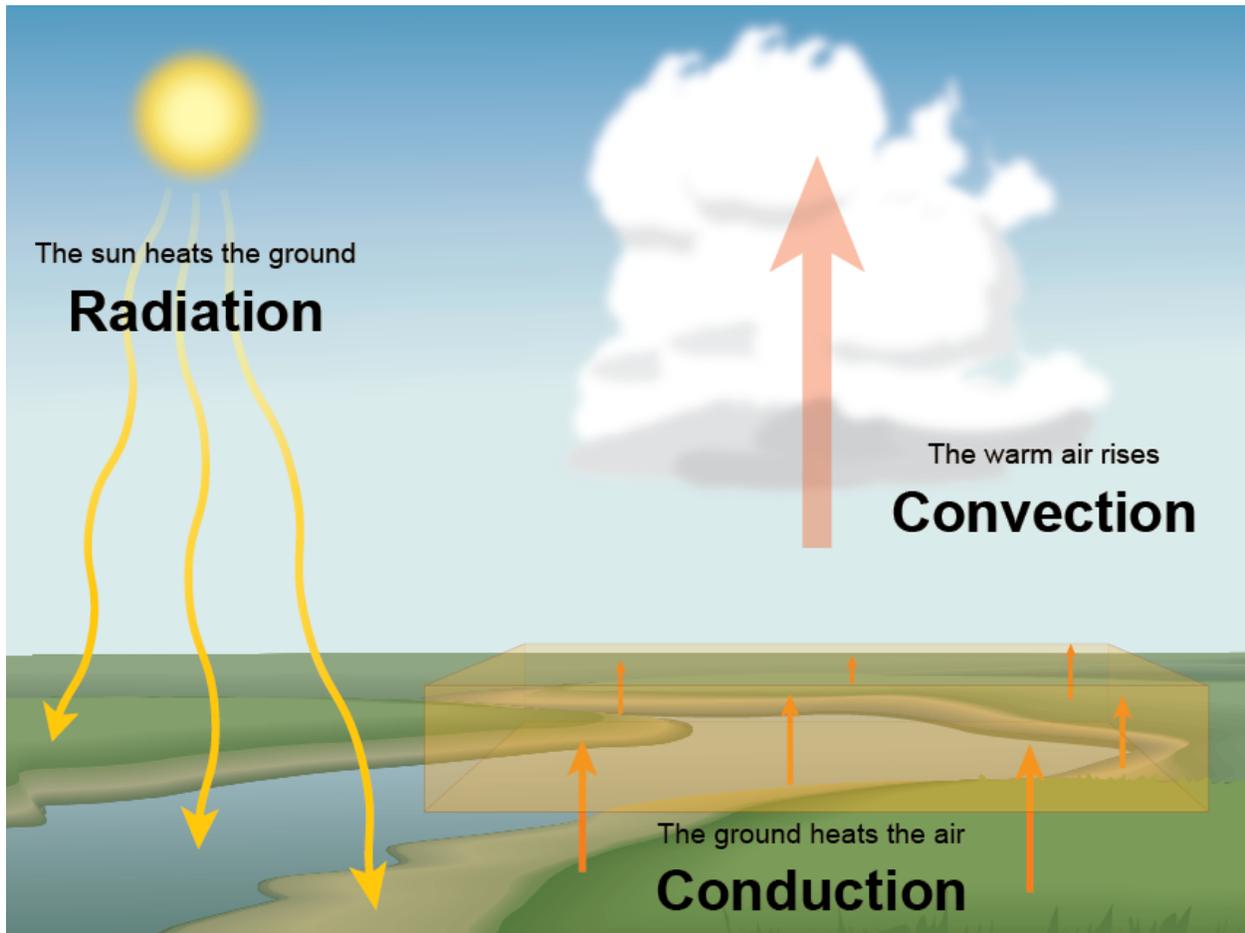


Figure 10 (Graphic courtesy of the U.S. National Weather Service). Energy from the sun in the form of electromagnetic radiation interacts with the molecules of ordinary matter that constitute the earth’s surface material. The earth’s surface “warms” from this radiation and then transfers this heat to the molecules of air above the surface via conduction. Since this warmed air is less dense (because its molecules are further apart resulting from the faster collisions between its molecules), this air rises.

Although each of the methods of heat transfer play important roles in earth’s climate and weather, we must first understand how the sun’s electromagnetic energy transfers heat to warm the earth. Then, we must understand the basic physics involved in how and why greenhouse gases trap heat energy and warm the planet.

Chapter 6 – Understanding the Physics of Global Warming

6.1 – The Electromagnetic Spectrum

Since the sun is the primary source of heat for the earth, we must understand a bit about radiative energy. The general rule is that all objects above absolute zero emit radiation. That rule, known as Planck's Law, applies to stars, planets, human beings, and any other object composed of ordinary matter. The graph below shows the electromagnetic radiation spectrum including the visible spectrum, which you likely recall from the mnemonic ROY G BIV. It's easy to forget that our familiar visible spectrum is only a small part of the entire electromagnetic spectrum. It's hard to underestimate the importance of the various parts of the electromagnetic spectrum humans use, including X-rays, radio waves and microwaves. The difference between these various parts of the spectrum depends upon the wavelength and frequency of the various waves.

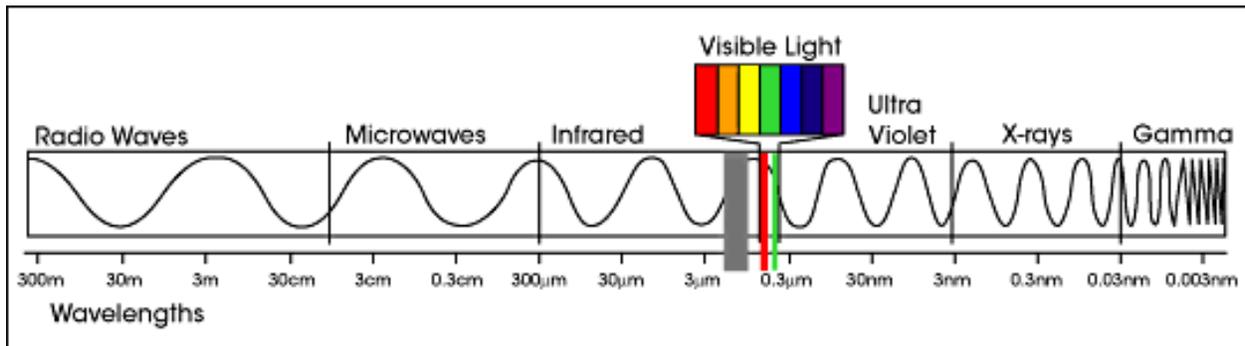


Figure 11 (Graphic courtesy of NASA). This graphic illustrates the electromagnetic spectrum. We classify radiant energy by wavelength and organize it into a chart known as the “electromagnetic spectrum.” A portion of that chart is pictured above. Wavelength is the distance between the crests of the waves in a beam of light. The shorter the wavelength, the more energy the wave has.

6.2 – Emissions Spectra of Sun and Earth

Importantly, the wavelengths and frequency of the electromagnetic energy emitted by any object depends only on the temperature of the object. The Sun, being extremely hot, emits prodigious amounts of radiation (technically, at all wavelengths), but the most intense radiation is centered on the “visible” portion of its emission spectrum, which we call sunlight. It is not a coincidence that humans have evolved eyes that “see” in the visible part of the spectrum since those are the exact wavelengths where the sun emits its most intense radiation.

At a temperature of about 5800°C , the most intense radiation from the sun centers on the shorter wavelength, visible part of the electromagnetic spectrum. This is significant because at these “short” wavelengths, virtually all of the sun’s radiation penetrates the earth’s atmosphere, which is transparent to these wavelengths. In other words, the earth’s atmosphere does not absorb incoming solar radiation at these wavelengths. The solar irradiance (flux of radiant energy per unit area) warms the earth to a temperature of about 15°C (59°F). At this temperature, the earth emits back towards space radiation centered on the infrared wavelengths, which are precisely the wavelengths that greenhouse gases absorb.

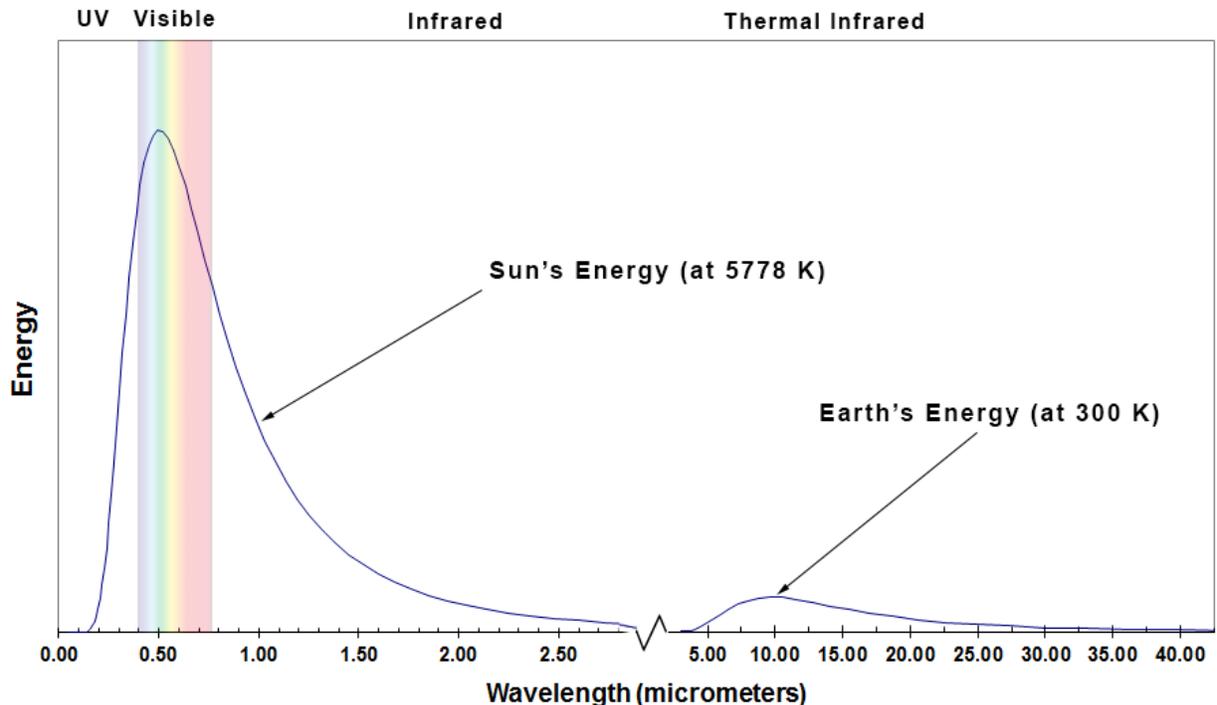


Figure 12. (Graphic courtesy of Humboldt State University, Geospatial Online). The graph above portrays symbolically the emissions of the sun and the earth. Please note that the representation of intensity is NOT to scale and the units of intensity (Energy) for the Y axis are intentionally omitted. All objects emit radiation, whether a star, a planet, or a person. The intensity of that radiation as well as the wavelengths the object emits are determined solely by the temperature of the emitting object. According to the radiation laws, the hotter the temperature, the more intense the radiation emitted (Stefan-Boltzmann Law) and the shorter the wavelengths emitted (Wien's Displacement Law).

6.3. – Thermodynamic Equilibrium: Energy In = Energy Out

Earth Must Radiate Back to Space an Amount of Energy Equal to the Solar Energy it Receives

According to the First Law of Thermodynamics, a planet *in thermodynamic equilibrium* must reradiate back to space the same amount of energy it receives from the sun. This makes sense. If the earth did not radiate exactly the same amount of energy to space that it receives, it would just keep getting warmer. If the planet is not in equilibrium, if “Energy In” is greater than “Energy Out”, the planet must warm to a higher temperature and reemit more radiation to space.

Although sunlight hits only half of the earth’s surface at any given time, the fact that the earth is rotating on its axis means that the entire surface warms. Additionally, the presence of greenhouse gases traps heat in the atmosphere, warming the earth to 15⁰C (59⁰F) making the planet habitable for humans.

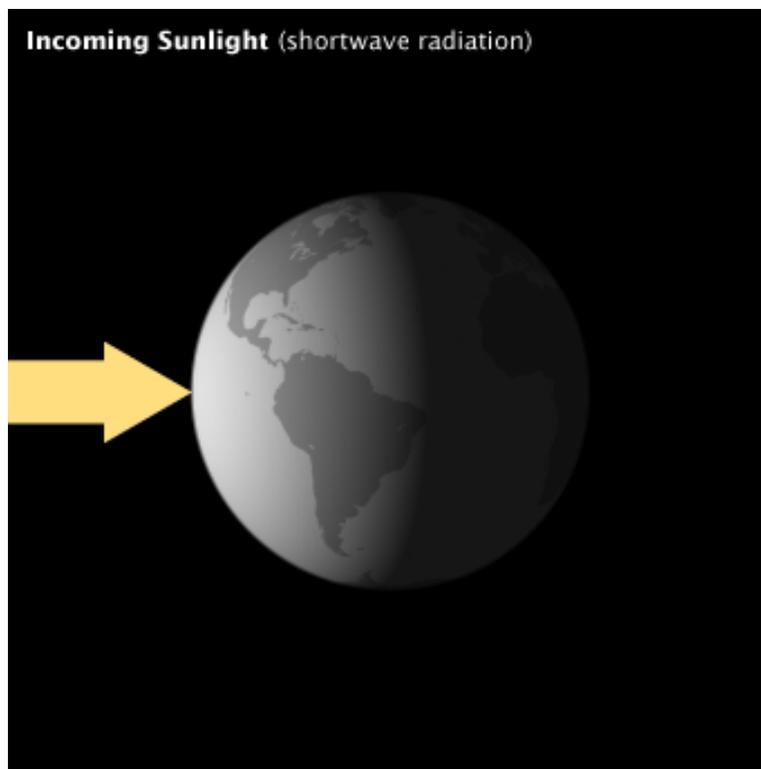


Figure 13 (Graphic courtesy of NASA, Earth Observatory). The earth receives virtually all of its energy from the sun. Solar radiation arrives at the earth as sunlight, centered on the shortwave, visible portion of the electromagnetic spectrum which warms the earth to an average global temperature of 15⁰C (59⁰F). The earth’s atmosphere is transparent to this incoming solar radiation.

Warmed by the sun's energy, the earth radiates that energy back to space from its entire surface in the form of longwave, infrared electromagnetic energy.

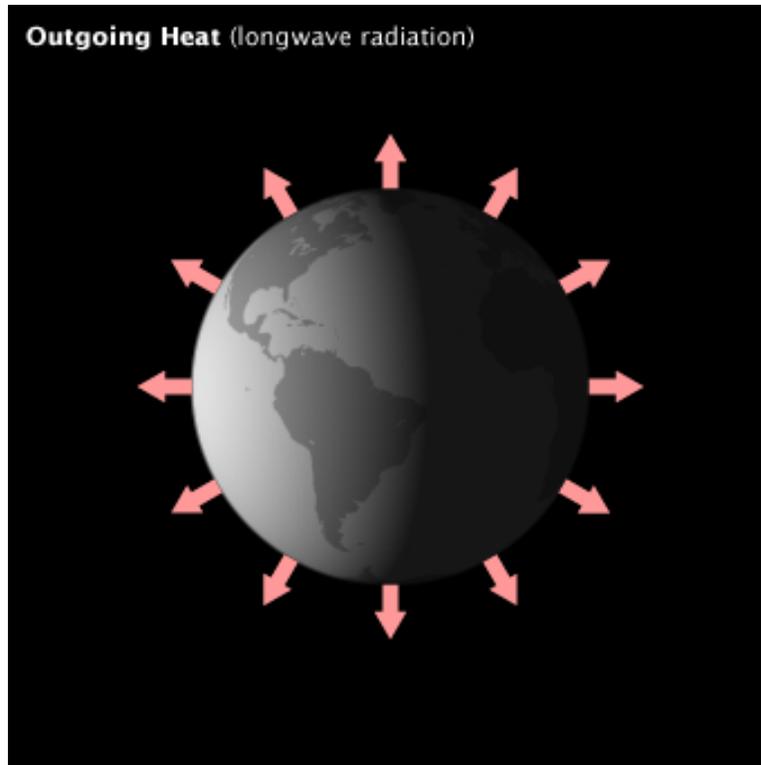
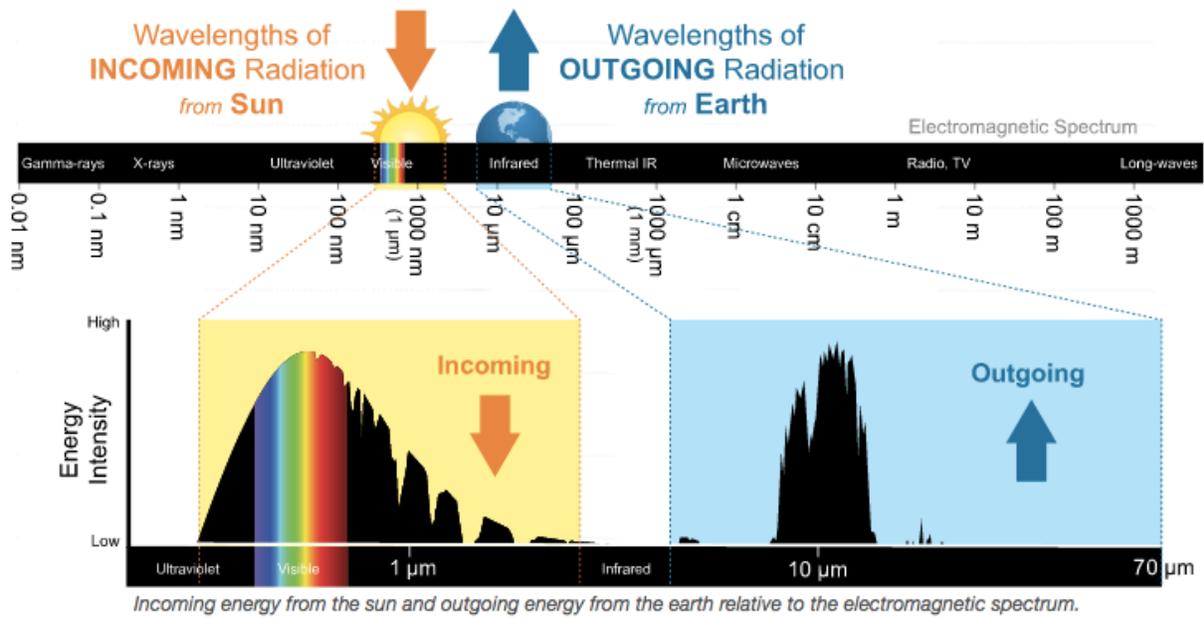


Figure 14 (Graphic courtesy of NASA, Earth Observatory). At 15⁰C, the earth reradiates to space in the infrared wavelengths. The fact that the earth reradiates in these specific wavelengths is important for global warming because it is these specific infrared wavelengths that are intercepted and absorbed by molecules of greenhouse gases, trapping heat and causing the earth's temperature to increase.

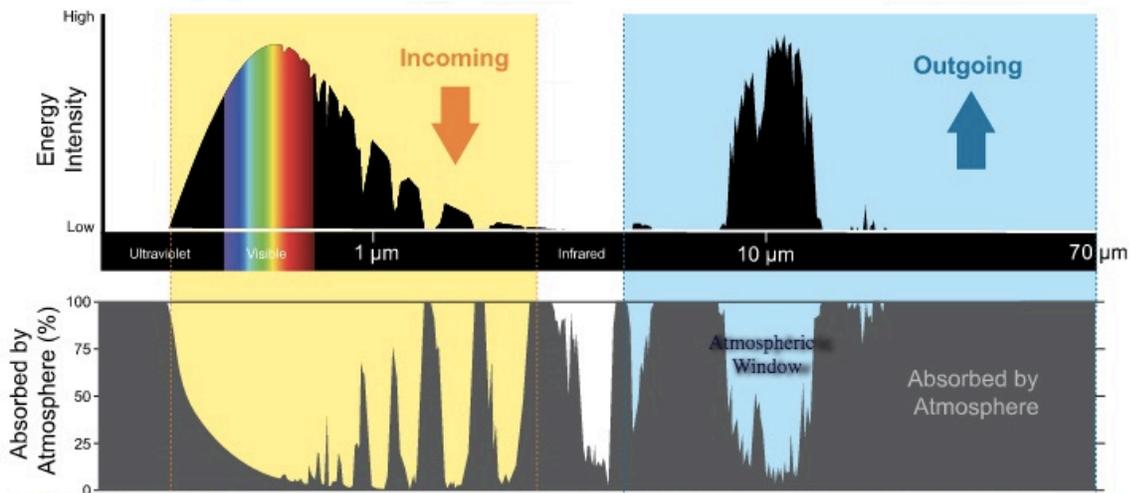
6.4 – Why the Earth Emits Radiation at Infrared Wavelengths

As described by the radiation laws, both the intensity of the radiation emitted and the wavelength emitted depend only on the temperature of the object. The hotter the object, the more intense the radiation emitted and the shorter the wavelength emitted. Because its temperature is 15⁰C, the earth radiates to space in lower wavelength, infrared radiation.

The fact that earth emits radiation in the infrared band centered around 10 μm (microns) is important for two reasons. First, infrared wavelengths are precisely the wavelengths absorbed by greenhouse gases causing the “greenhouse effect”. Second, an “atmospheric window” exists at 10 μm , a gap in the electromagnetic spectrum where greenhouse gases do not absorb outgoing radiation. This “atmospheric window” allows earth to radiate heat back to space maintaining thermodynamic equilibrium – a balance between the energy it receives and the energy it emits.



The dips in the incoming and outgoing energy are where the atmosphere absorbs energy. Some of the incoming energy is absorbed by the atmosphere whereas most of the infrared energy emitted by the earth is absorbed.



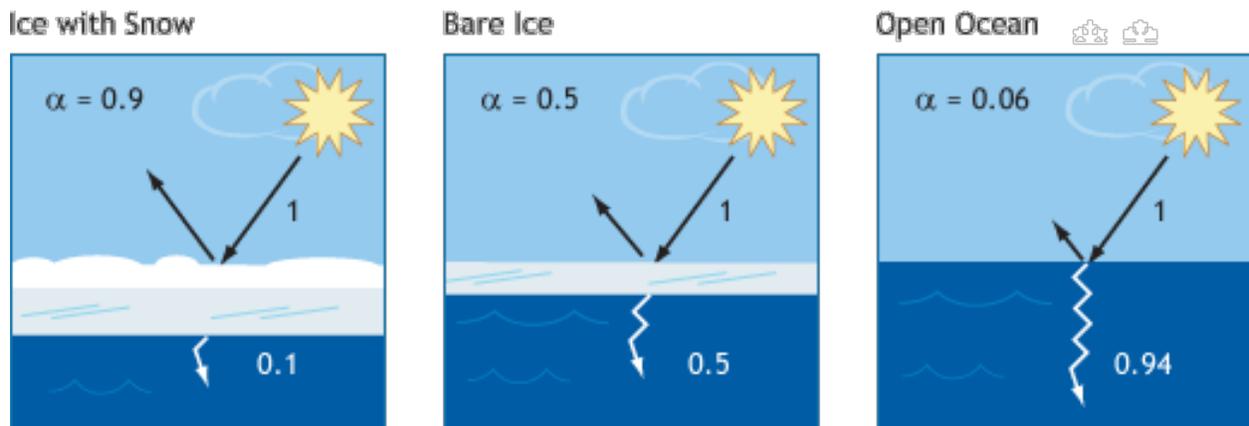
The places with limited or almost no absorption by the atmosphere is known as the atmospheric window - allowing us to peer into the atmosphere at various wavelengths.

Figure 15 (Graphic courtesy of the U.S. National Weather Service). This graph shows a comparison of the emission spectra of both the sun and earth. Very basically, both the luminosity and wavelength vary directly with temperature. The hotter the object, the more intense the radiation (luminosity) and the shorter the wavelengths emitted. The cooler the object, the lower the luminosity and the longer the wavelengths emitted. Please note that the scales for the earth and the sun are hugely different. The vertical axis shows the relative intensity of the radiation emitted or the % of radiation absorbed by the atmosphere while the horizontal axis shows the wavelengths emitted. The earth's emission spectrum is in the infrared wavelengths centered around 10 μm (microns).

Note that the earth's infrared emissions are almost entirely absorbed by GHG molecules with an "atmospheric window" open to emissions to space centered around the 10 μm wavelength.

6.5 – The Earth’s Albedo or Reflectivity

Although incoming solar radiation is not absorbed by atmospheric molecules, not all of the sunlight reaches the earth’s surface; some of the sun’s rays are reflected directly back to space without warming the planet (see Figure 16). The earth’s overall reflectivity is termed its *albedo* and scientists have determined that currently about 30% of the sun’s rays are reflected back to space. The albedo effect is important because the amount of sunlight being absorbed or reflected directly influences the earth’s global average temperature. Reflecting surfaces include clouds, aerosol particulates, or bright colored areas of the surface, such as new snow, which reflects almost 100% of incoming solar radiation. Any decrease in the earth’s albedo acts as a positive feedback loop that enhances warming; an increase in albedo is a negative feedback loop that causes cooling.



*Figure 16 (Graphic courtesy the National Snow and Ice Data Center). As a radiative forcing factor, the earth’s albedo (“ α ” in above graphic) plays an important role in global warming. A higher albedo causes more of the sun’s radiation to be reflected back to space without warming the earth’s surface, which cools the planet. A lower albedo allows more of the sun’s energy to be absorbed by the earth’s surface and the planet becomes warmer. In the Arctic, sea ice is disappearing at an alarming rate. The exposed ocean is much darker than the sea ice decreasing the albedo and allowing more solar radiation to reach the surface. This is called the **ice-albedo effect** and could increase global warming significantly.*

6.6 – Radiative Transfer: How Solar Radiation Warms the Earth’s Surface

Electromagnetic radiation, “light” can be thought of as either a wave or a particle. To understand global warming, we should consider light traveling through space as a wave. However, when sunlight reaches the earth and interacts with matter, it’s best to think of light as particles, packets of energy called photons.

Solar radiation warms the surface of the earth by causing the molecules of the surface material (rocks, soil, etc.) to vibrate more rapidly. Energetic photons of sunlight strike the molecules of solid matter composing the surface causing the molecule’s electrons to jump to an excited state. The “excited” molecules of the surface material return to the stable “ground” state by vibrating more rapidly, a process termed “radiationless transition” or “radiationless de-excitation” because no photon is reemitted by the molecule as it drops to its ground state. Since temperature is just a measure of the motion of molecules, the increased vibrational energy of the surface material means an increase in heat content of the surface molecules. This heat energy transfers, or spreads, to adjacent molecules via conduction – the earth’s surface warms.

6.7 – How Greenhouse Gases Warm the Earth

Because the earth’s temperature is about 15⁰C, it radiates energy back to space in infrared wavelengths, precisely the wavelengths that greenhouse gases efficiently absorb. But molecules that efficiently absorb infrared wavelengths are also efficient emitters of those infrared wavelengths. For example, greenhouse gases absorb infrared radiation efficiently, therefore they also emit infrared radiation efficiently.

The mechanism for global warming is based upon the fact that greenhouse gases absorb some of the infrared photons earth is emitting to space. There are actually two possible mechanisms for greenhouse gases to absorb infrared radiation and warm the earth.

Method One: Reemitting Infrared Photons. When a photon of infrared radiation encounters a greenhouse gas molecule such as carbon dioxide, the photon is absorbed and the GHG molecule “jumps” to an excited state. Technically, when the infrared photon is absorbed, the bonds holding the carbon and oxygen atoms together bend, twist or stretch changing the internal arrangement of electric charge within the molecule (changing the “dipole moment”). This causes the molecule to jump to an “excited” state but this “excited” state is unstable. The GHG molecule normally returns to its ground state by emitting a photon of light of the same infrared wavelength that it absorbed. A good absorber is a good emitter.

The catch is this: Greenhouse gases that have absorbed an infrared photon rising from earth’s surface reemit this infrared radiation in every direction *including back towards earth*. From the perspective of the earth, the infrared radiation that has been redirected back towards earth by the greenhouse gas molecule is an increase in “Energy In”. This extra “Energy In” throws the earth’s “energy budget” out of balance and the earth must warm and then emit more heat back towards space to restore thermodynamic equilibrium. The University Corporation for Atmospheric Research has a wonderful graphic and explanation at:

<https://scied.ucar.edu/carbon-dioxide-absorbs-and-re-emits-infrared-radiation>

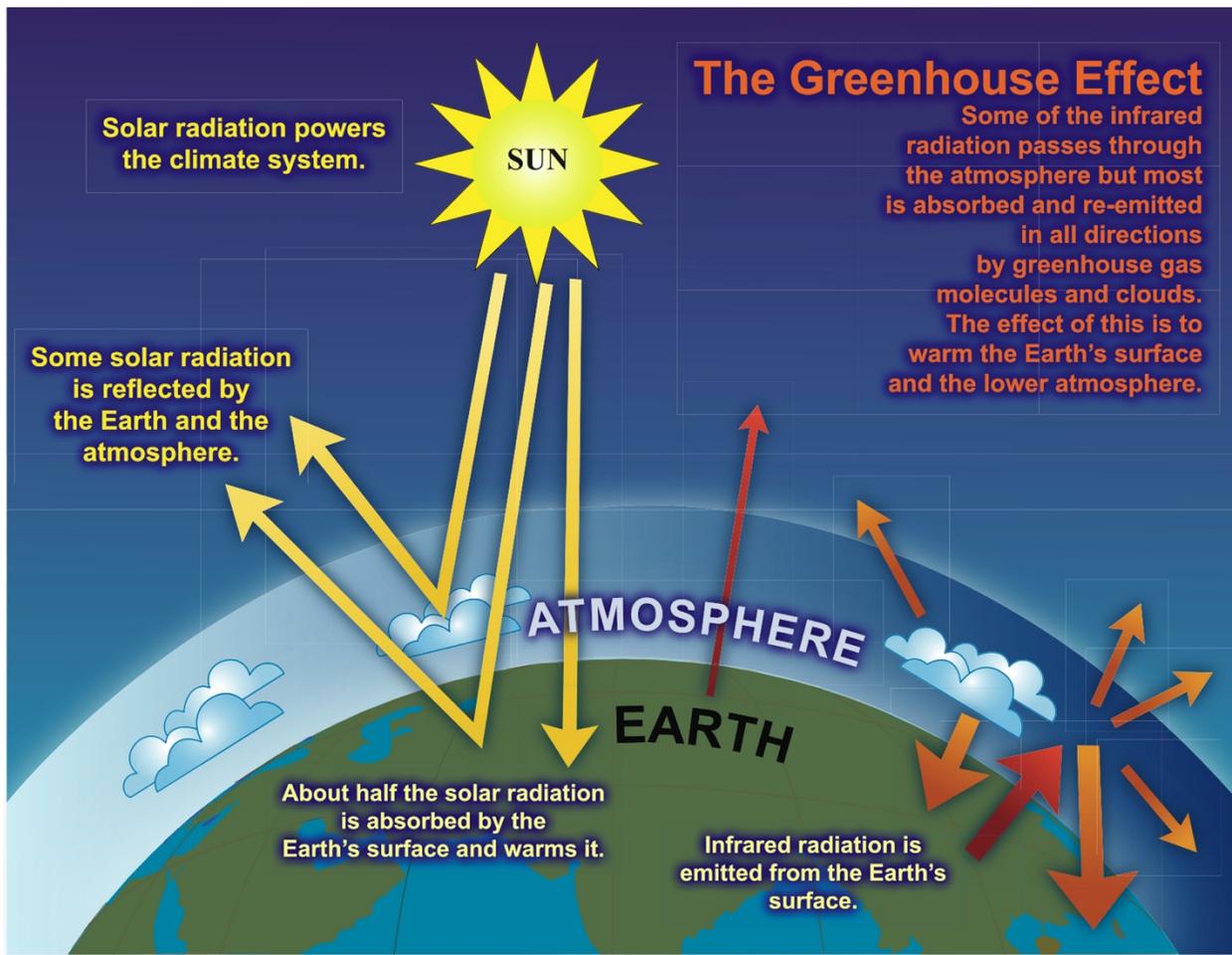


Figure 17 (Graphic courtesy of IPCC). The sun's shortwave radiation passes unimpeded through our atmosphere and warms the earth's surface (yellow arrows). Following the law of conservation of energy (First Law of Thermodynamics), the earth must reradiate the same amount of energy back to space at wavelengths that depend only on the earth's temperature. Warming to 15°C , the earth reradiates this energy as longwave radiation in the infrared wavelengths (red arrow), which are absorbed by greenhouse gases and then re-emitted in every direction including back towards earth's surface (orange arrows). This reemitted radiation directed back towards the earth is an increase in "Energy In" causing an imbalance in the earth's energy budget forcing the earth to warm.

Method Two: "Collisional De-excitation". There is also a second mechanism by which an excited carbon dioxide molecule can warm the atmosphere called "collisional de-excitation". If the excited CO_2 molecule collides with another atmospheric gas molecule (most likely nitrogen or oxygen) before it reemits an infrared photon, it can drop to its stable ground state by transferring its internal energy to the kinetic energy (speed of motion) of the gas molecule that it collides with. This increases the kinetic energy of the gas and since temperature is nothing more than the average speed of motion of the molecules, any increase in the kinetic energy (speed) of the gas molecules must increase the temperature of the gas. In this case, the molecules of the atmosphere increase their speed of motion and the temperature of earth's atmosphere increases. The increase in temperature of the atmosphere transfers by conduction to the surface and the entire earth warms.

6.8 – Why Carbon Dioxide is the Most Important Greenhouse Gas

Water vapor is the most prolific greenhouse gas, responsible for most of the global warming the earth experiences, about 70%. However, water vapor recycles through the hydrologic cycle with a molecule of H₂O remaining in the atmosphere an average of ten days. Since water is so abundant on earth, and the water cycle of evaporation, condensation and precipitation occurs constantly, water vapor can be considered a “constant” and, consequently, cannot be the cause of the current warming we observe. Also, water vapor leaves an “atmospheric escape window” for infrared wavelengths that water vapor does not absorb. This “escape window” allows the earth to radiate heat back to space. Carbon dioxide and the other greenhouse gases absorb wavelengths not covered by water vapor, which closes the “window” a bit, warming Earth.

After water vapor, carbon dioxide (CO₂) is the next most abundant GHG despite the fact that it exists in only trace amounts. To place these “trace” amounts of CO₂ into the proper perspective, remember that this same “trace” amount is responsible for all the photosynthesis conducted by all the green plants on the planet. Carbon dioxide rates the distinction of “most important” GHG for several reasons. First, as mentioned above, CO₂ absorbs infrared radiation at wavelengths not absorbed by water vapor fairly close to the center of the wavelength spectrum the earth is radiating to space. Second, carbon dioxide mixes extremely well in all layers of the atmosphere, including the upper reaches of the troposphere, where it exerts a strong absorbing influence. Finally, a carbon dioxide molecule can last for hundreds and even thousands of years before it is removed from the atmosphere by the long-term carbon cycle.

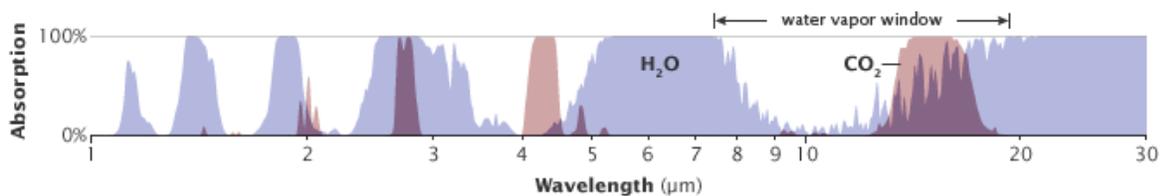


Figure 18 (graphic and caption courtesy of NASA). “All atmospheric gases have a unique pattern of energy absorption: they absorb some wavelengths of energy but are transparent to others. The absorption patterns of water vapor (blue peaks) and carbon dioxide (pink peaks) overlap in some wavelengths. Carbon dioxide is not as strong a greenhouse gas as water vapor, but it absorbs energy in wavelengths (12-15 micrometers) that water vapor does not, partially closing the “window” through which heat radiated by the surface would normally escape to space.”

The graph above shows the “absorption spectra” of the two most important greenhouse gases, water vapor and carbon dioxide. The graph also clearly shows the “water vapor window” where little absorption occurs allowing the earth to emit radiation to space cooling the planet.

Methane, an increasingly important greenhouse gas, absorbs at 8 μm closing a bit more of the window very close to the earth’s maximum emissions at 10μm. Methane is fairly short-lived, lasting only about ten years in the atmosphere before decomposing. Unfortunately, methane decomposes via oxidation into carbon dioxide and water vapor – the two most important greenhouse gases.

Chapter 7 – Understanding the Carbon Cycle

7.1 – The Carbon Cycle Basics: “Sources”, “Sinks” and “Flows” of Carbon

Carbon dioxide is critically important to maintaining a temperature that allows life to thrive but scientists speak more often of the importance of “carbon”, because carbon flows through many different chemical formulations and plays many roles that affect the earth’s climate. The following quote from NOAA nicely summarizes the “carbon cycle”:

“What is the carbon cycle? Carbon is the chemical backbone of all life on Earth. All of the carbon we currently have on Earth is the same amount we have always had. When new life is formed, carbon forms key molecules like protein and DNA. It's also found in our atmosphere in the form of carbon dioxide or CO₂. The carbon cycle is nature's way of reusing carbon atoms, which travel from the atmosphere into organisms in the Earth and then back into the atmosphere over and over again. Most carbon is stored in rocks and sediments, while the rest is stored in the ocean, atmosphere, and living organisms. These are the reservoirs, or sinks, through which carbon cycles. The ocean is a giant carbon sink that absorbs carbon. Marine organisms from marsh plants to fish, from seaweed to birds, also produce carbon through living and dying. Sometimes dead organisms become fossil fuels that go through combustion, giving off CO₂, and the cycle continues.” (NOAA, National Ocean Service, transcript from video, “What Is the Carbon Cycle”)

From the perspective of climate scientists and the problem of global warming, our focus must be on the “sources”, “sinks” and “flows” of carbon through the various elements of the earth’s climate system. A *source* is any process that releases any form of carbon, while a *sink* is a reservoir that takes up and stores carbon. The manner in which carbon moves through the many elements of the earth is termed the “flow” or “flux”. As we shall see, the most important form of carbon for understanding climate change is carbon dioxide.

It’s important to remember that there are natural sources of carbon dioxide that add to the concentration of atmospheric CO₂ but these natural sources have been in balance for hundreds of thousands of years. Only relatively recently has the earth’s carbon budget been disrupted by human activities. To quote David Herring of NOAA:

“There are natural sources of carbon dioxide, such as decomposing biomass, venting volcanoes, naturally occurring wildfires, human and animal respiration, etc. Over geological time spans before the industrial revolution, these natural sources of carbon dioxide were in balance with natural “sinks”—such as the ocean, phytoplankton, and plants on land that absorb carbon dioxide. The only new process on Earth that has been identified that can account for the significant tipping of Earth's carbon balance is humans burning ever increasing amounts of fossil fuels together with other large-scale activities like deforestation, biomass burning, and cement production. Since the industrial revolution, human activities have increased the abundance of carbon dioxide in the lower atmosphere by about 40%.” (NOAA, Climate Q&A, January 23, 2014)

7.2 – The “Short-term” or Organic Carbon Cycle

To understand the dynamics of the “Short-term Carbon Cycle”, concentrate on the flows of carbon in the diagram below indicated by the arrows. From the perspective of climate change, living organisms fall into two basic categories, plants and animals. Plants absorb carbon dioxide and metabolize it via photosynthesis producing the carbohydrates they need for survival and release oxygen back into the atmosphere as a byproduct. Animals utilize this oxygen to metabolize the carbohydrates they need to sustain life and release carbon dioxide back into the atmosphere. These sources, sinks, and flows between plants and animals are very nearly in balance. The land surfaces of the earth absorb carbon dioxide via chemical processes and also release CO₂ back to the atmosphere in processes that are again very nearly in balance. And carbon dioxide flows back and forth into and out of the oceans of the world again in a nearly steady-state balance. Considering only these “natural” sources, sinks and flows of carbon, the world’s carbon energy budget is roughly in balance. Human activities are the wild card that create an imbalance in the flows of carbon that are causing global warming and climate change.

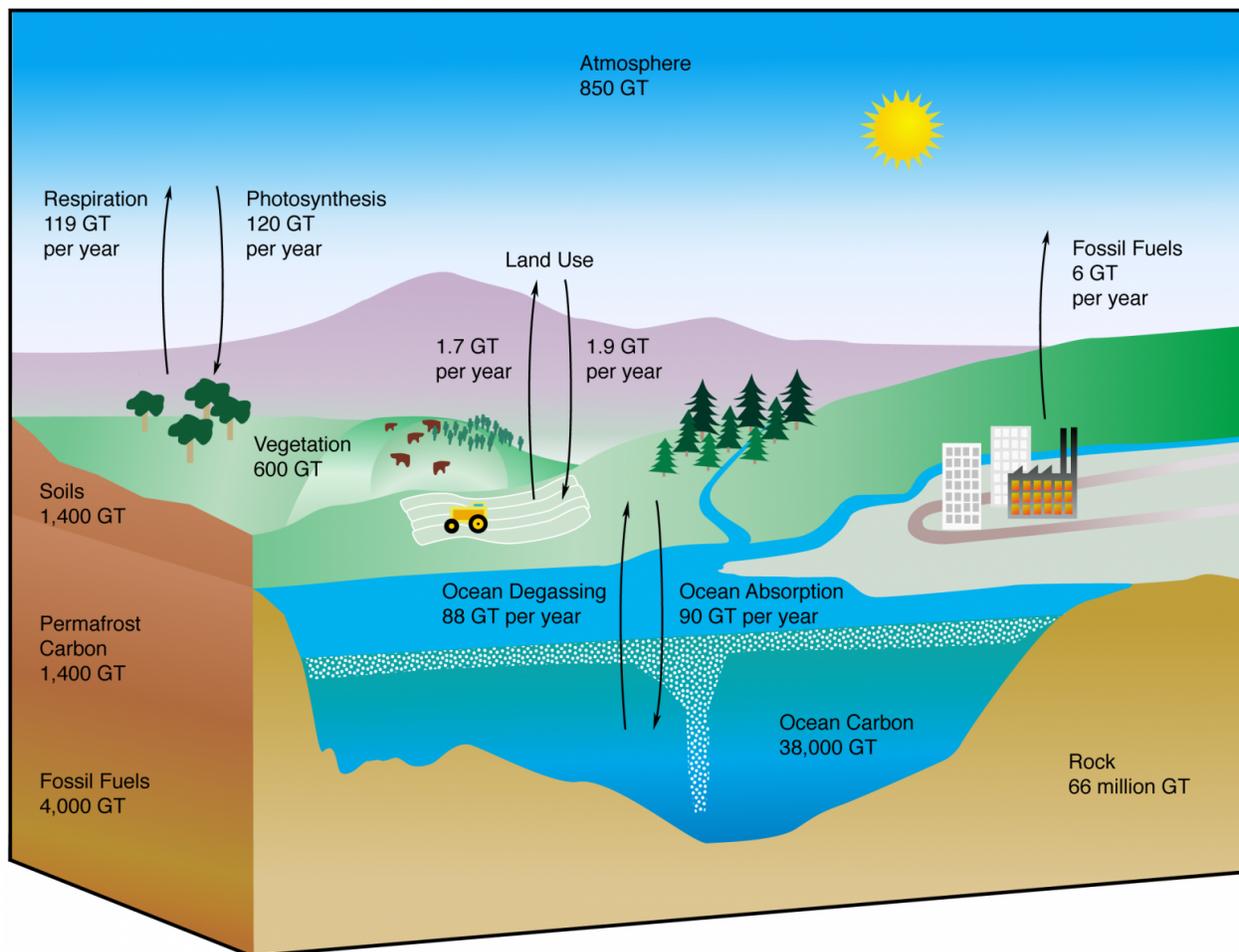


Figure 19 (Graphic courtesy of the National Snow and Ice Data Center). The diagram shows the “stocks” or reservoirs of carbon as well as the “flux” or flow of carbon denoted by the arrows. Focusing on the fluxes, we can see that the carbon flows are almost in balance with the exception of “Fossil Fuels”. It is this “source” of carbon that throws earth’s “Carbon Budget” out of balance and it originates from human activities and primarily from the combustion of fossil fuels.

7.3 – Earth’s Thermostat: The “Long-term” or Inorganic Carbon Cycle **How Carbon Dioxide Regulates Earth’s Temperature**

Carbon dioxide is sometimes considered to be the earth’s “thermostat” operating through the “Long-term Carbon Cycle”. Carbon dioxide regulates Earth’s temperature via chemical interactions with the lithosphere (the earth’s rocky crust) creating chemical substances that eventually reach the world’s oceans. In the ocean, calcifying organisms use these building blocks to create their shells. When these organisms die, their shells sink to the deep ocean floor forming limestone deposits that effectively store the carbon for hundreds of millions of years.

Looking at the chemical processes a bit more closely is worthwhile. Basically, carbon dioxide reacts with water to form carbonic acid, a weak acid, and this chemical process can occur either in the oceans of the world, in the atmosphere, or in the soils of the earth. The chemistry of weathering via carbonic acid is complex but for our purposes we only need to understand the basics. To quote NASA, Earth Observatory, “The Slow Carbon Cycle”:

“The movement of carbon from the atmosphere to the lithosphere (rocks) begins with rain. Atmospheric carbon combines with water to form a weak acid—carbonic acid—that falls to the surface in rain. The acid dissolves rocks—a process called chemical weathering—and releases calcium, magnesium, potassium, or sodium ions. Rivers carry the ions to the ocean.

In the ocean, the calcium ions combine with bicarbonate ions to form calcium carbonate, the active ingredient in antacids and the chalky white substance that dries on your faucet if you live in an area with hard water. In the modern ocean, most of the calcium carbonate is made by shell-building (calcifying) organisms (such as corals) and plankton (like coccolithophores and foraminifera). After the organisms die, they sink to the seafloor. Over time, layers of shells and sediment are cemented together and turn to rock, storing the carbon in stone—limestone and its derivatives.

The slow cycle returns carbon to the atmosphere through volcanoes. Earth’s land and ocean surfaces sit on several moving crustal plates. When the plates collide, one sinks beneath the other, and the rock it carries melts under the extreme heat and pressure. The heated rock recombines into silicate minerals, releasing carbon dioxide.

When volcanoes erupt, they vent the gas to the atmosphere and cover the land with fresh silicate rock to begin the cycle again. At present, volcanoes emit between 130 and 380 million metric tons of carbon dioxide per year. For comparison, humans emit about 30 billion tons of carbon dioxide per year—100–300 times more than volcanoes—by burning fossil fuels.”

Carbon dioxide has earned the title, “Earth’s Thermostat” because when atmospheric concentrations of carbon dioxide are high (and the earth’s temperature is high), more carbonic acid is formed and weathering speeds up. Unfortunately, this “thermostat” is not useful in mitigating human-caused global warming because the chemical processes require many millions of years to weather rocks of the lithosphere. Over geological time periods, this weathering process does remove carbon dioxide from the atmosphere, effectively lowering earth’s temperature and earning CO₂ the nickname, “Earth’s thermostat”.

Chapter 8 – Greenhouse Gas Emissions and Concentration

8.1 – Understanding the Difference between GHG Emissions and Atmospheric Concentration of Greenhouse Gases

It's critically important to understand the relationship between *emissions* of greenhouse gases and the *concentration* of GHGs in the atmospheric reservoir. *Emissions* are *additions* to the atmospheric reservoir of GHG while global warming is caused by the *concentration*, the accumulated total amount of GHGs in the atmospheric reservoir. The relationship is somewhat counter-intuitive. The best way to grasp the relationship is to ask this question, "If human emissions of greenhouse gases are immediately cut by half, what will happen to the concentration of greenhouse gases in the atmosphere?" It would be comforting to think that the concentration, the total amount of atmospheric GHGs, will drop also but that is incorrect. In fact, cutting emissions in half means that we are still adding *the other half* to the reservoir of greenhouse gases in the atmosphere, so the concentration of GHGs will continue to rise causing global temperatures to rise, although more slowly. Think of it this way. We are filling a bathtub with water and the faucet is on full blast. If we slow the inflow of water by half, we are still filling the tub with water – the total amount of water continues to increase. This is why scientists are emphasizing "zero emissions" of GHGs.

The Carbon 'Bathtub' and its Components

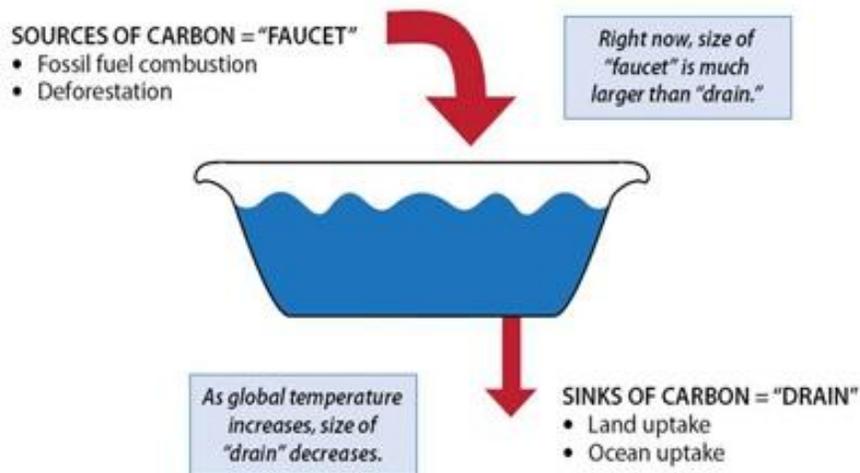
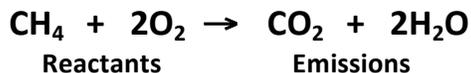


Figure 20 (Graphic courtesy of EPA). For 800,000 years, the natural sources and sinks of carbon were in balance. The "faucet" and "drain" were roughly equal. When humans began to dominate the earth, forests were cut down to provide land for grazing and cultivating crops. This removed a natural carbon sink, effectively reducing the size of the drain, causing the carbon reservoir to increase. When humans discovered fossil fuels and the Industrial Age began, we turned the faucet up increasing the inflow of carbon. The combustion of fossil fuels, combined with deforestation, cement production (increased CO₂), use of nitrogen fertilizers (increased N₂O) and other human activities, have created an imbalance between the inflow and outflow of carbon into the atmosphere. More precisely, human activities, and especially the emissions of greenhouse gases, are increasing the concentration of greenhouse gases in the atmosphere causing the current global warming and climate change we are experiencing.

8.2 – Increasing Emissions = Increasing Concentration of CO₂

The bathtub analogy is cute but are there real world data and observations that support the position that increasing emissions of carbon dioxide are actually causing an increase in the atmospheric concentration of CO₂? The formula for the combustion of natural gas (primarily methane), which is the cleanest burning fossil fuel is as follows:



It stands to reason that releasing carbon dioxide and water vapor into the atmosphere must cause a corresponding increase in the atmospheric concentration of those greenhouse gases but do we have any actual evidence or observations that support this conclusion? We do. The graph below documents this evidence.

CO₂ in the atmosphere and annual emissions (1750-2019)

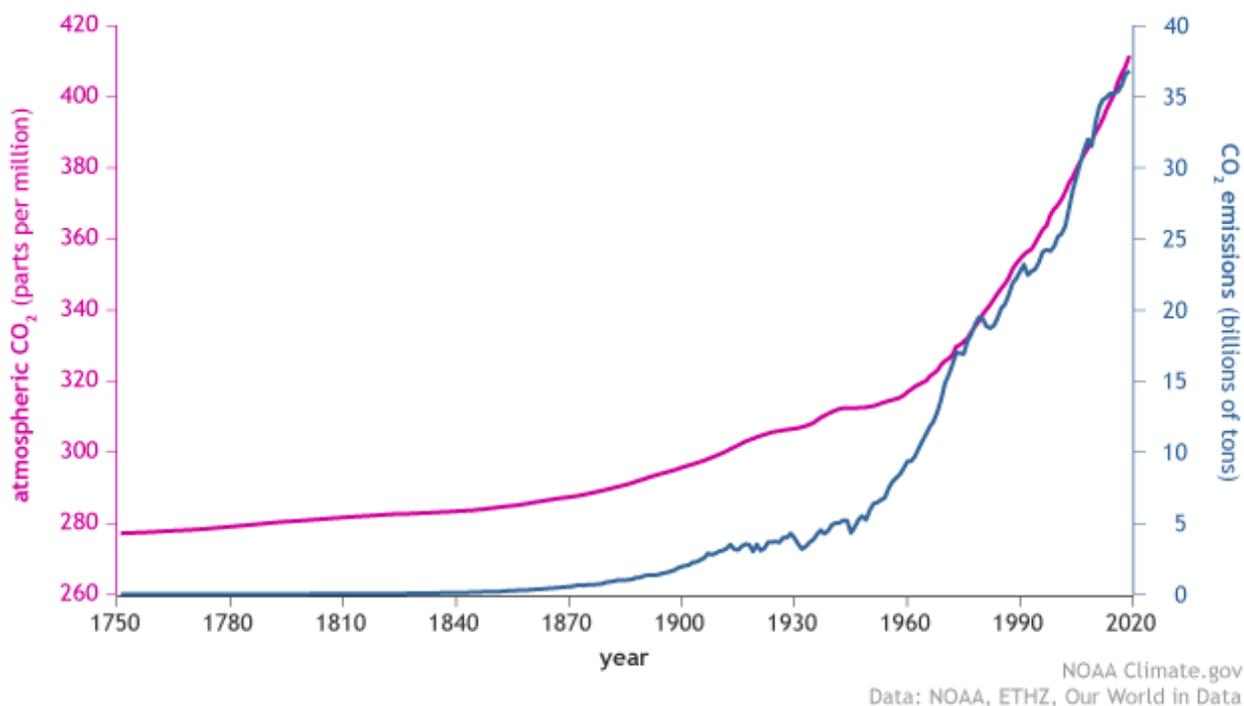


Figure 21 (Graphic courtesy of NOAA Climate). The graph shows CO₂ emissions depicted by the blue line and atmospheric concentration of CO₂ by the pink line. Note the close correlation between rising emissions and increasing levels of atmospheric carbon dioxide. The rate of emissions is indicated by the slope of the line. The steeper slope clearly shows the dramatic acceleration in both emissions and atmospheric concentration of CO₂ beginning around 1960 and continuing to the present.

But what about the H₂O? Why don't we see an increase in atmospheric concentration of H₂O? Unlike a CO₂ molecule that can remain in the atmosphere for centuries, water molecules typically last about a week before condensing and precipitating out of the atmosphere, becoming part of the water cycle. The atmospheric concentration of H₂O remains relatively constant (H₂O concentration does increase slightly because a warmer atmosphere can hold more water vapor). We do, however, see heavier rainfall events.

8.3 – Do All Fossil Fuels Emit the Same Amount of CO₂?

Although all fossil fuels produce carbon dioxide and water vapor as products of combustion, but different fuels emit different amounts of carbon dioxide in relation to the energy they produce when burned. The following chart from the United States Energy Information Agency summarizes the carbon dioxide emissions from the various fossil fuels.

Pounds of CO₂ emitted per million British thermal units (Btu) of energy for various fuels

Coal (anthracite)	228.6
Coal (bituminous)	205.7
Coal (lignite)	215.4
Coal (subbituminous)	214.3
Diesel fuel and heating oil	161.3
Gasoline (without ethanol)	157.2
Propane	139.0
Natural gas	117.0

Figure 22 (Graphic and caption courtesy of U.S. Energy Information Agency). “The amount of CO₂ produced when a fuel is burned is a function of the carbon content of the fuel. The heat content, or the amount of energy produced when a fuel is burned, is mainly determined by the carbon (C) and hydrogen (H) content of the fuel. Heat is produced when C and H combine with oxygen (O) during combustion. Natural gas is primarily methane (CH₄), which has a higher energy content relative to other fuels, and thus, it has a relatively lower CO₂-to-energy content. Water and various elements, such as sulfur and noncombustible elements in some fuels, reduce their heating values and increase their CO₂-to-heat contents.”

8.4 – Human Sources of Greenhouse Gases

The following human activities release carbon dioxide and other greenhouse gases as byproducts or remove carbon “sinks”.

- Combustion of fossil fuels consumes oxygen and releases carbon dioxide and water as products of the chemical reaction and both are greenhouse gases.
- Cement production also releases CO₂ when limestone is crushed and heated to produce lime, the most important ingredient in cement.
- Nitrogen-based fertilizers release nitrous oxide (N₂O), also a greenhouse gas.
- Agriculture causes greenhouse gas emissions from livestock, agricultural soils and rice production. “Rice paddies” release large amounts of methane (CH₄), which is a greenhouse gas about 40 times more potent than CO₂.
- Human-created chemicals, chloroflourocarbons, hydroflourocarbons and others, which are manufactured for use as coolants, solvents, and propellants are extremely potent greenhouse gases.
- Ozone is released as a byproduct of human industrial processes and ozone is a greenhouse gas in the troposphere.
- Land use and forestry can either contribute to global warming or act as a “sink”. Deforestation increases GHGs but proper land management can remove GHGs.

Chapter 9 – How Human Activities Warm the Earth

9.1 – Human Activities Increase the Atmospheric Concentration of CO₂

The fact that human activities are causing the increase in the concentration of atmospheric carbon dioxide becomes obvious when one considers the graph below. Although the earth's atmospheric CO₂ has fluctuated between 180 ppm and 280 ppm, for over 800,000 years it has never exceeded 300 ppm. This relative stability of atmospheric CO₂ results from the balance in the natural sources and sinks of CO₂ until the 1800's when human activities, and especially the combustion of fossil fuels, cause an increase in emissions of carbon dioxide. The increase in *emissions* increases the *concentration* of carbon dioxide in the atmosphere.

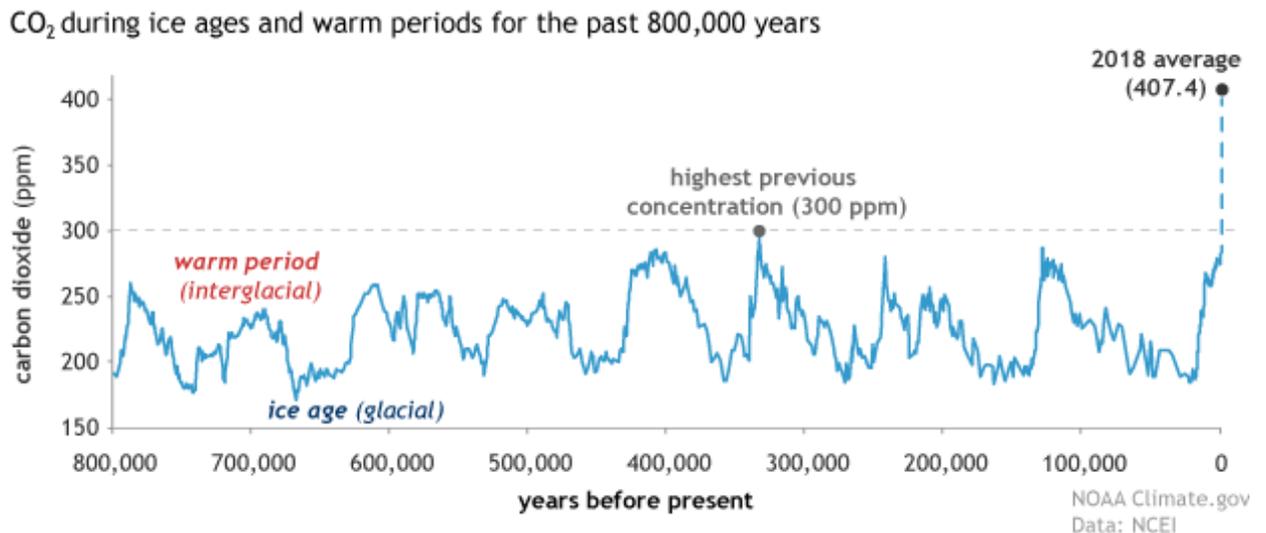
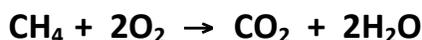


Figure 23 (Graphic courtesy of NOAA). For 800,000 years concentrations of carbon dioxide had remained under 300 ppm. May 2019 carbon dioxide monthly average was 414.83 and rising. The last time atmospheric carbon dioxide levels were this high was roughly 3 to 5 million years ago during the Pliocene period. Earth was wetter with global average temperatures 3 to 4 degrees Celsius (5.4F to 7.2F) warmer than today. Sea levels were about 100 feet higher than today.

Climate deniers often make the argument that over timespans of millions of years, carbon dioxide levels have been much higher, sometimes reaching 1000 ppm, suggesting that scientists are excessively preoccupied with current levels of CO₂. While it's true that natural megavolcanic processes have released huge amounts of CO₂ in the distant past, those extremely high levels caused the earth to be about 5°C (9°F) warmer than today with sea levels 200 feet higher than current levels. More importantly, the argument is irrelevant. As the graph above clearly shows, for the entire span of human history (we've been around for about 200,000 years), carbon dioxide sources and sinks have been roughly in balance. We only see rising levels of CO₂ beyond 300 ppm when human activities increased atmospheric greenhouse gases, throwing earth's energy budget out of balance and causing today's global warming. Looking to the earth's distant past can be instructive; an entire branch of science, paleoclimatology, is dedicated to it. Paleoclimatology informs us that the consequences of high levels of atmospheric CO₂ would be extremely harmful to humanity.

9.2– The Proofs that Human Activities Cause Global Warming

- 9.2.1 Experimental Proof** - In 1859, John Tyndall provided the first experimental proof that carbon dioxide traps heat in the atmosphere. Many thousands of additional experiments confirm this fact, including the U.S. Air Force Geophysical Laboratory, which conducted research on heat-trapping gases while developing heat-seeking missiles in the 1950's and 1960's. The fact that carbon dioxide traps heat in the atmosphere is simply irrefutable. A classroom demonstration designed by the EPA using infrared heat lamps, water bottles, thermometers and Alka Seltzer tablets that produce carbon dioxide confirms these experiments for students in a striking manner.
- 9.2.2 Theoretical "Proof"** – For any evidence to be accepted by the scientific community, it must be consistent with well-established scientific theory. The evidence that greenhouse gases, and especially carbon dioxide, trap heat in the earth's atmosphere is grounded in electromagnetic theory, quantum theory, thermodynamics, and classical physics. These theories are time tested and provide the theoretical foundation for understanding human-caused global warming. While this is not technically a "proof" of human-caused global warming and climate change, all of the evidence presented is consistent with these solid, well-founded theories. "Natural" claims of global warming offer no discernible cause for current warming. Nonexistent causes cannot be verified and therefore cannot be consistent with scientific theories.
- 9.2.3 The Chemistry of Fossil Fuel Combustion.** Scientists have known the chemical formulas for the combustion of fossil fuels for over a hundred years. The formulas allow us to understand what happens when humans burn fossil fuels. Using the simplest fossil fuel, natural gas (methane) as an example, the chemical formula provides important information. The formula is:



This reaction tells us two things about the combustion of fossil fuels:

- a) Carbon dioxide is a product of the reaction therefore the atmospheric concentration of carbon dioxide should increase.
- b) Oxygen is a reactant and consumed during the combustion reaction therefore the atmospheric concentration of oxygen should decrease.

Both of these facts are observed in today's atmosphere: Carbon dioxide levels are increasing and oxygen levels are decreasing. No "natural" process can account for these two observations.

Fact 1: Levels of atmospheric carbon dioxide are increasing.

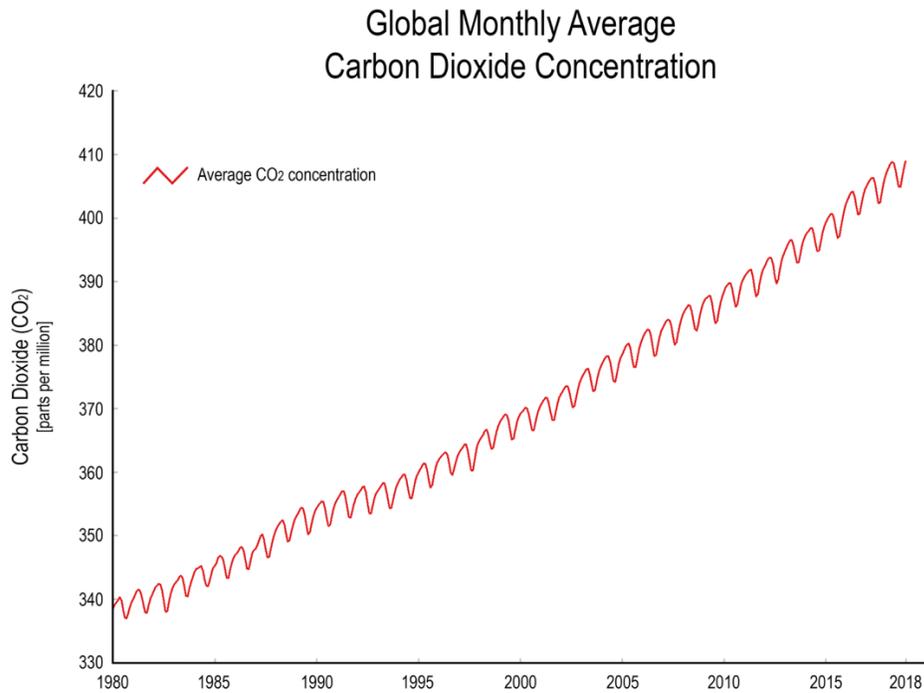


Figure 24 (Graphic courtesy of U.S. Global Change Research Program). This graph clearly shows the dramatic increases in atmospheric carbon dioxide from 1980 to 2019. The global monthly CO₂ average for the month of December, 2019 was 411.85 and continues to rise. The increase in CO₂ levels are consistent with the amount carbon dioxide emitted from the various human emission sources.

Fact 2: Levels of atmospheric oxygen are decreasing.

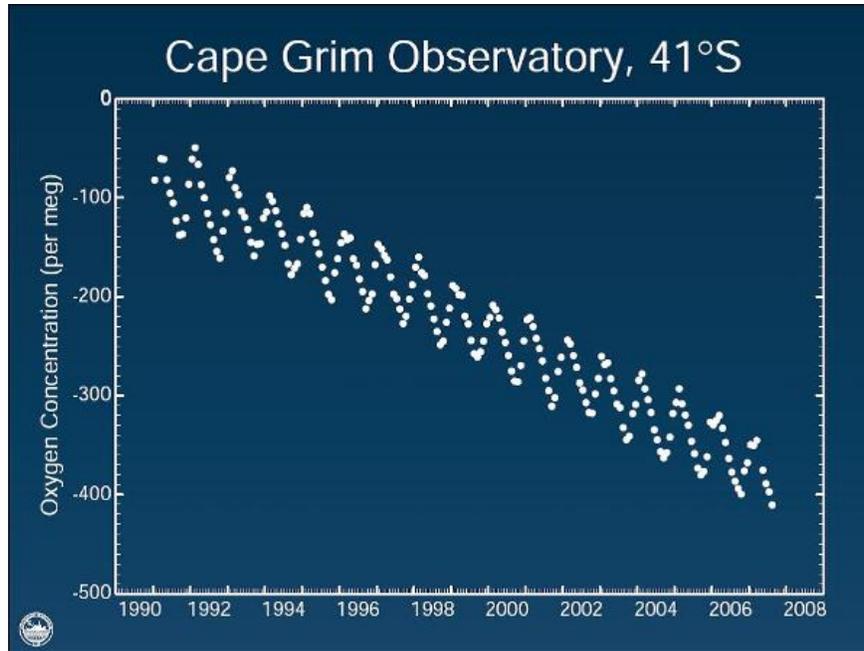


Figure 25 (Graphic and caption courtesy of Skeptical Science). “Burning carbon requires oxygen (O_2), and when we burn an atom of carbon, the required oxygen becomes part of the CO_2 molecule. So, if the CO_2 increase is caused by burning carbon (fossil fuels), we would expect atmospheric O_2 levels to decrease at the same rate. And that's indeed what we observe. There's no reason to expect that a natural release of CO_2 would have any effect on atmospheric O_2 levels.”

9.2.4 “Real World” Carbon Emissions. Since we know the chemical formulas for the combustion of all fossil fuels, if we knew the actual quantity of fossil fuels combusted we could calculate exactly how much carbon dioxide has been produced. Fortunately, that data exists. Accurate bookkeeping information since the mid-1800’s exists and provides detailed data about the amount of fossil fuels humans have burned. This allows us to calculate how much carbon has been emitted and the results are consistent with observed increases in atmospheric carbon dioxide. The Carbon Dioxide Information Analysis Center (CDIAC) of the U.S. Department of Energy reports that:

“Since 1751 just over 400 billion metric tonnes of carbon have been released to the atmosphere from the consumption of fossil fuels and cement production. Half of these fossil-fuel CO₂ emissions have occurred since the late 1980s.”

The graph below shows the amount of carbon produced from various human sources.

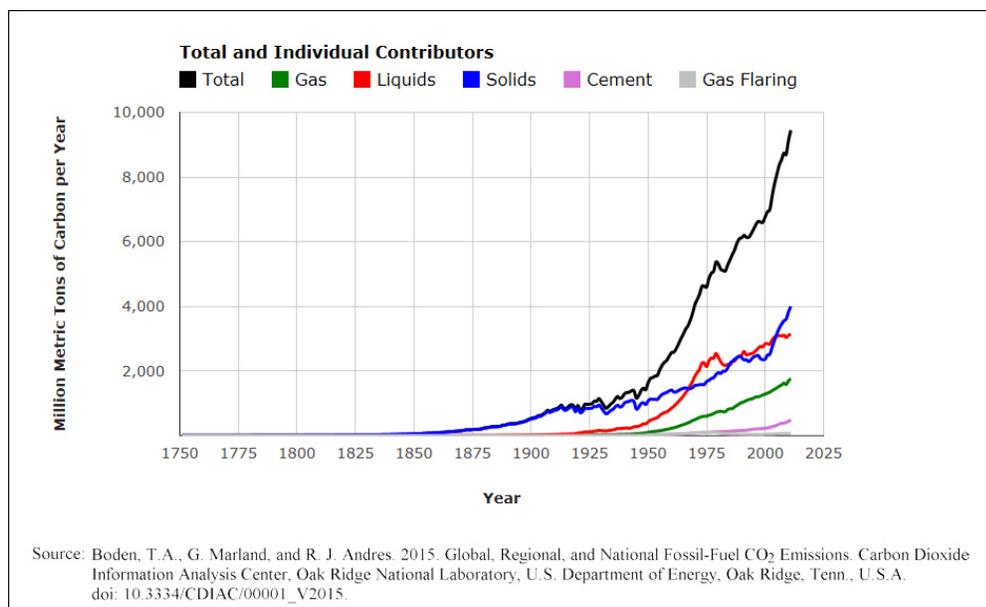
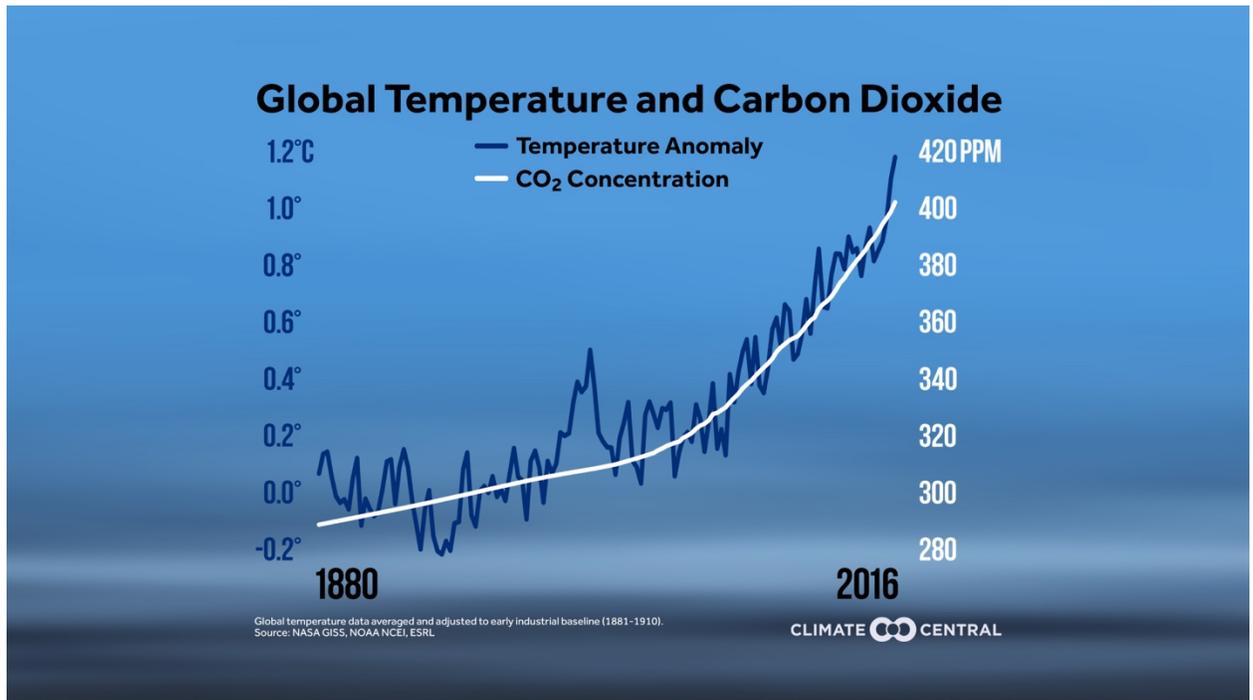


Figure 26 (Graphic courtesy of Carbon Dioxide Information Analysis Center). Whether we calculate emissions factors using energy statistics and the chemical formulas for various fossil fuels or measure the atmospheric concentration of carbon dioxide directly, the results are consistent. Both data sets reveal the same story: Human combustion of fossil fuels is the primary cause for global warming.

9.2.5 Observational Proof: Increasing CO₂ & Increasing Global Temperature. As atmospheric concentrations of carbon dioxide have increased, so too has the earth's temperature, which we call global warming. Experimental evidence and established scientific theories have established that carbon dioxide is a greenhouse gas capable of causing a rise in temperature. The observed data strongly supports the contention that increasing concentrations of atmospheric CO₂ causes the earth's temperature to increase.



*Figure 27 (Graphic courtesy of Climate Central). The graph clearly shows the correlation between atmospheric carbon dioxide and increasing temperature anomalies. It's important to remember that the graph is produced from datasets compiled from many thousands of temperature measurements that are analyzed and converted to temperature anomalies. Temperature anomalies are preferred over raw global mean temperature data because they clearly show warming or cooling **trends**. For data representing a longer timescale, see Figure 23 on page 42.*

9.2.6 Radiative (Climate) Forcing: Natural vs. Anthropogenic Forcings. The following quote from NOAA Climate describes radiative forcing:

“In accordance with the basic laws of thermodynamics, as Earth absorbs energy from the sun, it must eventually emit an equal amount of energy to space. The difference between incoming and outgoing radiation is known as a planet’s radiative forcing (RF). In the same way as applying a pushing force to a physical object will cause it to become unbalanced and move, a climate forcing factor will change the climate system. When forcings result in incoming energy being greater than outgoing energy, the planet will warm (positive RF). Conversely, if outgoing energy is greater than incoming energy, the planet will cool.”

Incoming Energy – Outgoing Energy = Radiative Forcing

“Another way to refer to climate forcings is to call them climate drivers. Natural climate drivers include changes in the sun’s energy output, regular changes in Earth’s orbital cycle, and large volcanic eruptions that put light-reflecting particles into the upper atmosphere. Human-caused, or anthropogenic climate drivers include emissions of heat-trapping gases (also known as greenhouse gases) and changes in land use that make land reflect more or less sunlight energy. Since 1750, human-caused climate drivers have been increasing, and their effect dominates all natural climate drivers.” (NOAA Climate)

Year	Radiative Forcing (RF) Relative to 1750 (W m ⁻²)
1750	0.0
1950	0.57
1980	1.25
2011	2.29

Figure 28 (Graphic courtesy of NOAA). Prior to 1750, before the Industrial Revolution, earth’s average RF remained relatively stable. To document how the atmosphere has changed since then, scientists calculate current RF levels as if it were zero in 1750. The zero indicates that the earth was in thermodynamic equilibrium. A positive RF indicates warming while a negative RF indicates cooling. Source: IPCC AR5 WG1 Figure SPM.5.

A more comprehensive examination of all known radiative forcings operating since 1750 is quite revealing.

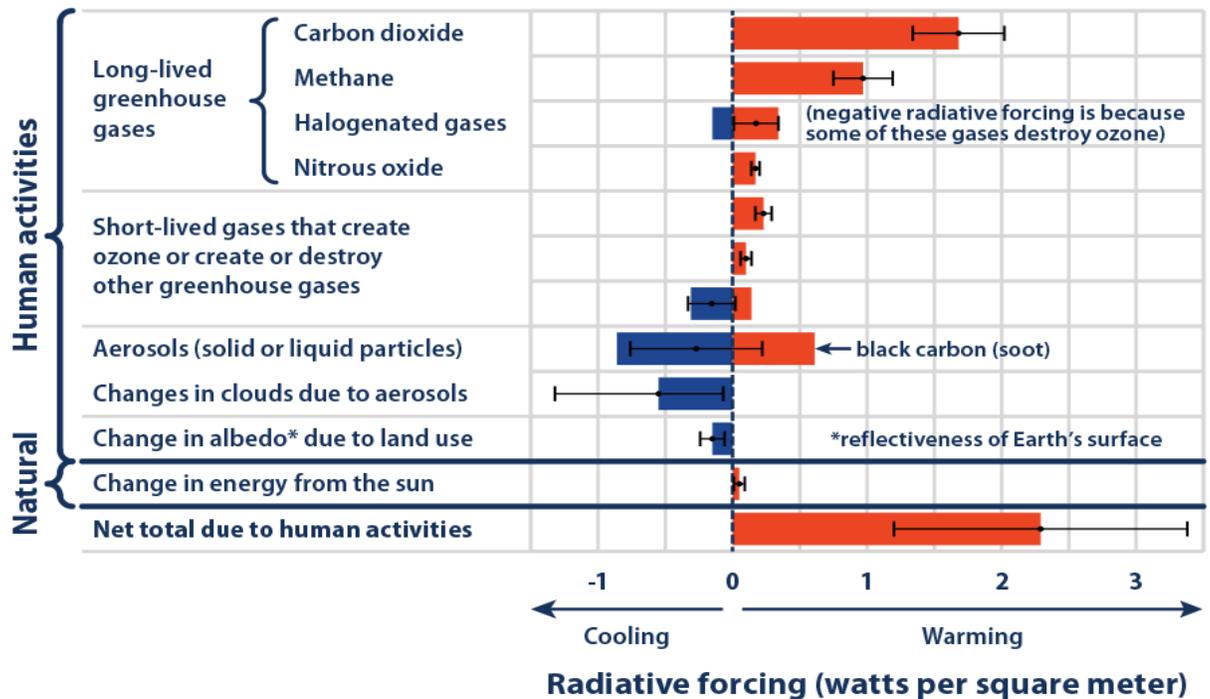


Figure 29 (Graphic and caption courtesy of EPA). “Global annual average radiative forcing change from 1750 to 2011 due to human activities and changes in total solar irradiance. Black bars indicate the uncertainty in each. Radiative forcing is a measure of the influence a factor (such as carbon dioxide) has in changing the global balance of incoming and outgoing energy. Radiative forcings greater than zero (positive forcings) produce climate warming; forcings less than zero (negative forcings) produce climate cooling. Over this time period, solar forcing has oscillated on approximately an 11-year cycle between -0.11 and $+0.19$ W/m^2 . Radiative forcing due to volcanic emissions is always negative (cooling) and can be very large immediately following significant eruptions but is short-lived. Over the industrial era, the largest volcanic forcing followed the eruption of Mt. Tambora in 1815 (-11.6 W/m^2). This forcing declined to -4.5 W/m^2 in 1816, and to near-zero by 1820. Forcing due to human activities, in contrast, has becoming (sic) increasingly positive (warming) since about 1870, and has grown at an accelerated rate since about 1970. There are also natural variations in temperature and other climate variables that operate on annual to decadal time-scales. This natural variability contributes very little to climate trends over decades and longer.”

9.2.7 Isotopic Analysis: The Human Fingerprint. Scientists consider isotopic analysis the definitive proof that increasing concentrations of carbon dioxide result *only* from human combustion of fossil fuels and no natural source. All carbon atoms have six protons but the number of neutrons in the nucleus varies creating carbon isotopes with different atomic masses: ^{14}C , ^{13}C , and ^{12}C . “Natural” processes, such as volcanoes or sea floor spreading, produce these three isotopes in a very specific ratio. Carbon 12 accounts for about 99% of the carbon atoms in CO_2 , carbon 13 about 1% with trace amounts of carbon 14.

But the carbon 14 isotope is radioactive with a half-life of 5730 years, decaying into undetectable levels in 50,000 years or so. Fossil fuels, being millions of years old, have no ^{14}C left. Adding ancient carbon from burning fossil fuels should lower the proportion of ^{14}C in the atmosphere—and it has. For the last 50 years, the total amount of carbon in the atmosphere has increased but the ratio of ^{14}C has fallen steadily. This result could not occur from any “natural” source but only from the combustion of fossil fuels by humans.

But there’s more. The “natural” ratio of carbon 12 to carbon 13 is about 99 to 1. But carbon 12 has slightly less mass than carbon 13 making carbon 12 slightly lighter and “faster”, making it more likely to be absorbed through plant stomata (leaf pores). In other words, carbon 12 is taken up by plants much more easily than carbon 13. This means that carbon 13 is “depleted” in plants. Since fossil fuels are made from plants that have decayed for millions of years, burning fossil fuels will result in atmospheric carbon dioxide that is depleted of carbon 13. This depleted ratio of carbon 13 to carbon 12 is observed in the current atmospheric concentration of carbon dioxide, which could only result from the burning of fossil fuels with their lower content of carbon 13. No “natural” source could cause this depleted carbon 13 ratio.

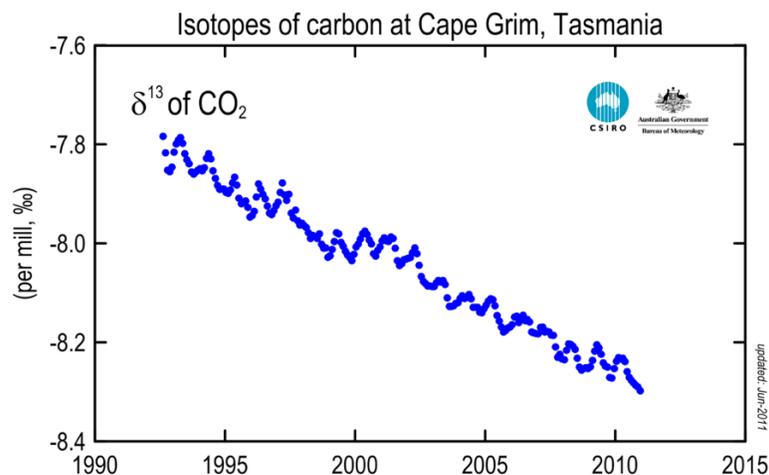


Figure 30 (Graphic and caption courtesy of Skeptical Science). “Reconstructions of atmospheric carbon isotope ratios from various proxy sources have determined that at no time in the last 10,000 years are the carbon-13 to 12 ratios in the atmosphere as low as they are today. Furthermore, the carbon-13 to 12 ratios begin to decline dramatically just as the CO_2 starts to increase — around 1850 AD. This is exactly what we expect if the increased CO_2 is in fact due to fossil fuel burning beginning in the Industrial Revolution.” In the graph, the Greek letter, δ^{13} , denotes carbon 13.

Chapter 10: Why Scientists Are Worried: Climate Feedbacks

10.1 – Overview: Climate Feedbacks

Climate feedbacks are processes that can either amplify or diminish the effects of climate warming or cooling. A feedback that increases warming is called an “amplifying” or “positive” feedback. A feedback that reduces warming is called a “diminishing” or “negative” feedback. Obviously, since the earth is currently warming, scientists are more concerned with amplifying feedbacks that might greatly increase the potency of future global warming.

Positive and Negative Climate Feedbacks

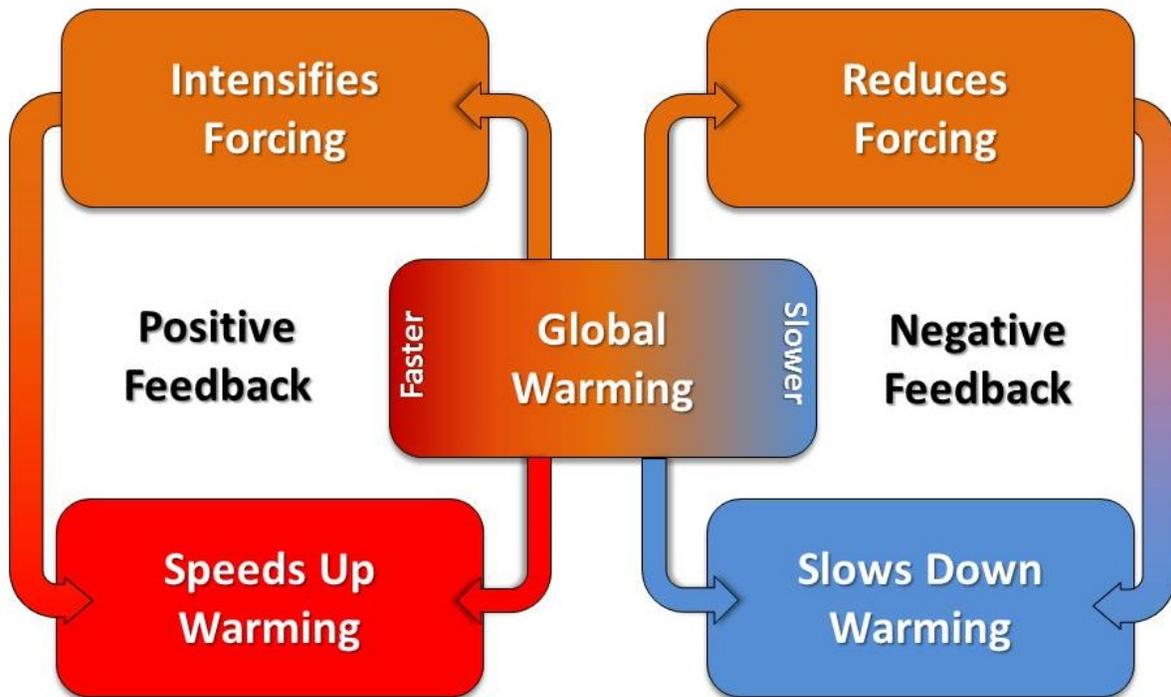


Figure 31 (Graphic courtesy of NASA, Climate Science Investigations). Currently, scientists have identified several positive feedbacks that are operating today to increase global warming and they are likely to intensify as warming increases. On the other hand, there do not appear to be any negative feedbacks capable of modifying anthropogenic global warming. The one negative feedback that will operate is the blackbody radiation feedback (Stefan-Boltzmann feedback) that results from a warmer earth emitting more radiation to space. This feedback, however, only operates because the earth is warming.

10.2 Amplifying Feedbacks

Amplifying (positive) feedbacks – Occurring now and likely to increase in potency, these feedbacks *intensify* global warming.

10.2.1 Ice-Albedo Feedback – This feedback could work both ways, as either an amplifying feedback if global ice cover melts, or as a diminishing feedback if global ice cover expands. Currently, global ice cover is melting significantly, especially Arctic sea ice. This melting of the Arctic sea ice reduces the earth's albedo and exposes darker sea water. The darker sea water absorbs more solar radiation, which causes increased warming.

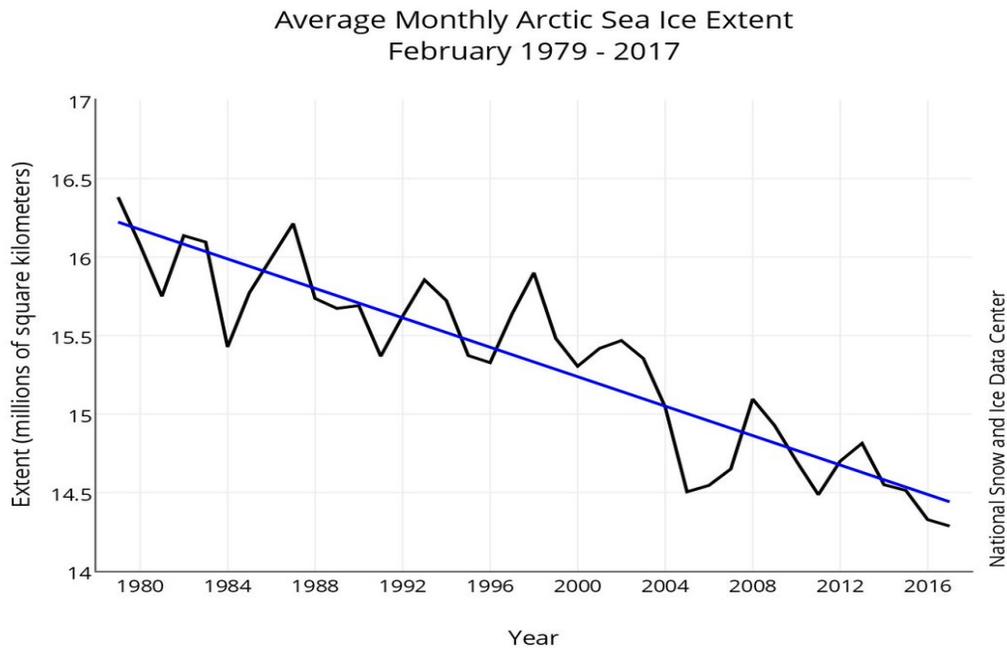


Figure 32 (Graphic courtesy of National Snow and Ice Data Center). Continued Arctic sea ice loss reduces the earth's albedo resulting in a positive feedback loop increasing global warming. This occurs because sea ice is brighter and reflects more sunlight than the darker Arctic Ocean waters. Since the ice-free ocean absorbs more of the sun's energy, there is an increase in ocean warming contributing to an increase in global mean temperatures.

10.2.2 **Water Vapor Feedback** – We know that water vapor is the most prolific greenhouse gas responsible for most of the “greenhouse” warming. Recall that water vapor is abundant on earth and its overall quantity has not noticeably changed, therefore it cannot be the cause of the current warming. However, there is a variable that can cause the atmospheric concentration of water vapor to increase, constituting an amplifying feedback. That variable is the warming of earth itself, because a warmer atmosphere is physically capable of holding more water vapor. Since water vapor is a greenhouse gas, adding water vapor to the atmosphere causes additional global warming; it is an amplifying feedback. And a second factor compounds the warming problem. A warmer earth causes an increase in evaporation, which is the mechanism that places more water vapor into the atmosphere. This is a powerful and significant feedback mechanism that amplifies global warming initially caused by increased concentration of atmospheric carbon dioxide from human activities.

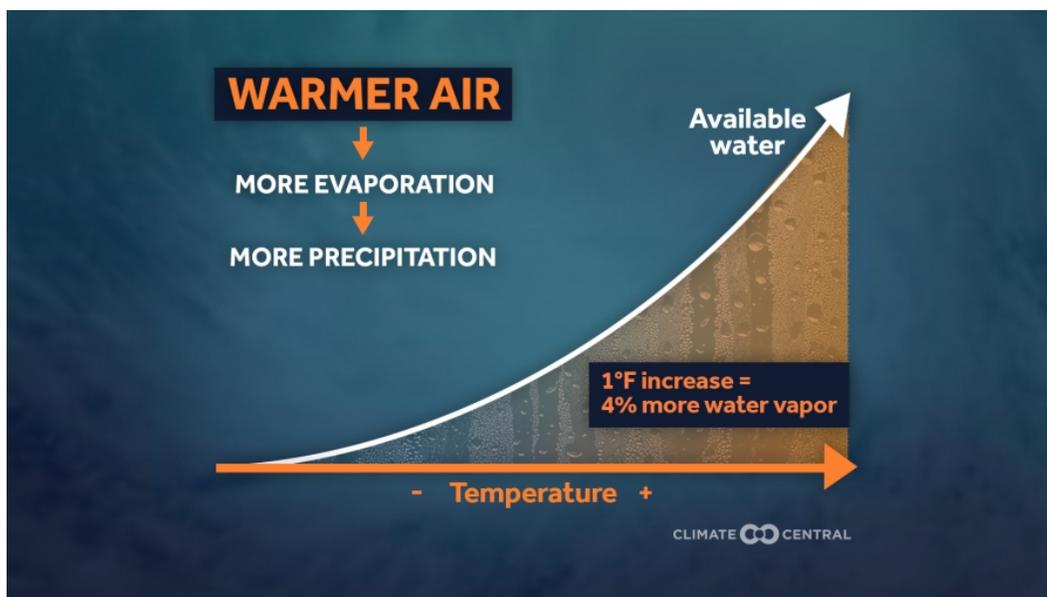


Figure 33 (Graphic courtesy of Climate Central). For every 1°F increase in temperature, the atmosphere can hold around 4 percent more water vapor. Since water vapor is a GHG, increased atmospheric water vapor causes a positive feedback loop intensifying global warming. Also, a warming atmosphere causes more evaporation, meaning more water is available for precipitation, leading to heavier rainfall and increased risk of flooding. Currently, earth has warmed by 1°C or 1.8°F.

10.2.3 Permafrost-Carbon Feedback – “Permafrost” is “permanently frozen soil” and can be found in great abundance in the polar regions of the earth, especially the regions surrounding the Arctic. Permafrost contains large quantities of dead and decayed organic matter that could be a source of carbon dioxide and methane if the permafrost melts, exposing the decayed organic matter to bacterial processing. In fact, permafrost contains as much as 1.8 trillion tons of carbon, which is twice as much carbon as currently exists in the atmosphere. As we know, the earth is warming and the Arctic is warming faster than the rest of the planet, a phenomenon called the “Arctic Amplification”. Currently, melting permafrost has exposed decayed matter to bacterial action releasing carbon dioxide and methane. Since both are greenhouse gases, melting permafrost becomes an amplifying feedback that causing additional warming.

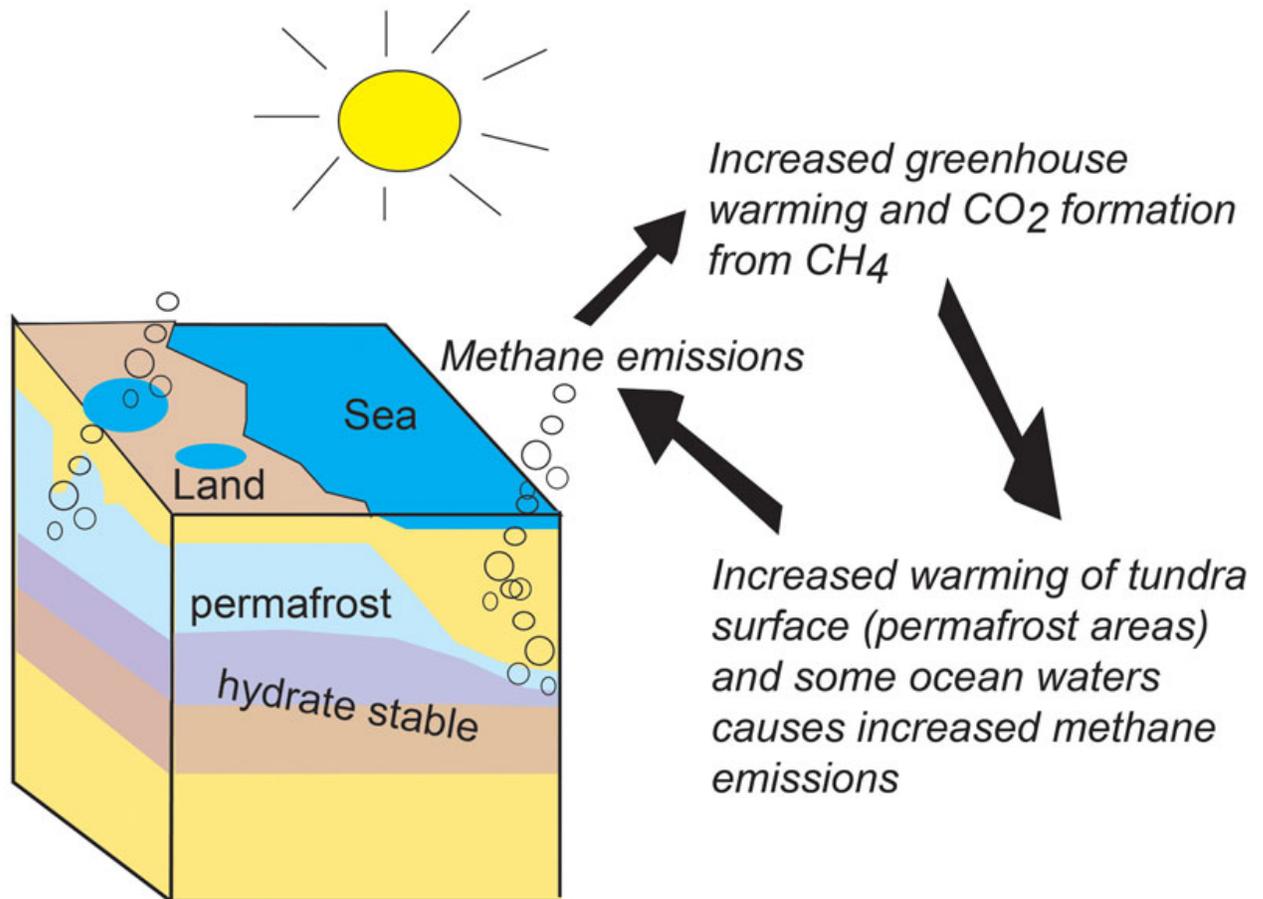


Figure 34 (Graphic courtesy of U.S. Geological Survey). Vast areas of permafrost around the world warmed significantly over the past decade. Scientists are concerned that permafrost warming might release significant quantities of methane (CH₄), a greenhouse gas twenty times more potent than CO₂. Microbes decompose the thawing organic soils releasing both methane and carbon dioxide as metabolic byproducts. Methane is a bit of a double-edged sword. It is a greenhouse gas 20 to 40 times more potent than CO₂ but it is relatively short-lived. Although methane has a lifetime of only about ten years in the atmosphere, it decomposes into carbon dioxide and water vapor, both greenhouse gases.

10.2.4 Methane Reservoir Emissions Feedback – Methane is a naturally occurring gas that is the primary component of natural gas. It is produced biologically by bacteria that decompose organic matter and geologically, vented from volcanoes and sea floor vents. Methane is a potent greenhouse gas, twenty to forty times more potent than carbon dioxide. Although its lifespan is relatively short, about ten years in the atmosphere, it decomposes into carbon dioxide and water vapor – both greenhouse gases. Recall that carbon dioxide has a lifespan of centuries. Methane exists trapped in reservoirs at the site of oil deposits and in vast deposits in shale – the source of natural gas from “fracking”. Methane also exists in huge deposits in permafrost, trapped in pools in the bottom of polar lakes, and locked in a lattice of ice crystals at the bottom of oceans in the form of methane hydrates (also called methane clathrates). Global warming could destabilize these deposits of methane causing the release of this potent greenhouse gas that will act as an amplifying feedback causing additional warming.

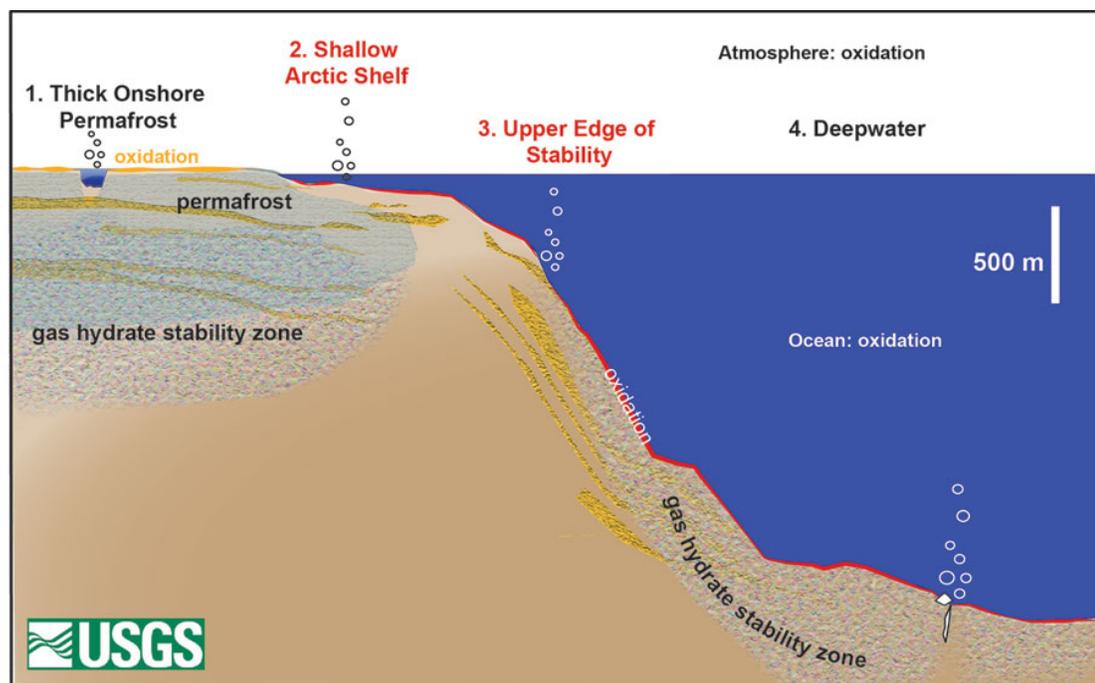


Figure 35 (Graphic and caption courtesy of U.S. Geologic Survey). “Gas-hydrate deposits by sector. Currently, gas hydrates are most likely dissociating in sectors 2 and 3. Only sector 2 is likely to release methane that could reach the atmosphere.”

10.3 Diminishing Feedbacks

Diminishing (negative) feedbacks – Despite claims from some climate change denialists, there do not appear to be any significant negative feedbacks currently acting to diminish global warming except for the technical “blackbody radiation” feedback. In the 1970’s, a group of climate scientists formed the “Ad Hoc Group on Carbon Dioxide and Climate”. The group, chaired by Jule Charney of MIT, produced “The Charney Report”, the first modern assessment of the effect of rising levels of carbon dioxide on earth’s climate. The group searched for any negative feedback loops and reached this conclusion:

“We have examined with care all known negative feedback mechanisms....We have tried but been unable to find any overlooked or underestimated physical effects that could reduce the currently estimated global warmings due to a doubling of atmospheric carbon dioxide to negligible proportions or reverse them altogether.”

That evaluation hasn’t changed. The only significant negative feedback mechanism operating today is the technical “Blackbody Radiation Feedback”. Clouds can act as a negative feedback mechanism but also as an amplifying feedback, so the overall effect is complicated.

10.3.1 Blackbody Radiation Feedback (Stefan-Boltzmann Feedback or Planck Feedback) – As the temperature of the earth increases, the Stefan-Boltzmann Law states that the emission of (infrared) radiation back into space must increase until a new thermodynamic equilibrium temperature is reached. By increasing the amount of outgoing radiation as the earth warms, there is a slight cooling, or stabilizing, effect bringing the earth back to an equilibrium temperature.

10.3.2 Evaporation/Cloud Feedback – As the temperature of the earth’s surface, sea surface and atmosphere increases, so also does evaporation. As noted above, a warmer atmosphere can hold more water vapor, which condenses around aerosol particulates to form clouds. Unfortunately, the cloud feedback effect is highly complex. Whether clouds act as amplifying or diminishing feedbacks depends on a number of variables including the type of cloud, relative darkness of the cloud, water vapor content, altitude of the cloud, and other factors. Currently, climate scientists believe that clouds cause a slight cooling effect.

10.3.3 Long-term Carbon Dioxide Feedback (Inorganic Carbon Cycle) – Although not often mentioned as a feedback loop, carbon dioxide acts as the “earth’s thermostat” over the span of geologic time – millions of years. When earth warms due to increased levels of carbon dioxide, the weathering of silicate minerals of the earth’s rocky surface increases. This occurs because carbon dioxide reacts with water to form carbonic acid (H_2CO_3) that reacts with silicate minerals producing bicarbonate ions that eventually reach the oceans where they encourage the growth of carbonate secreting organisms. As these organisms die, their carbonate shells form deposits of limestone that effectively removes carbon dioxide from the atmosphere cooling the earth (See Chapter 7, the “Long Term” Carbon Cycle).

10.4 – Other Factors That Could Influence Global Warming

Deforestation – Forests and especially tropical rain forests act as very important carbon dioxide “sinks”. These forests absorb huge amounts of carbon dioxide from the atmosphere during photosynthesis and emit oxygen. When these forests are cut down, less carbon dioxide is removed and therefore stays in the atmosphere warming the earth.

Reforestation – Of course, the flip side holds true also. By replanting forests, the trees will absorb more carbon dioxide from the atmosphere and removing any greenhouse gas will help prevent future warming.

Geoengineering – Humans have already devised technologies that can slow global warming. The most promising involve physically removing carbon dioxide from the atmosphere and either sequestering the carbon deep in the earth or converting the carbon to some useful purpose, such as fuel. These strategies must be developed and implemented. However, while geoengineering holds promise and might actually be necessary in the future, some of the strategies are risky since we don’t know exactly how the complex climate system of the earth will react. For example, spraying aerosols into the stratosphere will reduce the amount of sunlight that reaches earth’s surface. However, the potential “unintended consequences” make this “solution” extremely problematic and most scientists are reluctant to endorse these strategies. See quote on pages 67-68.

Chapter 11 – Why Scientists Are Worried: Climate Tipping Points

11.1 – What Are Climate Tipping Points?

A climate tipping point is a hypothetical point at which a change to some climate variable caused by global warming will continue to occur and there is nothing humans can do to stop it. More technically, a climate tipping point is a condition in which a small additional change to some climate element causes a large transition in the internal dynamics of that system creating a new equilibrium state. Scientists suspect that there are several hypothetical tipping points that, once reached, could dramatically change our planet’s climate system.

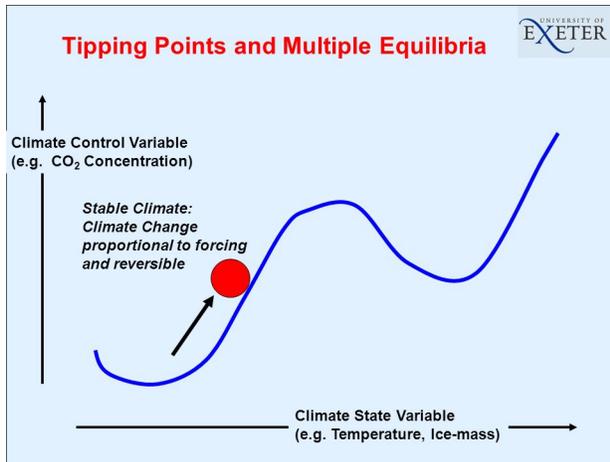


Diagram 1

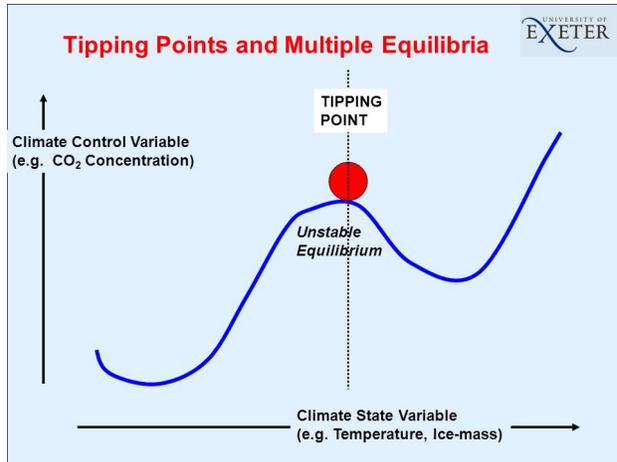


Diagram 2

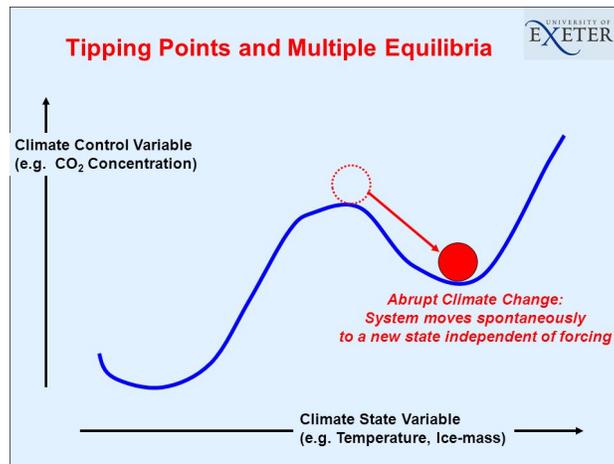


Diagram 3

Figure 36 (Graphic courtesy of University of Exeter: “Rate-dependent Tipping Points in the Earth System” by Peter Cox, Cat Luke, and Owen Kellie-Smith).

Figure 36 illustrates symbolically what a climate tipping point might look like. In diagram 1, a climate variable exists in a stable state symbolized by the lowest point in the curve to the left. A variable in a stable state can be pushed in either direction but it tends to return to its stable

state by the dynamics of the climate system. But if a “climate forcing” continues pushing the variable in one direction with no counter acting force, the variable could be pushed to a point where it becomes unstable, as depicted in diagram 2. The climate variable is now at its “tipping point” and only a small additional force is required to push it over the threshold causing that variable to drop into a new, different stable state, as depicted in diagram 3.

For example, the extent of Arctic sea ice is one of those climate elements that might be approaching its tipping point. Arctic sea ice is sensitive to climate forcing from increasing global mean temperatures, a factor compounded by the fact that the Arctic is warming twice as fast as the rest of the world. This doubling of the temperature increase is known as the “Arctic Amplification” and is likely caused primarily by local factors such as the ice-albedo feedback and warming deep ocean waters under the ice pack. Measurements clearly show that Arctic sea ice is declining at astonishing rates. The following quote is taken from NOAA’s Arctic Report Card, Update for 2018:

“As a result of atmosphere and ocean warming, the Arctic is no longer returning to the extensively frozen region of recent past decades. In 2018 Arctic sea ice remained younger, thinner, and covered less area than in the past. The wintertime maximum sea ice extent measured in March of 2018 was the second lowest in the 39-year record, following only 2017. For the satellite record (1979-present), the 12 lowest sea ice extents have occurred in the last 12 years. The disappearance of the older and thicker classes of sea ice are leaving an ice pack that is more vulnerable to melting in the summer, and liable to move unpredictably. When scientists began measuring Arctic ice thickness in 1985, 16% of the ice pack was very old (i.e., multiyear) ice. In 2018, old ice constituted less than 1% of the ice pack, meaning that very old Arctic ice has declined by 95% in the last 33 years.” (Executive Summary)

If a climate tipping point is reached for Arctic sea ice, the resulting new stable state might be a substantially reduced permanent Arctic ice cap surrounding the North Pole with large areas of the Arctic Ocean ice free year-round, impacting the Ice-Albedo amplifying feedback.

Scientists are concerned that the earth is reaching the precipice of several other tipping points.

11.2 – Potential Climate Tipping Points

Humans are running an experiment on the earth’s climate and the consequences could be disastrous if tipping points are reached. Tipping point candidates include the following:

11.2.1 Arctic Sea Ice – The initial “stable” condition of the earth’s Arctic region involved permanent sea ice covering the Arctic Ocean. Human-caused global warming has caused significant melting of the sea ice bringing into play the Ice-Albedo Feedback that has caused additional warming of the Arctic region relative to the rest of the earth, called the “Arctic Amplification”. If a “tipping point” of global warming is reached, the Arctic could “collapse” into a new, ice-free stable condition. This would decrease earth’s reflectivity increasing global warming. Scientists believe the likely tipping point for Arctic sea ice is 2⁰C of global warming. Melting of the Arctic sea ice will not increase global sea levels since the ice is already part of the ocean surface.

- 11.2.2 Greenland Ice Sheet** – This large ice sheet covers almost the entire island of Greenland. Observations and measurements indicate that this ice sheet is losing mass at an accelerating rate – 6% faster today than the 1990’s. If the Greenland ice sheet “collapses” into a new stable condition that results in an ice-free Greenland, sea levels will rise by 6-7 meters or about 20 feet. This is not immediately imminent but definitely a concern for the future. Once again, scientists believe that a global mean temperature of 2⁰C is the tipping point for the Greenland ice sheet.
- 11.2.3 West Antarctic Ice Sheet** – The scenario is similar to the Greenland ice sheet but a significant meltdown of the West Antarctic ice sheet creates the possibility of substantially greater increase in sea level. This region is of particular concern because it is melting at an accelerating rate (again, 6% faster than the 1990’s) and it holds considerably more potential for sea level rise compared to Greenland. The temperature tipping point for West Antarctica is more complex and has not been estimated. However, evidence suggests that this ice sheet is already undergoing significant structural changes.
- 11.2.4 Atlantic Meridional Overturning Circulation (AMOC)** – The “Gulf Stream” is part of this ocean current that brings warmer water north to Arctic regions affecting the weather of the North American and European continents. Its circulation transports heat around the globe like a conveyor belt, and if its movement were to stop or substantially diminish, the effects on weather patterns would be significant and dramatic. Unfortunately, the complexity of weather patterns and the many climatic mitigating factors make predictions extremely difficult. Scientists have already determined that this ocean current is slowing, which is one reason the Atlantic East Coast is experiencing a rate of sea level rise greater than the global mean increase.
- 11.2.5 Coral Reefs Collapsing** – Coral reefs might well be the “canary in the coal mine” for climate change. There are several causes for coral die-offs but there is no doubt that ocean warming is one of the mitigating factors. When water temperatures become too high, the corals expel the algae living in their tissues that give the corals their color. This is coral bleaching. Corals can survive bleaching events but they are stressed and if water temperatures remain high, the corals could die. Other causes of bleaching include agricultural fertilizer runoff that affect the corals ability to metabolize nitrogen and phosphorous, strongly suggesting that local water quality is intimately related to the corals ability to survive warming waters.
- 11.2.6 Substantial Permafrost Meltdown** – As we know, permafrost is “permanently frozen” ground that contains large amounts of organic matter that could decompose and release methane, a very potent greenhouse gas, as well as carbon dioxide. Scientists are concerned that rising temperatures could reach a tipping point that causes vast areas of permafrost to melt, exposing this biomass to bacterial action releasing vast amounts of methane and carbon dioxide. This release of huge amounts of greenhouse gases is also a positive feedback that increases global warming.

Chapter 12 – Why Scientists Are Worried: Earth’s Oceans

12.1 – Ocean Warming

The world’s oceans cover 70% of the earth’s surface and absorb most of the heat the earth receives from the sun as well as absorbing 25% to 30% of the carbon dioxide that humans are emitting into the atmosphere. These factors combine to create very significant warming of the world’s oceans. Since water has a high specific heat capacity, the oceans can absorb a lot of heat before warming significantly but at some point, the oceans must return that heat to the atmosphere in order to return earth to thermodynamic equilibrium.

Where is global warming going?

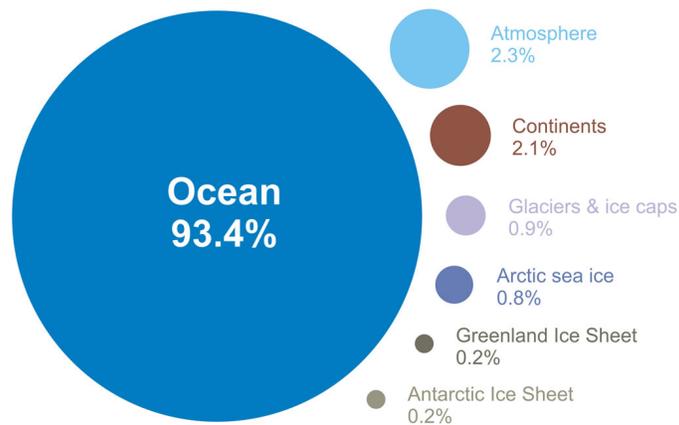


Figure 37 (Graphic courtesy of Skeptical Science). This graphic clearly shows how the oceans are absorbing most of the heat energy of earth. Because of the high specific heat of water, the oceans can hold a lot of heat. Eventually, the oceans must return this heat to the atmosphere to establish thermodynamic equilibrium that stabilizes earth’s overall temperature. This is the reason scientists speak of another half degree centigrade of warming that’s already “in the pipeline.”

As the graph below clearly shows, the oceans of the world are warming at every level, storing vast amounts of heat that must eventually be returned to the earth's atmosphere and surface. When thermodynamic equilibrium is once again reached between the oceans and the atmosphere, the earth must warm. See Chapter 12.3, Committed Warming.

Annual ocean heat content compared to average (1993-2018)

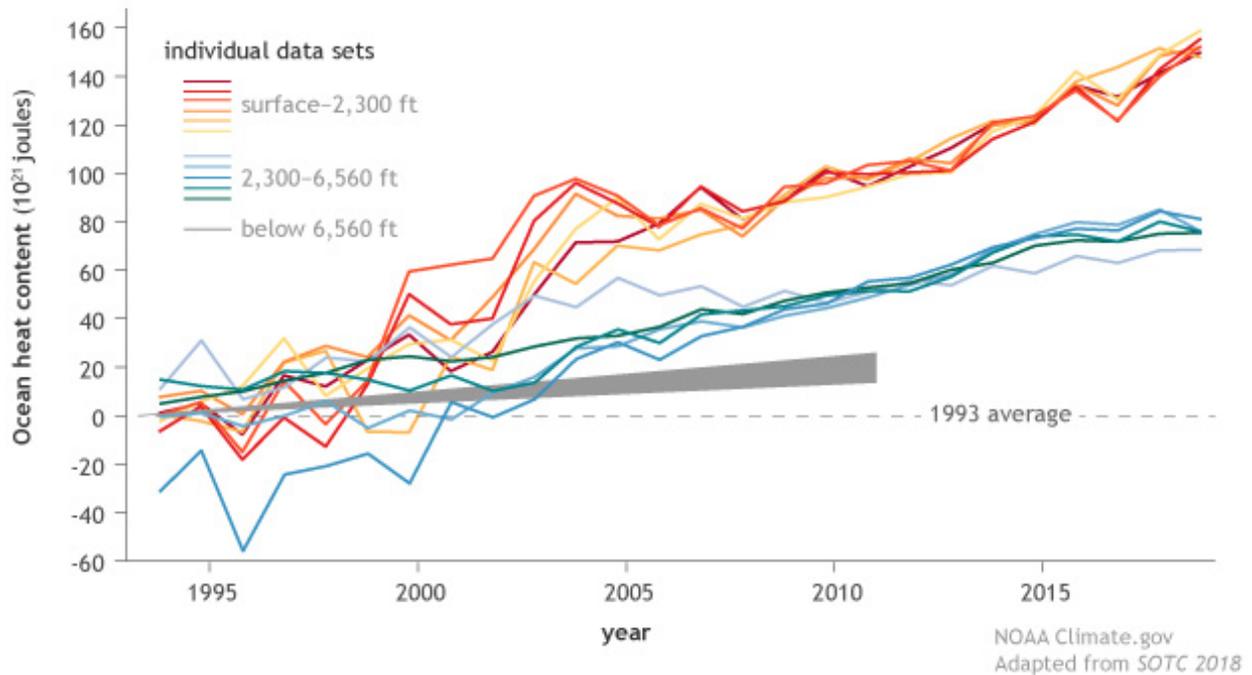


Figure 38 (Graphic courtesy of NOAA). This graph shows the warming trend of the world's oceans, which have stored a large amount of heat generated by solar irradiance and atmospheric warming. Again, a great deal of heat energy has been stored in the oceans that will take a very long time to reestablish thermal equilibrium with the earth's surface and atmosphere. This effect is termed "thermal inertia" and causes the "committed warming" discussed in section 12.3.

12.2 – Effects of Ocean Warming

The physical warming of ocean waters stresses some of the marine organisms causing mobile organisms to migrate toward colder waters. For example, at the bottom of the marine food change are the plankton, minute single cell organisms that are divided into free-floating phytoplankton and the more mobile zooplankton. A study reported in *Nature* found that the composition of the world's plankton has changed since preindustrial times. Reporting on the article, YaleEnvironment360 (May 22, 2019) stated this:

“The composition of the world’s plankton has changed significantly since before the Industrial Revolution, with zooplankton communities shifting poleward by an average 374 miles as a result of warming ocean temperatures... Zooplankton is a critical component of the marine food web, and scientists warned that while some species will be able to follow their food source to new waters, many others will not.”

Other marine organisms unable to migrate to cooler waters are even more vulnerable. Corals are particularly vulnerable to warming waters with observed die-offs in many diverse areas worldwide.

Another problem is the fact that warmer waters are capable of holding less dissolved gases than colder waters. All marine animals require dissolved oxygen for respiration and a warmer ocean holds less oxygen than a colder ocean. Pollution of coastal waterways from fertilizer runoff and other sources compounds the problem often leading to “dead zones” – regions of coastal waters that are hypoxic (low in oxygen). Hypoxia is the cause of many fish die-offs and warming oceans increase the likelihood of these hypoxic events.

12.3 – Committed Warming

An article in NOAA Climate, February 12, 2020 written by Rebecca Lindsey nicely summarizes the notion of committed warming.

“Just like your car doesn’t reach top speed the instant you step on the gas, Earth’s temperature doesn’t react instantly to each year’s new record-high carbon dioxide levels. Thanks to the high heat capacity of water and the huge volume of the global oceans, Earth’s surface temperature resists rapid changes. Said another way, some of the excess heat that greenhouse gases force the Earth’s surface to absorb in any given year is hidden for a time by the oceans. This delayed reaction means rising greenhouse gas levels don’t immediately have their full impact on surface temperature.”

This delayed reaction occurs because water has a high “specific heat capacity”. “Specific heat” refers to the amount of heat required to raise the temperature of one gram of a substance 1⁰C. Consequently, the earth’s ocean can absorb a great deal of heat before its temperature increases significantly. Eventually however, the heat being stored in the oceans must “even out” to restore the planet’s thermodynamic equilibrium. But this will take time. This lag time is termed “thermal inertia” and could be hundreds of years. Most scientists consider that there is already .5⁰C of additional “committed warming” stored in the oceans that must be returned to the earth’s atmosphere and surface. This additional warming is “in the pipeline”.

12.4 – Ocean Acidification: The “Other CO₂ Problem”

Since 1800, the atmospheric concentration of carbon dioxide has increased from 280 ppm to over 400 ppm and it continues to increase. The world’s oceans cover 70 % of the earth’s surface and absorb huge amounts of CO₂ helping regulate the atmospheric CO₂ concentration but this uptake of carbon dioxide from the atmosphere changes the ocean’s chemistry. One of the most important effects of absorbing this CO₂ is *ocean acidification*.

The following summary is taken from the booklet, *Ocean Acidification* published by the National Research Council of the National Academies:

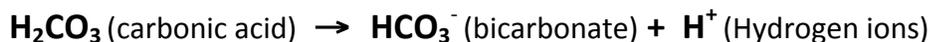
“Atmospheric carbon dioxide is absorbed by the ocean, where it reacts with seawater to form carbonic acid (H₂CO₃). Almost immediately, carbonic acid dissociates to form bicarbonate ions (HCO₃⁻) and hydrogen ions (H⁺). As the concentration of hydrogen ions increases, the water becomes more acidic. Some of the extra hydrogen ions react with carbonate ions (CO₃²⁻) to form more bicarbonate. This makes carbonate ions less abundant – a problem for many marine species that absorb carbonate from seawater and use it to build calcium carbonate shells and skeletons in a process called calcification. As carbonate becomes less abundant, these organisms, such as corals and clams, have more difficulty building and maintaining their shells and skeletons. Increased acidity can even cause some carbonate shells to dissolve. Hydrogen ions react with the solid calcium carbonate (CaCO₃) and convert it to soluble bicarbonate (HCO₃⁻) and (Ca²⁺) ions.” (page 6)

The chemistry is a bit complex but worth a little effort.

Step 1. Carbon dioxide flows into and out of the oceans relatively easily but some of the CO₂ is absorbed by the oceans. The dissolved CO₂ combines with water molecules to form relatively weak carbonic acid.



Step 2. Almost immediately, the carbonic acid dissociates to form bicarbonate ions and hydrogen ions. It is the increase in hydrogen ions that causes the pH of the oceans to decrease; the ocean become more acidic.



Step 3. Some of the hydrogen ions react with carbonate ions to produce bicarbonate, which removes the carbonate from the seawater making it more difficult for calcifying marine organisms to construct their shells.



12.5 – Local Stressors, Hypoxia and Ecosystem Resilience

The ability of our coastal ecosystems to cope with acidification is influenced by the local stressors they must contend with, such as high nutrient input, or changes in temperature or salinity. Excess nutrients from river inputs and fertilizer runoff can cause algal blooms. When these algal blooms die, they consume oxygen and release carbon dioxide. If too much oxygen is consumed by these dying blooms, hypoxia (low oxygen levels) can result. These local oxygen depletion events can lead to marine die-offs and the excess carbon dioxide causes additional acidification. The ability of any marine ecosystem to deal with the general increase in acidification from rising levels of atmospheric CO₂ is also impacted by these local events. Controlling and minimizing these local stressors is an important mitigating factor in helping these coastal ecosystems cope with ocean acidification. The following quote from NOAA Ocean Service Education, “Estuaries, Nutrient Pollution – Eutrophication”, summarizes the problem.

“Nitrates and phosphates are nutrients that plants need to grow. In small amounts they are beneficial to many ecosystems. In excessive amounts, however, nutrients cause a type of pollution called eutrophication. Eutrophication stimulates an explosive growth of algae (algal blooms) that depletes the water of oxygen when the algae die and are eaten by bacteria. Estuarine waters may become hypoxic (oxygen poor) or anoxic (completely depleted of oxygen) from algal blooms. While hypoxia may cause animals in estuaries to become physically stressed, anoxic conditions can kill them.”

12.6 – Sea Level Rise

Sea level rise concerns scientists and policy makers because so many people live on or near the coastlines of the world. According to NOAA, National Ocean Service (Ocean Facts: Is Sea Level Rising):

“With continued ocean and atmospheric warming, sea levels will likely rise for many centuries at rates higher than that of the current century. In the United States, almost 40 percent of the population lives in relatively high-population-density coastal areas, where sea level plays a role in flooding, shoreline erosion, and hazards from storms. Globally, eight of the world’s 10 largest cities are near a coast, according to the U.N. Atlas of the Oceans.”

Currently, global sea levels are rising primarily because of thermal expansion (water expands as it warms) and meltwater from mountain glaciers and polar ice sheets.

Contributors to global sea level rise (1993-2018)

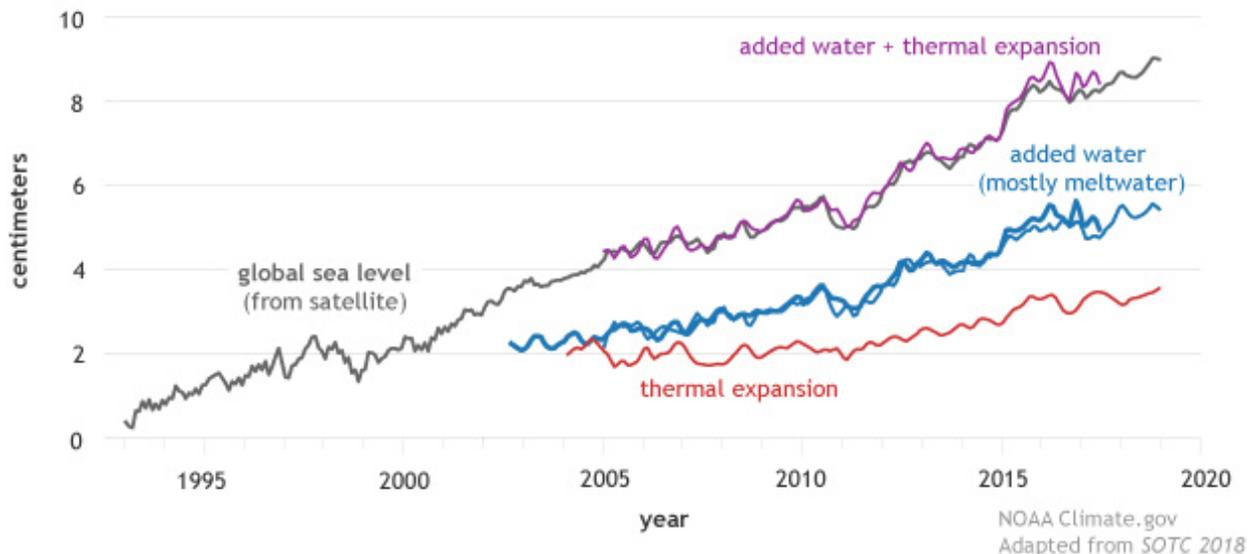


Figure 39 (Graphic and caption courtesy of NOAA). “Observed sea level since the start of the satellite altimeter record in 1993 (black line), plus independent estimates of the different contributors to sea level rise: thermal expansion (red) and added water, mostly due to glacier melt (blue). Added together (purple line), these separate estimates match the observed sea level very well. NOAA Climate.gov graphic, adapted from Figure 3.15a in *State of the Climate, 2018*.”

Additionally, local sea level rise could be substantially higher than the global mean sea level rise since other factors influence rising waters. Again, to quote NOAA, National Ocean Service:

“Sea level rise at specific locations may be more or less than the global average due to local factors such as land subsidence from natural processes and withdrawal of groundwater and fossil fuels, changes in regional ocean currents, and whether the land is still rebounding from the compressive weight of Ice Age glaciers. In urban settings, rising seas threaten infrastructure necessary for local jobs and regional industries. Roads, bridges, subways, water supplies, oil and gas wells, power plants, sewage treatment plants, landfills—virtually all human infrastructure—is at risk from sea level rise.”

Ultimately, we know that global sea levels will continue to rise as the atmospheric concentration of carbon dioxide increases causing global temperatures to rise. The question is, “How much will sea level rise?” The answer to that question depends upon how humanity responds to the challenge of global warming. Scientists do not like to make predictions with insufficient data, yet they must in order to guide the decisions of policy makers. Most recent estimates of projected global sea level rise forecast about 1 meter (3 feet) of increase by 2100 but the recent rate of increase has been accelerating. Also, as noted, local regions such as the U.S. East Coast are likely to experience greater sea level rise due to regional influences. The East Coast is still experiencing “rebound subsidence” from the Laurentide glaciation as well as the slowing of the Atlantic Meridional Overturning Circulation (AMOC) causing water to “pile up” along the coast.

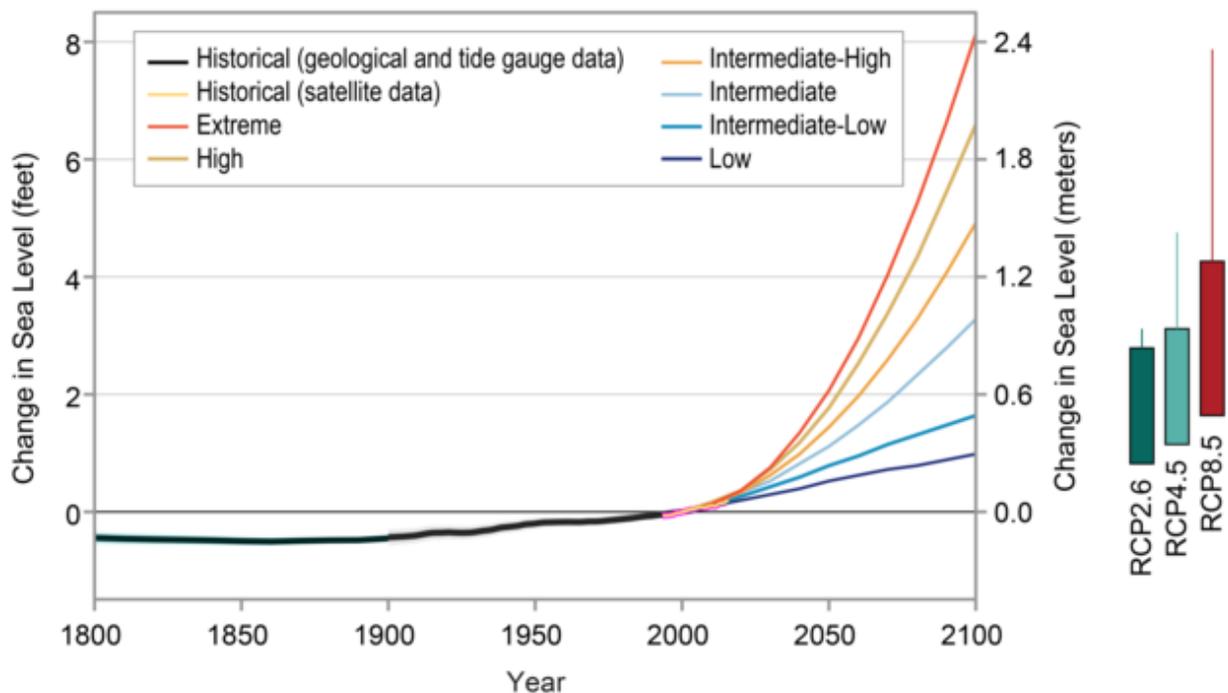


Figure 40 (Graphic courtesy of National Climate Assessment, Chapter 2, KM4: Sea Level Rise). Current emissions of greenhouse gases indicate that we are close to the worst scenario (RCP 8.5) but recent research questions that conclusion. A better estimate suggests that current emissions are likely to decrease as alternative energy sources, such as natural gas, replace coal, and renewable energy sources become more economically feasible. It now appears that global sea levels will rise between 1 and 1.5 meters by 2100.

Chapter 13 – Why Scientists Are Worried: Extreme Weather Events

Over the past decade, scientists have established a link between global warming and extreme weather events and evidence for the connection between global warming grows stronger each day. Extreme weather events that have been linked to global warming include, tropical cyclones, heat waves, droughts, intense rainfall events, flooding, wildfires, and even winter blizzards. Possible links to other extreme weather events such as tornadoes cannot be ruled out. The toll for these events is paid not just in human suffering and death but in huge amounts of economic resources.

The following excerpt from the National Academies of Sciences, Engineering and Medicine, “Based on Science” article entitled, “Global warming is making extreme weather events worse”, summarizes the topic nicely:

“As Earth’s climate has warmed, a new pattern of more frequent and more intense weather events has unfolded around the world. Scientists identify these extreme weather events based on the historical record of weather in a particular region. They consider extreme weather events to be those that produce unusually high or low levels of rain or snow, temperature, wind, or other effects. Typically, these events are considered extreme if they are unlike 90% or 95% of similar weather events that happened before in that same area.

Global warming can contribute to the intensity of heat waves by increasing the chances of very hot days and nights. Warming air also boosts evaporation, which can worsen drought. More drought creates dry fields and forests that are prone to catching fire, and increasing temperatures mean a longer wildfire season. Global warming also increases water vapor in the atmosphere, which can lead to more frequent heavy rain and snowstorms.

A warmer and more moist atmosphere over the oceans makes it likely that the strongest hurricanes will be more intense, produce more rainfall, and possibly be larger. In addition, global warming causes sea level to rise, which increases the amount of seawater, along with more rainfall, that is pushed on to shore during coastal storms. That seawater, along with more rainfall, can result in destructive flooding. While global warming is likely making hurricanes more intense, scientists don’t know yet if global warming is increasing the number of hurricanes each year. The effect of global warming on the frequency, intensity, size, and speed of hurricanes remains a subject of scientific research.”

The increasing costs of extreme weather events in the United States is clearly depicted in the following graph.

1980-2018 Year-to-Date United States Billion-Dollar Disaster Event Frequency (CPI Adjusted)

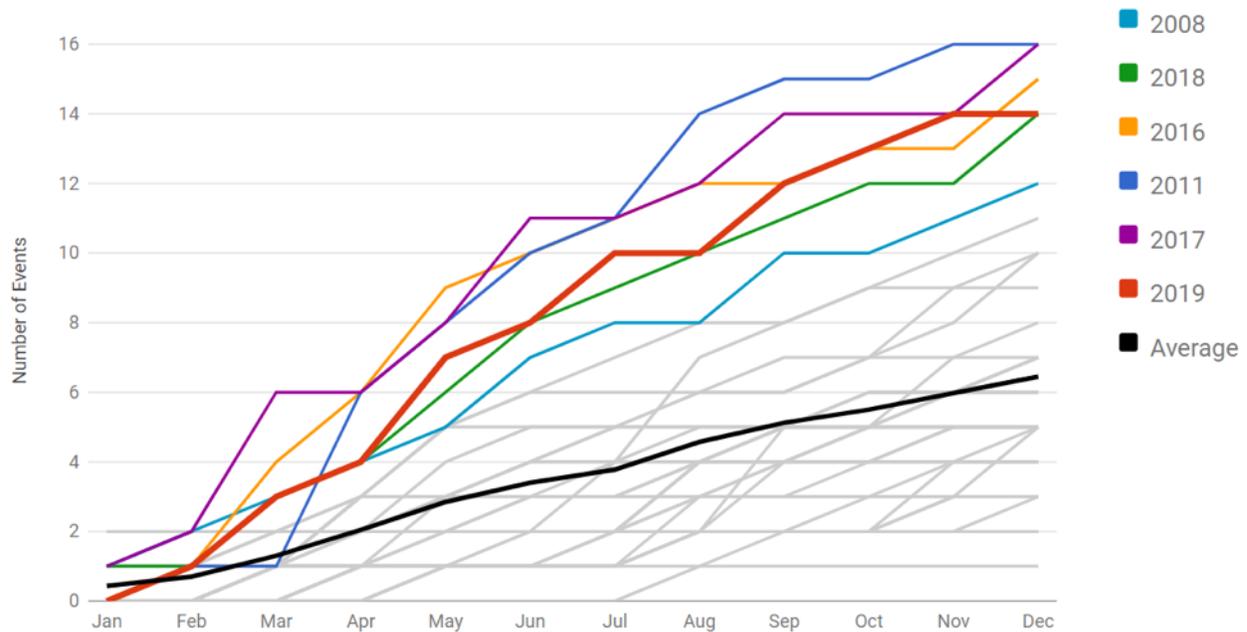


Figure 41 (Graphic courtesy of NOAA). The graph depicts the number of events that cost over a billion dollars. It does not include the expenses for those weather events that cost less than a billion dollars. More importantly, the graph does not show the number of deaths or the degree of human suffering caused by these events. In 2019, there were 14 weather and climate disaster events in the United States continuing the trend towards increasing extreme weather events as the earth continues to warm.

Although the graph above shows data only for the United States, the worldwide data reflects the same upward trend. In particular, tropical cyclones are getting stronger, producing greater amounts of rainfall, and their forward motion is slowing. The increasing strength of tropical cyclones has some meteorologists recommending increasing the Saffir-Simpson Hurricane Wind Scale to include a Category 6. Hurricane Harvey is a classic example of what future hurricanes might look like. Harvey hit the gulf coast of the United States dropping 2 feet of rainfall in the first 24 hours flooding one-third of the city of Houston. Similar tropical cyclones have recently devastated areas of Asia in similar fashion.

Chapter 14 – What Can We Do About Global Warming and Climate Change

The secret of getting ahead is getting started. Mark Twain

14.1 – Adaptation, Mitigation, and Geoengineering

Climate change affects everyone, which means that everyone must engage this threat. However, being practical, only governments have the resources to significantly address the problem in a meaningful way and there are only three strategies available: adaptation, mitigation, and geoengineering.

14.1.1 Adaptation. Adaptation involves anticipating the adverse effects of climate change and taking appropriate action to prevent or minimize the damage they can cause. Examples of adaptation include: using scarce water resources more efficiently; adapting building codes designed to minimize damage from extreme weather events; building flood defenses, such as berms or dikes; raising the levels of roadways and bridges; developing drought-tolerant crops; choosing tree species and forestry practices less vulnerable to storms and fires; and setting aside land corridors to help species migrate. Adaptation can also mean taking advantage of opportunities that may arise from global warming and climate change. For example, a longer growing season can offset some of the negative impacts global warming can have on crops.

In one sense, adaptation is an easy sell. When sea level rise creates problems, as it has for the U.S. Navy at its Norfolk Naval base, the solution is not only obvious but immediately necessary. The Navy has spent about \$250 million to raise two piers just to accommodate its ships and will have to make further adjustments. New York City suffered costly damage from Super Storm Sandy and several plans have been floated to adapt to future storm surges. The latest is a \$119 billion proposal from the U.S. Army Corps of Engineers to protect New York and New Jersey, a plan that has many critics because of the scale and cost. Coastal cities worldwide are investigating various plans to adapt to sea level rise but if a roadway regularly floods with astronomical high tides, the solution is clear and necessary – raise the roadway.

As necessary as adaptive solutions might be, they have one fatal flaw: Adaptation deals only with the effects of climate change, not the cause. Adaptation strategies are ultimately doomed to fail without addressing the source of the problem – human emissions of greenhouse gases. Building a six foot wall is effective... until sea levels rise seven feet.

14.1.2 Mitigation. Mitigation actually deals with the cause of global warming and involves strategies designed to reduce the effects of human-caused global warming and climate change. The following quotes are taken from the Fourth National Climate Assessment, Mitigation Section, Introduction:

“Mitigation refers to actions that reduce the human contribution to the planetary greenhouse effect. Mitigation actions include lowering emissions of greenhouse gases like carbon dioxide and methane, and particles like black carbon (soot) that have a warming effect. Increasing the net uptake of carbon dioxide through land-use change and forestry can make a contribution as well. As a whole, human activities result in higher global concentrations of greenhouse gases and to a warming of the planet – and the effect is increased by various self-reinforcing cycles in the Earth system (such as the way melting sea ice results in more dark ocean water, which absorbs more heat, and leads to more sea ice loss).”

“The amount of future climate change will largely be determined by choices society makes about emissions. Lower emissions of heat trapping gases mean less future warming and less severe impacts. Emissions can be reduced through improved energy efficiency and switching to low-carbon or non-carbon energy sources.”

14.1.3 Geoengineering. Scientists are concerned that efforts to mitigate climate change might not be sufficient to prevent the disastrous consequences that appear to be in our future. If mitigation fails to stop emissions of greenhouse gases, we might have to resort to geoengineering: deliberately manipulating physical, chemical, or biological aspects of the earth’s climate system to reduce the effects of global warming. According to the Policy Statement of the American Meteorological Society:

“Geoengineering could lower greenhouse gas concentrations, provide options for reducing specific climate impacts, or offer strategies of last resort if abrupt, catastrophic, or otherwise unacceptable climate-change impacts become unavoidable by other means. However, research to date has not determined whether there are large-scale geoengineering approaches that would produce significant benefits, or whether those benefits would substantially outweigh the detriments. Indeed, geoengineering must be viewed with caution because manipulating the Earth system has considerable potential to trigger adverse and unpredictable consequences.

Geoengineering proposals fall into at least three broad categories: 1) reducing the levels of atmospheric greenhouse gases through large-scale manipulations (e.g., ocean fertilization or afforestation using non-native species); 2) exerting a cooling influence on Earth by reflecting sunlight (e.g., putting reflective particles into the atmosphere, putting mirrors in space, increasing surface reflectivity, or altering the amount or characteristics of clouds); and 3) other large-scale manipulations designed to diminish climate change or its impacts (e.g., constructing vertical pipes in the ocean that would increase downward heat transport).

Geoengineering proposals differ widely in their potential to reduce impacts, create new risks, and redistribute risk among nations. Techniques that remove CO₂ directly from the air would confer global benefits but could also create adverse local impacts. Reflecting sunlight would likely reduce Earth's average temperature but could also change global circulation patterns with potentially serious consequences such as changing storm tracks and precipitation patterns. As with inadvertent human-induced climate change, the consequences of reflecting sunlight would almost certainly not be the same for all nations and peoples, thus raising legal, ethical, diplomatic, and national security concerns.

Exploration of geoengineering strategies also creates potential risks. The possibility of quick and seemingly inexpensive geoengineering fixes could distract the public and policy makers from critically needed efforts to reduce greenhouse gas emissions and build society's capacity to deal with unavoidable climate impacts. Developing any new capacity, including geoengineering, requires resources that will possibly be drawn from more productive uses. Geoengineering technologies, once developed, may enable short-sighted and unwise deployment decisions, with potentially serious unforeseen consequences.

Even if reasonably effective and beneficial overall, geoengineering is unlikely to alleviate all of the serious impacts from increasing greenhouse gas emissions. For example, enhancing solar reflection would not diminish the direct effects of elevated CO₂ concentrations such as ocean acidification or changes to the structure and function of biological systems."

14.1.4 Project Drawdown. Project Drawdown is a comprehensive mitigation project initiated by Paul Hawken and climate activist Amanda Joy Ravenhill. The project focuses on 100 solutions that are currently technologically viable and listed according to the amount of carbon they would remove from the environment.

The book **Drawdown: The Most Comprehensive Plan Ever Proposed To Reverse Global Warming** is a must read for anyone interested in *solutions* to the problem of human caused global warming. According to Project Drawdown:

"Drawdown describes the 100 most substantive solutions to global warming. For each solution, we describe its history, the carbon impact it provides, the relative cost and savings, the path to adoption, and how it works. The goal of the research that informs Drawdown is to determine if we can reverse the buildup of atmospheric carbon within thirty years. All solutions modeled are already in place, well understood, analyzed based on peer-reviewed science, and are expanding around the world."

Chapter 15 – Conclusion

*“The good thing about science is that it’s true whether or not you believe in it.”
Neil deGrasse Tyson*

15.1 – Science and “Uncertainty”

A skeptic might say, “But are you 100% certain that you know the final speed of a falling object?” Good point, but “certainty” does not exist in the realm of science, and that is a good thing. In science, there is no dogma and no unerring authority who proclaims the truth. Science is evidence-based and all theories are *conditionally* accepted based upon *current* evidence, which ensures that science is honest and self-correcting. Scientists must always allow for the possibility that evidence from a currently unknown variable exists that could influence their position. This is why scientific knowledge grows and is so successful at explaining nature. Scientists do not talk about 100% certainty regarding anything in nature, they speak in terms of probability or level of confidence – things we would call “likelihood”.

But this does not mean science is “unsure” of its beliefs. Let’s look at the terminal velocity of an object falling to earth. We already know the formula for acceleration due to gravity ($a=32\text{ft/s}^2$) but are scientists absolutely “certain” this formula predicts the terminal velocity of a human falling from a two-thousand foot tower? No, they are not, because other variables will influence the terminal velocity. For one thing, air resistance will slow the object. The shape and mass of the object, surface area exposed to air resistance, humidity, precipitation, and other factors all influence final velocity. For example, a spider can jump from that 2000 foot tower, land and walk away unharmed. Its mass is small and its surface area with hairy legs splayed out provides sufficient air resistance to slow its final velocity to a survivable speed. But, knowing that there is some uncertainty involved in predicting the terminal velocity of a human in freefall, would you step confidently off the tower thinking your fate would be similar to the spider? Of course not. The degree of uncertainty is insignificant relative to the danger and scientists can provide you with a predicted terminal velocity that will be very close to a real world event. For a typical human, the body will reach 99% of terminal velocity after falling 2,000 feet, which takes anywhere from 10-14 seconds, and the velocity will be between 118 and 125 miles per hour. And yes, scientists are extremely confident in that prediction.

Just as scientists are 99% confident in the terminal velocity of a falling object on earth, they are equally 99% confident that human activities are the cause of the current global warming and climate change. The questions scientists are now concerned with involve how much the earth will warm, how quickly it will happen, and how this warming will impact life as we know it. Scientists term this “climate sensitivity”. Unfortunately, virtually every month, new studies suggest that the earth’s climate is much more sensitive than the IPCC predictions.

It is literally true that fossil fuels have provided us with the standard of living we enjoy today. But the fossil fuel industry is a 19th century technology that now threatens our very existence. It is time to develop a 21st century technology – one that does not increase the concentration of greenhouse gases. This is an opportunity we must embrace – developing an economy based upon renewable energy resources. We have the technology to accomplish this and grow the world economy in a socially responsible way. All we need now is the will to do it.

But if we fail to engage this challenge today, we will lose a window of opportunity that is quickly closing. Hopefully, this summary has provided some of the necessary information to help us make informed decisions. Whether we are teachers, policy makers, or students we will be forced to live with the decisions we make, or fail to make, today. Tomorrow will be too late.

Epilogue

The Epilogue for the story of anthropogenic climate change must be written by future generations. The following quote is taken from a monument recently erected in Iceland commemorating the death of Ok, an Icelandic glacier “killed” by global warming.

“Ok is the first Icelandic glacier to lose its status as a glacier.

In the next 200 years all our glaciers are expected to follow the same path.

This monument is to acknowledge that we know what is happening and what needs to be done.

Only you know if we did it.”