Chemistry in the Earth System Unit 5

Carbon Dioxide and Climate Change

Background for Teachers and Instructional Suggestions

In this instructional segment, students apply their understanding of chemical reactions to global climate. Many of the key issues illustrated build on concepts related to thermodynamics and ***energy*** balances within systems (from instructional segment 2) and the products of chemical reactions (from instructional segment 4). The instructional segment focuses on the natural cycle of carbon and human impacts on it (*EP&Cs III, IV*). Since the carbon cycle is intricately linked to all life on Earth, the instructional segment integrates with life science units where students explore the impact of this physical science concept on the Earth system.

Food Calorimetry, Revisited

Students can now revisit the introductory activity in instructional segment 1 on combustion through the lens of their new mental **models**. Students likely have prior knowledge combustion requires oxygen and gives off ***energy*** in the same way as aerobic respiration. In fact, looking at the initial and final products, combustion reactions are identical to the aerobic reaction shown in Figure 9. The energy obtained by chemical reactions inside our bodies is the same as the energy released in the combustion reaction in food calorimetry, which is why we can burn food to figure out how much energy it will give us. They can also understand why a match or lighter is needed to provide the initial activation energy to start the chemical reaction. Students also likely have prior knowledge that they exhale CO_2, and by feeling the moisture in their breath, they can realize that they also exhale water also in a gaseous form. Despite the fact that they cannot see either of these gases, both have mass. When they exhale, they are “losing weight” (and in fact, vigorous exercise that makes them exhale more will indeed allow them to lose more weight). In the food calorimetry experiment, students measured the mass of the food at the beginning and compared it to the remaining mass and noticed that some of the mass 'disappeared.' They can now revise their model to show that it was released as hot CO_2 and H_2O gas. Its mass flowed out of the smaller ***system*** of their laboratory investigation and into the air of the room around it (much like mass flowed into the system to provide the oxygen for the reactants). If they considered the entire room as their ***system*** and were able to measure its mass, they would have seen that it remained unchanged during the experiment.

Combustion can occur in a range of materials besides food. Combustion that involves molecules made entirely of carbon, hydrogen, and oxygen ('hydrocarbons') will always release the same reaction products (albeit in different ratios; See instructional segment 5). Most of the fuels we use in everyday life are hydrocarbons, including logs of firewood, natural gas on our stovetops, and the gasoline we put in our cars. All of these hydrocarbons produce carbon dioxide as they provide us the energy we use every day. In fact, as more and more people inhabit the planet, we are emitting more carbon dioxide into the atmosphere every day that accumulates in our atmosphere (Figure 10).

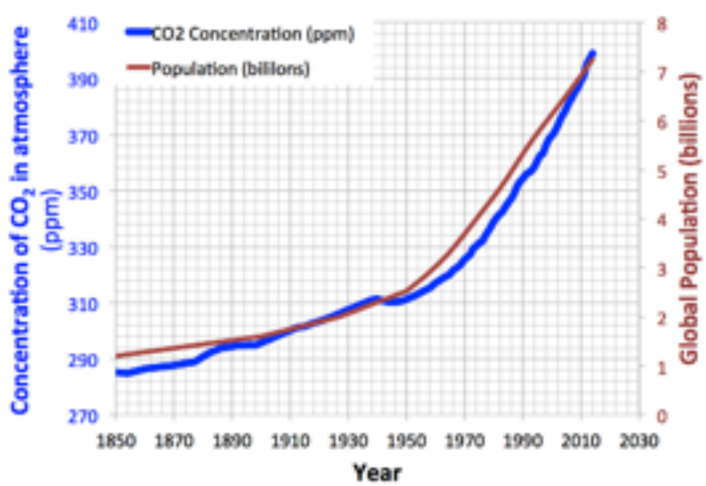

Figure 10. Relationship between global population and atmospheric CO_2. With a few notable economic slowdowns, more people equates to more emissions that raises the concentration of CO_2 in our atmosphere. In recent years, global population is slowing its growth but changes to lifestyles that burn more hydrocarbons for energy are causing emissions to continue to grow. Image Credit: M. d'Alessio using data from various sources.

The carbon dioxide produced by combustion plays a crucial role in regulating Earth's climate system (EP&C IV, see also EEI curriculum instructional segment on the Greenhouse Effect[1]). In this instructional segment, students apply their understandings of conservation of ***energy*** and heat flow (from instructional segment 2) and interactions between ***energy and matter*** (from the physics course) to understand this role. The topic of global climate change offers an excellent opportunity to explore the concept of planet Earth as a ***system*** (*ESS2.A*), and to apply science and engineering practices to a very important and highly visible societal issue (*HS-ETS1-1*). While the details of global climate change can be very complex and technical, the underlying science has been known for a long time and is quite understandable. The main ideas relate to:

- the ***flows of energy*** into, within and out of the Earth system;
- Earth's ***cycles of matter***, especially the carbon cycle; and
- the ***effects*** of human activities, especially the combustion of fossil fuels.

The PE's in this instructional segment build on significant work on DCIs related to weather and climate (*ESS2.D*) in the middle grade standards where students learned that ocean and atmospheric currents are the equivalent of Earth's circulation system, transferring heat from the warm equator towards the cooler poles and bringing the planet closer to thermal balance (*MS-ESS3-4*, now understood more deeply through *HS-PS3-4*). Students have also learned about the role that moving air masses play in determining short term weather (*MS-ESS2-5*). They have been introduced to climate change and that global average temperatures have risen in the last century and have investigated possible causes (*MS-ESS2-6*). In this instructional segment, they must delve into a more sophisticated understanding of Earth's ***energy*** balance and its relationship to the global carbon ***cycle***.

The crosscutting concept of ***systems*** is crucial to understanding Earth's climate. When scientists think about a system, they need to consider the ***energy and matter*** that flow into or out of the system, as well as the inner workings of the system. In some systems, it is hard to decide where to draw the boundaries between what is considered

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[1] CalRecycle, "The Greenhouse Effect on Natural Systems", http://www.californiaeei.org/curriculum/

‘inside the system’ and what is considered outside (such as the example of the ‘missing’ mass in the food calorimetry investigation that wasn’t really missing if we considered the room as a system). Earth’s climate, however, does not present such a challenge if we consider the entire planet Earth as a system. Earth is somewhat isolated out in space, with relatively little matter entering or leaving the planet. ***Energy***, however, flows into and out of the Earth as shown in Figure 11.

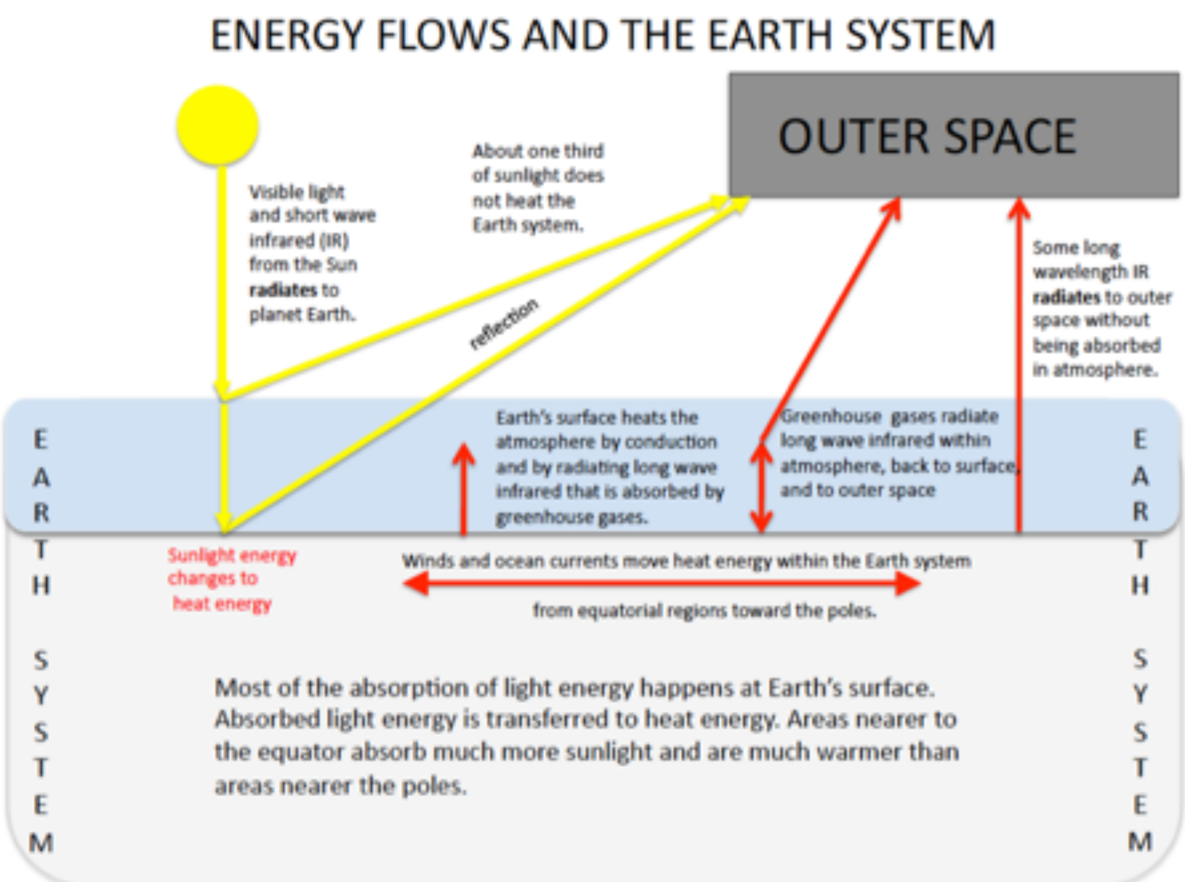


Figure 11. Energy flows in the Earth system, an illustration of a systems model. Image credit: (Figure by A. Sussman)

Students can make a conceptual model of Earth’s ***energy*** budget using an analogy of the line for a ride at an amusement park. The constant stream of eager visitors arriving at the end of the line represents solar radiation. As visitors get on the ride at the front of the line, they act like energy radiating out into space. Earth’s global average temperature measures the amount of heat stored internally in Earth’s system and so it is like the number of people waiting in line at any given point in time. The line will remain the same length if people get on the ride as quickly as new people arrive at the end of the line.

Earth's ***energy*** input comes almost entirely from the Sun. While there is a small amount of radioactive decay within Earth's interior that generates heat, the flow of solar energy to Earth's surface is about 4,000 times greater than the flow of energy from Earth's interior to its surface. Relatively small changes in the solar input can result in an Ice Age or the melting of all of Earth's ice, much like the sudden arrival of a large group at an amusement ride can cause the line to quickly grow longer. The line will stabilize at this new length (without continuing to grow) as long as the influx of people returns back to its original rate. Planets can do the same thing, maintaining their temperature at a new value after a temporary disturbance.

Most of the sunlight that reaches Earth is absorbed and is transformed to thermal ***energy***. If there were no atmosphere to hold that energy, it would radiate right back out into space as infrared radiation (like an amusement park ride that is not very popular such that people get on as soon as they arrive). Gases in the atmosphere, such as CO_2, absorb infrared energy heading into space and ***cause*** it to remain within the Earth's system for a longer period of time. Because these gases have the same effect as a greenhouse where heat is trapped inside the system, gases like CO_2 are referred to as 'greenhouse gases.' Calculations by scientists show that if Earth had no greenhouse gases, its surface temperature would be near 0°F (or -18°C) instead of its current value of much warmer 59°F (15°C). The energy coming into the Earth is still balanced almost exactly by what is leaving the planet but there is a enough heat trapped in the system to allow life to thrive (like the amusement park ride whose line is always the same length).

By increasing the amount of greenhouse gases in the atmosphere, human activities are increasing the greenhouse effect and warming Earth's climate. In a given year, less energy leaves Earth than arrives. It's like one of the seatbelts breaks on the amusement park ride and fewer people are able to get on the ride at a time. All of a sudden, the line gets longer and longer as new people arrive because people aren't able to leave the line as quickly at the front. At the amusement park, this might lead to impatient children. On Earth, the imbalance in energy flows leads to an overall rise in average temperature.

Amusement parks and planets are ***systems*** with complicated inner workings. When lines for one ride at an amusement park get too long, visitors inside the park may respond by going to another ride or park operators may add additional workers or cars to help move people through more quickly. Similar changes happen in Earth's system of systems. While the greenhouse effect seems like a simple ***cause and effect*** relationship viewed from outside the system, interactions *within* the system can often give rise to more complicated chains of cause and effect referred to as feedbacks. Climate scientists are particularly concerned about feedback effects that could increase the amount and rate of global climate change. One example is that warming is clearly reducing the amount of ice on our planet. Glaciers around the world are shrinking in size and even disappearing. The amount of ice covering the ocean in summer and fall is also shrinking. As the ice melts, the surface beneath it is darker in color and absorbs more incoming sunlight. More absorption causes more heating, and more heating then causes even more absorption of sunlight. This kind of feedback loop amplifies or reinforces the change, and the distinction between '***cause***' and '***effect***' begins to blur, as each effect causes more change. The clarification statements in CA NGSS and many scientists use the term 'positive feedback', but this term should be replaced because it leads to confusion, as many reinforcing feedbacks have very negative outcomes.

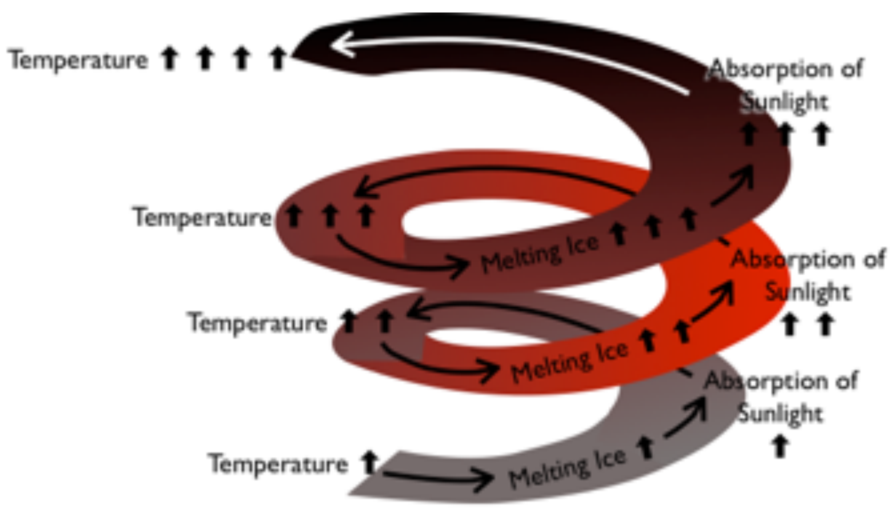


Figure 12. A reinforcing ('positive') feedback in Earth's climate system. As the planet warms, more ice will melt, which will expose darker ground surfaces that absorb more sunlight, which will in turn make temperatures rise even more. Image credit: (CC-BY-NC-SA) by M. d'Alessio, based on a draft by A. Sussman)

A different kind of feedback loop reduces the amount of change. For example, warmer temperatures ***cause*** more water to evaporate which enables more clouds to form. Since clouds reflect sunlight back into space, more clouds cause more incoming solar energy to be reflected before it has a chance to be absorbed by the planet. This causes decreasing global temperatures. More warming could cause more reflection, which would then lead to less warming again. This kind of feedback balances out changes.

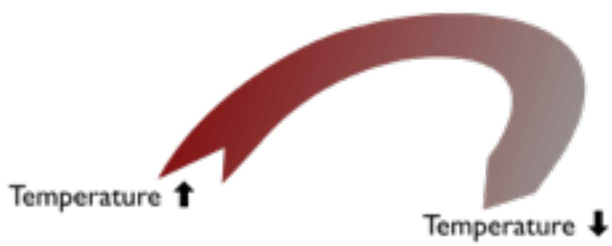


Figure 13. Counter-balancing ('negative') feedback. Global warming may increase the amount of clouds. These clouds could reflect more sunlight, thereby causing temperatures to decrease. Temperatures stabilize as when an air conditioner turns on and off to control the temperature in a climate controlled house. Image credit: (CC-BY-NC-SA) by M. d'Alessio based on a draft by A. Sussman

Scientists discover these complicated interactions between different components of Earth's ***systems*** by looking for trends and ***patterns*** in climate data. The ***CA NGSS*** have a strong emphasis on data analysis, especially in the sections related to weather and climate:

"An important aspect of Earth and space science involves making inferences about events in Earth's history based on a data record that is increasingly incomplete that farther you go back in time…. Students can understand the analysis and interpretation of different kinds of geoscience data allow students to construct explanations for the many factors that drive climate change over a wide range of time scales." (NGSS Lead States 2013b)

Some of the strongest evidence about our changing climate comes from ice core records. As snow accumulates over time in glaciers around the globe, it traps both the water that recently fell as precipitation and air bubbles. These air bubbles can act as tiny time capsules that allow scientists to study actual samples of the ancient atmosphere. Since the snow and ice buildup seasonally, the timing of each layer of ice and its trapped air bubbles can be counted like tree rings. Scientists make detailed chemical analyses of the water to reconstruct the global average temperature. Details of how this isotopic analysis provides a proxy for global temperature is beyond the scope of high school performance expectations, but is a fascinating example of physics, chemistry, and earth science working together.

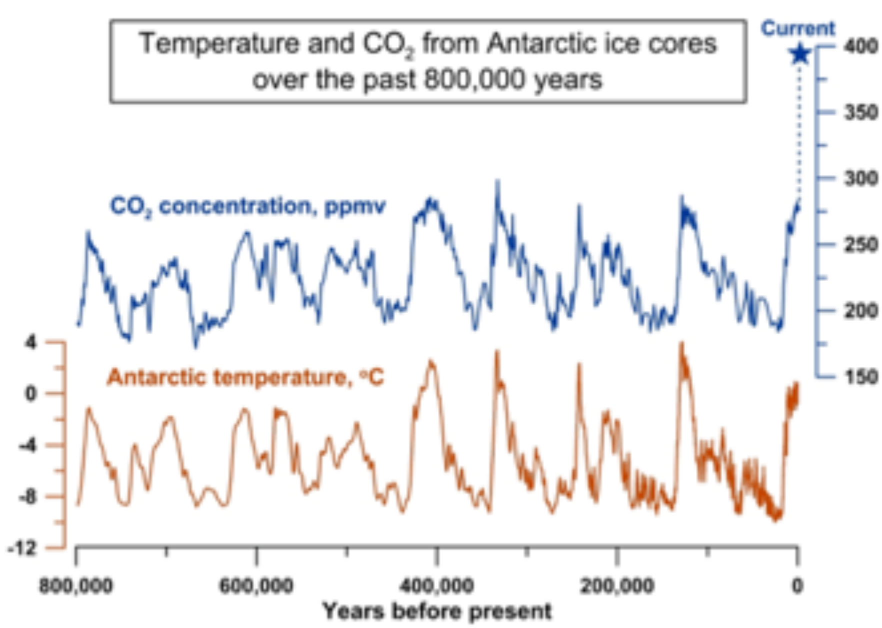


Figure 14. Temperature changes over the last 800,000 years correlate with changes in carbon dioxide.

Snapshot: Trends and Patterns in Modern Atmospheric CO

After students have been introduced to the idea that a portion of Earth's atmosphere is composed of CO

and how it has changed over time. She introduces the units of parts per million (ppm), relating it to the familiar concept of percent (parts per hundred). She also uses her city, which has almost a million people in it, as an analogy where the school's population of 2,700 equates to 2,700 ppm of the city. CO

rarer than that at about 400 ppm. Ms. R distributes a poster size piece of graph paper to each team, along with sticker dots and a table showing one year's worth of atmospheric CO

team places stickers to plot data from a different year, but all graph papers have identical axes with identical scales. She asks students to identify trends and ***patterns*** they see in their one year of data and almost every group indicates that the graph goes up and down once over the course of the year, with the peak value sometime in the middle of the year. Students associate the changes with the seasons since they repeat once a year. The pattern of fluctuating CO

since there is more vegetated land area in the northern hemisphere, the consumption of CO_2 by plants varies as seasons shift from the productive summer months in the northern hemisphere to summer in the southern hemisphere. The class tapes their graphs side-by-side to the wall in sequence so that they create one long time series graph. Each class period is assigned additional data from different years and by the end of the school day, her classes have filled the entire length of the hallway with 35 years of data. She shows an interactive visualization of global CO

students can observe the trend using a more dynamic visualization, and she asks students to **evaluate** the benefits of using each format. Ms. R begins the following class period having students walk along the entire graph. She asks each team of students to **analyze** the past data and draw a graph predicting the next 5 years, extrapolating both the long term trend of increasing CO

has them calculate the year in which atmospheric CO

(approximately double the pre-industrial CO

continue. When students compare their predictions, she has them discuss assumptions they made about how quickly the CO

Connections to the CA NGSS: **Science and engineering practices** **Disciplinary core ideas** **Cross cutting concepts** Analyzing and Interpreting Data; Obtaining, Evaluating, and Communicating Information ESS2.D Weather and Climate Patterns
Connections to the CA CCSSM: MP.4; A1.N-Q.1; A1.F-LB.1b,c; A1.S-ID.6,7
Connections to CA CCSS for ELA/Literacy: SL.9-10.1c, SL.9-10.1d, SL.11-12.1c, SL.11-12.1d
Connection to CA ELD Standards: ELD.PI.9-10.1.Ex, ELD.PI.9-10.2.Ex, ELD.PI.9-10.3.Ex
Connections to the CA EP & Cs: Principles II and III

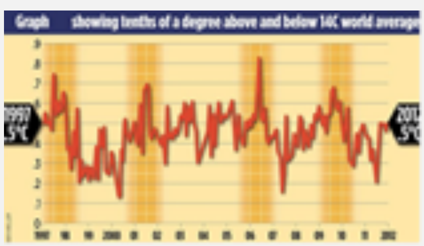
The temperature record from the last half million years reveals some dramatic ***patterns*** as temperatures go up and down with a periodicity of about 100,000 years, each low temperature an ice age (National Oceanic and Atmospheric Administration 2015). When students examine such data, they should be able to **ask questions** about which parts of the climate ***system*** might have ***caused*** these changes. If students compare temperature reconstructions with reconstructions of the amount of ***energy*** received from the Sun (which varies as the Earth's orbit wobbles and the Sun's energy output changes cyclically over time), they will discover that the data sets have a similar ***pattern***: many warm periods in the ice core data correspond to periods of higher solar energy input (EP&C II). This seems quite reasonable because the Sun's input should influence our temperature. However, there are also time intervals where the Earth was hot that do not correspond to high solar energy. The ***pattern*** in the history of the concentration of CO_2 in Earth's atmosphere and temperatures is very similar; the two are highly correlated. This correlation is a key piece of **evidence** that CO_2 also plays a role in affecting Earth's temperature. In a classroom, this correlation can motivate a discussion of Earth's *energy* budget and the greenhouse effect.

Snapshot: "Dear Editor," evaluating climate change graphs

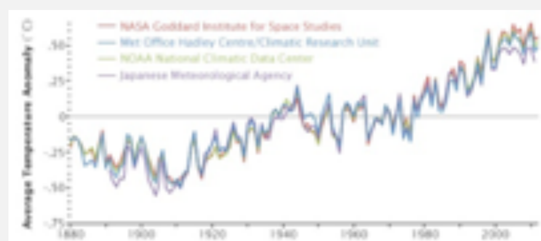
Earlier in the year, Ms. Q had her students read about how to **evaluate** the scientific arguments made in media sources using a checklist called the Science Toolkit from the UC Museum of Paleontology (http://undsci.berkeley.edu/article/sciencetoolkit_01). She now has them read two internet articles with radically different headlines that each use a graph of global temperature as **evidence**. Students work in pairs to evaluate the two articles based on the criteria outlined in the Science Toolkit. Walking around the room, Fernando asks her about the sources: "this article is from NASA, but what is the Daily Mail? Who wrote it?" She encourages him to do a quick internet search about the newspaper's editorial board. A bit later, Cynthia mentions that both articles use graphs, "but they look totally different."

Global warming stopped 16 years ago, reveals Met Office report quietly released... and here is the chart to prove it

Long-Term Global Warming Trend Continues



(Rose 2012)



(Earth Observatory 2013)

Ms. Q then asks the whole class to discuss the graphs and construct an **argument** about which graph contains stronger **evidence**. Ali notices that one graph includes a much longer span of time, "and climate is supposed to be a long term thing." Jenni says, "this graph has four lines from scientists all over the world that all show the same ups and downs. That shows science is repeatable, and I like that." To conclude the lesson, students write letters to the editor in response to the Daily Mail article articulating their **argument.**

Connections to the CA NGSS: **Science and engineering practices Disciplinary core ideas Crosscutting concepts** Obtaining and evaluating information; Engaging in argument from evidence ESS3.D Global Climate Change (analyzing geoscience data about the rate of climate change is part of HS-ESS3-5) Scale (timescales of the graphs)
Connections to the CA CCSSM: MP. 1, MP. 2, MP. 3
Connections to CA CCSS for ELA/Literacy: WHST.9-10.4, WHST.9-10.6, WHST.9-10.9, WHST.9-10.10, RST.9-10.1, RST.9-10.7, RST.9-10.9.
Connection to CA ELD Standards : ELD.PI.9-10.1.Ex, ELD.PI.9-10.2.Ex, ELD.PI.9-10.3.Ex, ELD.PI.9-10.6a-b.Ex, ELD.PI.9-10.11a.Ex, ELD.PII.9-10.1.Ex
Connections to the CA EP & Cs: EP & C Principle II

The *CA NGSS*, students combine their general understanding with **computational thinking** by using simple computer simulations[2] to model the ***flow of energy*** into and out of the Earth and the role that CO_2 and other greenhouse gases play in that process (*HS-ESS2-4*). Scientists use simulators of Earth's climate called global climate **models** (GCM's) that are much more detailed and include many other processes and interactions between Earth systems. The assessment boundary of *HS-ESS3-6* states that students should not be required to run their own models, though simplified versions of GCM's exist for educational purposes[3],[4]. The advantage of these models is that they enable students to turn on and off different parts of the Earth ***system*** to see how they affect the climate. For example, students can compare a model of the Earth without the biosphere to a model that includes the biosphere. As CO_2 increases in the atmosphere, plant growth flourishes and decreases the impact of global warming. This is an example of a balancing feedback. Comparing a model that allows

[2] http://phet.colorado.edu/en/simulation/greenhouse

[3] Columbia University, EdGCM: http://edgcm.columbia.edu/

[4] Java Climate Model: http://jcm.climatemodel.info/

ice to melt with one in which ice is not allowed to melt reveals the reinforcing feedback shown in Figure 12. Examining the predictions of computer models is another form of **analyzing and interpreting data** and can help build on students' mental models of the climate system. **Models**, as defined in the *CA NGSS*, represent a system that allows for predicting outcomes, so the output of a computational model can sometimes be more useful at anticipating the future than simply examining historical data. Ultimately, students need to be able to communicate their mental model by describing specific feedbacks in the Earth ***system*** using an argument (*HS-ESS2-2*). In a classroom, different student teams could examine different elements of the Earth ***system***, using teacher-provided results of **model** runs or creating their own with educational GCM's. They could then compile brief reports to share with their classmates about the ***effects*** of these different processes on global climate.

Another crucial observation about Earth's climate is that the concentration of CO_2 and other greenhouse gases in our atmosphere has been growing steadily since the dawn of the industrial era. Students should be able to make connections to the previous unit and know that the vast majority of this increase comes from humans' extraction and combustion of fossil fuels. GCMs allow scientists and students to see how the climate is expected to change as greenhouse gases trap more ***energy*** in the atmosphere. Because of the linkages between different components of Earth's ***systems***, the impacts extend to all of Earth's ***systems*** (Figure 15 shows an example of a few of these linkages). In a classroom, different student groups could **obtain information** from library and internet resources to construct a report on the impact predicted for different parts of the world so that the class as a whole could create a product to share with the rest of their school that summarizes the global impacts (*HS-ESS3-6*).

The rest of the instructional segments in this course investigate different Earth ***systems*** and their interactions. By placing climate change early in the course, teachers can use climate impacts in California as a common thread that highlights the interdependence of Earth's ***systems*** (***ESS2.A***). This document describes specific climate impacts in each of the subsequent instructional segments.

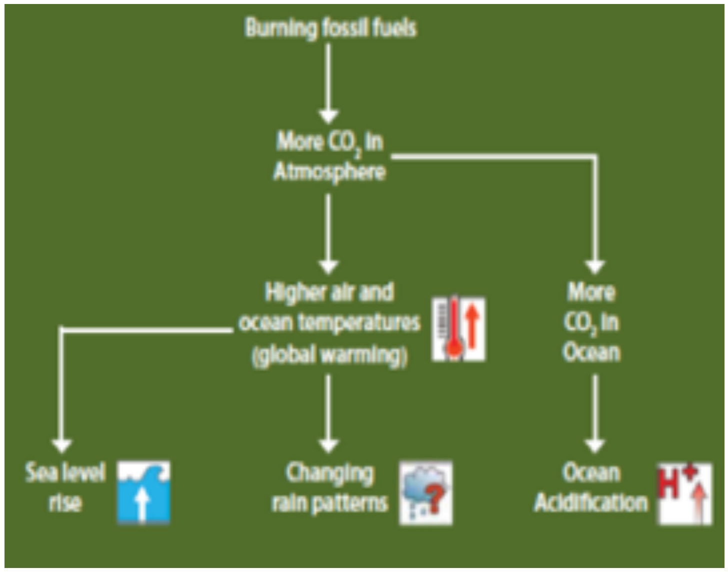


Figure 15. One example of how humans affect the climate, which impacts all parts of Earth's systems. Image credit: (Figure by A. Sussman)

Ultimately, any discussion of climate change should also begin to explore technological solutions that could reduce emissions of greenhouse gases. In a classroom, students can calculate their own carbon footprint to further understand how they contribute to the human impacts on the global carbon ***cycle***. They can explore renewable ***energy*** options and debate the pros and cons of each possible ***energy*** source for meeting society's needs[5] (*HS-ESS3-2*, *HS-ETS1-1*). They can complete the project by creating another summary product for their school that documents some steps that individuals could take to reduce their impact on the climate ***system***, or recommend broader actions that their school and community could take that will have an even larger impact.

[5] National Energy Education Development Project, The Great Energy Debate: http://www.switchenergyproject.com/education/CurriculaPDFs/SwitchCurricula-Secondary-Introduction/SwitchCurricula-Secondary-GreatEnergyDebate.pdf