Curriculum Units by Fellows of the Yale-New Haven Teachers Institute
2021 Volume IV: The Earth's Greenhouse and Global Warming

Chemistry of Greenhouse Gases

Curriculum Unit 21.04.05
by Michael Petrescu, ESUMS

Introduction

The Sun serves as the primary energy source for Earth's climate. Some of the incoming sunlight is reflected directly back into space, especially by bright surfaces such as ice and clouds, and the rest is absorbed by the surface and the atmosphere. Much of this absorbed solar energy is re-emitted as heat (longwave or infrared radiation). The "greenhouse" in the atmosphere in turn absorbs and re-radiates this heat, although some of which escapes to space. Any disturbance to this balance of incoming and outgoing energy will affect the climate on Earth.

If all heat energy emitted from the surface passed through the atmosphere directly into space, Earth's average surface temperature would be tens of degrees colder than today.

The gases nitrogen and oxygen that make up the bulk of the atmosphere neither absorb nor emit thermal radiation. Certain gases in the atmosphere block that heat from escaping into space. These gases are greenhouse gases.

Water vapor, carbon dioxide and some other gases present in the atmosphere in much smaller quantities than oxygen and nitrogen, absorb some of the thermal radiation that leave the surface, and act as a partial blanket for this radiation. That causes the difference of 21◦ C or so between the actual average surface temperature on the Earth of about 15 ◦ C and the figure of -6 ◦ C which applies when the atmosphere contains nitrogen and oxygen only. This trapping of heat is the natural greenhouse effect and the gases are known as greenhouse gases. It is 'natural' because all the atmospheric gases (apart from the chlorofluorocarbons - CFCs) were there long before human beings came on the scene. The enhanced greenhouse effect, or global warming, is the added effect caused by the gases present in the atmosphere due to human activities such as the burning of fossil fuels and deforestation [1].

Greenhouse gases in the atmosphere, including water vapor, carbon dioxide, methane, and nitrous oxide, act to make the surface much warmer than this because they absorb and emit heat energy in all directions (including downwards), keeping Earth's surface and lower atmosphere warm (Figure 1). Without this greenhouse effect, life as we know it could not have evolved on our planet. Adding more greenhouse gases to the atmosphere makes it even more effective at preventing heat from escaping into space. When the energy

leaving is less than the energy entering, Earth warms until a new balance is established [1].

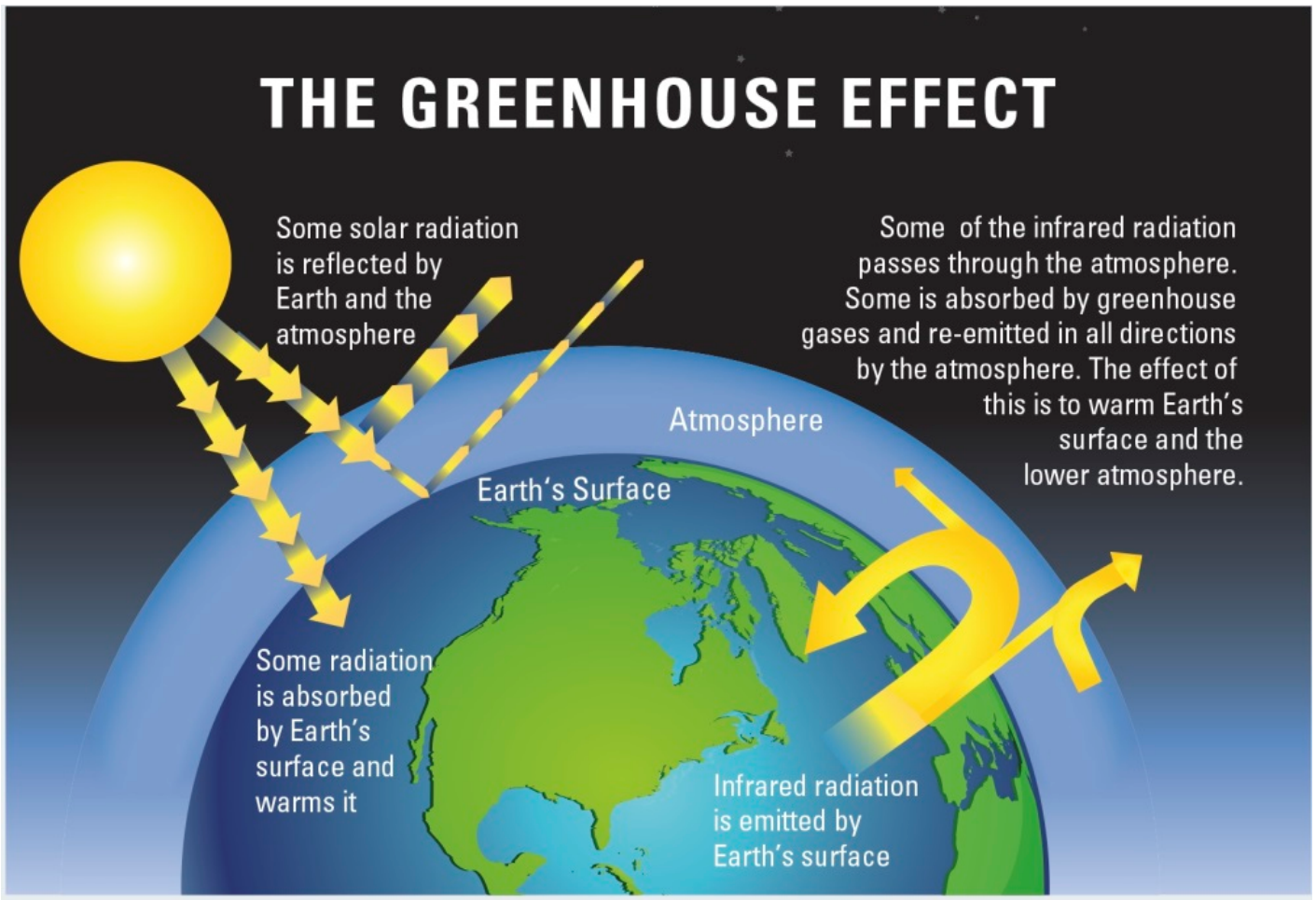

Figure 1. The Greenhouse Effect. Source: https://www.environmentblog.net/what-is-the-greenhouse-effect/

By trapping more energy, greenhouse gases emitted by human activities alter Earth's energy balance and therefore, its climate. Humans also affect climate by changing the nature of the land surfaces (for example by clearing forests for farming) and through the emission of pollutants that affect the amount and type of particles in the atmosphere. Scientists have determined that, when all human and natural factors are considered, Earth's climate balance has warmed, with the biggest contributor being increases in carbon dioxide.

This unit will include an overview of the three main greenhouse gases (carbon dioxide, methane and nitrous oxide). The unit will be a mix of organic and inorganic chemistry and will describe the physical and chemical properties of the three main gases and the most important chemical reactions that move the greenhouse gases into and out of the atmosphere. The unit will include a chapter of chemical reactivity, how these gases work (by atmospheric absorption and scattering of electromagnetic waves at different wavelengths), their residence time in the atmosphere and analyze the mitigation (what humans can do to reduce or limit the concentration of greenhouse gases in the atmosphere).

One section of the unit will discuss the "global warming potential" (what makes a stronger or a weaker greenhouse gas) and the relationship between physical properties of greenhouse gases and their lifetime (how long they remain in the atmosphere).

Unit Content

The Five Main Greenhouse Gases

Gases that contribute to the greenhouse effect include:

Carbon dioxide (CO_2)

A minor but very important component of the atmosphere, carbon dioxide, is released through natural processes such as respiration and volcano eruptions and through human activities such as deforestation, land use changes, and burning of fossil fuels. Humans have increased atmospheric CO_2 concentration by 47% since the Industrial Revolution began. This is the most important long-lived driving force of climate change.

Processes or regions that predominately produce atmospheric carbon dioxide are “sources”. Carbon dioxide is added to the atmosphere naturally when organisms respire or decompose (decay), during forest fires, when volcanoes erupt and by carbonate rocks formation. Carbon dioxide is also added to the atmosphere through human activities, such as the burning of fossil fuels and forests and the production of cement.

The process of respiration produces energy for organisms by combining glucose with oxygen from the air. Cellular respiration, consumes glucose and oxygen and produces energy and carbon dioxide. The carbon dioxide is released into the atmosphere during the process of cellular respiration, as follows:

$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + H_2O$ + energy

glucose + oxygen → carbon dioxide + water + energy

When organisms die, they are decomposed by bacteria. Carbon dioxide is released into the atmosphere or water during the decomposition process.

An important component of the global carbon cycle is represented by transfer of carbon dioxide from inland waters (rivers, lakes and reservoirs) to the atmosphere. The process is known as carbon dioxide evasion. The global carbon dioxide evasion rate is estimated around 2.1 Pg (petagrams) of carbon per year [4].

Over geologic time, limestone may become exposed (due to tectonic processes or changes in sea level) to the atmosphere and to the weathering of rain. The carbonic acid that forms when carbon dioxide dissolves in water, in turn, dissolves carbonate rocks. This reaction consumes carbon dioxide, as seen in the following two equations:

Carbonate weathering/production

$CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^-$

Silicate weathering (example)

$CaAl_2Si_2O_8 + 2CO_2 + 3H_2O \rightarrow Al_2Si_2O_5(OH)_4 + Ca^{2+} + 2HCO_3^-$

The clay formation produces carbon dioxide, as seen in the following example:

$Al_4SI_4O_{10}(OH)_8 + 3Fe_2^+ + 6HCO_3^- \rightarrow Fe_3Al_2Si_4O_{10}(OH)_8 + 2Al(OH_3) + 6CO_2$

Carbon dioxide is added to the atmosphere by human activities. When hydrocarbon fuels (i.e. wood, coal, natural gas, gasoline, and oil) are burned, carbon dioxide is released. During combustion or burning, carbon from fossil fuels combine with oxygen in the air to form carbon dioxide and water vapor.

These natural hydrocarbon fuels come from once-living organisms and are made from carbon and hydrogen, which release carbon dioxide and water when they burn.

The basic chemical reaction looks like this:

$CH_2O + O_2 \rightarrow CO_2 + H_2O$ + energy

Not only does the burning of forests release carbon dioxide, but deforestation can also affects the level of carbon dioxide. Trees reduce the amount of carbon dioxide from the atmosphere during the process of photosynthesis, so fewer trees mean more carbon dioxide left in the atmosphere.

Plants and phytoplankton are the main components of the fast carbon cycle. Phytoplankton (microscopic organisms in the ocean) and plants take carbon dioxide from the atmosphere by absorbing it into their cells. Using energy from the Sun, both plants and plankton combine carbon dioxide (CO_2) and water to form sugar (CH_2O) and oxygen, as shown in the following chemical reaction:

$CO_2 + H_2O$ + energy $\rightarrow CH_2O + O_2$

Four things can happen to move carbon from a plant and return it to the atmosphere, but all involve the same chemical reaction. Plants break down the sugar to get the energy they need to grow. Animals (including people) eat the plants or plankton, and break down the plant sugar to get energy. Plants and plankton die and decay (are eaten by bacteria) at the end of the growing season. Or fire consumes the plants or stored plant organic matter. In each case, oxygen combines with sugar to release water, carbon dioxide, and energy.

In all four processes, the carbon dioxide released in the reaction usually ends up in the atmosphere. The fast carbon cycle (the movement of carbon through life forms on Earth) is so tightly tied to plant life that the growing season can be seen by the way carbon dioxide fluctuates in the atmosphere. In the Northern Hemisphere winter, when few land plants are growing and many are decaying, atmospheric carbon dioxide concentrations climb. During the spring, when plants begin growing again, concentrations of atmospheric carbon dioxide drop.

Processes or regions that predominately absorb atmospheric carbon dioxide are referred to as sinks. Carbon dioxide may be removed from the atmosphere when it is used by plants and algae for photosynthesis and stored in tissue, dissolved in water, or deposited in the sediments on land or in the ocean (Figure 2).

The average residence time of carbon dioxide in the atmosphere is 4 years.

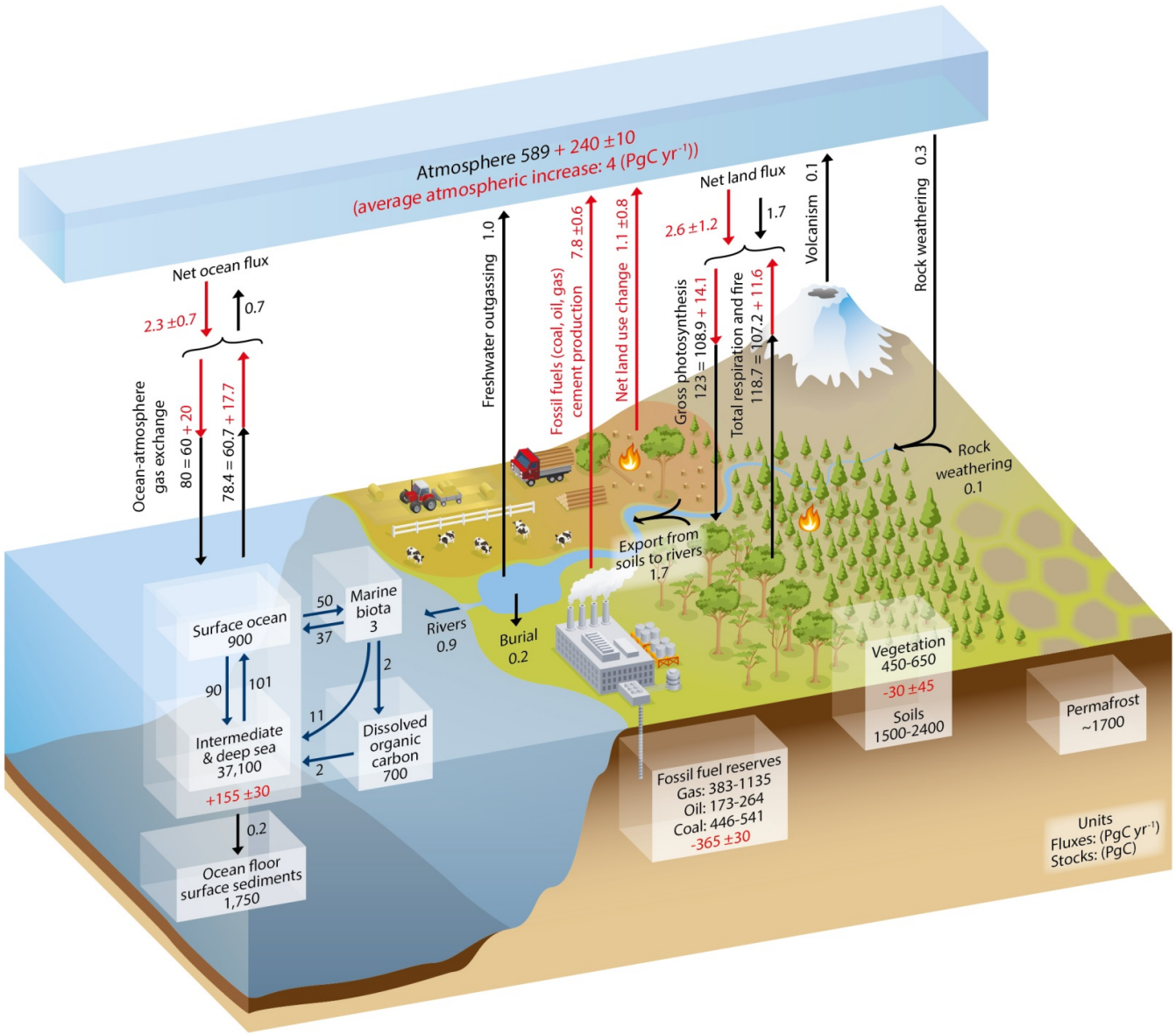

Figure 2. Global Carbon Cycle. Source: https://www.researchgate.net/figure/Simplified-schematic-of-the-global-carbon-cycle-IPCC-2013

Green plants use water from the soil and carbon dioxide from the atmosphere to make carbohydrates (glucose) and oxygen during the process of photosynthesis. In the ocean, algae carry on the same process. During photosynthesis, plants and algae convert the radiant energy of the sun into chemical energy to make carbohydrates (glucose) and produce oxygen as a byproduct. Plants and algae make more glucose in photosynthesis than they consume in respiration. The excess glucose produced by these photosynthetic organisms becomes the food consumed by animals or can be stored as live or dead organic matter and become a carbon sink.

$6CO_2 + 6\ H_2O + \text{energy} \rightarrow C_6H_{12}O_6 + 6O_2$

carbon dioxide + water + energy → glucose + oxygen

Oxygen is then used by the animals and plants to oxidize this organic matter and produce energy. When animals consume plants or they consume other animals that eat plants, they use the carbohydrates (glucose) as a source of energy.

Carbon dioxide can also be absorbed in the surface water of the ocean. As the concentration of carbon dioxide in the atmosphere increases, some of this carbon dioxide will be dissolved in the oceans. When the water is cooler than the atmosphere, more carbon dioxide is dissolved. Gases are more soluble in cooler water than in warmer water due to the Second Law of Thermodynamics. Gases are exchanged through the ocean surface until equilibrium is reached.

When carbon dioxide combines with water, it forms carbonic acid.

$CO_2 + H_2O \rightarrow H_2CO_3$

dissolved CO_2 + water → carbonic acid

The oceans provide a huge reservoir of carbon. Scientists estimate that the oceans hold more than 50 times the total atmospheric carbon dioxide content. Rainwater dissolves atmospheric carbon dioxide producing carbonic acid. Carbonic acid also reacts with rock through chemical weathering to form bicarbonate ions (HCO_3-) that are carried by groundwater and streams to the ocean. Marine organisms use bicarbonate and the calcium (Ca^{2+}) in seawater to produce the calcium carbonate ($CaCO_3$) that they need to make their shells, skeletons, and spines. A coral reef is one example - a coral reef is a huge colony of organisms that use calcium carbonate to build a hard outer skeleton.

When marine organisms die, their remains slowly sink and reach the ocean floor. Over time, these organic materials are compressed by their own weight and other sediments, gradually changing into organic deposits.

The anthropogenic budget of carbon dioxide (Figure 3) can be summarized by the following equation:

$E_f + E_{luc} = G_{atm} + S_{ocean} + S_{land} + B_{im}$, where

E_f represents the Fossil Emissions

E_{luc} is the amount of Land Use Change Emissions

G_{atm} means Atmospheric Growth

S_{ocean} represents Ocean Storage

S_{land} is Land Storage

B_{im} represents the Imbalance

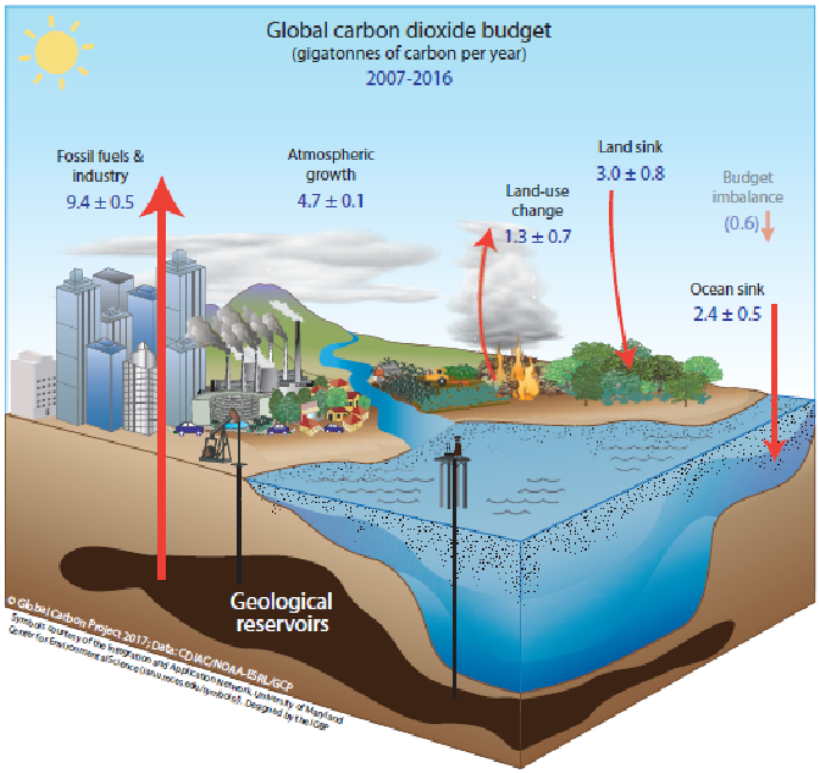

Figure 3. Global Carbon Dioxide budget for 2007-2016. Source: https://www.globalcarbonproject.org/carbonbudget/archive/2017/GCP_CarbonBudget_2017.pdf

Outside of the greenhouse effect, higher atmospheric carbon dioxide levels can have both positive and negative effects on crop yields. Some laboratory experiments suggest that elevated CO_2 levels can increase plant growth. However, other factors, such as changing temperatures, ozone, and water and nutrient constraints, may counteract any potential increase in yield. If optimal temperature ranges for some crops are exceeded, earlier possible gains in yield may be reduced or reversed altogether.

Although rising CO_2 can stimulate plant growth, research has shown that it can also reduce the nutritional value of most food crops by reducing the concentrations of protein and essential minerals in most plant species. Climate change can cause new patterns of pests and diseases to emerge, affecting plants, animals and humans, and posing new risks for food security, food safety and human health [2].

Methane (CH_4)

After carbon dioxide (CO_2), methane (CH_4) is the second most important greenhouse gas contributing to human-induced climate change. Methane is responsible for 20% of the global warming produced by all greenhouse gases so far. As of 2020, the concentration of methane in the atmosphere is 150% above pre-industrial levels. On a molecule-for-molecule basis, methane is a far more active greenhouse gas than carbon dioxide, but also one that is much less abundant in the atmosphere.

Methane (CH_4) is composed of one atom of carbon surrounded by four atoms of hydrogen. Methane is the main component of natural gas. Methane enters the atmosphere and eventually combines with oxygen (oxidizes) to form more CO_2. Methane converts to carbon dioxide by this simple chemical reaction:

$CH_4 + O_2 \rightarrow CO_2 + 2H_2$

methane + oxygen → carbon dioxide + hydrogen

Methane is produced both through natural sources and human activities. It is worth to mention that anthropogenic sources are now greater than natural sources. The natural sources include the decomposition of organic plant and animal matter in such places at wetlands (e.g., marshes, mudflats, flooded rice fields), living plants and termites.

Wetlands are the largest natural global methane source. The resulting global flux range for natural wetland emissions is 153-227 Tg (teragrams) methane per year for the decade of 2003-2012, with an average of 185 Tg methane per year.

The anthropogenic sources of methane include agriculture, and especially rice cultivation, as well as ruminant digestion and manure management associated with domestic livestock, sewage treatment plants, leakage from natural gas pipelines and from oil wells, biomass burning, coal mining and natural gas production.

Biologically, methane is produced via methanogenesis or fermentation by microbes after systems go anoxic (lose all their oxygen), according to the following two equations:

$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$

$CH_3COOH \rightarrow CO_2 + CH_4$

Methane is broken down biologically by methanotrophs (bacteria that utilize methane as their source of carbon and energy). Methane is also broken down abiotically in atmosphere. In the troposphere, the OH (hydroxyl) radical, produced through a series of reactions that include oxygen, ozone and water, is highly reactive and constitutes the major sink for methane, according to the general reaction:

$CH_4 + HO^- \rightarrow CH_3^- + H_2O$

Permafrost is permanently frozen ground that traps moisture, heat, carbon and produces methane. Permafrost may be as thin as a few meters or as thick as more than 1,000 meters. Vast regions of permafrost in Canada, Alaska, Siberia, and the Tibetan Plateau are starting to thaw. As permafrost melts, carbon dioxide or methane is released, further increasing the concentration of atmospheric greenhouse gases.

In the ocean sediments there are hotspots of thermogenic or biological methane storage. At high pressures and low temperatures of ocean bottom water, methane and water mixtures can for a hydrate or chlathrate. They are fairly stable and can sit around for many centuries. When the hydrate melts, methane is released. The Arctic Ocean’s chlathrates, with higher warming and shallow shelf is particularly worrisome for scientific community.

Methane also contributes to tropospheric production of ozone, a pollutant that harms human health and ecosystems.

The fraction of atmospheric methane reached 1857 ppb in 2018, approximately 2.6 times greater than its estimated pre-industrial equilibrium value in 1750 (Figure 3).

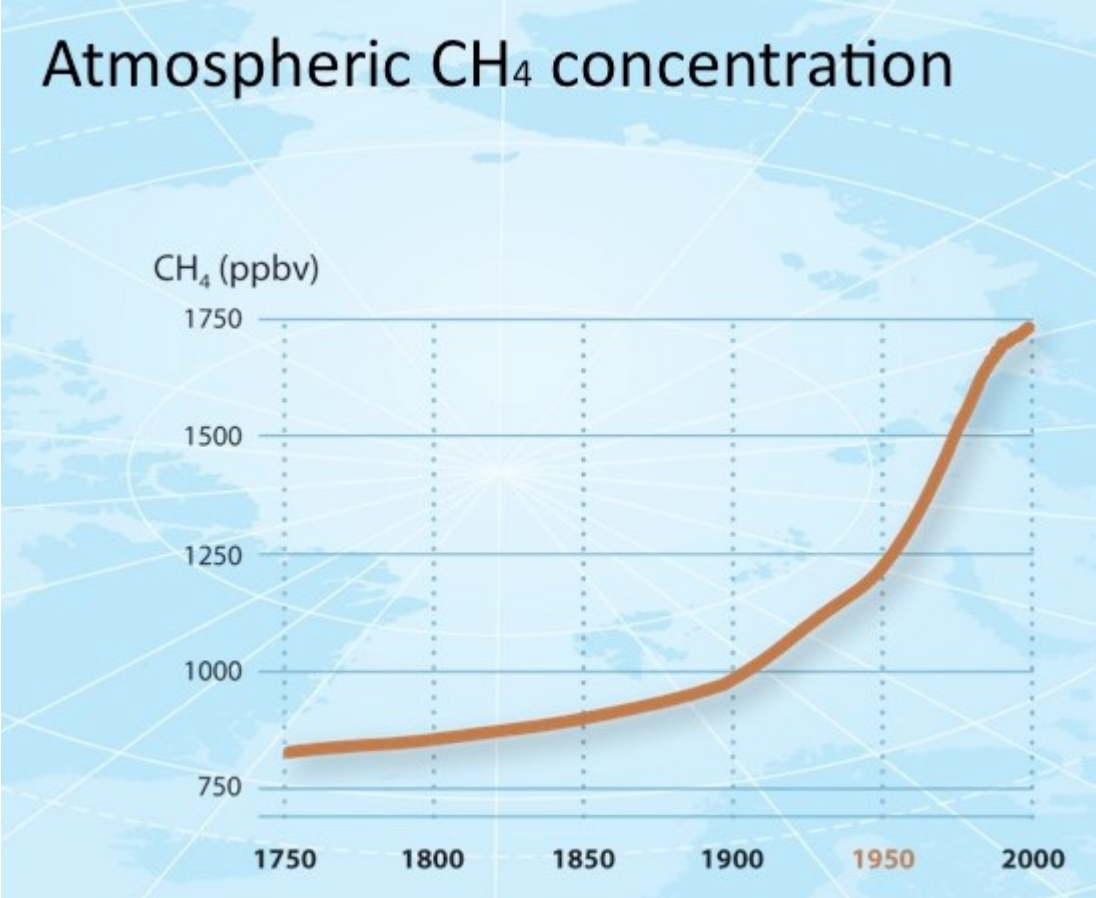

Figure 4. Atmospheric Methane Concentration. Source: https://en.wikipedia.org/wiki/File:Atmosphericmethaneconcentrations.jpg#/media/File:Atmosphericmethaneconcentrations.jpg

Atmospheric methaneis a stronger absorber of Earth's emitted thermal infrared radiation than carbon dioxide, as assessed by its global warming potential (GWP) relative to CO_2. Although global anthropogenic emissions of CH_4 are estimated at around 366 Tg (teragrams) CH_4 /year, representing only 3 % of the global CO_2 anthropogenic emissions in units of carbon mass flux, the increase in atmospheric CH_4 concentrations has contributed approximately 23 % (~ 0.62 W/m^2) to the additional radiative forcing accumulated in the lower atmosphere since 1750 [9].

Nitrous oxide (N_2O)

Nitrous oxide (N_2O), like carbon dioxide, is a long-lived greenhouse gas that accumulates in the atmosphere. Over the past 150 years, increasing atmospheric N_2O concentrations have contributed to stratospheric ozone depletion and climate change, with the current rate of increase estimated at 2 per cent per decade.

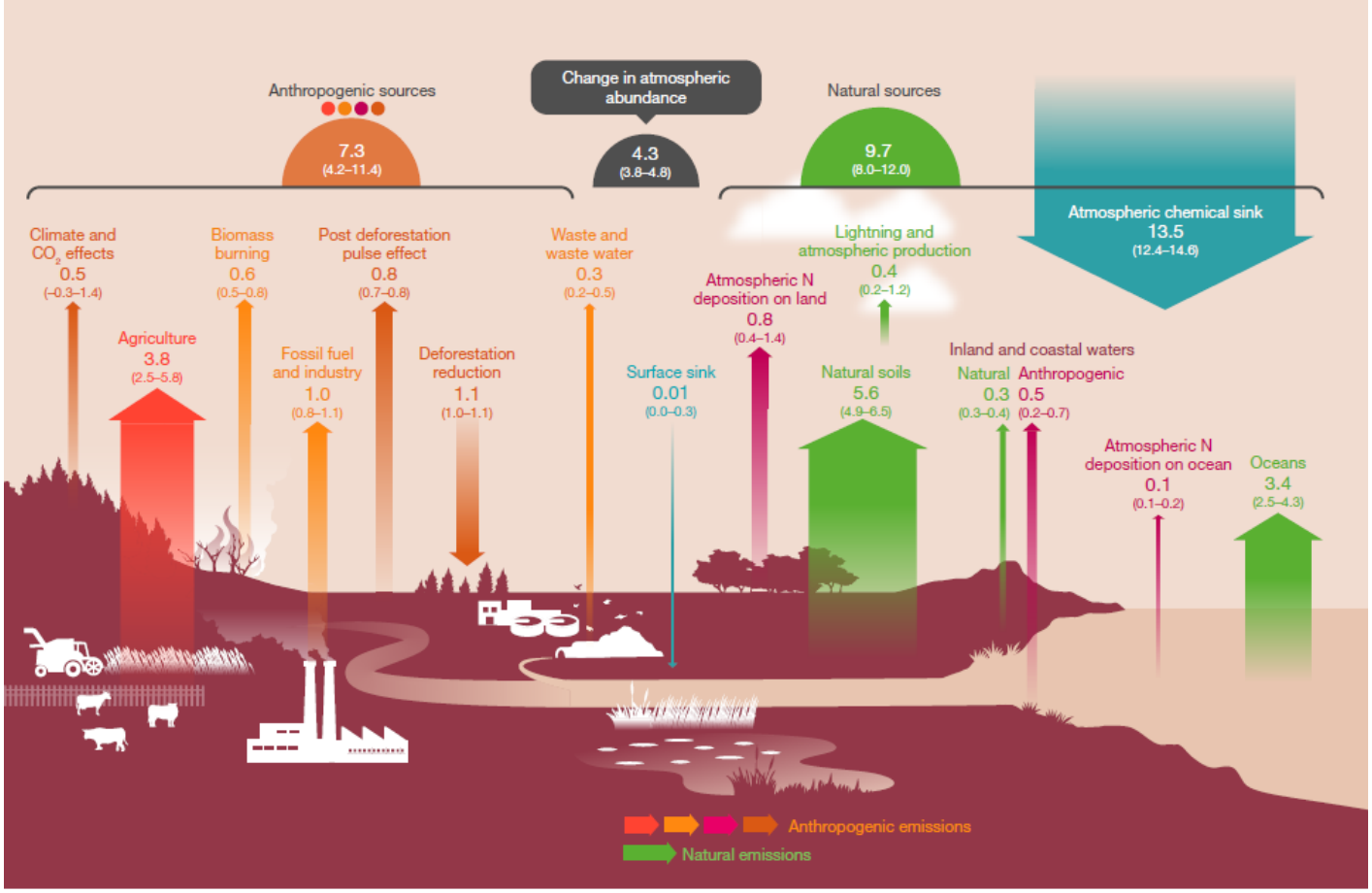

Figure 5. Global Nitrous Oxide budget for 2006-2017. Source: https://www.globalcarbonproject.org/nitrousoxidebudget/

Nitrous oxide is produced by soil cultivation practices, especially the use of commercial and organic fertilizers, fossil fuel combustion, nitric acid production, and biomass burning.

Nitrate (NO_3^-) and ammonia (NH_3) are used as fertilizers. Bacteria convert a small amount of this nitrate and ammonia into the form of nitrous oxide as byproducts of the nitrification and denitrification processes, as follows:

$2NH_3 + 3O_2 \rightarrow 2NO_2 + 2H^+ + 2H_2O$

$NO_3^- + 2H^+ + 2e^- \rightarrow NO_2^- + H_2O$

$NO_2^- + 2H^+ + 2e^- \rightarrow NO + H_2O$

$2NO + 2H^+ + 2e^- \rightarrow N_2O + H_2O$

$N_2O + 2H^+ + 2e^- \rightarrow N_2 + H_2O$

Internal combustion engines also produce nitrous oxide.

Nitrous oxide has a long residence time in the atmosphere, an average of about 120 years.

Global nitrous oxide emissions were around17 teragrams of nitrogen per year between 2007 and 2016 (Figure 5). Global human-induced emissions, which are dominated by nitrogen additions to croplands, increased by 30% over the past four decades to 7.3 teragrams of nitrogen per year. This increase was mainly responsible for the growth in the atmospheric burden.

Studies point to growing nitrous oxide emissions in emerging economies - particularly Brazil, China and India. Analysis of process-based model estimates reveals an emerging N_2O - climate feedback resulting from interactions between nitrogen additions and climate change. The recent growth in nitrous oxide emissions exceeds some of the highest projected emission scenarios underscoring the urgency to mitigate N_2O emissions [10].

Chlorofluorocarbons (CFCs)

Synthetic compounds entirely of industrial origin are used in a number of applications, but now are largely regulated in production and release to the atmosphere by international agreement for their ability to contribute to destruction of the ozone layer. They are also greenhouse gases.

Halocarbons, which are composed of carbon, chlorine, fluorine, and hydrogen, include chlorofluorocarbons (CFCs). Chlorofluorocarbons are synthetic gases that were used in cleaning solvents, refrigerants, and plastic foam.

Chlorofluorocarbons are tightly bound, nonreactive molecules. They are not soluble in water. They do not absorb visible or near-ultraviolet radiation. As a result of these properties, chlorofluorocarbons have long atmospheric residence times (ranging from 50 to several hundred years) and are able to provide their constituent atoms to the stratosphere.

In the late 1980s, the Montreal protocol led to a drastically reduction in CFC production. Consequently, the atmospheric concentrations of CFCs leveled off. Presently, the atmospheric concentrations of CFC11 and CFC 113 are decreasing significantly. The atmospheric concentration of CFC12 has reached a plateau and will drop at a lower rate in the future.

Water vapor

Water vapor is the most abundant greenhouse gas, but importantly, it acts as a feedback to the climate and it has no direct anthropogenic source. Water vapor increases as the Earth's atmosphere warms, but so does the possibility of clouds and precipitation, making these some of the most important feedback mechanisms to the greenhouse effect.

If there is too much water vapor in the air, it will condense out as rain. Conversely, if the air is extremely dry, any available liquid water will tend to evaporate into it. Water vapor is also involved in a positive feedback loop acting on global temperature. Because warmer air holds more water vapor than cooler air, warming allows more water to evaporate before it rains. The water vapor feedback is powerful enough to more or less double the climate impact of rising carbon dioxide concentration. If it were not for the water vapor feedback, Earth’s climate would be much less sensitive to carbon dioxide and maybe we would not be worrying so much about global warming [3].

Water vapor molecules absorb some shortwave radiation. Buildup of water vapor in the atmosphere leads to global dimming, that is, reduction of solar radiation at the Earth’s surface. The rate of reduction is about 1 to 3

W/m^2 K. As a result of more water vapor in the atmosphere, there will be more longwave radiation from the atmosphere to the Earth's surface [2].

The rate of increase of longwave radiation received at the surface is about 6 W/m^2 K. Another consequence of water vapor buildup is that rain intensity will increase. Many people estimate that individual rain intensity will increase at the rate of about 7% per Kelvin.

Global Warming Potential

Greenhouse gases (GHGs) warm the Earth by absorbing energy and slowing the rate at which the energy escapes to space; they act like a blanket insulating the Earth. Different GHGs can have different effects on the Earth's warming. Two key ways in which these gases differ from each other are their ability to absorb energy (their "radiative efficiency" - related to how they interact with longwave radiation and their concentration in the atmosphere), and how long they stay in the atmosphere (also known as their "lifetime").

The Global Warming Potential (GWP) was developed to allow comparisons of the global warming impacts of different gases. Specifically, it is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2). The larger the GWP, the more that a given gas warms the Earth compared to CO_2 over that time period. The time period usually used for Global Warming Potentials is 100 years. GWPs provide a common unit of measure, which allows analysts to add up emissions estimates of different gases and allows policymakers to compare emissions reduction opportunities across sectors and gases [11].

Carbon dioxide, by definition, has a GWP of 1 regardless of the time period used, because it is the gas being used as the reference. Carbon dioxide remains in the climate system for a very long time: emissions cause increases in atmospheric concentrations of CO_2 that will last thousands of years.

Methane (CH_4) is estimated to have a GWP of 28-36 over 100 years. A methane molecule is 30 times stronger than a molecule of carbon dioxide (CH_4 absorbs much more energy than CO_2), but methane is present in smaller concentrations and has a shorter lifetime than carbon dioxide. The atmospheric life time of CH_4 is 9 ± 2 years, making it a good target for climate change mitigation. The net effect of the shorter lifetime and higher energy absorption is reflected in the GWP. The methane's GWP also accounts for some indirect effects, such as the fact that CH_4 is a precursor to ozone, and ozone is itself a greenhouse gas.

Nitrous Oxide (N_2O) has a GWP 265–298 times that of carbon dioxide for a 100-year timescale. N_2O emitted today remains in the atmosphere for more than 100 years, on average.

Classroom Activities

---

1. Covalent Bonds Lesson Plan (three class periods)

Learning objectives

Students will be able to:

- Write the correct chemical formula for different covalent compounds
- Use the electron dot diagrams to show the formation of single, double and triple covalent bonds
- Describe and give examples of compounds with molecules made by covalent bonds

Materials and teacher-developed resources

Paper (Student Notebook), pencils, software (ActivInspire/Promethean)

Learning activities

The teacher will review the concepts of ionic and molecular compounds, emphasizing the differences between the two. Students will be reminded the definitions of molecule and molecular compound. Molecular compounds are composed of molecules and almost always contain only nonmetals. Molecular compounds form covalent bonds. Non-metals hold onto their valence electrons. They cannot give away electrons to bond, but still want noble gas configuration and get it by sharing valence electrons with each other. (Octet rule still applies.)

The teacher will explain that single covalent bonds form by sharing a pair of valence electrons. Bonds that involve two shared pairs of electrons are called double covalent bonds and bonds that involve three shared pairs of electrons are called triple covalent bonds. Students will draw Lewis structures of molecules with single covalent bonds (fluorine, chlorine, bromine, iodine, hydrogen, water, ammonia, methane), double covalent bonds (oxygen, carbon dioxide, ethene) and triple covalent bonds (nitrogen, acetylene carbon monoxide).

The teacher will emphasize that carbon, nitrogen, oxygen, fluorine, chlorine, bromine and iodine are atoms contain unshared pairs of electrons (also called lone pairs or nonbonding pairs). The teacher will show on the board the completion of orbitals 2p with electrons. Students will note that the chemical formulas for ionic compounds describe formula units, while chemical formulas for covalent compounds describe molecules. The teacher will also emphasize that ionic compounds are not composed of molecules and there are no single units of an ionic compound, while individual molecules actually do exist.

The students will be asked to write the correct Lewis dot diagrams and structural formulas for several compounds. They will be provided with pairs of elements and will be asked to select the pairs that are likely to form molecular compounds with a single covalent bond.

2. The Carbon Dioxide Lesson Plan (one class period)

Learning Objectives

Students will be able to:

- understand how do molecules of CO_2 gas interact with electromagnetic radiation
- explain the molecular structure of carbon dioxide and how it bends that make it able to absorb energy
- explain the greenhouse effect of Earth’s atmosphere

Materials & Teacher-developed Resources

Student handouts, pencils, textbooks, Carbon Cycle Interactive Lab Simulation software

Learning Activities:

The teacher will explain that molecules of carbon dioxide (CO_2) can absorb energy from infrared (IR) radiation. Students will watch a simulation that shows a molecule of CO_2 absorbing an incoming infrared photon. The energy from the photon causes the CO_2 molecule to vibrate. Sometime later, the molecule gives up this extra energy by emitting another infrared photon. Once the extra energy has been removed by the emitted photon, the carbon dioxide molecule stops vibrating.

Molecules are constantly in motion, colliding with other gas molecules and transferring energy from one molecule to another during collisions. In the more-complex, real-world process, a CO_2 molecule would most likely bump into several other gas molecules before re-emitting the infrared photon. The CO_2 molecule might transfer the energy it gained from the absorbed photon to another molecule, adding speed to that molecule's motion. Since the temperature of a gas is a measure of the speed of the molecules in the gas, the faster motion of a molecule that eventually results from the IR photon that was absorbed by a CO_2 molecule raises the temperature of the gases in the atmosphere.

3. Methane, The Simplest Organic Compound Lesson Plan (one class period)

Learning Objectives

Students will be able to:

- understand the molecular structure of methane
- explain the geometry of methane molecule
- explain the role of methane as greenhouse gas

Materials & Teacher-developed Resources

Student handouts, pencils, textbooks, Methane Structure Interactive Lab Simulation software

Learning Activities:

The teacher will ask students what do the gases of decomposing plants, natural gas, and the atmosphere of Saturn's moon, Titan, all have in common? The answer is they all contain methane. The teacher will explain that methane is a colorless, odorless, highly flammable gas at room temperature and can be found in a wide variety of sources on Earth. On Earth, methane can be found as a major component of natural gas that is stored in the earth's crust. Methane is also a common by-product of the decomposition of biological matter, such as decaying plants or animals.

Methane is classified as an organic compound, a substance composed of mainly carbon and hydrogen or a hydrocarbon. With a formula of CH_4, that is, four hydrogen atoms bonded to a single carbon atom, methane is the simplest of the hydrocarbons, a group also referred to as the alkanes.

The students will learn that chemical bonds found within methane are single covalent bonds.

For methane the covalent bonds form from the sharing of a single electron from each hydrogen with the four unpaired valence electrons of a single carbon atom. The teacher will explain that hydrogen atoms are arranged around the central carbon atom in a geometry known as a tetrahedral geometry.

Even though methane is involved in a wide variety of reactions, two reactions in particular are of fundamental importance, combustion and halogenation. Combustion of methane by industrial sources or when mixed with other hydrocarbons in natural gas is used extensively within industry to generate electrical power and within homes to generate heat. Halogenation involves the addition of a halogen, one of the elements found in Group 17 of the periodic table, to produce compounds known as methyl halides. The products of halogenation are used in the production of everything from plastics to pharmaceuticals.

4. Nitrous Oxide, The Laughing Gas Lesson Plan (one class period)

Learning Objectives

Students will be able to:

- understand the molecular structure of nitrous oxide
- explain the geometry of nitrous oxide molecule
- explain the role of nitrous oxide as greenhouse gas

Materials & Teacher-developed Resources

Student handouts, pencils, textbooks, The Greenhouse Effect Lab Simulation software

Learning Activities:

The teacher will explain that nitrous oxide or dinitrogen oxide, is a colorless, sweet tasting, non-flammable gas at room temperature and is known as “the laughing gas”. Continued breathing of the vapors may impair the decision making process. Although it is non-flammable, nitrous oxide will accelerate the burning of combustible material in a fire, due to the increase of available oxygen.

Students will learn that nitrous oxide is soluble in water and its vapors are heavier than air. It is used as an anesthetic, in pressure packaging, and to manufacture other chemicals.

Students will draw the Lewis structure of nitrous oxide, that is $N^{+}=N^{-}=O$.

Then, the teacher will present a simplified diagram to explain the nitrogen cycle in agricultural practices and the resultant emission of nitrous oxide (N_2O) by the application of nitrogen fertilizers.

Students will discuss the role of microbes in the nitrogen cycle and how the bacterial actions on nitrogen-based fertilizers (added to the soil) can cause the emission of nitrous oxide (N_2O) into the atmosphere.

Then, they will watch a video clip that presents the best management practices (BMPs) to mitigate the adverse effects of fertilizer use on global warming.

5. Global Warming Potential Lesson Plan (two class periods)

Learning Objectives

Students will be able to:

- define the greenhouse effect
- explain which are the greenhouse gases and how do they contribute to global warming

- define the Global Warming Potential
- predict some of the effects of global warming on the climate

Materials & Teacher-developed Resources

Student handouts, pencils, textbooks, The Greenhouse Effect Lab Simulation software

Learning Activities:

The teacher will start the lesson by asking students to write and share their opinions about the influence of human activity on Earth's climate for the past 100 years. Then, the teacher will introduce the concept of greenhouse effect and its influence on global warming of Earth.

Next, the teacher will list the five main greenhouse gases (carbon dioxide, methane, nitrous oxide, chlorofluorocarbons and water vapor) and how do they contribute to global warming (have the students watch the PBS video called "Global Warming: The Physics of the Greenhouse Effect").

On the next section, the teacher will introduce the concepts of lifetime - how long a gas stays in the atmosphere - and Global Warming Potential (GWP). The teacher will explain the reason the GWP was developed by the scientific community - to allow comparisons of the global warming impacts of different gases.

Students will discuss the actions that humans and policy makers should take to address the global warming issue and to slow the climate change.

Appendix on Implementing District Standards

CT New Generation Science Standards:

HS-PS1-2. Construct and revise an explanation for the outcome of a simple chemical reaction based on the outermost electron states of atoms, trends in the periodic table, and knowledge of the patterns of chemical properties

HS-PS1-4. Develop a model to illustrate that the release or absorption of energy from a chemical reaction system depends upon the changes in total bond energy

HS-PS1-5. Chemical processes, their rates, and whether or not energy is stored or released can be understood in terms of the collisions of molecules and the rearrangements of atoms into new molecules, with consequent changes in the sum of all bond energies in the set of molecules that are matched by changes in kinetic energy.

HS-ESS2D. Current models predict that, although future regional climate changes will be complex and varied, average global temperatures will continue to rise. The outcomes predicted by global climate models strongly depend on the amounts of human-generated greenhouse gases added to the atmosphere each year and by the ways in which these gases are absorbed by the ocean and biosphere.

HS-ESS3-5. Analyze geoscience data and the results from global climate models to make an evidence-based forecast of the current rate of global or regional climate change and associated future impacts to Earth's systems.

HS-ESS3-6. Use a computational representation to illustrate the relationships among Earth systems and how those relationships are being modified due to human activity.

District Standards:

D 1. Describe the effects of adding energy to matter in terms of the motion of atoms and molecules, and the resulting phase changes.

D 11. Describe how atoms combine to form new substances by transferring electrons (ionic bonding) or sharing electrons (covalent bonding)

D 19. Explain how chemical and physical processes cause carbon to cycle through the major earth reservoirs.

Describe the existence and uses of some organic compounds.

Be able to draw structural formulas and name organic compounds.

Reading List

---

1. https://royalsociety.org/topics-policy/projects/climate-change-evidence-causes/basics-of-climate-change/
2. https://climate.nasa.gov/causes/
3. Archer, David. Global Warming, (2012). 2nd Ed.
4. Raymond, P. A., et al. 2013. *Global carbon dioxide emissions from inland waters, Nature*, 503, 355–359, https://doi.org/10.1038/nature12760
5. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_summary-for-policymakers.pdf
6. Global Carbon Budget 2020 https://essd.copernicus.org/articles/12/3269/2020/
7. Dolman, H. *Biogeochemical Cycles and Climate*. (Oxford University Press, 2019).
8. Houghton, J. *Global Warming: The Complete Briefing*. 5th Ed., (Cambridge University Press, 2015).
9. https://essd.copernicus.org/articles/12/1561/2020/
10. https://www.nature.com/articles/s41586-020-2780-0
11. https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

---