that chemical reactions result in the rearrangement of these elements into other whole-number ratios. Students can develop a deeper understanding of the principles involved in HS-PS1-7 by massing and comparing the reactants and products of simple chemical reactions. For example, if students dehydrate copper sulfate pentahydrate ($CuSO_4 \cdot 5H_2O$) into the anhydrous salt ($CuSO_4$) by heating, they will find that the ratio of the mass of the resulting copper sulfate (dry mass) to water (the mass lost in dehydration) is always the same, regardless of how much copper sulfate pentahydrate is used. Students can infer that because the ratio of the component molecules in such a dehydration reaction remains constant, then the ratio of component elements must also remain constant. By applying **mathematical thinking [SEP-5]**, students learn to balance chemical reactions and predict relative quantities of products.

IS4 Chemistry in the Earth System Instructional Segment 4: Chemical Reactions

CHEMISTRY IN THE EARTH SYSTEM INSTRUCTIONAL SEGMENT 4: CHEMICAL REACTIONS

Guiding Questions

- What holds atoms together in molecules?
- How do chemical reactions absorb and release energy?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-PS1-3. Plan and conduct an investigation to gather evidence to compare the structure of substances at the bulk scale to infer the strength of electrical forces between particles. [Clarification Statement: Emphasis is on understanding the strengths of forces between particles, not on naming specific intermolecular forces (such as dipole-dipole). Examples of particles could include ions, atoms, molecules, and networked materials (such as graphite). Examples of bulk properties of substances could include the melting point and boiling point, vapor pressure, and surface tension.] *[Assessment Boundary: Assessment does not include Raoult's law calculations of vapor pressure.]*

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. [Clarification Statement: Emphasis is on the idea that a chemical reaction is a system that affects the energy change. Examples of models could include molecular-level drawings and diagrams of reactions, graphs showing the relative energies of reactants and products, and representations showing energy is conserved.] *[Assessment Boundary: Assessment does not include calculating the total bond energy changes during a chemical reaction from the bond energies of reactants and products.]*

CHEMISTRY IN THE EARTH SYSTEM INSTRUCTIONAL SEGMENT 4: CHEMICAL REACTIONS

HS-PS1-5. Apply scientific principles and evidence to provide an explanation about the effects of changing the temperature or concentration of the reacting particles on the rate at which a reaction occurs. [Clarification Statement: Emphasis is on student reasoning that focuses on the number and energy of collisions between molecules.] *[Assessment Boundary: Assessment is limited to simple reactions in which there are only two reactants; evidence from temperature, concentration, and rate data; and qualitative relationships between rate and temperature.]*

HS-PS1-7. Use mathematical representations to support the claim that atoms, and therefore mass, are conserved during a chemical reaction. [Clarification Statement: Emphasis is on using mathematical ideas to communicate the proportional relationships between masses of atoms in the reactants and the products, and the translation of these relationships to the macroscopic scale using the mole as the conversion from the atomic to the macroscopic scale. Emphasis is on assessing students' use of mathematical thinking and not on memorization and rote application of problem- solving techniques.] *[Assessment Boundary: Assessment does not include complex chemical reactions.]* (Introduced in IS3 and revisited again in IS6)

HS-PS2-4. Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects. [Clarification Statement: Emphasis is on both quantitative and conceptual descriptions of gravitational and electric fields.] *[Assessment Boundary: Assessment is limited to systems with two objects.]*

HS-PS3-5. Develop and use a model of two objects interacting through electric or magnetic fields to illustrate the forces between objects and the changes in energy of the objects due to the interaction. [Clarification Statement: Examples of models could include drawings, diagrams, and texts, such as drawings of what happens when two charges of opposite polarity are near each other.] *[Assessment Boundary: Assessment is limited to systems containing two objects.]*

The bundle of performance expectations above focuses on the following elements from the NRC document *A Framework for K–12 Science Education*:

Highlighted Science and Engineering Practices	Highlighted Disciplinary Core Ideas	Highlighted Crosscutting Concepts
[SEP-2] Developing and Using Models [SEP-3] Planning and Carrying Out Investigations [SEP-5] Using Mathematical and Computational Thinking [SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering)	PS1.A: Structure and Properties of Matter PS1.B: Chemical Reactions PS2.B: Types of Interactions PS3.C: Relationship Between Energy and Forces	[CCC-1] Patterns [CCC-2] Cause and Effect [CCC-5] Energy and Matter: Flows, Cycles, and Conservation

CHEMISTRY IN THE EARTH SYSTEM INSTRUCTIONAL SEGMENT 4: CHEMICAL REACTIONS

CA CCSS Math Connections: A-SSE.1a–b, 3a–c; N-Q.1–3; MP.2; MP.4

CA CCSS for ELA/Literacy Connections: SL.11–12.5; RST.11–12.1, 2, 8; WHST.11–12.7, 8, 9

CA ELD Connections: ELD. PI.11–12.1, 5, 6a–b, 9, 10, 11a

Students were introduced to chemical reactions in the middle grades. In particular, they learned that substances react chemically in characteristic ways; and in a chemical process, the atoms that make up the original substances are regrouped into different molecules, and these new substances have different properties from those of the reactants. In addition, they learned that the total number of each type of atom is conserved, and thus the mass does not change; and that some chemical reactions release energy, others store energy (PS1.B). Students in the middle grades demonstrated their understanding by **analyzing and interpreting data [SEP-4]** on the properties of substances before and after the substances interact to determine if chemical reactions have occurred (MS-PS1-2), and by **developing and using models [SEP-2]** to describe how the total number of atoms does not change in a chemical reaction and thus mass is conserved (MS-PS1-5).

Chemical Bonds as Attractions Between Particles

In this instructional segment, students build upon this understanding and their newly acquired understanding of the properties and structure of matter (IS1 and IS2) to learn how elements combine to form new compounds, the forces that hold them together, the forces between particles and molecules, and the energy needed to break or form bonds. Students will expand their conceptual **model [SEP-2]** of chemical bonding, which requires a shift towards the three-dimensional learning of the CA NGSS (table 7.5).

Table 7.5. Instructional Shifts for Chemical Bonding in the CA NGSS

LESS OF ...	MORE OF ...
Students are told, and memorize, that ionic bonds result from the transfer of electrons from one atom to another and covalent bonds result from the sharing of electrons between two atoms. Students are then presented with differences in the two types of bonding. They conduct experiments to verify these differences.	Students observe how materials behave on their own and with other substances. They recognize **patterns [CCC-1]** that allow them to determine that there must be two different categories of materials. They use evidence about the properties to infer the strength and properties of the bonds that hold the materials together. Eventually, they label these categories with the appropriate scientific terms of ionic and covalent bonds.

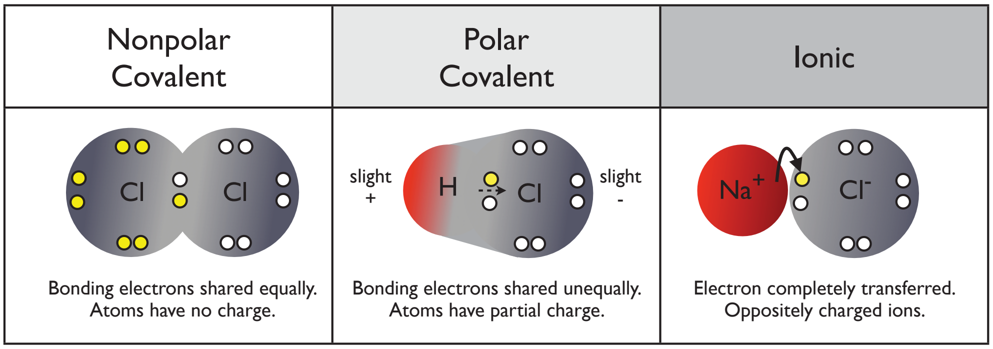
Observations at the macroscopic level give clues about the nature of chemical bonding (HS-PS1-3). When students **conduct an investigation [SEP-3]** to measure the conductivity of different solutions (salts, acids, bases, hydrocarbons, and oxides), they gather evidence that there must be some relationship between electricity and material properties.

They use this evidence to support a **model [SEP-2]** of different types of chemical bonds and attractions. When considering ionic bonds, this model includes attractions between charged particles related to Coulomb's Law, which is assessed in the high school Physics of the Universe course (HS-PS2-4 and HS-PS3-5). Students will learn how the nuclei of some atoms have enough attractive force to pull one, two, or three electrons away from another nucleus that does not have the same attractive force on its own electrons. By applying the principles of electrostatic attraction, students should be able to predict that the resulting cations and anions will be attracted to each other and form ionic bonds. However, if either ion feels a stronger attraction to a different particle, then the existing bond is easily broken. Knowing that when salt dissolves in water, its bonds are broken, what can students infer about the charge of water molecules?

Pure materials with high boiling points are more likely to be bonded together more stably than materials with lower boiling points. As two non-metals come very close to one another, the respective orbitals of the atoms overlap, trapping two electrons in the energy field, creating the covalent bond (HS-PS3-5). Differences in how these ionic and covalent bonds are created (figure 7.26) are often overlooked, resulting in oversimplified definitions. To properly **explain [SEP-6]** the link between bulk effects and microscopic **causes [CCC-2]** (HS-PS1-3), students must develop robust models of how these bonds form.

Students can also **investigate [SEP-3]** other forms of attraction such as polar attractions and intermolecular forces. The clarification statement of HS-PS1-3 specifies that students do not need to refer to these attractions by name, but they should be able to investigate properties like surface tension and viscosity and provide a model-based explanation of how these properties relate to microscopic electromagnetic attractions.

Figure 7.26. Covalent, Polar Covalent, and Ionic Bonding



Bonding electrons shared equally. Atoms have no charge.

Bonding electrons shared unequally. Atoms have partial charge.

Electron completely transferred. Oppositely charged ions.

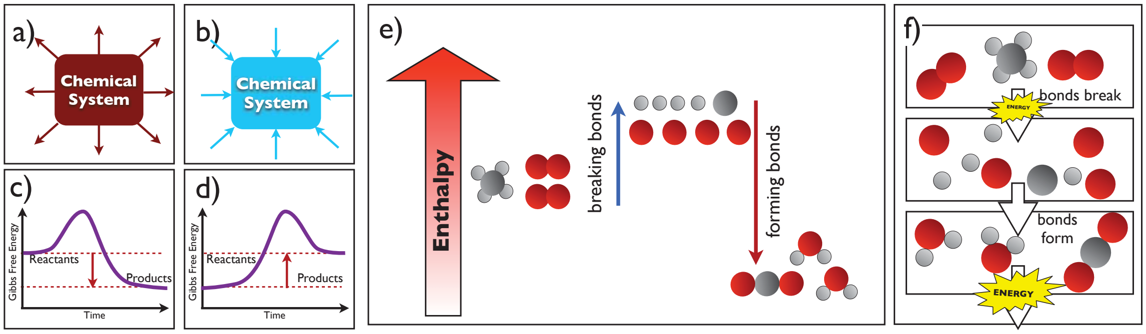
Students should be able to develop and explain models of covalent, polar covalent, and ionic bonding.
Source: M d'Alessio

Energy in Chemical Bonds

From their work in the middle grades, students know that chemical reactions can absorb and release energy (MS-PS1-6), but they did not develop a model of the mechanisms of this energy release. HS-PS1-4 requires students to **develop models [SEP-2]** that illustrate the **release or absorption of energy [CCC-5]** from chemical reactions. They begin their model development by relating back to investigations at the bulk scale. Students can build on their model of the ionic bond breaking between sodium and chlorine when salt is dissolved in water. They can observe the water temperature decrease when they add salt, even when both materials start at the same temperature. Does breaking the bond absorb energy from the water? When sodium mixes with water, students observe that it gives off a dramatic amount of energy as light and sound. Does sodium release energy when it forms new bonds?

Students are now ready to use graphs, diagrams, and drawings to **model [SEP-2]** changes in total bond energy, such as those shown in figure 7.27 and use these tools to explain energy changes accompanying chemical reactions. The models in figure 7.27, like many pictorial models that appear in textbooks, were drafted by scientists. The models that those scientists produced when they were students were unlikely as simple and complete as these final products, but they refined their models over the years. Revising **models [SEP-2]** is an integral part of the nature of science.

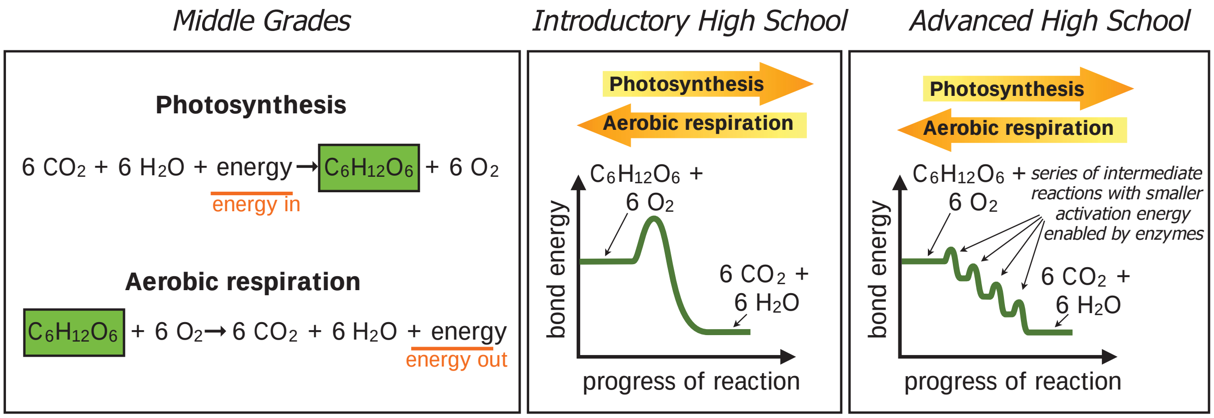
Figure 7.27. Models of Energy Changes in Chemical Reactions



Examples of a range of graphs, diagrams and drawings developed by scientists as models of changes in total bond energy. Students develop their own mental models for energy changes in chemical reactions that they can express in pictorial models that may look like these. *Source*: M. d'Alessio.

In students' **models [SEP-2]** of chemical reactions, original chemical bonds are broken and new bonds form. Each of these changes affects the distribution of energy within the chemical system, so they must extend their **model [SEP-2]** to include these energy flows. **Energy conservation [CCC-5]** in chemical processes is, however, an abstract concept and must be discussed and developed with care. Students **conduct investigations [SEP-3]** to collect and **analyze data [SEP-4]** (both quantitative and descriptive observations) to discover that some reactions appear to release energy to their environment while others absorb it. In a more detailed **model [SEP-2]** of the energy flow, however, all chemical reactions both absorb and release energy, just in differing amounts. Chemical bonds are not tangible objects but actually the name given to a situation where two atoms are attracted together by electric forces. Chemical reactions involve separating two atoms (requiring work to overcome their attraction, just like lifting a heavy load against the force of gravity) and bringing a different combination of the atoms closer together (which releases energy, much like a falling ball converts gravitational potential energy to kinetic energy as it is attracted to the Earth and moves closer to it). Whether or not a chemical reaction gives off energy overall depends on the relative magnitudes of these two energies. Chemists usually refer to the potential energy related to the relative position of two interacting atoms in a chemical bond as the *bond energy*. By comparing the bond energy of the products with the bond energy of the reactants, students can construct mathematical **models [SEP-2]** of the energy in the system and predict whether or not energy will be absorbed or released. When salt dissolves in water, new attractions between water and the sodium and chlorine are weak, so the particles remain relatively far apart (releasing relatively little potential energy). The temperature of water goes down when salt dissolves in it because much energy goes into breaking bonds, but less energy is released when the new attractions form. Another example is the classic set of reactions that comprise photosynthesis and respiration. The complex biochemistry of photosynthetic reactions is not necessary at this stage, but the fact that the formation of biomass from carbon dioxide and water requires energy input is an important understanding that has been stressed in earlier grades. Energy input now can be understood in greater detail given the students' comprehension of the energetics of chemical bonds. The equations in figure 7.28 are the net result of a number of other chemical reactions along the way (the various cycles involving ATP and other intermediate molecules). The reason these other reactions are required is because of the energy required to break bonds of the reactants apart (often called the *activation energy*, which some models in figure 7.27 depict as a temporary increase in energy during the chemical reaction). The intermediate stages involve certain proteins encoded by deoxyribonucleic acid (DNA) to re-orient the molecules and reduce the activation energy.

Figure 7.28. Developmental Progression of Models of Energy in Chemical Reactions



Students can revise their models and make them more detailed over time. In the middle grades, students use simplified equations for photosynthesis and aerobic respiration as a model of energy in chemical reactions (left: note that middle grades students are not assessed on balancing chemical equations). An introductory high school model of energy changes during these chemical reactions includes details about bonding energy (middle). A more advanced model that integrates core ideas from life science shows a series of intermediate chemical reactions inside cells each with a smaller activation energy (right). *Source*: M. d'Alessio

Chemistry in the Earth System Snapshot 7.7: Chemical Energetics

Both the CA NGSS and the California Common Core State Standards for Mathematics (CA CCSSM) include the practice of **developing and using models [SEP-2]**. CA CCSS Math Practice Standard 4 (MP.4) states that high school students should be able "to identify important quantities in a practical situation and map their relationships using such tools as diagrams, two-way tables, graphs, flowcharts and formulas." Having taught for a number of years, Mr. S realized that his chemistry students often memorized diagrams and charts presented in the textbook without being able to apply these models to solving problems or **explaining [SEP-6]** the complex phenomena that they represent.

Anchoring phenomenon: Hot and cold packs look identical on the outside but use different ingredients to "spontaneously" change their temperature warmer or cooler.

Mr. S developed a two-day lesson about modeling the energy in chemical bonds (HS-PS1-4) as part of a larger instructional segment on chemical reactions. At the beginning of class, Mr. S distributed reusable hot and cold packs used to treat sports injuries and instructed his students to flex the bags, feel the change in temperature, measure the temperature change using infrared thermometers obtained from the local building supply store, and record these changes in a collaborative online database. Despite variations in individual recordings among classmates, students noticed similar **patterns [CCC-1]** in the temperature gains or losses for the hot and cold packs.

California Common Core State Standards for English Language Arts/Literacy in History/Social Studies, Science, and Technical Subjects (CA CCSS for ELA/Literacy) standard L.11–12.4b requires students "to apply knowledge of Greek, Latin, and Anglo-Saxon roots and affixes to draw inferences concerning the meaning of scientific and mathematical terminology." Mr. H. wrote the words *endothermic* and *exothermic* on the board and asked students to enter as many words as they know or can find that use the roots: *end-*, *ex-* and *therm-* into an online form. Within a couple of minutes, the collaborative cloud-based list had grown to several dozen words, including *exit*, *extinct*, *exotic*, *exoskeleton*, *exocrine*, *extraterrestrial*, *endemic*, *endocrine*, *endosperm*, *thermometer*, *thermistor*, *thermophilic*, and *thermoregulation*. Mr. S then prompted his students to predict the meaning of these roots based upon the meanings shared by the words that contain them. Mr. S monitored their predictions as they entered them in an online input form and called upon students whose digital responses demonstrated understanding and who had not shared with the class recently. He asked these students to explain the meanings of these roots and predict the meanings of the words *endothermic* and *exothermic*. After clarifying that *endothermic* means absorbing heat, while *exothermic* means releasing heat, Mr. S

Chemistry in the Earth System Snapshot 7.7: Chemical Energetics

asked students to identify the hot and cold pack reactions as being either endothermic or exothermic, and he once again assessed their responses from the online form.

Confident that his students had an intuitive understanding of exothermic and endothermic reactions as well as the vocabulary to describe these reactions, Mr. S projected a slide comparing several different annotated graphs (figure 7.27) and said, “Different people drew these diagrams to describe chemical reactions. What **patterns [CCC-1]** do you observe? Submit your thoughts to our online form.” Scanning student responses, Mr. S formatively assessed the ability of his class to observe salient patterns, and noticed that the majority had noted that multiple drawings included one or more of the following features: two axes, time/progress axis, energy/enthalpy axis, changing molecular models, changing chemical formulas, changing energy values, and/or arrows indicating that energy is absorbed or released. Mr. S then selected Isabella, a student who had not had an opportunity to share in the last few days, to explain her observations. Isabella was confident that she has something significant to share because she knew that Mr. S pre-screened student responses in the cloud and only called on students who had demonstrated that they had something worth sharing. Isabella commented on the similarities and differences between the diagrams and explained that the model in the upper left might represent the heat pack while one next to it might represent the cold pack. Mr. S asked her to **provide evidence to support her argument [SEP-7]**, which she did. Mr. S then asked other students to share their observations and concluded by emphasizing that there are multiple ways to model or represent natural phenomena, and that each has its strengths and weaknesses. He then emphasized that some models are better at explaining or predicting phenomena than others, and that we should strive to improve our **models [SEP-2]** of the natural world to better explain the complex processes they represent.

Mr. S emphasized the idea that a chemical reaction affects the energy change of a system and can be **modeled [SEP-2]** with molecular-level drawings and diagrams of reactions, graphs showing the relative energies of reactants and products, and representations showing energy is conserved (also represented in figure 7.27). After explaining each model, Mr. S assigned as homework an online quiz that assessed student understanding of each type of model.

Chemistry in the Earth System Snapshot 7.7: Chemical Energetics

Investigative phenomenon: Different chemical reactions produce different temperature changes.

On day 2, students planned and **conducted investigations [SEP-3]** using probes and computer probeware to continuously monitor the temperature change accompanying the following reactions:

1. $CaO(s) + H_2O(l) \rightarrow Ca(OH)_2(s)$
   (lime + water)
2. $NH_4NO_3(s) + H_2O\ (l) \rightarrow NH_4^+(aq) + NO_3^-(aq)$
   (ionization of ammonium nitrate, a fertilizer)
3. $HCl(dilute) + NaOH(dilute) \rightarrow H_2O + NaCl$ (neutralization)
4. $NaCl + H_2O \rightarrow Na^+(aq) + Cl^-(aq)$ (dissolving table salt)
5. $CaCl_2 + H_2O \rightarrow Ca^+(aq) + 2Cl^-(aq)$ (de-icing roads)
6. $NaHCO_3(s) + HCl(aq) \rightarrow H_2O(l) + CO_2(g) + NaCl(aq)$ (neutralization)
7. $CH_3COOH(aq) + NaHCO_3(s) \rightarrow CH_3COONa(aq) + H_2O(l) + CO_2(g)$
   (baking soda and vinegar)
8. $C_{12}H_{22}O_{11} + H_2O$ (in 0.5M HCl) $\rightarrow C_6H_{12}O_6$ (glucose) $+ C_6H_{12}O_6$
   (fructose) (decomposing table sugar)
9. $KCl + H_2O \rightarrow K^+(aq) + Cl^-(aq)$ (dissolving potassium chloride)
10. $NaCl + CH_3COOH(aq) \rightarrow Na^+(aq) + CH_3COO^- + HCl$
    (preparing HCl to clean tarnished metals)

Students took screen captures of the temperature plots, classified each reaction as endothermic or exothermic, and represented it using two or more of the model types shown in figure 7.27, or an additional model type that they developed on their own. When writing their lab reports, students applied scientific principles and evidence to **construct explanations [SEP-6]** for the thermal **changes [CCC-7]** that they had observed in each reaction.

Mathematical Models of Chemical Energy

Students observed differences in the relative strength of different types of bonds and attractions. Would they expect these differences to correlate to different amounts of energy stored in these bonds? Students can **analyze data [SEP-4]** about binding energy from published data tables or from their own investigations to look for **patterns [CCC-1]**.

The assessment boundary of HS-PS1-4 states that students will not be assessed within the CA NGSS on calculations of total bond energy in chemical reactions. Even though students' models of bond energy are only required to be conceptual, these calculations can provide more advanced students opportunities to apply and improve their stoichiometry skills. For example, students can predict the temperature change when they react a certain mass of reactants.

IS5

Chemistry in the Earth System Instructional Segment 5: Chemistry of Climate Change

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 [CCC-5]** balances within systems (from IS2) and the products of chemical reactions (from IS4). This 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, this instructional segment integrates with life science units in which students explore the impact of this physical science concept on the Earth system.

CHEMISTRY IN THE EARTH SYSTEM INSTRUCTIONAL SEGMENT 5: CHEMISTRY OF CLIMATE CHANGE

Guiding Questions

- What regulates weather and climate?
- What effects are humans having on the climate?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-ESS2-2. Analyze geoscience data to make the claim that one change to Earth's surface can create feedbacks that cause changes to other Earth systems. [Clarification Statement: Examples should include climate feedbacks, such as how an increase in greenhouse gases causes a rise in global temperatures that melts glacial ice, which reduces the amount of sunlight reflected from Earth's surface, increasing surface temperatures and further reducing the amount of ice. Examples could also be taken from other system interactions, such as how the loss of ground vegetation causes an increase in water runoff and soil erosion; how dammed rivers increase groundwater recharge, decrease sediment transport, and increase coastal erosion; or how the loss of wetlands causes a decrease in local humidity that further reduces the wetland extent.]