Global climate change: review of important causal mechanisms and consequences

Brian W. Bodah
Doctor in Biological Systems Engineering, Washington State University.
E-mail: <bbodah@wsu.edu>.

Eliane T. Bodah
Doctor in Horticulture, Washington State University.
E-mail: <elianeb@uw.edu>.

Abstract

The process known as global climate change is very serious. While we do not exactly know what the future may hold, our scientific models and studies of similar past events can give us a good idea. Our goal is to provide some background information on the processes that contribute to climate change as well as to list some of the consequences. Our approach was a bibliographical research that included a literature review on the topic accompanied by conceptual discussion. Our results indicated that the major problem that we run into today is that we are taking the carbon in coal and petroleum, carbon that was gradually sequestered by ancient plants over millions of years, and re-releasing it back into our atmosphere at rates far faster than we plants are able to re-sequester it. Furthermore, we have contributed to the increased release of different, mostly anthropogenic, greenhouse gases into the atmosphere. Understanding the basic mechanisms that potentially cause global climate change is important to help us make intelligent and informed daily decisions to help limit global climate change as much as possible.
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1 Introduction

Global climate change has been the buzz word of the environmental movement for the past decade or so. Many of you may know it by the name global warming. When the concept of global climate change was first introduced, it was done so as global warming, a decision that many scientists now regret. The name global climate change is more appropriate because although the overall temperature of the globe is forecast to get warmer, some parts of the world will actually cool down. Scientists also predict some areas will receive greater rain fall while others will become dryer. Climactic patterns are somewhat hard to predict, even today, so exact forecasts of what the future may bring are varied.

In colder climates, such as the northern United States, people generally joke around regarding global warming, especially on cold days. We have personally heard comments such as "When is that global warming coming – it's freezing out," or, "Thank goodness for this global warming" on unusually warm winter days. The truth is, global climate change is no joke, it is a very real, very serious phenomenon that scientific consensus agrees is anthropogenic, meaning human caused. We know that our emissions are causing global climate change, and we also know that we have the ability to limit it, but first we have to take it seriously.

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2 Closed System

You and I, the paper this article is printed on or the computer screen on which you may be reading this, and the chair you are sitting in are all composed of atoms. The atom is the basic building block of matter, and an element is the purest form of matter. Elements react and combine with one another to form compounds, which together combine to form all of the matter in our universe. The law of conservation of mass teaches us that matter is neither created nor destroyed, it merely changes form (CHANG, 2005). This basic scientific law is profound in that it tells us that every atom in our body used to be part of something else. Indeed, when we die, the atoms that were once part of our body will go on to form something else, which will eventually break down to form yet something else, and so on and so forth. As you read this, you are exhaling air containing carbon dioxide (CO_2). The atom of carbon attached to those two oxygen atoms was once part of your body, now it is part of the atmosphere.

Using this basic law, we can deduce that the mass of a closed system, a system that allows the transfer of energy but not mass (CHANG, 2005), will remain constant, regardless of the processes acting inside the system. Earth, our home planet, is a closed system, although not a perfectly closed one. Very small amounts of matter, relative to the size of the earth, are added to our planet daily as micro-meteors and other space debris enter our atmosphere. In addition, very small amounts of light gasses such as hydrogen are capable of leaving our atmosphere and entering the void of space. However, generally speaking, Earth is closed system.

What this means is that everything that was ever on Earth is still on Earth. Our planet has gone through many changes throughout its 4.4 billion year history. Different land masses, atmospheres, and oceans have all come and gone, but their matter remains with us.

3 Carbon Based Life

All life on planet Earth is carbon based. That means that the chemical makeup of every plant and every animal on this planet is based around the element carbon. Carbon is found in all of our cells, and is necessary for life on Earth. When we die, the carbon that is in our cells enters the environment through the process of decay. Decaying organisms emit a variety of chemical compounds to the surrounding soil and atmosphere. Most of the carbon in our bodies will be combined with oxygen in the air by organisms of decay after we die, being emitted as carbon dioxide (CO_2). Anaerobic decay, also known as fermentation (AGGIE, 2009), is decay that proceeds in the absence of oxygen. Fermentation and methanogenesis are two of the major anaerobic processes that occur in wetlands (Mitsch & Gosselink, 2000). Methanogenesis, performed by the anaerobic bacteria methanogens, releases carbon in the form of methane (CH_4) (MITSCH; GOSSELINK, 2000). Both CO_2 and CH_4 are known as greenhouse gasses (which will be discussed later on).

In a natural system, at natural rates, the carbon dioxide that is emitted by decaying organisms is easily taken in by plant life and converted back into oxygen (O_2) through a process known as photosynthesis. Photosynthesis is how plants manufacture their own food by producing the simple sugar glucose ($C_6H_{12}O_6$). This is done by utilizing the energy of sunlight to transform carbon dioxide in the air and water into glucose through the basic equation $6CO_2 + 6H_2O$ (+ light energy) à $C_6H_{12}O_6 + 6O_2$ (FARABEE, 2007). Plants remove carbon from the atmosphere (in the form of CO_2) and incorporate that atom of carbon into their tissues (cells), creating oxygen as a waste product. This process, which has occurred steadily since plants first evolved, is responsible for every atom of oxygen in our atmosphere today. Earth's early atmosphere was completely void of oxygen (KASTING, 1993).

4 Fossil Energy

Roughly 358 million years ago, a period of geologic time known as the Carboniferous Period was beginning on Earth. Following the Carboniferous Period, and lasting until roughly 251 million years ago, was a period of geologic time known as the Permian Period (SKINNER et al., 2004). During this time, spanning 107 million years, lush tropical and subtropical swamps covered much of the land surface of the earth. Gymnosperms (trees with needles for leaves) and giant ferns dominated these lush swamps and thrived in the warm, moist climate (SKINNER et al., 2004). These prehistoric plants removed naturally occurring carbon in the atmosphere (through photosynthesis) and used it to build their bodies and produce glucose throughout their lives. Eventually these giants of the plant world died and fell within the swamp. A large portion of their remains were decomposed by microorganisms, fungi, insects, and other decomposers; re-releasing this stored carbon back into the atmosphere. Some of this plant matter, however, eventually made its way to the bottom of the swamp; a place largely void of oxygen and high in acidity, two conditions that greatly slow rates of decomposition.

The aerobic decay of organic matter (that takes place on the surface of the earth) requires two main things, oxygen and liquid water (AGGIE, 2009). Without either one, this process of decay cannot proceed. This is why trees that fall into a lake and sink to the bottom can last for hundreds of years, and why dead organic matter in the desert persists for so long.

The depths of these prehistoric swamps had plenty of liquid water, but virtually no oxygen. Without oxygen for the decomposing bacteria and macroinvertebrates to utilize, some was decomposed anaerobically, but much of this organic matter simply remained at the bottom of the swamp, forming a deposit known as peat. The carbon that was removed from the atmosphere and incorporated into the plant tissues through the process of photosynthesis while these plants were alive, remained trapped within the peat deposits at the bottom of the swamp.

Over many millennia these great swamps continued to accumulate their peat deposits. Over time, as more and more peat was accumulated, the swamps eventually filled themselves in. Steady, long lasting erosional processes such as sedimentation or rapid geologic events such as volcanic eruptions would eventually cover these peat deposits. As the earth continued to deposit layer upon layer of sedimentary materials on top of this peat, it was thrust downward within the earth, heated (as the interior of the earth is molten), and condensed under the pressure exerted by the increasing weight being added on top of it. Over millions of years, this organic peat was gradually transformed into coal (roughly 80% carbon), resulting in the large coal beds of modern Europe and the eastern United States. Other periods of significant coal formation have also occurred throughout the earth's history (SKINNER et al., 2004).

Oil and natural gas (collectively known as petroleum) are formed in a similar fashion from the decomposition of organic matter that is trapped in sediments (SKINNER et al., 2004). These sediments are also gradually overlain by younger sediments with time. Like the peat, they are sent deeper into the earth, heated, and exposed to immense pressure. The difference in coal and petroleum is that petroleum migrates through geologic substrate with time, eventually making its way to the surface of the earth (SKINNER et al., 2004) In areas where the petroleum encounters impermeable layers, it pools to form deposits of either oil or natural gas (whose principal component is methane).

5 Sequestered Carbon

The carbon that makes up coal and petroleum deposits used to be part of the atmosphere. It was converted by prehistoric plants millions of years ago into plant matter, which in turn was converted through geologic processes into its current form. While stored underground the carbon was confined. Scientists refer to this confinement as sequestration. Under natural processes, sequestered carbon has no way to return to the atmosphere, it is trapped underground and part of the geologic record.

The formation of these immense coal and petroleum deposits continued for millions of years, continuing even in the peatlands and swamps of today. Countless generations of swamp plants incorporated carbon into their plant tissues over the millennia (releasing oxygen into the atmosphere in the process). As this happened, the amount of carbon contained within the atmosphere was slowly reduced. This reduction in atmospheric carbon resulted in a gradually cooling climate on earth (as will be discussed later).

The plant and animal life that remained on the earth gradually evolved with the changing climate. Ice ages came and went; ecosystems advanced and retreated under changing climate patterns. Life persevered and adapted. This adaptation and evolution was a slow process, just as the gradual sequestration of atmospheric carbon was a slow process. It took several millions of years to complete. Gradually, as the amount of carbon in the atmosphere was reduced by photosynthesis, the amount of oxygen was increased. By the mid

1700's, just before the start of the industrial revolution, natural carbon sequestration had reduced the atmospheric CO_2 level to 280 ppmv (parts per million by volume) (NOAA, 2008).

6 Combustion

Combustion is a chemical reaction very similar to decay. It happens much more rapidly, but the end products are very similar. The vast majority of combustion today is of organic matter. Organic matter such as wood, coal, or petroleum is burned to fuel our automobiles, heat our homes, or generate electricity in large power plants. A combustion reaction cannot proceed in the absence of an oxidizer, most often oxygen. Oxygen is present in our atmosphere at approximately 21% (CHANG, 2005).

We will use the example of a piece of paper. Take a small piece of paper and set it in a small metal container or fire ring. Once it is there, light a match and set fire to it. What follows is a highly exothermic (heat releasing) reaction resulting in heat and light (flames). Once the flames burn out we are left with a small amount of ash, a much smaller amount of matter than originally made up that piece of paper. Where did the rest of the matter go? We know that we can never create nor destroy matter, so it must have changed form, and it did. While that piece of paper was burning, a noticeable plume of smoke was rising from it. That smoke was created during the chemical reaction of that fire. Chemical bonds that held the paper together were broken, and a good portion of the carbon in that paper was bonded to oxygen in the air (the oxidizer) to form carbon dioxide (CO_2). Every single complete combustion reaction has two products in common, carbon dioxide and water vapor (PARMAR et al., 2008). No matter what you burn: a stick, a tire, a house, garbage, hydrocarbons, etc., the two main components that make up the smoke will be carbon dioxide and water vapor. Depending on what is burning there will also be other pollutants in the smoke, but all complete combustion releases CO_2 and H_2O as its two main by-products.

Had we instead taken that piece of paper and tossed it out the window, the results would be very similar. The paper would gradually decay with the addition of water and natural microorganisms in the surrounding soil. The chemical bonds that held the paper together would have been broken through chemical reactions performed by the decomposers. The carbon in the wood fibers of the paper would have been attached to oxygen in the atmosphere (aerobic decay) releasing carbon dioxide, and the entire process would take several weeks.

7 The Problem

The problem that we run into today is that we are taking the carbon in coal and petroleum, carbon that was gradually sequestered by ancient plants over millions of years, and re-releasing it back into our atmosphere. We are burning the compressed wetland plants of the Carboniferous and Permian Periods. By doing this we are bringing our atmosphere back to what it was (at least as carbon dioxide concentration is concerned) 300 million years ago, and we are doing it very rapidly. We are upsetting our natural system of regulation by releasing carbon faster than our modern plants can sequester it. Couple that with deforestation, and we are only exacerbating the problem.

Since the industrial revolution began in the mid 1700's, human actions have raised the atmospheric carbon content to 385 ppmv as of January 2008 (Trans 1). The estimated mean (average) annual growth rate for anthropogenic emissions of CO_2 in the year 2007 was an astounding 2.15 ppmv/yr (Trans 1). Scientific models that chart both the atmospheric concentration of CO_2 and the growth rate in the use of fossil fuels suggest that if CO_2 emissions continue at these elevated rates, we will double the pre-industrial concentration of CO_2 in the atmosphere (280 ppmv) by the year 2100, if not sooner (SKINNER et al., 2004).

That new concentration of CO_2 (560ppmv) would lead to an increase in average global temperatures of between 1.5° and 4.5° C. That may not seem like much, but stop to consider this. The difference in the average temperature of the coldest part of the last ice age and the present was only 5° C (SKINNER et al., 2004)!

8 Adaptation

Life forms simply cannot adapt this fast. We cannot reverse climactic changes that took millions of years to occur naturally in a matter of centuries and expect our ecosystems to adapt. It simply is not plausible. This is the problem that we run into with global climate change. We are not changing the makeup of the atmosphere to something it has never been, we are not changing it to un-natural levels, we are simply changing it much too fast! Our natural systems cannot keep up with our emissions. They cannot sequester that carbon as fast as we are releasing it.

Carbon dioxide is a naturally occurring compound. It has been with us for the entire history of this planet, but life cannot adapt to the predicted rapid changes brought about by this rapid shift in concentration.

9 Greenhouse Effect

9.1 Carbon Dioxide (CO_2)

Carbon Dioxide is often labeled as the scapegoat of global warming, when in reality, it is a relative weak greenhouse gas (this will be discussed shortly). The reason that so many scientists focus on CO_2 is the sheer amount of it being released by anthropogenic activities. Even though it is a low strength gas, it is one of the biggest contributors to global climate change due to the enormous daily amounts we are releasing.

When scientists refer to the greenhouse effect, what they are talking about is the trapping of heat within the earth's atmosphere by certain gasses. This phenomenon is known as the greenhouse effect because it is similar to the way a greenhouse retains heat. In a greenhouse, radiation (energy) from the sun enters through the glass ceiling. Some is reflected by the glass panels, but most makes it through. Inside the greenhouse, some is absorbed by the plants for photosynthesis and some is reflected by the plants back toward the sky. The glass ceiling of the greenhouse re-reflects some of this reflected radiation (energy) back toward the plants. This alone, however, is not what causes the increased temperature within the greenhouse. The glass panels also restrict air flow within the greenhouse (CHANG, 2005) and prevent convective heat exchange by eliminating outside wind. The combination of reduced air flow and re-reflected radiation lead to a higher average temperature within the greenhouse.

10 Other Greenhouse Gasses

In our atmosphere, certain gasses known as greenhouse gasses perform a similar function as the glass panels of a greenhouse. Of the 100% of incoming solar radiation that enters the earth, roughly 45% is absorbed at the earth's surface, 25% is absorbed in the atmosphere, and the remaining 35% is reflected and scattered back out into space by clouds, air molecules, and the earth's surface (Lydolph, 1994). In order for the radiation that is reflected by the earth's surface to reach outer space, it has to go through the atmosphere a second time. Greenhouse gasses capture and absorb some of that outgoing radiation. Due to the physics of how molecules vibrate, these gas molecules can hold on to that radiation (heat) and become excited (heated), or they spontaneously re-radiate some of it back to the earth's surface a second time (CHANG, 2005). They can also absorb some of that incoming radiation the first time it passes through, increasing that 25% that is absorbed by the atmosphere. Therefore, greenhouse gasses literally form a blanket around the earth, holding in heat and raising surface temperatures. The more greenhouse gasses there are in the atmosphere, the thicker that blanket becomes, and the more heat is retained.

The greenhouse effect is natural, and in fact, it is necessary for life on this planet. The reason it is under scrutiny is that it is out of control. It has been estimated that what little percentage of CO_2 is in the atmosphere, 0.33% by volume, warms the Earth an incredible 30° C (CHANG, 2005)!

11 Water Vapor (H_2O)

The most prevalent greenhouse gas in our atmosphere is actually water vapor (NOAA, 2008). That's right; water vapor contributes more to the greenhouse effect than any other gas in our atmosphere. However, unlike other gasses, water vapor is continually removed from the atmosphere by the hydrologic cycle in the form of rain. It is also continually added to the atmosphere through the process of evaporation. Suspended water vapor in the atmosphere forms clouds. Since clouds are white, they reflect a great deal of incoming solar radiation (heat). As more radiation is reflected by the atmosphere, global temperatures cool.

So, while water vapor contributes to the greenhouse effect, it also helps to mediate that effect to a small degree. As the overall climate of the earth continues to warm, scientists predict that more and more water vapor will enter the atmosphere through evaporation. Since warmer air can hold more moisture than cooler air (EPA, 2016), more water vapor is likely to be retained as average global temperatures rise.

12 Methane (CH_4)

Scientists rate the "strength" of long-lived greenhouse gasses that are well mixed in the atmosphere according to their global warming potential (GWP) (GWP, 2008). The GWP for a particular greenhouse gas is the ratio of heat trapped by one unit mass of the greenhouse gas to that of one unit mass CO_2 over a specified time period (EPA, 2016). The time period most often used is 100 years. Greenhouse gases that have relatively short life spans in our atmosphere, or that do not mix well within the atmosphere, such as water vapor, nitrogen oxides (NO_X) and tropospheric ozone (see below) (EPA, 2016) are not assigned GWPs.

Due to its physical structure, one unit mass of methane (CH_4) is able to absorb about 21 times as much infrared radiation (heat) in the atmosphere as one unit mass of carbon dioxide (EPA, 2016). Since carbon dioxide is the most widely studied and talked about greenhouse gas, other greenhouse gasses are given a numerical rating based on the properties of carbon dioxide. Carbon dioxide has a rating of 1. Methane's rating is 21, since it is 21 times "stronger" with regards to heat absorbing capability, over a 100 year time span, than carbon dioxide.

Methane is naturally released through anaerobic decomposition in oxygen poor environments such as wetlands (MITSCH; GOSSELINK, 2000). The cultivation of rice, which takes place in human created wetlands, supplies an ever growing amount of methane to our atmosphere. Methane is also released by the anaerobic processes that take place in landfills. In addition, copious amounts of methane are created in the digestive processes of ruminant animals (animals with a four compartment stomach) as their food is fermented by microorganisms in their digestive tract (GAJEVIĆ et al., 2006). Popular domesticated ruminant animals include cattle, goats, and sheep. The large amount of domestic livestock grown for food by humans constitutes the largest agricultural emissions of methane, while landfills are the largest overall source of anthropogenic methane emissions (GAJEVIĆ et al., 2006).

13 Tropospheric Ozone (O_3), Nitrogen Oxides (NO_X), and Nitrous Oxide (N_2O)

Many people have heard of the earth's ozone layer and the relatively recent ozone hole of the past two decades. Ozone (O_3) is ozone no matter where it is found in the atmosphere, but it is a pollutant and greenhouse gas in the lowest level of the atmosphere, the troposphere; while it is a necessary ingredient for life as part of the ozone layer in the second to lowest level of the atmosphere, the stratosphere.

The ozone layer, found in the stratosphere, contains 90% of the world's ozone, and is responsible for the pale blue color of our sky. Earth's ozone layer absorbs 97 – 99% of the harmful ultraviolet radiation emitted by the sun (SPARLING, 2008). This protection is necessary for life on this planet.

The other 10% of the world's ozone, located down by us in the troposphere, on the other hand, is an irritating and corrosive gas with a smell something like burning electrical wiring (SPARLING, 2008). Ozone is a major component of photochemical smog in cities worldwide.

The production of photochemical smog is a complex process that is fueled by sunlight. Automobile exhaust contains mostly nitric oxide (NO), carbon monoxide (CO), and various unburned hydrocarbons, collectively known as primary pollutants. These primary pollutants react with sunlight to form the secondary pollutants, chiefly NO_2 and O_3, that are responsible for the buildup of photochemical smog (CHANG, 2005).

At standard atmospheric temperatures, both oxygen (O_2) and nitrogen (N_2) are stable gasses that together make up 99% of our atmosphere. High temperatures and solar radiation together power a series of reactions that convert these two stable, prevalent gasses into ozone (O_3) and nitrogen oxides (NO_X). The following is the various steps of ozone creation adapted from Chang (2005):

Inside the high temperatures of an automobile engine, N_2 and O_2
combine to form nitric oxide through the reaction: $N_2 + O_2$ à 2NO.
Once released in the automobile's exhaust, nitric oxide combines with atmospheric oxygen to form nitrogen dioxide (NO_2) through the
reaction: $2NO + O_2$ à $2NO_2$. Sunlight then breaks up the NO_2 back
into NO and the highly unstable, highly reactive oxygen radical (O)
through the reaction: NO_2 + (light energy) à NO + O. This highly
reactive oxygen radical then attaches to atmospheric oxygen (O_2) to
form ozone (O_3) in the reaction: $O + O_2 + M$ à $O_3 + M$, where M
is some inert substance such as N_2. The role of M in this exothermic
reaction is to absorb some of the excess energy released and prevent
the spontaneous decomposition of the O_3 molecule.

Tropospheric ozone is very irritating to the respiratory tract, especially to people with chronic respiratory illness. In the United States, cities notify their residents when elevated levels of ozone pose a risk to public health, advising people to limit their time outdoors if possible. The International Panel on Climate Change now considers tropospheric ozone to be the third most important greenhouse gas after carbon dioxide and methane (NOAA, 2016).

Nitrous oxide (N_2O), not to be confused with nitrogen oxides (NO_X), is a potent greenhouse gas. Primary emissions result from the use of manure and synthetic nitrogen based fertilizers, wastewater treatment, the production of nylon, and the combustion of waste and biomass (EPA, 2016). N_2O does have useful qualities as an anesthetic, and is chiefly used for dental procedures and minor surgery (Chang, 2005). You may know it by its common name, laughing gas. Nitrous oxide has a rather high 100 year GWP of 310 (EPA, 2008) (remember, CO_2 has a GWP of 1, and CH_4 has a GWP of 21).

14 CFCs (chlorofluorocarbons) & the Ozone Hole

CFCs are molecules made up of the elements chlorine (chloro), fluorine (fluoro) and carbon (carbon). CFCs are synthetic chemicals (do not naturally occur) that were once widely used as refrigerants, aerosol propellants, and cleaning solvents (NOAA, 2016). It was eventually discovered that CFCs destroy stratospheric ozone. Their relative inertness (low reactivity) allows them to slowly diffuse, unchanged, up to the stratosphere where they begin to destroy stratospheric ozone in the ozone layer (CHANG, 2005). This discovery has resulted in a great reduction in their use (in industrialized countries) in recent decades.

When the CFCs reach the stratosphere, ultraviolet (UV) radiation causes them to decompose, releasing highly unstable, highly reactive chlorine radicals (Cl·). Ultraviolet radiation also decomposes ozone molecules as UV energy is absorbed, but the resulting highly reactive oxygen radical combines with atmospheric oxygen to again form ozone, maintaining a consistent amount of ozone in the ozone layer. Chang (2005) lists the stratospheric UV reactions as follows:

Ozone Formation	Ozone Destruction
O_2 + (UV light) à O + O	O_3 + (UV light) à $O + O_2$
$O + O_2 + M$ à $O_3 + M$	

CFC Decomposition
$CFCl_3$ + (UV light) à $CFCl_2$ + Cl
OR
CF_2Cl_2 + (UV light) à CF_2Cl + Cl

Chlorine Radical Reactions
$Cl + O_3$ à $ClO + O_2$
ClO + O à $Cl + O_2$

The chlorine radical released by the decomposition of CFCs encounter either molecules of ozone or oxygen radicals. The resulting chlorine monoxide (ClO) then encounters another oxygen radical, forming stable elemental oxygen and re-releasing the chlorine radical. Through this process, a single Chlorine radical can destroy up to 100,000 ozone molecules before it is removed by another reaction (CHANG, 2005)!

While this destruction of stratospheric ozone is a significant problem, it is a minimal contributor to global climate change. However, CFCs are also greenhouse gasses, with incredibly high 100 year GWPs ranging from 3,400 to 7,000 (The Energy ImBalence 1) (remember, CO_2 has a GWP of 1, and CH_4 has a GWP of 21), and their long atmospheric lifetimes ensure that some concentration will remain with us in the atmosphere for over 100 years (NOAA, 2016).

15 Consequences of Global Climate Change

15.1 Rising Sea Levels

Perhaps one of the most widely known warnings of global climate change is the anticipated rise in sea levels resulting from the melting of the polar ice caps. To date, there is no scientific consensus on just how much sea levels will rise in the future. We can only measure ongoing sea level rise and make predictions based on current and projected future increases in greenhouse gas emissions, resulting in a warmer overall climate. The earth contains three large reserves of ice: the Antarctic ice sheet, the Greenland ice sheet, and the polar ice-cap.

Elementary physics teaches us that while ice has a greater volume (is bigger) than liquid water, ice displaces (weighs) the same amount of water as it creates when melted. This concept can be displayed in your own home. First, take a glass and add a few ice cubes. Next, fill the glass to the very brim with water. Once the glass is full, make sure none of the ice cubes are touching the bottom of the glass. If they are, remove enough so that they no longer touch the bottom and fill the glass to the brim again. Leave the glass out on the kitchen table and return once all of the ice cubes have melted. You will observe that the water level in the glass is exactly the same as it was while the ice was floating in it (be sure not to confuse condensation with spilled water).

Now to the point, both the Greenland and Antarctic ice sheets are located on land. Their weight is supported by the continents on which they lie. The polar ice cap has no continent, instead, it floats in the Arctic Ocean, displacing the same amount of water it will create when melted. Therefore, if rising temperatures cause the polar ice cap to melt, as they increasingly have in recent years, there will be virtually no change in sea level (not accounting for the negligible change caused by thermal expansion). However, the very real, very serious problem of global climate change poses a threat for the 28.56 x 10^6 km^3 of ice collectively held in both the Greenland and Antarctic ice sheets (IPCC 1). If these entire bodies of ice were to melt, they would raise global sea levels more than 68 meters (IPCC 1), but scientists are confident that this is largely impossible. However, these ice sheets have been melting at increasing rates recently, leading to a reported 12 – 22 cm. average global sea level rise during the 20^{th} century (EPA, 2016). The large gap in numbers is due to non-uniform rise throughout the coastlines of the world.

16 Thermo-Haline Disruption

What is potentially the largest threat to our climate as we know it is a disruption, or even a complete halt, to the oceanic thermo-haline system. The thermo-haline circulation system, also referred to as the oceanic conveyer belt, is the system that drives the currents of the earth's oceans. Thermo, meaning temperature, and haline, meaning salt, tell us that this system is driven by temperature and salinity. Elementary physics teaches us that matter has different densities at different temperatures. Generally, but not always, as matter increases is temperature, density decreases. Ocean water has different densities depending on both its temperature and amount of dissolved solids (salts).

Fresh water is densest at a temperature of 4° C (CUTNELL; JOHNSON, 2005). In fresh water ecosystems around the world, seasonal overturning of water masses occurs as water at or near the surface approaches its freezing point. Once it reaches 4° C, it becomes heavier than the water below it and sinks to the bottom, displacing water that was previously on the bottom and forcing that water further up toward the top. This continues until the entire body of water is a uniform 4° C, at which time the water closest to the surface begins to freeze. This phenomenon is known as overturning, and it is how oxygen and other nutrients are replenished in the benthic, or bottom, waters of temperate bodies of freshwater around the world.

A similar, but all together different process occurs in the world's oceans. Unlike fresh water, salt water does not have a maximum density at 4° C, instead it continues to increase in density as it gets colder, all the way to its freezing point of -1.9° C. (FAD, 2016).

When you increase the temperature of water to its boiling point, the water molecules expand to form a gas. Anything that may have been dissolved in that water is left behind when this happens. This is why if you were to boil a pot of sea water until all of the water was gone you would still be left with salt in your pot. This is also what leaves those mineral spots on household surfaces when tap water evaporates.

Water does not need to reach its boiling point to evaporate though. We have all seen water on the road or sidewalk after a rainstorm. Once the sun comes out, sometimes even if it doesn't, that water evaporates into the air again. Chances are that the surface of that road was not 100° C (212° F), the boiling point of water. The only thing that needs to happen for liquid water to evaporate is contact with a body of air that is not already saturated with (full of) water vapor. Remember that air's ability to hold water vapor is determined by its temperature.

Although the polar oceans are very cold, not all of their surface layers freeze over, and despite the bone-chilling temperatures of polar air masses, some of them are warm enough to hold some water vapor. When the resulting evaporation of sea water happens, instead of the salt being encrusted on a pot, it is merely re-dissolved in the surrounding ocean water. As the amount of salt dissolved in the water increases, the water gains weight. This makes logical sense. If we add mass to something, salt to water for example, the resulting combination is heavier than either of the two initial ingredients alone.

The formation of sea ice also increases the salinity of surrounding water. As liquid water freezes, it forces out any dissolved salt as it forms the crystalline structure of ice. This again adds to local salinity content, thereby making the surrounding water more dense (LAMONT-DOHERTY, 2016).

Since, the density of surface water is increased by the process of evaporation, the formation of sea ice, and cooling (FAD, 2016), fierce, steady winds in the Arctic steadily increases the density of its ocean waters.

This very cold, very heavy water makes its way along the ocean floor, beneath the less dense water atop it, filling in the low lying oceanic topography just as rivers and streams flow over the land. This large displacement of oceanic waters creates a vacuum of sorts, drawing in warmer, lighter, less salty waters from the tropics. Once these warmer waters reach the polar regions, they undergo the same processes previously mentioned, causing them to become denser and the process continues, just as a conveyer belt continues to cycle over and over again.

The oceanic conveyer belt is an immense system, spanning the entire globe. While it is driven mainly by the sinking action of the very cold, salt rich waters of the Artic and Antarctic, these cold waters must eventually surface somewhere for the conveyer belt to continue.

There are two regions in the earth's oceans where these cold, dense waters undergo a process known as diapycnal flow (NILSSON; WALIN, 2008). That is where these waters gradually rise among the thermally (temperature based) stratified layers of the oceans, warming and mixing with less haline (salty) waters. This is believed to happen in small, localized mixings (NILSSON; WALIN, 2008). One hypothesis is that tidal influenced, intra-oceanic currents ride undersea topography, in places affecting the thermocline (area of rapid temperature change where denser and lighter waters meet), enabling some of the dense waters to "splash" up into the lighter water (Jayne, Abstract).

As the waters rise, they slowly gain heat and loose salt, becoming less dense. This less dense water then flows back, on top of the "river" of dense salty water below, eventually destined to again reach the poles and repeat the cycle yet again; thus completing the oceanic conveyer belt.

The earth's thermohaline system is currently under great study as scientists try to understand and determine what exactly enables this mid-oceanic mixing to continue, in addition to where exactly it happens. Scientists know that it happens in the Indian Ocean and the Northern Pacific, but specific locations, and exact causes, are little more than educated guesses.

17 Why is this important?

The reason that we should be concerned about the thermo-haline system of the oceans is that oceanic temperatures have an incredible impact on landmass climate. Bodies of water heat and cool very slowly. It takes a lot more energy to heat an area of water than it does to heat the same area of land. Oceans and large lakes store this excess energy, releasing it very gradually over time

(GORE, 2007). Therefore, large bodies of water insulate the land masses around them.

Perhaps the best known example of this is the Gulf Stream current in the north-central Atlantic Ocean. We will come back to this example after reviewing a little bit about how the earth's atmosphere circulates.

18 How Our Climate Works

18.1 Hadley, Ferrel, and Polar Cells

Winds on planet Earth are driven by three large cells in both the northern and southern hemispheres (IPF, 2008). These cells, known as the Hadley, Ferrel, and Polar cells, are responsible for the wind patterns, and subsequent climate, on Earth. Both the Hadley and Polar cells are similar in that they are both driven by surface temperatures (IPF, 2008).

Physics teaches us that warm air is less dense than cool air; otherwise, hot air balloons would not rise. Warm air can also hold more moisture than cool air. The warmest air in the troposphere is found at the equator, the region of the earth that receives the greatest amount of solar radiation. Logic suggests then, that this is the lightest air on the planet. Indeed, at the equator the northern and southern Hadley cells meet. The warmest, moistest air on earth rises from the earth's surface at the equator to the top of the troposphere (the lowest layer of the atmosphere) (SHORT, 2006). As this air rises, it cools and begins to loose its ability to hold water; hence the great amount of rainfall that supports the Earth's tropical rain forests. Once these air masses reach to top of the troposphere they begin to move toward the poles (SHORT, 2006); either south or north depending on which Hadley cell they are part of. The air gradually looses heat as it moves. Once it has reached roughly 30° latitude, it has cooled enough to become denser than the surrounding air, and begins to descend back to the earth's surface (SHORT, 2006). This cool, dense air is very arid (dry). As it moves downward, it warms and gains the ability to again hold moisture, absorbing any moisture as it falls. This is why most of the earth's deserts are located at roughly 30° latitude north or south. The continual rise of warm air at the equator creates a sort of vacuum, drawing this cooler air back toward the equator. As the air mass moves through the tropics it gradually gains heat and moisture. By the time it reaches the equator it has gained enough heat to again begin to rise, repeating the cycle again and again.

The Polar cells are driven by the same basic principles, just in reverse. The coldest, densest air in the troposphere must be found at the poles. This dense air spreads along the ground toward the equator, gaining heat and moisture as it moves over land and sea. Remember, Earth is a sphere. When located exactly on one of the poles, any direction you move will be toward the equator. Once it has reached approximately 60° latitude, it has gained enough heat to become lighter than the surrounding air, causing it to rise (SHORT, 2006). It heads toward the top of the troposphere and migrates toward the pole, cooling and loosing moisture as it goes. This rising again creates a "vacuum" that feeds the process, cycling it over and over again.

The Ferrel cells, caught in-between the Polar and Hadley cells, act as a counterbalance between the two (SHORT, 2006). As the warm, moist Polar cell air begins to rise at 60° latitude, it draws in some of the cool, sinking Hadley cell air at 30° latitude. Because of this, the Ferrel cells flow in the opposite direction of the Hadley and Polar cells. The "engine" that drives the Ferrel cell is just energy (air movements) lost from the Hadley and Polar "engines." Because of this, winds within the Ferrel cells are not nearly as consistent as Polar or Hadley winds, allowing localized weather systems to occasionally overpower the general direction and flow of wind within the Ferrel cells (IPF, 2008). This results in great variations of weather systems between 30° and 60° latitude.

19 Coriolis Effect

If the earth were a motionless sphere, the rising air at the equator and sinking air at the poles described above would result in a north to south windflow with stable and predictable weather patterns. However, since the earth rotates on its axis, at a speed of 1,700 km per hour (at the equator) (SHORT, 2006), this is not the case.

Due to the spherical shape of the earth, the rotational velocity changes as one changes latitude. Basically, if you are standing on the equator, the ground below you is rotating at 1,700 km/hr.

However, if you were to stand directly on top of the North or South Pole, you would hardly rotate at all. Similarly, if you were to stand half-way between the equator and the pole you would rotate at a different velocity still. An increase in latitude results in a lower velocity of the earth's rotation. This is the case because less distance is covered in the same amount of time (24 hours).

This difference in latitudinal velocities gives rise to an effect on the atmosphere known as the Coriolis Force (SHORT, 2006). This Coriolis Force exerts influence on the atmosphere through the creation of the Coriolis Effect. The Coriolis Effect causes a deflection of airborne matter to the right in the northern hemisphere and a deflection of airborne matter to the left in the southern hemisphere (SHORT, 2006), see Figure 1. This deflection is a combination of the rotational motion of the earth's surface as compared to the north to south flow of the earth's winds. Thus, the north to south windflow of the Polar and Hadley cells are transformed to an east to west windflow relative to the earth's surface (easterlies). Similarly, the south to north windflow of the Ferrel cells is transformed to a west to east pattern relative to the earth's surface (westerlies) (SHORT, 2006).

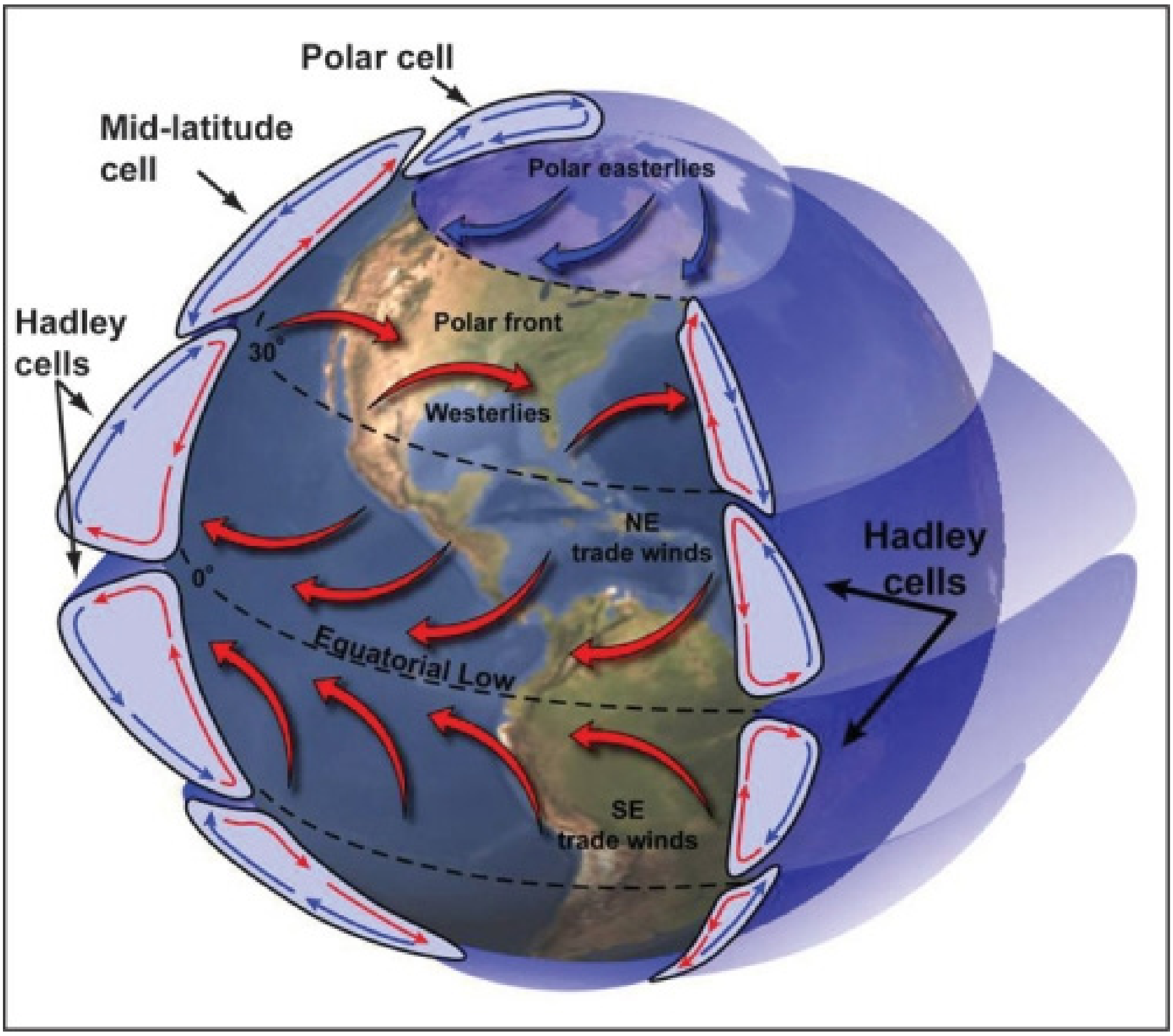

Figure 1: Graphic showing the Coriolis Effect and Hadley, Ferrel, and Polar Cells
Fonte: <https://www.seas.harvard.edu/climate/eli/research/equable/images/Hadley%20Cell.png>.

20 Gulf Stream

Perhaps the best example of how the oceanic thermo-haline cycle impacts land mass climate is the Gulf Stream. The Gulf Stream is widely credited with providing western Europe with a significantly milder climate (GYORY et al., 2013) that would generally occur at such a high latitude. Utilizing the concepts that we have just reviewed we can speculate that since nearly all of western Europe lies between 30° and 60° N latitude (within the Ferrel Cell), the prevailing winds are westerlies. By taking a glace at the map of the oceanic conveyer belt we can see that a band of warm water, officially known as the Gulf Stream (GYORY, 2013), flows eastward from the continental United States to Europe. This warm ocean water looses heat to the surrounding air as it flows (TWP 1), warming the westerlies that go on to move over the European subcontinent. The milder winter climate of western Europe can be directly associated with the presence of the Gulf Stream currents.

Paleoclimatologists, atmospheric scientists who study past atmospheric trends and events, have demonstrated that western Europe was not always like this. There have been times in the past where the Gulf Stream did not warm the European subcontinent. The most recent of these times is known as the Younger Dryas.

21 Younger Dryas

Scientists have looked to the past in an attempt to find a period when this Gulf Stream influence on western Europe was not as pronounced. One such event seems to show the great effect that the Gulf Stream has on western Europe, as well as foreshadowing a potential future of global climate change.

As the last ice age came to an end and global temperatures gradually rose, ice sheets and glaciers began to melt. As glaciers melt they leave behind a large amount of melt water. This water fills in depressions left by the glaciers as they moved across the land. It also forms rivers that drain these newly altered landscapes. This melting process is not rapid; instead it gradually takes place over many, many years. Sometimes, ice flows, earthen damns, or other glaciers impede this drainage, thereby forming glacial lakes. These glacial lakes are not permanent fixtures. They often times empty themselves in violent episodes as ice damns or weak substrate give way, causing flash flooding and great erosion to the surrounding area.

Scientists believe that about 13,000 years ago, a glacial lake in North America, Glacial Lake Agassiz, was rapidly drained in just such an episode. This happened as the Laurentian ice cap, which formed the northern shoreline of the lake, gradually retreated with warming temperatures. Scientists believe that an ice dam gave way, allowing large amounts of meltwater to begin flowing eastward into the North Atlantic (BROECKER, 2009). The previous Glacial Lake Agassiz outlet was to the south, following the Mississippi drainage into the Gulf of Mexico (BROECKER, 2009). This huge influx of fresh water, along with the already high amount of meltwater coming from other melting glaciers and ice caps, diluted the salinity of the North Atlantic to such a degree that the deepwater formation of the thermo-haline cycle was greatly reduced (NOAA, 2016). Some scientists believe that the deepwater may have stopped forming at all, leading to a complete shut down of the thermo-haline system (BLUE PLANET, 2009).

The consequences for northern Europe during the Younger Dryas were significant. Without the continual flow of warm ocean currents, brought in by the oceanic conveyer belt, northern European soils began to turn to permafrost. Forests retreated to the south, where summer temperatures still permitted liquid water. Previously forested land then reverted to tundra. This is evidenced in the pollen record, noting the specific prevalence of the flower *Dryas octopetala*, for which this event is named, which thrives on glacial tundras (BLUE PLANET, 2009). It has been speculated that mean (average) annual temperatures in the northern British Isles and Ireland at sea level were at or below -8° C during the coldest period of the Younger Dryas, while mean (average) annual temperatures ranged between -8° C and -1° C from 54° N to 50° N latitude (i.e. in central and southern England and Ireland, The Netherlands, upland Belgium, northern Germany and Poland) during this same time frame (GAJEVIĆ, 2006).

The Younger Dryas lasted for approximately 1,400 years. Although it is unclear exactly what caused the demise of the Younger Dryas, scientists are in consensus that it ended extremely rapidly. Analysis of ice core samples tell us that temperatures in Greenland as the Younger Dryas ended rose 10° C, in a single decade (NOAA, 2016)!

Whether halted by the decreasing temperatures of the Younger Dryas, or simply by the eventual melting of the North American glaciers, the amount of glacial meltwater spilling into the North Atlantic eventually shrank (BLUE PLANET, 2009). Scientists believe that with the resulting increase in salinity (due to less dilution by fresh water); deepwater formation was again initiated, leading to a return of the thermo-haline cycle (BLUE PLANET, 2009).

A project known as the Extreme Ice Survey, a collaboration between National Geographic magazine and The New Yorker magazine, is currently documenting the rapid melting of Arctic and high altitude ice in the northern hemisphere through the use of photography (EIS 1). While these fresh meltwaters may not be enough to raise global sea levels considerably, they are gradually diluting the salinity of the northern oceans as they melt.

The Younger Dryas demonstrated unambiguously that climate change can take place very rapidly (BLUE PLANET, 2009). Although North America is no longer in danger of a catastrophic flood by a glacial lake, we are gradually slowing the deepwater formation as our ice caps melt and larger amounts of fresh water are introduced into the world's oceans.

A study utilizing atmospheric models conducted by Broecker (1999) hypothesized that Earth would have to undergo a 4 to 5° C greenhouse warming in order to force an oceanic conveyer shutdown caused by meltwater. Does this bring to mind a previous statement?

A doubling of pre-industrial CO_2 (560ppmv) in our atmosphere, as is predicted to occur by 2100 (or sooner) at current emission levels, would lead to an increase in average global temperatures of between 1.5° and 4.5 °C (SKINNER et al., 2004).

Is this definitive proof that the northern hemisphere is headed for another Younger Dryas? No, but studies of our past show that it did happen more than once (there was also an Older Dryas), climate modeling tells us that it could possibly happen again, and emission rates tell us that we are headed down a very scary road.

22 A Self-Propagating System

22.1 The Snow Lines and Permafrost

Earlier in this chapter it was mentioned that global climate change will not cause warming in every region of the world. It will, however, cause the overall warming of the planet. The areas that will be hardest hit by this trend are the polar regions (NGEO, 2004). There is a concept known as the snow line. Merriam Webster's Dictionary defines the snow line as the lower margin of a perennial (present in all seasons) snowfield (MERRIAM-WEBSTER, 2016).

We all know that as we increase in latitude (move toward the poles) we loose temperature. This is why the poles are frozen while the equator is tropical. In addition, anyone who has ever climbed a mountain can tell you that you also loose temperature as you gain altitude. This is known as the environmental lapse rate, and is equal to a loss of 6.5° C for every 1000 meters of elevation gained (The Atmosphere 1).

The snow line varies quite heavily on Earth. You have to go very high in altitude for permanent snow to exist on the equator. However, in Alaska, you don't have to go very high at all to find permanent snow.

At the furthest reaches of the latitudinal snow line, the latitudinal snow line and altitudinal snow line intersect. This makes sense if we think about it. At the very edge of the latitudinal snow line, at sea level (0 meters altitude) there is permanent snow.

Once you increase in latitude (go toward the pole) past the intersection of the two snow lines, the altitudinal snow line turns negative. This means that even if you go below sea level, there would be permanent snow if snow could fall. Since snow can't fall below ground, this means that any moisture that is naturally found in the soil will freeze and stay frozen. As you continue increasing in latitude, the altitudinal snow line continues to decrease and soil moisture will be frozen to a greater and greater depth. We refer to this permanently frozen ground as permafrost.

As the average global temperature heats up, we begin to see an increase in the snow line. In other words we have to go higher and higher (in altitude and latitude) for there to be permanent snow. This permafrost that was once above the snow line, but is now below the snow line begins to melt. This has already been recorded in some areas of northern Canada, Alaska, and Russia (GOLDMAN, 2002).

Once these areas of permafrost begin to melt, many of these low lying areas that were previously frozen become wetlands. Remember, wetlands are a large source of methane. In those areas that do not become wetlands, liquid water returns to the soil, enabling soil microbes to commence aerobic decomposition of soil organic matter, thus releasing more carbon dioxide into the atmosphere.

23 Gas Hydrates

Polar and high altitude ice caps and permafrost do not only contain frozen water. Many of these areas also contain gas hydrates. Gas hydrates are ice-like solids in which gas molecules, mainly methane, are locked within the solid structure of H_2O (SKINNER et al., 2004). Gas hydrates are also found in some deep sea sediments. As global climate change begins to melt the world's glaciers, permafrost, and ice caps; the hydrates contained within become destabilized and begin to release their stored methane to the atmosphere, just like melting ice releases water. One estimate puts the worldwide concentration of carbon contained within these hydrates as high as 10,000 billion metric tons; twice the carbon in all the coal, oil, and gas reserves on land (SKINNER et al., 2004). Remember, methane has a GWP rating of 21.

24 Albedo

Albedo is the term that refers to the reflectivity of a surface. Anyone who has worn a dark shirt outside on a sunny day can testify to the heat trapping capability of dark materials. This is because a black object, such as a shirt, does not reflect light. Science teaches us that white light is composed of all the colors of the visible spectrum: red, orange, yellow, green, blue, indigo, and violet (SAMPLE, 2007). White light can be broken up into its components through the use of a prism. The colors that we see are the colors that are reflected by an object.

For example, if you were to wear a red shirt, the fabric of your shirt would absorb all of the wavelengths of orange, yellow, green, blue, indigo, and violet light that hit it and reflect only the red. Since only red light was reflected, the shirt appears red to the eye. Black objects absorb the entire spectrum of light and do not reflect any, therefore appearing black. White objects do not absorb any wavelengths of light, instead reflecting them all, thus appearing white.

Very similar to the law of conservation of mass mentioned earlier, there is also a law of conservation of energy. This law states the exact same thing, except we replace the word matter with the word energy. Energy can neither be created nor destroyed, it merely changes forms (CUTNELL; JOHNSON, 2005).

When an object absorbs light energy, that energy does not just disappear, it is instead transformed to heat energy. That is why you will be hotter if you wear a black shirt on a sunny day than if you wear a white one. A black shirt is absorbing all of the light energy that hits it while a white one is reflecting it all. The same is true for the surface of the Earth. Snow, which is white, has a very high albedo, it reflects almost all the energy that hits it back into the atmosphere and space. Nearly everything that underlies snow is darker in color: green or brown grass, brown dirt, black rock, dark blue ocean waters, etc. Consequently, when snow and sea ice are melted due to higher temperatures, the underlying area then has a lower albedo. Consequently it does not reflect as much light energy and absorbs more heat energy, thus melting more snow and ice.

25 Conclusion

The process known as global climate change is very serious. While we do not exactly know what the future may hold, our scientific models and studies of similar past events can give us a good idea. We strongly encourage you to do further research of your own into any of these topics that may interest or perplex you. There are also other topics, such as acid precipitation, derived from our reliance on fossil fuels, that exhibit localized, but no less extreme results.

This world belongs to each and every one of us, as well as those who are not yet born. It is up to us to make intelligent and informed daily decisions to help limit global climate change as much as possible. These decisions are as easy as turning off a light when leaving the room, recycling bottles and cans, or walking to the market instead of driving. Together we have caused this problem, but together we can also make it a thing of the past.

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