Chapter 6
Climate and Volcanic Eruptions

Resources

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  - Chapter 3: Magma, p. 21-34
  - Chapter 14: Volcanoes and Climate, p. 259-271.
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Activities
The material covered in this chapter builds on background information students have gained through the guidebook and emphasizes big picture and long-term contributions made by volcanism to the Earth's atmosphere.

These activities will allow students to understand the source and behavior of magmatic SO_2 and CO_2 and their contributions to atmospheric changes. By comparing a volcanic system to shaken soda bottles, students will understand that dissolved gases under pressure escape slowly over time at some volcanoes, and quickly during volcanic eruptions. Students will also identify Alaskan sources of volcanic gases and volcanic features associated with volcanic gases. Through a graphing exercise, students will observe that volcanic eruptions that eject large volumes of gases and ash into Earth's atmosphere can affect global climate for periods lasting from 1 to 3 years. The phenomena can be visualized using graphs that display changes in global average temperature following major volcanic eruptions. Students will compare the relative amounts of CO_2 contributed on an annual basis to the atmosphere through the burning of fossil fuels and by the emissions of volcanoes into the atmosphere by graphing values of each and interpreting their results. Students will learn that the amount of CO_2 contributed by the burning of fossil is orders of magnitude greater than the amount contributed by volcanoes.

Activity I. The Gas They Pass
Activity II. What Goes Up Must Come Down
Activity III. Globally Averaged Temperature and Volcanic Eruptions
Activity IV. An Order of Magnitude

Activity I. The Gas They Pass

Grade Level 6—11

Setting Classroom

Time 45 minutes

Vocabulary (see Glossary)
amphibole, anthropogenic, CO_2, composition, crust, crustal melting zone, dolomite, exsolve and exsolution, geothermal, H_2O, hydrothermal, magma, mantle, mica, phase, precipitate, SO_2, subduction zone, volcanogenic

Correlations to Alaska State Department of Education (2006) Performance Standards (Grade Level Expectations)
D1—Concepts of Earth Science
SD[6-11] Students develop an understanding of the concepts, processes, theories, models, evidence, and systems of earth and space sciences.
SD1[6-11] Students develop and understanding of earth's geochemical cycles.
SD2[6-11] Students develop an understanding of the origins, ongoing processes, and forces that shape the structure, composition, and physical history of the Earth.

Overview
Prior to a discussion concerning the possible affects of volcanic gases on climate change, it is important to identify the sources and types of the gases emitted by volcanoes.

Background
The area of melting within the Earth's crust (called the crustal melting zone) is an area of high pressures and temperatures tens of kilometers (miles to tens of miles) below the ground surface and is the boundary between the mantle and the overlying continental crust. In this zone, rocks melt to form magma—a mixture of three phases: liquid rock, which is the host of mineral crystals and dissolved gases. The proportions of these three phases correspond to the temperatures and pressures of the magma storage region and relate to the composition of the magma. The addition (by melting) of overlying rock (also known as host rock) to the magma, as well as the contribution of marine sediments in the case of a subduction zone (like that which forms the Aleutians), contributes to the types of gases that eventually escape from the magma. These gases, often called magmatic or volcanic gases, can come out passively (through continuous or long-term degassing) or rapidly during an eruption.

Gases exsolve from magma during the early stages of melting and include water (H_2O), carbon dioxide (CO_2), and sulfur dioxide (SO_2) available from the melting of the minerals amphibole, dolomite, and mica. These gases are important because their expansion during magma ascent provides the energy that propels magma to Earth's surface and outward during an explosive volcanic eruption. Minerals and free-floating chemical elements in the liquid rock arrange and re-arrange as pressure, temperature, and composition change.

As an ascending body of magma approaches the surface of the crust, magmatic gases separate from the magma, grow into bubbles that coalesce, and are expelled during explosive volcanic eruptions. Volcanic gases can also escape passively through local hydrothermal systems and fractures nearly at the surface of the earth.

During large explosive eruptions, gases can rise tens of kilometers (miles to tens of miles) into Earth's atmosphere. Once these gases are airborne, the prevailing winds carry the eruption cloud hundreds to thousands of kilometers (hundreds of miles) downwind from the volcano. These gases spread as an eruption cloud, primarily as acid sulfate aerosols (tiny acid droplets), compounds attached to tephra particles, and microscopic salt particles.

The wide body and narrow neck of a soda bottle roughly resemble the shape of a magma storage region and the ascending path of magma within and finally out of a volcano. The pressurized soda water represents gas-rich magma that is under pressure from overlying rocks. Carbonated beverages include dissolved CO_2. When the bottle is capped, carbon dioxide dissolves within the soda from the pressure exerted on it. It also occupies the void between the surface of the liquid and the cap. Shaking the bottle adds energy and causes gas in the soda water to separate, forming tiny bubbles throughout the liquid. Formation of the bubbles creates pressure inside the bottle. Quickly removing the cap releases this pressure and the bubbles immediately expand and coalesce. Forced up the narrow neck, the fluid and bubbles burst from the high-pressure environment of the bottle to the lower pressure of the atmosphere. Bubbles of water vapor, carbon dioxide, sulfur dioxide, and other gases within magma undergo a similar progression. The gasses initially are dissolved in magma and depressurization in the magma chamber frees the bubbles from the magma in a process called exsolution. The bubbles then rise to the top of the magma chamber. Pressure from the gas bubbles propels the magma and gas up the conduit. The gas bubbles rapidly expand to thousands of times their original volume when escaping up the conduit to the top of the erupting volcano.

Objectives
This activity will allow students to understand that magma includes a component of dissolved gases, which escape slowly over time at some volcanoes and quickly during volcanic eruptions. Students will also identify Alaskan sources of volcanic gas and volcanic features associated with volcanic gases.

Materials
_ 2 or more full, sealed bottles of soda, best if less than 1 liter
_ *Data Table* worksheet

Procedure

A. Discuss the concept of phase change

1. Initiate a classroom discussion about items within students' homes that change phase with a change in temperature. Here are some examples:
   - Ice cube – Solid when frozen, turns into a liquid when heated, and eventually into a gas with continued heat.
   - Brownies – Liquid mixture, changes to a "solid" state when baked, and baking releases gases – the aroma smelled throughout. Note to students that walnuts or some other additions may not change phase at the temperature needed to bake the brownies. Also note that the temperatures needed to achieve a phase change varies from one material to another.

B. Soda Bottle Eruption

1. Use a soda bottle eruption (real, or hypothetical) to illustrate an increase in pressure and the visual build up of gas bubbles at the top of a new, full, sealed, and shaken soda bottle. If you go through with a soda bottle eruption, note that when uncapped there is a sudden release of gases (and sticky liquid) into the air and onto everything nearby.
   - Shake one of the bottles of soda. Pass both bottles around the room and have students squeeze them (the shaken bottle may have to be re-shaken as it is passed around). Remind students that shaking the one bottle adds energy to it, causing the liquid and dissolved CO_2 gas to separate. Students should observe that the shaken bottle is firmer (more pressurized), relative to the unshaken bottle and point out that a foam (vat of connected bubbles) has formed at the top of the shaken bottle.
   - Develop a theory with the class about why one bottle is firmer than the other bottle and what will happen when you uncap both bottles. You may test the theory by uncapping both bottles. The sudden decrease in pressure due to uncapping, and constraint exerted by the narrow neck of the bottle, will force the foam and bubbles in the shaken bottle to escape rapidly.

C. Do volcanoes smell?

1. Have students recall and (or) research if volcanoes are smelly—if volcanoes have associated precipitates (and of what; sulfur is one common example) or other evidence of gas emissions (either while erupting or not; steam plumes are a common example). Ask students to recall local Alaskan eruptions and if any associated smells (rotten egg or match strike smells) or precipitates (yellowing at vents, cracks, and hydrothermal features) were reported. A quick web search should produce reports of sulfur smell (rotten egg and match strike odors) at several volcanoes in Alaska, including the recent activity at Augustine and Redoubt volcanoes in Cook Inlet, and at volcanoes in the Aleutians.

2. Use the included *Visible Degassing at Alaskan Volcanoes* handout and presentation as a resource to discuss your student's findings.

Extensions

1. This extension will introduce a solid component—to represent the mineral crystal component in magma. Partially freeze the bottle of soda used in this activity. Ask students to theorize about, or experiment with the varying proportion of solid material (based on the amount of time that the bottle remains in the freezer) and the possible differences in "eruption" style that results when the bottle is uncapped.

2. Have students explore
   - Annenberg Media Multimedia Collection, 2010, Interactives—Volcanoes—Can we predict volcanic eruptions—Melting rocks: Annenberg Media web page, accessed June 7, 2010, at http://www.learner.org/interactives/volcanoes/activty1/tempmain.html.

3. Review the Rock Cycle
   - U.S. Geological Survey, 2003, Overview of geologic fundamentals: U.S. Geological Survey web page. (Available at http://3dparks.wr.usgs.gov/nyc/common/geologicbasics.htm.)

4. Have students study how volcanologists measure volcanic gases using chemical analysis, hand-held and airborne instrumentation, and satellite image analysis. Have students study the use of spectrometry. Resources include:
   - OMI Sulfur Dioxide Group, 2008, Top stories: Joint Center for Earth Systems Technology at the University of Maryland Baltimore County (UMBC) and NASA Goddard Space Flight Center website, accessed June 7, 2010, at http://so2.umbc.edu/omi/
   - U.S. Geological Survey, 2005, Cascades Volcano Observatory—Description—Mount St. Helens volcanic gases: U.S. Geological Survey website. Available at http://vulcan.wr.usgs.gov/Volcanoes/MSH/Emissions/description_msh_gases.html.)
   - U.S. Geological Survey, 2007, Cascades Volcano Observatory—Volcanic gas and emissions: U.S. Geological Survey website. (Available at http://vulcan.wr.usgs.gov/Glossary/Emissions/framework.html.)
   - U.S. Geological Survey, 2009, Volcano Hazards Program—Monitoring volcanic gases: U.S. Geological Survey website. (Available at http://volcanoes.usgs.gov/activity/methods/gas.php.)

5. Perform "Soda Bottle Volcano" from

Driedger, C.L., Doherty, Anne, and Dixon, Cheryll, 2005, Living with a volcano in your backyard—An educator's guide with emphasis on Mount Rainier, Chap. 1: U.S. Geological Survey General Interest Product 19; produced in cooperation with the National Park Service. (Available at http://vulcan.wr.usgs.gov/Outreach/Publications/GIP19/chapter_one_soda_bottle_volcano.pdf.)

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- Riding the Magma Elevator http://vulcan.wr.usgs.gov/Outreach/Publications/GIP19/chapter_one_magma_elevator.pdf and
- Soda Bottle Volcano http://vulcan.wr.usgs.gov/Outreach/Publications/GIP19/chapter_one_soda_bottle_volcano.pdf.)

Glossary

Amphibole – Amphiboles are an important group of generally dark-colored rock-forming silicate minerals that include iron and magnesium in their compositions.

Anthropogenic – Caused by human activity

CO_2 – Carbon dioxide

Composition – The amounts and types of minerals and (or) elements a rock is comprised of (or a mineral is comprised of)

Crust – The outermost layer of the Earth. The crust is rigid and very thin compared with the other layers.

Crustal melting zone – An area of high pressures and temperatures tens of kilometers below the ground surface that is the boundary between the mantle and the overlying continental crust. In this zone, rocks melt to form magma—a mixture of three phases: liquid rock, mineral crystals, and magmatic gases.

Dolomite – A light colored rock-forming, carbonate mineral consisting of calcium magnesium carbonate.

Exsolve (and exsolution) – To separate from one another at a critical point in temperature; dissolved gases forming gas bubbles

Geothermal – Heat energy extracted from reservoirs in the Earth's interior

H_2O – Water

Hydrothermal – Water heated by magma or in association with magma.

Magma – Magma is molten or partially molten rock beneath the Earth's surface. When magma erupts onto the surface, it is called lava. Magma typically consists of (1) a liquid part (often referred to as the melt); (2) a solid part made of minerals that crystallized directly from the melt; (3) solid rocks incorporated into the magma from along the conduit or reservoir, called xenoliths or inclusions; and (4) dissolved gases.

Mantle – The mantle is a dense, hot layer of semi-solid rock that is approximately 2,900 km thick. The mantle, which contains more iron, magnesium, and calcium than the crust, is hotter and denser because temperature and pressure inside the Earth increase with depth.

Mica – Hydrous silicates of aluminum or potassium that crystallize in forms that allow perfect cleavage

Phase – A state: solid, liquid, or gas that is homogeneous in its structure and atomic arrangement.

Precipitate – Solid substances in suspension, or settling, or filtering out of a fluid

SO_2 – Sulfur dioxide

Subduction Zone – The zone of convergence of two tectonic plates, one of which usually overrides the subducting plate

Volcanogenic – Having a volcanic source

Source of Glossary Definitions

Bates, R.K., and Jackson, J.A., eds., 1987, Glossary of Geology (3rd ed.): Falls Church, Va., American Geological Institute, 571 p.

Kious, W.J., and Tilling, R.I., 1996, This dynamic Earth—The story of plate tectonics [online edition]: Reston, Va., U.S. Geological Survey website. (Available at http://pubs.usgs.gov/gip/dynamic/dynamic.html.)

U.S. Geological Survey, 2010, Volcano Hazards Program—USGS photo glossary of volcanic terms: U.S. Geological Survey website: (Available at http://volcanoes.usgs.gov/images/pglossary/index.php.)

U.S. Geological Survey, 2010, Volcano Hazards Program—Volcanic gases and their effects: U.S. Geological Survey website. (Available at http://volcanoes.usgs.gov/hazards/gas/index.php.)

Name ______________________________ Date ____________ Period _____

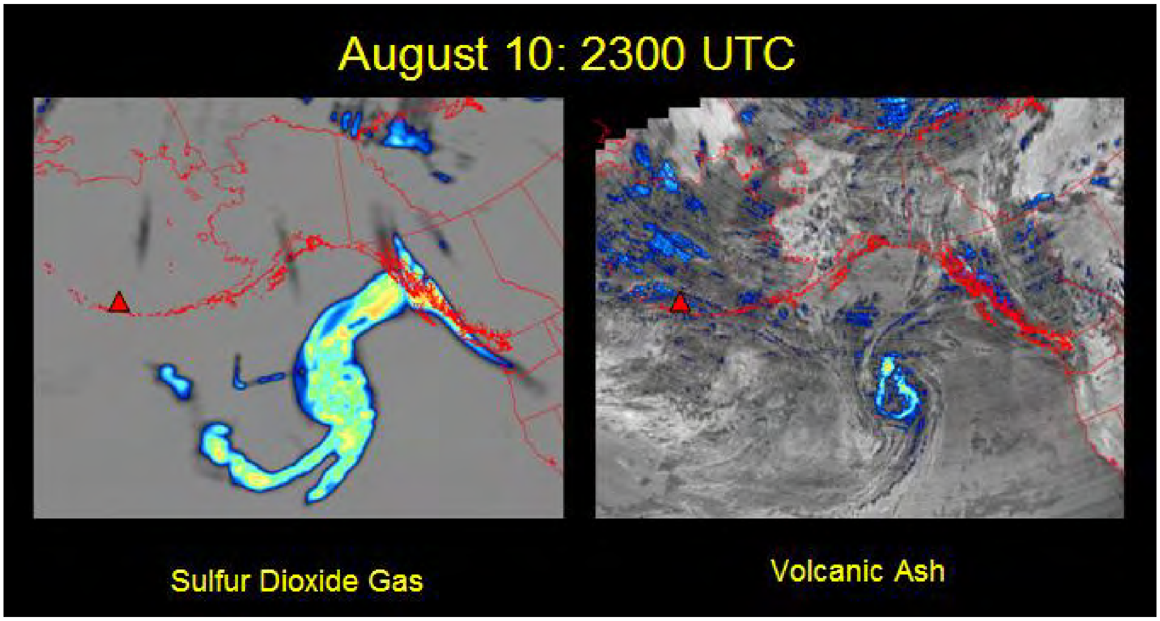
Visible Degassing at Alaskan Volcanoes Handout

1. Fumarole on northwest side of Fourpeaked Mountain. Yellow staining on the snow is the result of sulfur emission from the vent. Photograph taken by C. Read, U.S. Geological Survey, February 22, 2007.

2. Steam plume emanating from the summit ice cauldron of Mt. Spurr. Photograph taken September 10, 2006, courtesy of J. Copen. Used with permission.

3. View of the east-southeast flanks of Augustine Volcano and steaming summit. Photograph taken by G. McGimsey, U.S. Geological Survey, June 2, 2006.

4. Martin summit crater in Katmai National Park. The vigorous fumaroles at Martin and nearby Mageik often have been mistaken for volcanic eruptions. Photograph taken by C. Read, U.S. Geological Survey, August 26, 2006.



5. Kasatochi volcanic cloud as observed at 2300 UTC on August 10, 2008, approximately 3 days after the start and 2 days after end of the eruption. The image on the left shows SO_2 gas detected by the OMI sensor and the image on the right shows a smaller region of volcanic ash as indicated by a GOES thermal infrared brightness temperature difference image. The colors are related to the total column abundance (mass per area) of SO_2 and volcanic ash, with warmer colors indicating greater amounts of gas and ash. These data are from NASA's EOS-Aurasatellite and Ozone Monitoring Instrument (OMI), courtesy of Dr. Simon Carn, University of Maryland, Baltimore County. Graphic prepared by Dave Schneider, image courtesy of Alaska Volcano Observatory and U.S. Geological Survey.

6. View of the Okmok caldera’s eruption plume viewed from Fort Glenn (ranch building in foreground) on August 3, 2008. The small peak to the left is Tulik, a stratocone outside of the caldera. Photograph taken by J. Larson, University of Alaska Fairbanks Geophysical Institute, August 3, 2008.

Activity II. What Goes Up Must Come Down

Grade Level 6−11

Setting Classroom

Time 20 minutes

Vocabulary (see Glossary)
aerosol, chlorine monoxide (ClO), chlorofluorocarbon (CFC), eruption cloud, greenhouse effect, ozone (O_3), pollution, radiation, reflection, stratosphere, sulfate, volcanic ash, volcanic (or magmatic) gases

Correlations to Alaska State Department of Education (2006) Performance Standards (Grade Level Expectations)
B1—Concepts of Physical Science
SB[6-11] Students develop an understanding of the concepts, models, theories, universal principles, and facts that explain the physical world.
SB1[6-11] Students develop an understanding of the characteristic properties of matter and the relationship of these properties to their structure and behavior.

D1—Concepts of Earth Science
SD[6-11] Students develop an understanding of the concepts, processes, theories, models, evidence, and systems of earth and space sciences.
SD1[6-11] Students develop an understanding of Earth's geochemical cycles.
SD2[6-11] Students develop an understanding of the origins, ongoing processes, and forces that shape the structure, composition, and physical history of the Earth.

Overview
Scientists considered three historical, explosive volcanic eruptions in Indonesia: Tambora (1815), Krakatau (1883), and Agung (1963). They noted decreases in temperatures (0.18−1.3°C, [~2°F]) close to the ground surface after these eruptions, which were similar magnitudes. The overall amount of material injected during each eruption was different. Comparing the estimated amount of ash and sulfur with the amount of sulfur erupted into the stratosphere by each eruption, suggested that, in the long term, sulfate aerosols (SO_4^{-2}) formed in the atmosphere with the volcanogenic sulfur, not with the volcanic ash (which falls out within a few months of an eruption). Volcanogenic sulfur, therefore, is the ultimate controlling factor in decreasing temperatures on the Earth's surface following a large, explosive volcanic eruption.

Background
Studies of the eruption of El Chichon, Mexico, in 1982 conclusively demonstrated that it is the amount of sulfur in the erupting magma that contributes to the decreases in temperature measured on the Earth's surface following substantial, gas rich volcanic eruptions (not airborne volcanic ash!). The explosive eruption of El Chichon injected at least 8 million metric tons (MT) of sulfur into the atmosphere, and was followed by a measureable cooling of parts of the Earth's surface and a warming of the upper atmosphere. A similar-sized eruption at Mount St. Helens in 1980, however, injected only about 1 MT of sulfur aerosols into the stratosphere. The eruption of Mount St. Helens injected much less sulfur into the atmosphere and it did not result in a noticeable cooling of the earth's surface. The Total Ozone Mapping Spectrometer (TOMS) satellite launched in 1978 made it possible to measure these differences in the eruption clouds. Direct satellite measurements of the eruption clouds combined with surface temperatures make it possible to study the correlation between volcanic sulfur aerosols and temporary changes in the world's climate after some volcanic eruptions.

Objectives
Student will use a simple laboratory exercise to model minimally suspended volcanic ash and long term suspended airborne volcanogenic sulfate aerosols associated with an explosive volcanic eruption. Students will learn about the effects of a significant sulfur input into the atmosphere.

Materials
For a single demonstration (duplicate sets of materials for the number of students or groups to perform)

- large, clear plastic or glass beaker or other wide-mounted container
- source of water
- ~ ½ cup of breadcrumbs with herbs (homemade or store bought)
  or
- any other mixture of materials in which one will float (herbs) and one will sink (breadcrumbs)

Procedure
A. Set up

1. Set up as a demonstration or for an individual or group activity.

2. Fill a large clear container ~ $^2/_3$ full of tap water (represents the atmosphere). Prepare as many containers with water in them as there are individuals or groups performing this activity.

3. Mix ~ ½ cup of breadcrumbs with herbs; make as many ½-cup mixtures as you have individuals or groups performing the activity.

B. Float or sink

1. Inform students that the water represents Earth's atmosphere and the dry materials represent ash and sulfate aerosols formed in the atmosphere from a large, explosive volcanic eruption. The bottom of the container represents Earth's surface. *Note* You could start with the next step and ask the students to draw this analogy from the activity.

2. Gently pour (and/or have students gently pour) all of the dry mixture onto the surface of the water in the container.

3. Have students observe and record the settling of the materials, including observations of how fast and which material(s) settle to the bottom of the container, and in what order (if there is more than one kind of materials that does so). Let the materials settle in the container overnight if necessary. You and your students should see that the breadcrumbs rapidly sink to the bottom while the herbs will float at the surface.

4. Initiate a discussion about how the settled materials represent volcanic ash, and how it stays aloft briefly (afloat in this experiment) and then settles to the bottom of the container. The material(s) that remain floating the longest represents airborne sulfur expelled during an explosive volcanic eruption.

5. Review with your students the conversion of sulfur to sulfate aerosol. When sulfur dioxide (SO_2) gas is released, it reacts chemically with sunlight, oxygen, dust particles, and water in the air to form a mixture of sulfate aerosols (SO_4^{-2}) (tiny particles and droplets), sulfuric acid (H_2SO_4), and other oxidized sulfur species. *Note* For discussion about aerosols: students might not know about these colorless invisible substances, so you could provide some direct comparison to hairsprays, and so on.

6. Discuss with your students—Because sulfate aerosols stay aloft longer than ash in Earth's atmosphere (like the breadcrumb herbs), they have the most substantial effect in blocking heat and keeping solar radiation from reaching the Earth's surface. The airborne material that remains aloft also keeps heat radiating from the Earth from reaching the upper atmosphere.

C. Volcanic Gas

1. Using the *Volcanic Gas* figure to introduce or review the various materials, tephra, and gases produced by a volcanic eruption and the ways in which they react to modify Earth's atmosphere. This will also come in handy when proceeding to Activity IV. An Order of Magnitude.
   - SO_2
     - The conversion of SO_2 to sulfuric acid (H_2SO_4) condenses rapidly in the stratosphere to form fine sulfate aerosols. The aerosols increase the reflection of radiation from the Sun back into space and cool the Earth's lower atmosphere or troposphere; however, they also absorb heat radiated up from the Earth, thereby warming the stratosphere.

- The sulfate aerosols also promote complex chemical reactions on their surfaces that alter chlorine and nitrogen chemical species in the stratosphere. This effect, together with increased stratospheric chlorine levels from chlorofluorocarbon (CFC) pollution, generates chlorine monoxide (ClO), which destroys ozone (O_3).

- CO_2
  - Volcanoes release hundreds of millions metric tons of CO_2 into the atmosphere every year. This colorless, odorless gas usually does not pose a direct hazard to life because it typically becomes diluted to low concentrations quickly whether it is released continuously from the ground or during episodic eruptions. In certain circumstances, however, CO_2 may become concentrated at levels lethal to people and animals. Carbon dioxide gas is heavier than air and the gas can flow into low-lying areas; breathing air with more than 30 percent CO_2 can quickly induce unconsciousness and cause death. In volcanic or other areas where CO_2 emissions occur, it is important to avoid small depressions and low areas that might be CO_2 traps. The boundary between air and lethal gas can be extremely sharp; even a single step upslope may be adequate to escape death.
  - Volcanic eruptions can enhance global warming by adding CO_2 to the atmosphere; however, the amount of CO_2 from volcanoes is dwarfed by anthropogenic sources. This relation will be emphasized in *Activity IV. An Order of Magnitude*.
- Volcanic Ash

  On a short time frame, airborne volcanic ash can block out the earth's sunlight, reduce solar radiation and lower the mean global temperatures. This can generate red sunsets because of the scattering of red wavelengths by submicron-size particles in the stratosphere and upper troposphere.

Extensions

1. Ask students if there are positive contributions of volcanic gases. Have students conduct research projects to determine how volcanoes have been an important agent in the development of Earth’s atmosphere.

2. Elaborate on the concepts of photochemistry (reactions requiring energy from sunlight), albedo (the ability of a material to reflect sunlight), cirrus clouds (high, thin, wispy clouds), condensation, coagulation, dispersion, using the figure.
   - Use an animated version of a similar figure available at:
     National Aeronautics and Space Administration, 2005, Students On-Line Atmosphere Research (SOLAR)—Aerosols, what are they and why are they so important?: National Aeronautics and Space Administration webpage, accessed June 7, 2010 webpage, accessed June 7, 2010, at http://asd-www.larc.nasa.gov/SOLAR/learning-aerosol.html.

3. National Aeronautics and Space Administration, 2009, Total Ozone mapping Spectrometer (TOMS) Resource Materials for Science Educators: National Aeronautics and Space Administration website, accessed June 1, 2010, at http://toms.gsfc.nasa.gov/teacher/teacher.html.

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Camp, Vic, [n.d.], Climate effects of volcanic eruptions: San Diego State University, Department of Geological Sciences website, accessed June 7, 2010, at http://www.geology.sdsu.edu/how_volcanoes_work/climate_effects.html.

National Aeronautics and Space Administration, 2009, Earth observatory—Sulfur dioxide cloud from Aleutians' Kasatochi Volcano: National Aeronautics and Space Administration web page, accessed June 7, 2010, at http://earthobservatory.nasa.gov/IOTD/view.php?id=8998.

U.S. Geological Survey, 2010, Volcano Hazards Program—Volcanic gases and their effects: U.S. Geological Survey web page. (Available at http://volcanoes.usgs.gov/hazards/gas/index.php.)

U.S. Geological Survey, 2009, Volcano Hazards Program—Volcanic sulfur aerosols affect climate and the Earth's ozone layer—Volcanic ash vs. sulfur aerosols: U.S. Geological Survey web page. (Available at http://volcanoes.usgs.gov/hazards/gas/s02aerosols.php.)

Glossary

Aerosol – Fine liquid or solid particles suspended in the atmosphere. When sulfur dioxide (SO_2) gas is released, it reacts chemically with sunlight, oxygen, dust particles, and water in the air to form a mixture of sulfate (SO_4^{-2}) aerosols (tiny particles and droplets), sulfuric acid (H_2SO_4), and other oxidized sulfur species.

Chlorine monoxide (ClO) – Atmospheric gas that destroys ozone.

Chlorofluorocarbon (CFC) – Manufactured substances used as coolants and computer-chip cleaners. When these products break down they destroy stratospheric ozone, creating the Antarctic Ozone Hole in the Southern Hemisphere in spring (Northern Hemisphere in autumn). Although no longer in use, their long lifetime will lead to a slow removal from the atmosphere.

Eruption cloud – A cloud of tephra and gases that forms downwind of an erupting volcano. The vertical pillar of tephra and gases rising directly above a vent is an eruption column. Eruption clouds often are dark colored—brown to gray—but they also can be white, similar to weather clouds. Eruption clouds may drift downwind for thousands of kilometers, often spreading out over a large area as distance increases from an erupting vent. Large eruption clouds can encircle the Earth within days.

Greenhouse effect – The heating of the Earth's surface because out-going long-wavelength terrestrial radiation is absorbed and re-emitted by the carbon dioxide and water vapor in the lower atmosphere and eventually returned to the surface.

Ozone (O_3) – Ozone is a molecule consisting of three oxygen atoms that is formed by a reaction of oxygen and ultraviolet radiation. In the stratosphere, ozone has beneficial properties because it forms an ozone shield that prevents dangerous radiation from reaching the Earth's surface. Closer to the planet's surface, ozone is considered an air pollutant that adversely affects humans, plants, and animals, as well as a greenhouse gas.

Pollution – Pollution is the introduction of contaminants into an environment that causes instability, disorder, or harm to systems and (or) organisms.

Radiation – Energy from the Earth emitted from its surface toward the atmosphere and beyond.

Reflection – The change in the direction of sunlight heading toward the earth to be bounced back towards the sun.

Stratosphere – The stratosphere is the region of the atmosphere that extends from the top of the troposphere to the base of the mesosphere; an important area for monitoring stratospheric ozone.

Sulfate (SO_4) – Salt of sulfuric acid (H_2SO_4)

Volcanic ash – Rock, mineral, and volcanic glass fragments smaller than 2 mm (0.1 in.) in diameter, which is slightly larger than the size of a pinhead. Volcanic ash is not the same as the soft fluffy ash that results from burning wood, leaves, or paper. It is hard, does not dissolve in water, and can be extremely small—ash particles less than 0.025 mm (1/1,000th of an inch) in diameter are common. Ash is extremely abrasive, similar to finely crushed window glass, mildly corrosive, and electrically conductive, especially when wet. Volcanic ash is created during explosive eruptions by the shattering of solid rocks and violent separation of magma (molten rock) into tiny pieces. Explosive eruptions are generated when groundwater is heated by magma and abruptly converted to steam and also when magma reaches the surface so that volcanic gases dissolved in the molten rock expand and escape (explode) into the air extremely rapidly. After being blasted into the air by expanding steam and other volcanic gases, the hot ash and gas rise quickly to form a towering eruption column directly above the volcano.

Volcanic (or magmatic) gases – Magma contains dissolved gases that are released into the atmosphere during eruptions. Gases also are released from magma that either remains below ground (for example, as an intrusion) or is rising toward the surface. The most abundant gas typically released into the atmosphere from volcanic systems is water vapor (H_2O), followed by carbon dioxide (CO_2), and sulfur dioxide (SO_2). Volcanoes also release smaller amounts of others gases, including hydrogen sulfide (H_2S), hydrogen (H_2), carbon monoxide (CO), hydrogen chloride (HCL), hydrogen fluoride (HF), and helium (He).

Source of Glossary Definitions

Energy Information Administration, 2008, Greenhouse gases, climate change, and energy: U.S. Department of Energy Brochure DOE/EIA-X012, accessed June 7, 2010, at http://www.eia.doe.gov/bookshelf/brochures/greenhouse/Chapter1.htm.

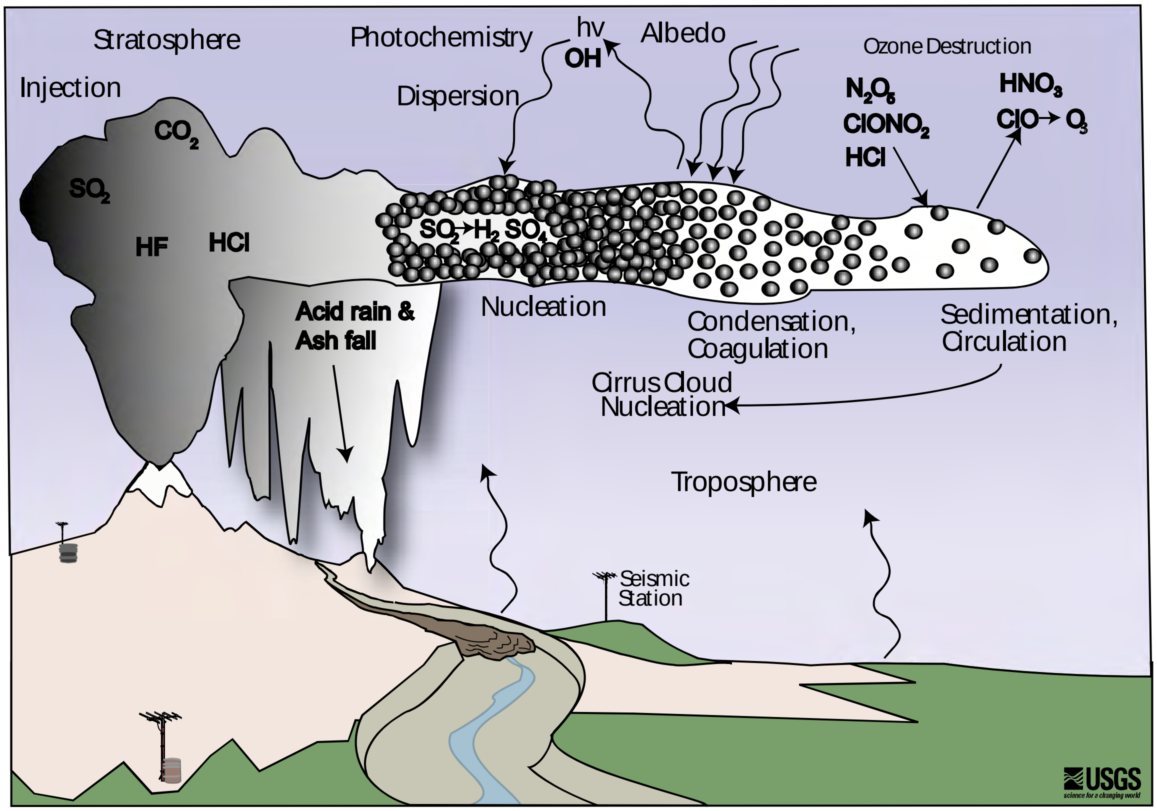
National Weather Service, 2010, Climate prediction center—Climate glossary: National Oceanic and Atmospheric Administration web page, accessed June 9, 2010, at http://www.cpc.noaa.gov/products/outreach/glossary.shtml.

U.S. Geological Survey, 2009, Volcano Hazards Program—Volcanic gases and their effects: U.S. Geological Survey website. (Available at http://volcanoes.usgs.gov/hazards/gas/index.php.)

U.S. Geological Survey, 2010, Volcano Hazards Program—USGS photo glossary of volcanic terms: U.S. Geological Survey website. (Available at http://volcanoes.usgs.gov/images/pglossary/index.php.)

U.S. Geological Survey, 2010, Volcano Hazards Program—Volcanic air pollution, Kilauea Volcano, Hawai`i—Long-lasting eruption of Kilauea Volcano, Hawai`i leads to volcanic-air pollution: U.S. Geological Survey web page. (Available at http://volcanoes.usgs.gov/hazards/gas/volgaspollution.php.)

Volcanic Gas



Large volcanic eruptions inject water vapor (H_2O), carbon dioxide (CO_2), sulfur dioxide (SO_2), hydrochloric acid (HCl), hydrofluoric acid (HF), and ash into the stratosphere (10-20 mi above the Earth's surface).

- CO_2 is a greenhouse gas and contributes to global warming.
- HCl and HF can dissolve in water and fall to the Earth as acid rain.
- The most significant impact is when SO_2 is converted to sulfuric acid (H_2SO_4), which condenses into a mist of fine particles (sulfate aerosols). These aerosols reflect radiation from the sun, cooling the troposphere; they also absorb the Earth's heat, warming the stratosphere. The aerosols, together with increased stratospheric chlorine levels from chlorofluorocarbon pollution, also promote ozone destruction by altering chlorine and nitrogen chemical species in the stratosphere. As the aerosols settle down into the upper troposphere, they can serve as nuclei for cirrus clouds, further affecting the Earth's radiation balance.
- Carbon dioxide allows short wavelength radiation from the sun to penetrate through the lower atmosphere to the Earth's surface and absorbs long wavelength radiation, which is the energy the earth reradiates back into space. The trapping of this infrared heat energy by these greenhouse gases results in warming.
- Most of the HCl and HF are dissolved in water droplets in the eruption cloud and fall to the quickly ground as acid rain. The injected ash also falls rapidly from the stratosphere; most of it is removed within several days to a few weeks.

Figure modified from Richard Turco, 1992, Volcanism and climate change: American Geophysical Union Special Report, May 1992.

Activity III. Globally Averaged Temperature and Volcanic Eruptions

Grade Level 8–12

Setting Classroom or computer lab

Time 60 minutes

Vocabulary (see Glossary)
anthropogenic, decadal, Volcano Explosivity Index (VEI)

Correlations to Alaska State Department of Education (2006) Performance Standards (Grade Level Expectations)
A1—Science as Inquiry and Process
SA1[6-11] Students will develop an understanding of the processes and applications of scientific inquiry.

E1—Science and Technology
SE1[6-11]Students develop an understanding of the relationships among science, technology, and society.

Overview
Scientists have observed that volcanic eruptions, which eject large volumes of gases and ash into Earth's atmosphere, can affect global climate for periods lasting from 1 to 3 years. This has been recognized by analysis of globally averaged temperature prior to and following volcanic eruptions. The general effect seen is a short-term cooling trend of one degree Celsius more or less for the subsequent 1–2 years. The phenomena can be visualized by using graphs that display changes in global average temperature following significant volcanic eruptions.

Background
When sulfur dioxide (SO_2) gas is released during a volcanic eruption, it reacts chemically with sunlight, oxygen, dust particles, and water in the air to form a mixture of sulfate (SO_4^{-2}) aerosols (tiny particles and droplets), sulfuric acid (H_2SO_4), and other oxidized sulfur species. Once formed, sulfate aerosols stay in the stratosphere for about 2 years; however, remnants of the layer can remain in the atmosphere longer. This limits the amount of time the temperature measured at the ground surface can be affected by volcanically erupted SO_2.

Objective
Students will quantify how global average temperatures have changed over the past 150+ years by plotting annual average temperatures over time. Students will identify temperature trends before and after major volcanic eruptions worldwide with an emphasis on Alaskan eruptions. Students will be able to correlate the size of one volcanic eruption to another using the Volcanic Explosivity Index (VEI).

Materials

To graph by hand

_ graph paper

_ colored pencils

_ data table of temperatures during the last 150 years

To graph using a computer spreadsheet program

_ computer with spreadsheet or graphing program

Procedure

A. Decadal-to-Century Variability and Trends worksheet

1. Use *Table 1: Ave. Global temp in °C and °F from 1880 – 2005* – in the section of handouts associated with this activity.
   - Students should make a scatter plot of annual temperature and time for the years 1880–1920 and then answer questions on the *Decadal-to-Century Variability and Trends* worksheet or in a group discussion.
   - Students then can make a scatter plot of the same data, but for the period 1921–65, and answer questions on the same worksheet or in a group discussion.
   - Finally, students should make a scatter plot for the period 1966–2005, and answer questions on the worksheet or in a group discussion.

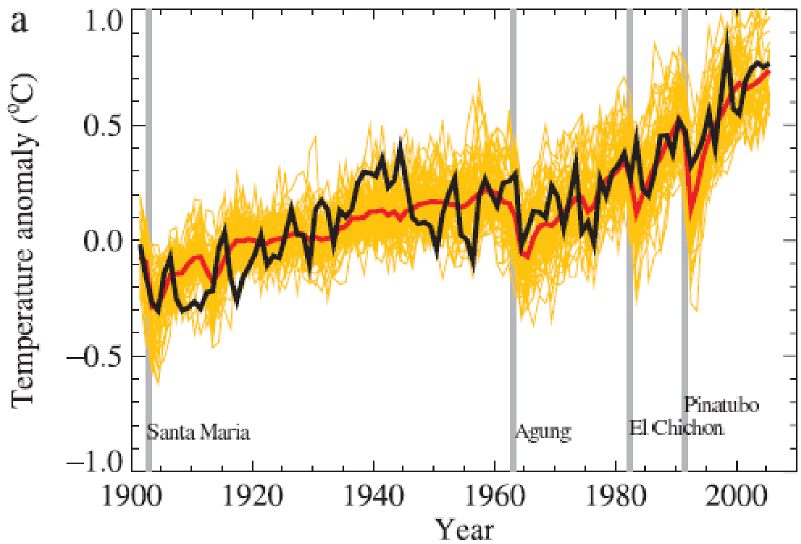
B. *Inter-annual Variability* worksheet

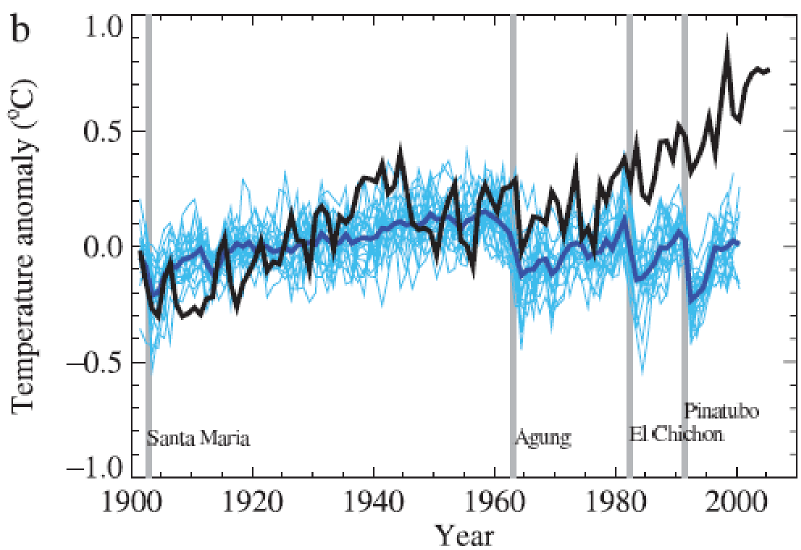
1. Students will use the table of major volcanic eruptions 1883–2005 on the worksheet.
   - Using *Table 1: Ave. Global temp in °C and °F from 1880–2005*, have students make a scatter plot of annual temperature and time for the periods designated in the worksheet and answer the associated questions.
   - Have students indicate these eruptions on their plots. Make sure students distinguish the Alaska eruptions from the others. The easiest way to do this may be to use colored straight, vertical lines through each year when there is an eruption and to label the lines. Students could identify all Alaskan eruptions using the same color for the designating line.

   Note The Volcanic Explosivity Index (VEI) is way to describe the relative size or magnitude of explosive volcanic eruptions. It is a 0-to-8 index of increasing explosivity. Each increase in number represents an increase about a factor of ten. The VEI uses several factors to assign a number, including volume of erupted pyroclastic material (for example, ashfall, pyroclastic flows, and other ejecta), height of eruption column, duration in hours, and qualitative descriptive terms. See http://volcanoes.usgs.gov/images/pglossary/vei.php for more information.

C.

1. Have students view and discuss the plots of comparison between global mean surface temperature anomalies (°C) from observations and simulations forced with (a) anthropogenic (man made) and natural forcings (solar and volcanic) and (b) natural forcings only.





Comparison between global mean surface temperature anomalies (°C) from observations (black) and simulations (computer model outputs) forced with (a) anthropogenic and natural forcings (solar and volcanogenic) and (b) natural forcings only.

(a) Global mean surface temperatures (°C) from observations (black) and simulations (multiple runs of multiple computer models with different variables – the average of which is shown by the red line) with anthropogenic and natural forcings.

(b) Global mean surface temperatures (°C) from observations (black) and simulations (multiple runs of multiple computer models with different variables – the average of which is shown by the dark blue line) with natural forcings (solar and volcanogenic) only.

On (a) and (b) the vertical grey lines indicate the timing of major volcanic events.

In essence, graph (a) shows computer model calculations that include anthropogenic and natural (volcanic and solar) inputs and the direct measurement of average global temperature match. Graph (b) also shows the direct measurement of average global temperature in black, increasing over time, but computer model calculations using only natural (volcanic and solar) inputs show a steady average global temperature. One could conclude from this figure that the anthropogenic sources or inputs are the cause of increasing average global temperatures. Graph (b) also illustrates that immediately following the noted volcanic eruptions there is a decrease in globally averaged temperatures for the next 2, 3, or 4 years, but the average achieved over a much longer time scale is attained within a few years.

Intergovernmental Panel on Climate Change (IPCC), 2007. http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm (download PDFs)

- FAQ 8.1, Figure 1, Chapter 8 Climate Models and their Evaluation
- Figure is 9.5, Chapter 9, Understanding and Attributing Climate Change, Fourth Assessment Report Climate Change

Modified from

Columbia University, 2007, The climate system—EESC 2100, Fall 2007: Columbia University webpage, accessed July 2, 2010, at http://eesc.ldeo.columbia.edu/courses/ees/climate/labs/globaltemp.

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Alaska State Department of Education and Early Development, 2006, Standards and grade level expectations, March 2006: State of Alaska website, accessed October 2009 at http://www.eed.state.ak.us/tls/assessment/GLEHome.html.

Intergovernmental Panel on Climate Change (IPCC), 2007, Fourth Assessment Report Climate Change—The Physical Science Basis, Working Group I contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Chapters 8 and 9, FAQ 8.1, figure 1; Figure 9.5: New York, Cambridge University Press, accessed December 14, 2009, at http://www.ipcc.ch/ipccreports/ar4-wg1.htm.

National Aeronautics and Space Administration, 1996, Facts online, atmospheric aerosols—What are they, and why are they so important?: National Aeronautics and Space Administration Fact Sheet FS-1996-08-11-LaRC, accessed June 1, 2010, at http://oea.larc.nasa.gov/PAIS/Aerosols.html.

The Climate System, 2007, EESC 2100V Fall 2007: Columbia University web page, accessed June 10, 2010, at http://eesc.ldeo.columbia.edu/courses/ees/climate/labs/globaltemp/.

Smithsonian Institution, [n.d.], Global volcanism program: Volcanic Explosivity Index (VEI): Smithsonian Institution database, accessed June 1, 2010, at http://www.volcano.si.edu/world/largeeruptions.cfm?sortorder=desc.

Glossary

Anthropogenic – Derived from human activities

Decadal – Pertaining to ten; consisting of tens.

Volcano Explosivity Index (VEI) – Proposed in 1982 as a way to describe the relative size or magnitude of explosive volcanic eruptions. It is a 0-to-8 index of increasing explosivity. Each increase in number represents an increase around a factor of ten. The VEI uses several factors to assign a number, including volume of erupted pyroclastic material (for example, ashfall, pyroclastic flows, and other ejecta), height of eruption column, duration in hours, and qualitative descriptive terms.

Source of Glossary Definitions

U.S. Geological Survey, 2010, Volcano Hazards Program—USGS photo glossary of volcanic terms: U.S. Geological Survey website. (Available at http://volcanoes.usgs.gov/images/pglossary/index.php.)

Name ______________________________ Date ____________ Period ____

Decadal-to-Century Variability and Trends

1. Using Table 1: *Ave. Global temp in ℃ and ℉ from 1880–2005* make a scatter plot of annual temperature and time for the period 1880−1920 only. Then answer the questions.

   - How would you describe the general appearance of this curve? Imagine you are a scientist in 1921 predicting the future by extrapolating this trend.

   - What would you predict the current global temperature in 2005 to be?

   - Describe the major features of the global temperature time series in words so that a person not seeing the graph can qualitatively construct it on a sheet of paper based on your description.

2. Now make a scatter plot of the same data but for the period 1921−65. Then answer the questions.

   - How would you describe your plot's appearance? Imagine you are a scientist in 1966 predicting the future by extrapolating this trend.

   - Based on this trend, what would you predict the temperature to be in 2005?

   - In 1966, would you have been more worried about global warming or a return to another Ice Age?

3. Now make a scatter plot for the period 1966–2005. Then answer the questions.

    - Based on the trend, what would you predict the temperature to be in 2006?

    - In 2005, would you have been more worried about global warming or a return to another Ice Age?

    - What are the five warmest years in the record?

    - The five coldest?

    - Have we come anywhere close to having one of the coldest years in the record during your lifetime?

    - How long a record is needed to see clear evidence of global warming?

Table 1: Ave. Global temp in °C and °F from 1880 – 2005, The Climate System, Columbia Univ. http://eesc.ldeo.columbia.edu/courses/ees/climate/labs/globaltemp

Year	Ave. Global Temp. (°C)	Ave. Global Temp. (°F)	Year	Ave. Global Temp. (°C)	Ave. Global Temp. (°F)	Year	Ave. Global Temp. (°C)	Ave. Global Temp. (°F)
1880	13.75	56.75	1922	13.76	56.77	1964	13.79	56.82
1881	13.8	56.84	1923	13.8	56.84	1965	13.89	57.00
1882	13.77	56.79	1924	13.79	56.82	1966	13.97	57.15
1883	13.76	56.77	1925	13.84	56.91	1967	14	57.20
1884	13.7	56.66	1926	13.99	57.18	1968	13.96	57.13
1885	13.7	56.66	1927	13.87	56.97	1969	14.08	57.34
1886	13.75	56.75	1928	13.89	57.00	1970	14.03	57.25
1887	13.65	56.57	1929	13.75	56.75	1971	13.9	57.02
1888	13.74	56.73	1930	13.93	57.07	1972	14	57.20
1889	13.85	56.93	1931	13.99	57.18	1973	14.14	57.45
1890	13.63	56.53	1932	13.94	57.09	1974	13.92	57.06
1891	13.72	56.70	1933	13.83	56.89	1975	13.95	57.11
1892	13.68	56.62	1934	13.95	57.11	1976	13.84	56.91
1893	13.68	56.62	1935	13.89	57.00	1977	14.13	57.43
1894	13.67	56.61	1936	13.96	57.13	1978	14.02	57.24
1895	13.73	56.71	1937	14.08	57.34	1979	14.09	57.36
1896	13.83	56.89	1938	14.11	57.40	1980	14.18	57.52
1897	13.88	56.98	1939	14.03	57.25	1981	14.27	57.69
1898	13.75	56.75	1940	14.05	57.29	1982	14.05	57.29
1899	13.83	56.89	1941	14.11	57.40	1983	14.26	57.67
1900	13.9	57.02	1942	14.03	57.25	1984	14.09	57.36
1901	13.84	56.91	1943	14.1	57.38	1985	14.06	57.31
1902	13.73	56.71	1944	14.2	57.56	1986	14.13	57.43
1903	13.69	56.64	1945	14.07	57.33	1987	14.27	57.69
1904	13.66	56.59	1946	13.96	57.13	1988	14.31	57.76
1905	13.75	56.75	1947	14.01	57.22	1989	14.19	57.54
1906	13.8	56.84	1948	13.96	57.13	1990	14.38	57.88
1907	13.61	56.50	1949	13.94	57.09	1991	14.35	57.83
1908	13.66	56.59	1950	13.85	56.93	1992	14.13	57.43
1909	13.65	56.57	1951	13.96	57.13	1993	14.14	57.45
1910	13.67	56.61	1952	14.03	57.25	1994	14.24	57.63
1911	13.66	56.59	1953	14.11	57.40	1995	14.38	57.88
1912	13.66	56.59	1954	13.9	57.02	1996	14.3	57.74
1913	13.68	56.62	1955	13.9	57.02	1997	14.4	57.92
1914	13.85	56.93	1956	13.83	56.89	1998	14.57	58.23
1915	13.91	57.04	1957	14.08	57.34	1999	14.33	57.79
1916	13.7	56.66	1958	14.08	57.34	2000	14.33	57.79
1917	13.6	56.48	1959	14.06	57.31	2001	14.48	58.06
1918	13.68	56.62	1960	13.99	57.18	2002	14.56	58.21
1919	13.8	56.84	1961	14.08	57.34	2003	14.55	58.19
1920	13.81	56.86	1962	14.04	57.27	2004	14.49	58.08
1921	13.87	56.97	1963	14.08	57.34	2005	14.63	58.33

Name ________________________________ Date ____________ Period _____

Inter-annual Variability

Using *Table 1: Ave. Global temp in °C and °F from 1880–2005* make a scatter plot of annual temperature and time for the entire period 1880 - 2005. Below is a list of major volcanic eruptions since 1883, their Volcanic Explosivity Index (VEI), location, and the year that each eruption occurred. Identify them on your plot. Distinguish the eruptions that took place in Alaska from the others.

Volcano	Location	VEI*	Year
Krakatau	Indonesia	6	1883
Colima	México	4	1890
Soufriere / Santa Maria	West Indies / Guatemala	4 / 6	1902
Novarupta	Alaska (USA)	6	1912
Aniakchak	Alaska (USA)	4	1931
Agung	Lesser Sunda Islands (Indonesia)	5	1963
Fernandina Island	Galápagos Islands	4	1968
Mt. St. Helens	Washington (USA)	5	1980
Augustine	Alaska (USA)	4	1986
Pinatubo	Luzon (Philippines)	6	1991
Spurr	Alaska (USA)	4	1992

*****The Volcanic Explosivity Index (VEI) is way to describe the relative size or magnitude of explosive volcanic eruptions. See http://volcanoes.usgs.gov/images/pglossary/vei.php for more information.

Using your plot, develop an Average Global Temperatures table. For all the above eruptions, note the average annual global temperature for the year in which the eruption occurred, the year before the eruption, the year after the eruption, 2 years after the eruption, and 3 years after the eruption. *Note:* Be sure to identify the temperature scale because the Ave. Global Temp. is recorded in °F or °C. Answer the following questions based on your plot and table.

- What is the typical magnitude and direction (warming or cooling) of the effect of volcanoes on global climate?

- How long does it take the climate to return to normal after a major eruption?

Name ________________________________ Date ____________ Period ____

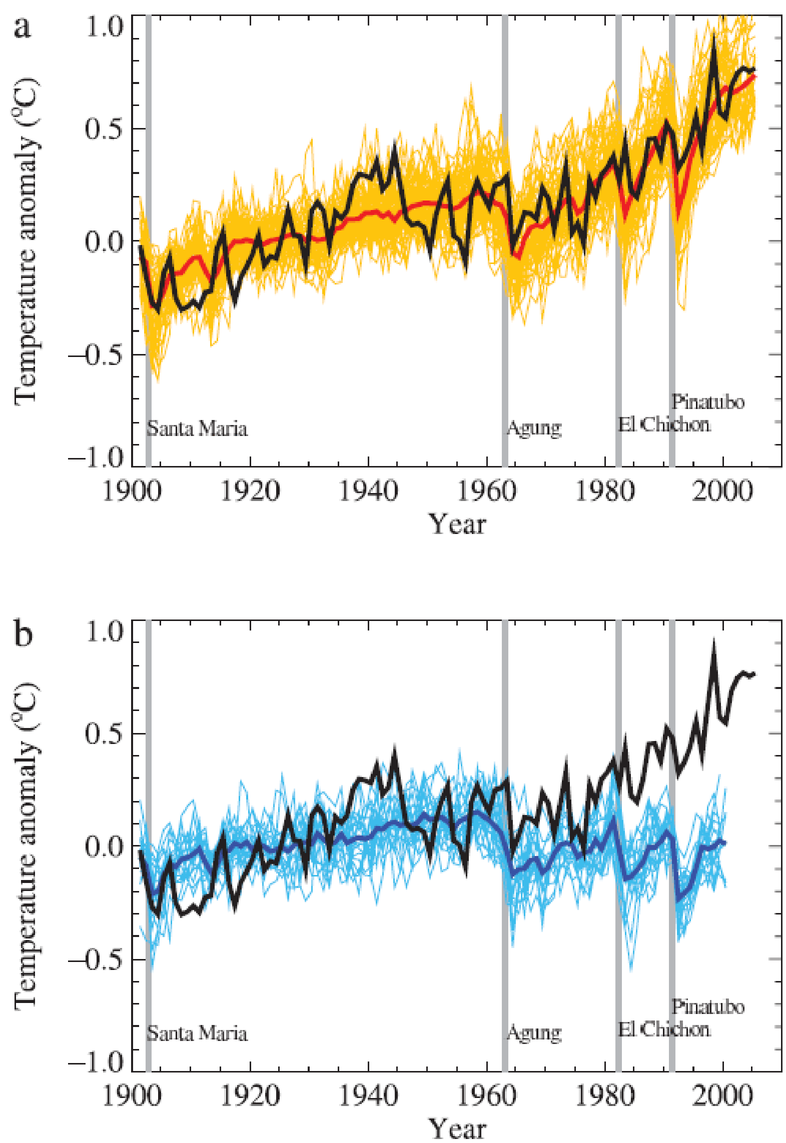
Mean Surface Temperature (°C) Anomalies Handout

Comparison between global mean surface temperature anomalies (°C) from observations (black) and simulations (computer model outputs) forced with (a) anthropogenic and natural forcings (solar and volcanogenic) and (b) natural forcings only.

(a) Global mean surface temperatures (°C) from observations (black) and simulations (multiple runs of multiple computer models with different variables—the average is shown by the red line) with anthropogenic and natural.

(b) Global mean surface temperatures (°C) from observations (black) and simulations (multiple runs of multiple computer models with different variables—the average is shown by the dark blue line) of natural forcings (solar and volcanogenic) only.

On (a) and (b) the vertical grey lines indicate the timing of major volcanic events.



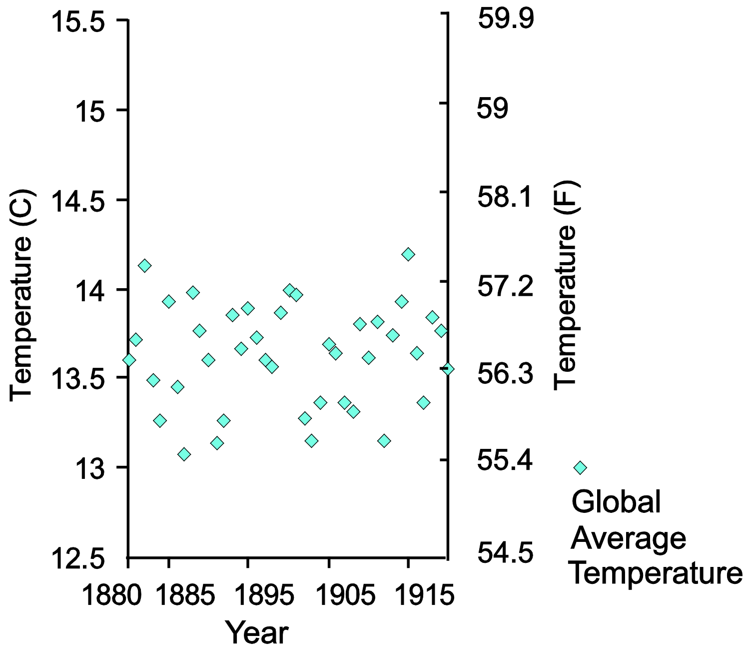
This is figure 9.5 from

Intergovernmental Panel on Climate Change (IPCC), 2007, Fourth Assessment Report Climate Change— The Physical Science Basis, Working Group I contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Chapters 8 and 9, FAQ 8.1, figure 1; Figure 9.5: New York, Cambridge University Press, accessed December 14, 2009, at http://www.ipcc.ch/ipccreports/ar4-wg1.htm.

- Graph (a): FAQ 8.1, Figure 1, Chapter 8 Climate Models and their Evaluation;
- Graph (b): Figure is 9.5, Chapter 9, Understanding and Attributing Climate Change, Fourth Assessment Report Climate Change.

Decadal-to-Century Variability and Trends Key

1. Using Table 1: Ave. Global temp in °C and °F from 1880 to 2005 create a scatter plot of annual temperature and time for 1880–1920 only. Then answer the questions.



- How would you describe the general appearance of this curve? Imagine you are a scientist in 1921 predicting the future by extrapolating this trend.

  Curve? It appears fairly flat. It is punctuated early on and towards the end, but overall the trend is flat and steady.

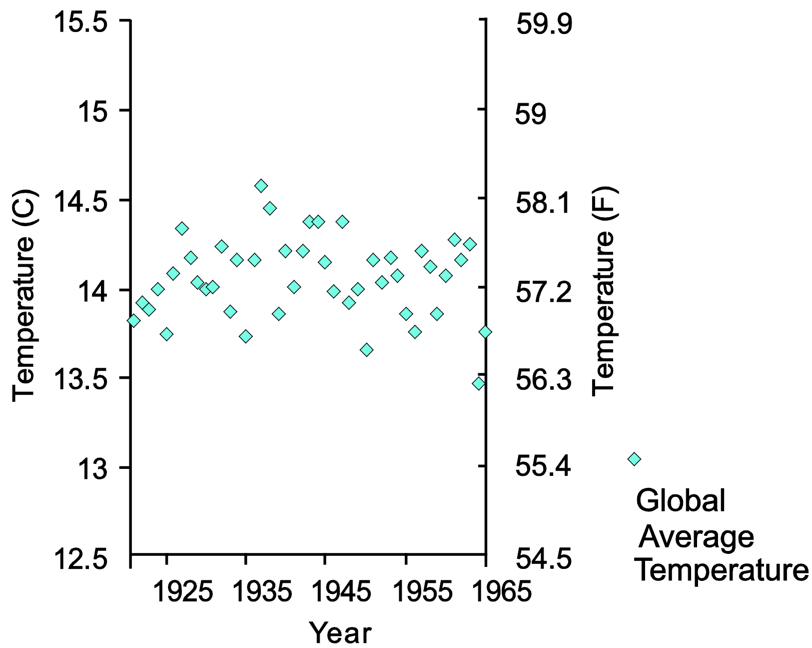
- What would you predict the current global temperature in 2005 to be?

  I imagine it will continue to be flat at the same temperature observed here.

- Describe the major features of the global temperature time series in words so that a person not seeing the graph can qualitatively construct it on a sheet of paper based on your description.

  The annual temperature between 1880 and 1920 varies from ~13.1 to 14.2°C (55.5–57.7°F). The lowest temperature was in 1887 and the highest temperature was in 1915, although no overall increase in temperature was recorded between those two dates.

2. Now make a scatter plot of the same data but for the period 1921–1965 instead. Then answer the questions.



- How would you describe its appearance? Imagine you are a scientist in 1966 predicting the future by extrapolating this trend.

  The data almost appear to arc, with a few highest temperatures between 1937 and 1947 of 14.3–14.6°C (57.8–58.1°F), but temperatures come back down to temperatures measured before 1937.

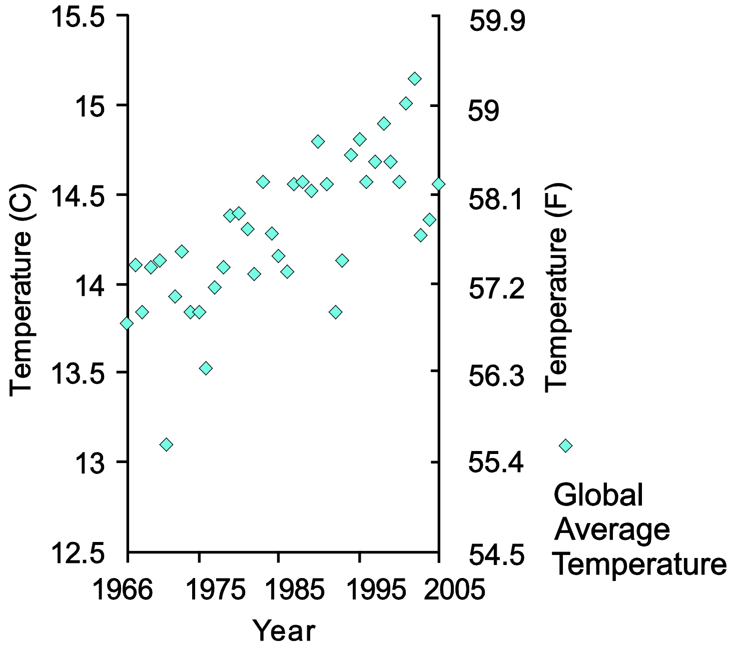
- Based on this trend, what would you predict the temperature to be in 2005?

  Although there may be more variance than there was in the previous data, I would imagine the data would maintain a flattish trend and remain steady between the previous described temperatures.

- In 1966, would you have been more worried about global warming or a return to another Ice Age?

  Nope.

3. Now make a scatter plot for the period 1966–2005. Then answer the questions.



- Based on the trend, what would you predict the temperature to be in 2006?

  There is a substantial increase in temperature each year. I would imagine that the 2006 temperature would be higher than the 3 years prior, but not the highest seen yet.

- In 2005, would you have been more worried about global warming or a return to another Ice Age?

  Global warming!

- What are the five warmest years in the record?

  2002, 2001, 1997, 1994, and 1993

- The five coldest?

  1968, 1971, 1974, 1975, and 1976

- Have we come anywhere close to having one of the coldest years in the record during your lifetime?

  No, but I am 31—likely not for your students either!

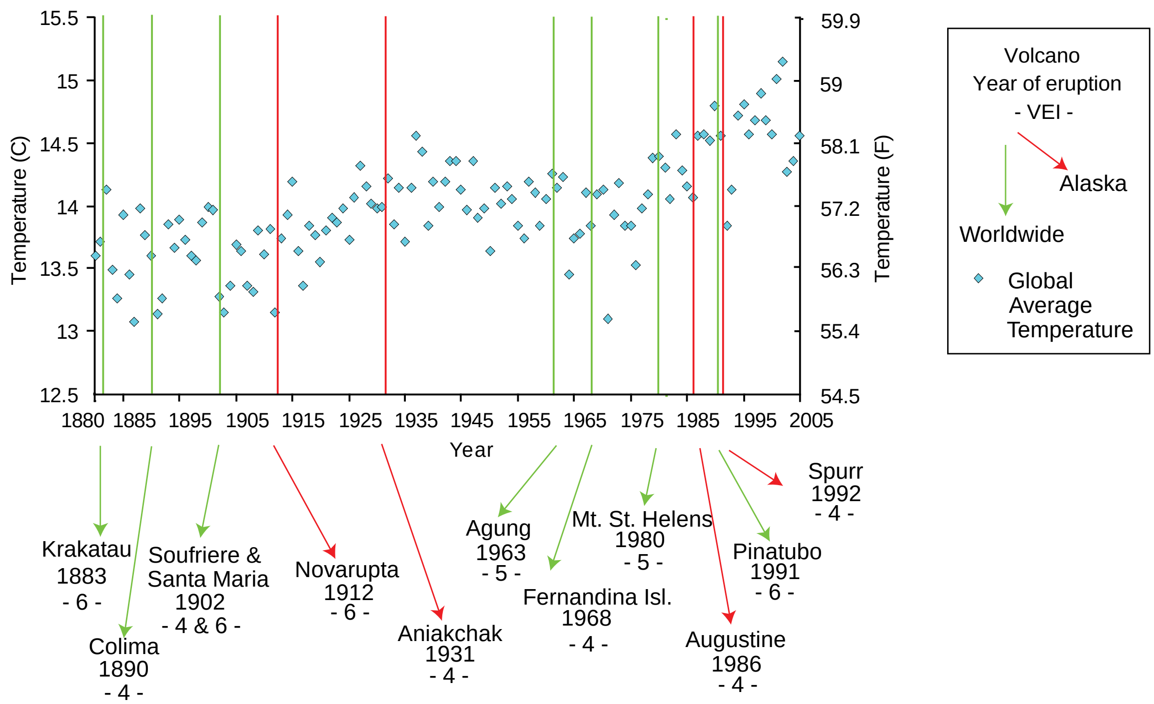
- How long a record is needed to see clear evidence of global warming?

  It seems to depend on the period of record observed, but the trend seen here is evident between 1966 and 1975, so maybe not very long.

Inter-annual Variability Key

Generate a scatter plot of annual temperature and time for 1880–2005. Identify the volcanic eruptions from the table provided (see question below) on your plot.

Using your plot, develop an Average Global Temperatures Table. For all of the above eruptions, note the average annual global temperature for the year in which the eruption occurred, the year before the eruption, the year after the eruption, 2 years after the eruption, and 3 years after the eruption. *Note:* Be sure to identify if the Ave. Global Temp. is recorded in °F or °C. Answer the following questions based on your plot and table.



Average Global Temperatures Key (temperatures are °F)

Volcano	Erupt. Year	Ave. Global Temp.	Erupt. Year -1	Ave. Global Temp.	Erupt. Y +1	Ave. Global Temp.	Erupt. Yr +2	Ave. Global Temp.	Erupt. Yr +3	Ave. Global Temp.
Krakatau	1883	56.77	1882	56.79	1884	56.66	1885	56.66	1886	56.75
Colima	1890	56.53	1889	56.93	1891	56.7	1892	56.62	1893	56.62
Soufriere / Santa Maria	1902	56.71	1901	56.91	1903	56.64	1904	56.59	1905	56.75
Novarupta	1912	56.59	1911	56.59	1913	56.62	1914	56.93	1915	57.04
Aniakchak	1931	57.18	1930	57.07	1932	57.09	1933	56.89	1934	57.11
Agung	1963	57.34	1962	57.27	1964	56.82	1965	57.00	1966	57.15
Fernandina Island	1968	57.13	1967	57.2	1969	57.34	1970	57.25	1971	57.02
Mt. St. Helens	1980	57.52	1979	57.36	1981	57.69	1982	57.29	1983	57.67
Augustine	1986	57.43	1985	57.31	1987	57.69	1988	57.76	1989	57.54
Pinatubo	1991	57.83	1990	57.88	1992	57.43	1993	57.45	1994	57.63
Spurr	1992	57.43	1991	57.83	1993	57.45	1994	57.63	1995	57.88

- What is the typical magnitude and direction (warming or cooling) of the effect of volcanoes on global climate?

  In many cases there is a tenth or hundredth of one degree increase in temperature within 1 year following the eruption, if anything at all. Relative to Activity 2, this seems much less clear—do volcanic eruptions increase or decrease average global temperature? There are many variables, and each eruption is different. Although some of the eruptions noted were followed by an increase in temperature, others were not. Other variables also can alter the global average temperature for any given year; however, these variables are not accounted for in this exercise. This plot indicates that regardless of the volcanic eruptions, the average mean temperature over time is increasing—illustrating no correlation between volcanic eruptions and longer-term (century long) changes in globally averaged annual mean temperatures.

- How long does it take climate to return to normal after a major eruption?

  Just a few years.

Activity IV. An Order of Magnitude

Grade Level 6–11

Setting Classroom, computer lab

Time 50 minutes

Vocabulary (see Glossary)
anthropogenic, atmosphere, CO_2, fossil fuels, greenhouse gas, order of magnitude, volcanogenic

Correlations to Alaska State Department of Education (2006) Performance Standards (Grade Level Expectations)
A1—Science as Inquiry and Process

SA2[6-11] Students develop an understanding that the processes of science require integrity, logical reasoning, skepticism, openness, communication, and peer review.

SA2.1[6] The student demonstrates an understanding of the attitudes and approaches to scientific inquiry by identifying and differentiating fact from opinion.

SA2.1[7] The student demonstrates an understanding of the attitudes and approaches to scientific inquiry by identifying and evaluating the sources used to support scientific statements.

SA2.1[8] The student demonstrates an understanding of the attitudes and approaches to scientific inquiry by recognizing and analyzing differing scientific explanations and models.

SA2.1[9] The student demonstrates an understanding of the attitudes and approaches to scientific inquiry by formulating conclusions that are logical and supported by evidence.

SA2.1[10] The student demonstrates an understanding of the attitudes and approaches to scientific inquiry by examining methodology and conclusions to identify bias and determining if evidence logically supports the conclusion.

SA2.1[11] The student will demonstrate and understanding of the attitudes and approaches to scientific inquiry by evaluating the credibility of cited sources when conducting the student's own scientific investigation.

D1—Concepts of Earth Science

SD[6-11] Students develop an understanding of the concepts, processes, theories, models, evidence, and systems of earth and space sciences.

SD1[6-11] Students develop an understanding of Earth's geochemical cycles.

E1—Science and Technology

SE[6-11] Students develop an understanding of the relationships among science, technology, and society.

SE2[6-11] Students develop an understanding that solving problems involves different ways of thinking, perspectives, and curiosity that lead to the exploration of multiple paths that are analyzed using scientific, technological, and social merits.

G1—History and Nature of Science

SG[6-11] Students develop an understanding of the history and nature of science.

SG1[6-11] Students develop an understanding that historical perspectives of scientific explanations demonstrate that scientific knowledge changes over time, building on prior knowledge.

SG2[6-11] Students develop an understanding that the advancement of scientific knowledge embraces innovation and requires empirical evidence, repeatable investigations, logical arguments, and critical review in striving for the best possible explanations of the natural world.

SG3[6-11] Students develop an understanding that scientific knowledge is ongoing and subject to change as new evidence becomes available through experimental and/or observational confirmation(s).

Overview

Students will learn about the relative amounts of CO_2 contributed on an annual basis to the atmosphere through the burning of fossil fuels and by the emissions of volcanoes into the atmosphere by graphing values of each and interpreting their results. Students will learn that the amount of CO_2 contributed by the burning of fossil is orders of magnitude greater than the amount contributed by volcanoes.

Background

Rising concentrations of greenhouse gases, including CO_2, produce an increase in the average surface temperature of the earth over time. Rising temperatures can produce changes in precipitation patterns, storm severity, and sea level collectively referred to as climate change. The Intergovernmental Panel on Climate Change (IPCC) suggests that the Earth's climate has warmed between 0.6 and 0.9°C (33.1 and 33.6°F). Energy-related CO_2 emissions, resulting from the burning of fossil fuels represented 82 percent of total U.S. anthropogenic greenhouse gas emissions in 2006.

Volcanoes release hundreds of millions of tons of CO_2 into the atmosphere every year. Through the burning of fossil fuels, humans emit tens to hundreds of thousands of millions of CO_2 into the atmosphere every year. For comparison, 110 tons (0.04 million tons) of CO_2 gas would fill approximately 1 million bottles of champagne, so millions of tons would fill billions of champagne bottles.

Volcanic CO_2 is difficult to measure and scientists do not have a steadfast, single value for the global volcanic contribution of CO_2 into Earth's atmosphere. Volcanic CO_2 is measured several different ways, and it is difficult to completely combine, compare, or assess values obtained from the various different measurement types and sources. Below are some resources explaining many of the ways volcanic CO_2 is measured.

U.S. Geological Survey

- U.S. Geological Survey, 2009, Volcano Hazards Program—Direct gas sampling and laboratory analysis: U.S. Geological Survey website. (Available at http://volcanoes.usgs.gov/activity/methods/gas/sample.php.)
- U.S. Geological Survey, 2009, Volcano Hazards Program—Measuring volcanic gases—Continuous on-site gas monitoring: U.S. Geological Survey website. (Available at http://volcanoes.usgs.gov/activity/methods/gas/continuous.php.)
- U.S. Geological Survey, 2009, Volcano Hazards Program—Measuring volcanic gases—Emission rates of sulfur dioxide and carbon dioxide in volcanic plume: U.S. Geological Survey website. (Available at http://volcanoes.usgs.gov/activity/methods/gas/plumes.php.)
- U.S. Geological Survey, 2009, Volcano Hazards Program—Measuring volcanic gases—Soil efflux: U.S. Geological Survey website. (Available at http://volcanoes.usgs.gov/activity/methods/gas/soil.php.)

Oregon State University, [n.d.], VolcanoWorld—Measuring volcanic gases—Remote sensing: Oregon State University website, accessed June 1, 2010, at http://volcano.oregonstate.edu/education/gases/remote.html

- Direct Sampling http://volcano.oregonstate.edu/education/gases/direct.html
- Estimates from Rocks, Minerals, and Inclusions http://volcano.oregonstate.edu/education/gases/estimates.html
- NASA Jet Propulsion Laboratory—Orbiting Carbon Observatory http://oco.jpl.nasa.gov/.

CO_2 contributions to the atmosphere at hydrothermal systems at volcanoes are rarely measured or considered in compilations and the estimates are riddled with uncertainties. The published values of contributions of CO_2 emissions by volcanoes globally are based on very few measurements, typically only at active volcanoes, and very few measurements have been made at volcanoes near the poles (Arctic and Antarctic). Many of the figures are calculated through inference by measuring other more easily and (or) more often measured volcanic gases and these inferences may not necessarily be correct. Until many more measurements are made, this is about as good as it gets, or in other words – it is an order of magnitude. That is to say that in all cases where a reasonable comparison is made between volcanogenic CO_2 and anthropogenic (burning of fossil fuels) CO_2, the anthropogenic values are orders of magnitude higher than volcanogenic values.

Objectives

Through independent reading and class discussion students will learn about greenhouse gases, CO_2, and climate change. Students will understand the varying amounts of volcanic and anthropogenic CO_2 contributed into the Earth's atmosphere over time and the significantly greater amount steadily contributed to the atmosphere by the burning of fossil fuels.

Procedure

A. Climate Change and Greenhouse Gas—CO_2

1. Assign students the task of researching climate change and greenhouse gases, CO_2 in particular, for a homework or classroom, library or on-line internet search exercise. In addition to the resources listed at the beginning of this chapter, additional suggested on-line sources include:
   - U.S. Geological Survey
     - Ager, Tom, 2010, Ecosystem and climate history of Alaska: U.S. Geological Survey Earth Surface Process Team web page. (Available at http://esp.cr.usgs.gov/research/alaska/.)
     - U.S. Geological Survey, 2010, Climate Change Science—Exchanges of greenhouse gases, water vapor, and heat at the Earth's surface: U.S. Geological Survey web page. (Available at http://geochange.er.usgs.gov/carbon/ghg/.)
   - USGS Microbiology Climate Change, Permafrost Monitoring http://microbiology.usgs.gov/climate_permafrost.html
     - Ager, Thomas, 1997, How does climate change influence Alaska's vegetation? Insight from the fossil record: U.S. Geological Survey Fact Sheet 071-97. (Available at http://pubs.usgs.gov/fs/fs-0071-97/.)
     - U.S. Geological Survey, DATE, CoreCast climate change—Interview with Tom Armstrong, Senior Advisor to the Director on Climate Change: U.S. Geological Survey webcast. (Available at http://gallery.usgs.gov/audios/2.)
   - United States Global Change Research Program: Alaska http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts/regional-climate-change-impacts/alaska
   - Environmental Protection Agency, Climate Change—Greenhouse Gas Emissions: Carbon Dioxide webpage http://www.epa.gov/climatechange/emissions/co2.html
   - The Nature Conservancy—Carbon Footprint Calculator: What's My Carbon Footprint? http://www.nature.org/initiatives/climatechange/calculator/

B. Volcanogenic vs. Anthropogenic CO_2

1. Using the table provided, have students graph by hand or use a computer graphic program to make two graphs, one using the volcanogenic CO_2 and a second using the anthropogenic CO_2 values. Bar graphs will suffice.

Table 1. Emissions from specific volcanic regions, volcanoes, burning of fossil fuels, and anthropogenic sources

Estimates of annual volcanic CO_2 emissions	**Millions of tons/year CO_2**
Global estimate for submarine and subaerial volcanoes[1]	416
I. Global CO_2 emissions by volcanoes [2]	308
II. Global CO_2 emissions by volcanoes [3]	200
III. Global CO_2 emissions by volcanoes[4]	130
Estimates of annual anthropogenic CO_2 emissions	**Millions of tons/year CO_2**
Anthropogenic CO_2 in 2003[5]	26,800
Global CO_2 emissions from the burning of fossil fuels 2006[6]	83,800

Sources

[1] Arthur, M.A. 2000, Volcanic contributions to the carbon and sulfur geochemical cycles and global change, *in* Sigurdsson, H. and others, eds., Encyclopedia of Volcanoes: Academic Press, p. 1047.

[2] Brantley, S.L., and Koepenick, K.W., 1995, Measured carbon dioxide emissions from Oldoinyo Lengai, and the skewed distribution of passive volcanic fluxes: Geology, v. 23, no. 10, p. 933–936.

[3] Gerlach, T.M., 1991, Present-day CO_2 emissions from volcanoes: Transactions of the American Geophysical Union (EOS), v. 72, p. 249, and 254-255.

[4] U.S. Geological Survey, 2009, Volcano Hazards Program—Volcanic gases and their effects—Carbon dioxide: U.S. Geological Survey website. (Available at http://volcanoes.usgs.gov/hazards/gas/index.php#CO2.)

[5] Compiled by Earth Policy Institute from G. Marland, T. A. Boden, and R. J. Andres, 2007, Global, regional, and National CO_2 emissions, Trends—A compendium of data on global change: Oak Ridge, Tenn., Carbon Dioxide Information Analysis Center, London, BP, Statistical Review of World Energy website, accessed June 1, 2010, at http://www.earthpolicy.org/Indicators/CO2/2008_data.htm#fig3.

[6] Moore, F.C., 2008, Carbon emissions—Carbon dioxide emissions accelerating rapidly: Earth Policy Institute, Eco-Economy Indicators webpage, accessed June 1, 2010, at http://www.earthpolicy.org/Indicators/CO2/2008.htm.

2. Students may mention that they have come across figures that vary from those in the table. Discuss the difficulties mentioned in the Background section in establishing a clear, single set of values to use for a comparison such as this.

3. Discuss the concept of an order of magnitude with your students using the graphs as examples. For every multiple of 10, an order of magnitude is accounted for. The volcanogenic values are measured in the hundreds of millions of tons, and the anthropogenic and fossil fuel values are in the tens of thousands of millions of tons. The anthropogenic/fossil fuel values are two orders of magnitude greater than the volcanic values.

Extensions

1. Ask students if they think that volcanic eruptions in Alaska can alter the flow of the Niger River in Africa or if rain can cause volcanic eruptions. Review and use:
   - Mastin, L.G., 1993, Can rain cause volcanic eruptions?: U.S. Geological Survey Open-File Report 93-445. (Available at http://vulcan.wr.usgs.gov/Projects/Mastin/Publications/OFR93-445/OFR93-445.html.)
   - National Aeronautics and Space Administration, 2006, Goddard Space Flight Center—Historic volcanic eruption shrunk the mighty Nile River: National Aeronautics and Space Administration web page, accessed June 1, 2010, at http://www.nasa.gov/centers/goddard/news/topstory/2006/volcano_nile.html.

2. Use the DLESE Teaching Boxes—Ways of wind–Lesson sequence http://www.teachingboxes.org/jsp/teachingboxes/weatherEssentials/wind/index.jsp

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Alaska State Department of Education and Early Development, 2006, Standards and grade level expectations, March 2006: State of Alaska website, accessed October 2009 at http://www.eed.state.ak.us/tls/assessment/GLEHome.html.

Arthur, M.A., 2000, Volcanic contributions to the carbon and sulfur geochemical cycles and global change *in* H.S. Sigurdsson and others, eds., Encyclopedia of Volcanoes: San Diego, Calif., Academic Press, p. 1045-1056.

Brantley, S.L., and Koepenick, K.W., 1995, Measured carbon dioxide emissions from Oldoinyo Lengai and the skewed distribution of passive volcanic fluxes: Geology, v. 23, no. 10, p. 933-936.

Energy Information Administration, 2008, Greenhouse gases, climate change, and energy: U.S. Department of Energy Brochure DOE/EIA-X012, accessed June 7, 2010, at http://www.eia.doe.gov/bookshelf/brochures/greenhouse/Chapter1.htm.

Hilton, D.R., Fischer, T.P., and Bernard, M., 2002, Noble gases and volatile recycling at subduction zones: Reviews in Mineralogy and Geochemistry, v. 47, p. 319-370.

Oppenheimer, C., 2003, Volcanic degassing, *in* K.K. Turekian, and Holland, H.D., eds., Treatise on Geochemistry, Chap. 6: Elsevier, v. 3.

U.S. Geological Survey, 2007, Hawaiian Volcano Observatory: U.S. Geological Survey Hawaiian Volcano Observatory Volcano Watch,web pages. (Available at

- February 15, 2007—Which produces more CO_2, volcanic or human activity? http://hvo.wr.usgs.gov/volcanowatch/2007/07_02_15.html and
- October 22, 1998—Greenhouse gases in our backyard http://hvo.wr.usgs.gov/volcanowatch/1998/98_10_22.html.)

U.S. Geological Survey, 2009, Volcano Hazards Program—Volcanic gasses and their effects: U.S. Geological Survey web page. (Available at http://volcanoes.usgs.gov/hazards/gas/index.php.)

U.S. Geological Survey, 2009, Volcano Hazards Program—Measuring volcanic gasses—emission rates of sulfur dioxide and carbon dioxide in volcanic plumes: U.S. Geological Survey web page. (Available at http://volcanoes.usgs.gov/activity/methods/gas/plumes.php.)

U.S. Geological Survey, 2009, Long Valley Observatory—Carbon dioxide and helium discharge from Mammoth Mountain: U.S. Geological Survey website. (Available at http://lvo.wr.usgs.gov/CO2.html.)

Werner, C., and Brantley, S., 2003, CO_2 emissions from the Yellowstone volcanic system: Geochemistry Geophysics Geosystems, v. 4, iss. 7, p, 1061, doi:10.1029/2002GC000473.

Glossary

Anthropogenic–Derived from human activities

Atmosphere – A layer of gases surrounding the Earth that is retained by gravity and that varies with altitude.

CO_2 – Carbon dioxide

Fossil fuels – Fuels derived from hydrocarbon deposits such as coal, petroleum, natural gas, and to some extent, peat.

Greenhouse gas – Specific gases in the atmosphere—water vapor, carbon dioxide, nitrous oxide, and methane, for example, that can trap energy from the sun and warm the surface of the Earth.

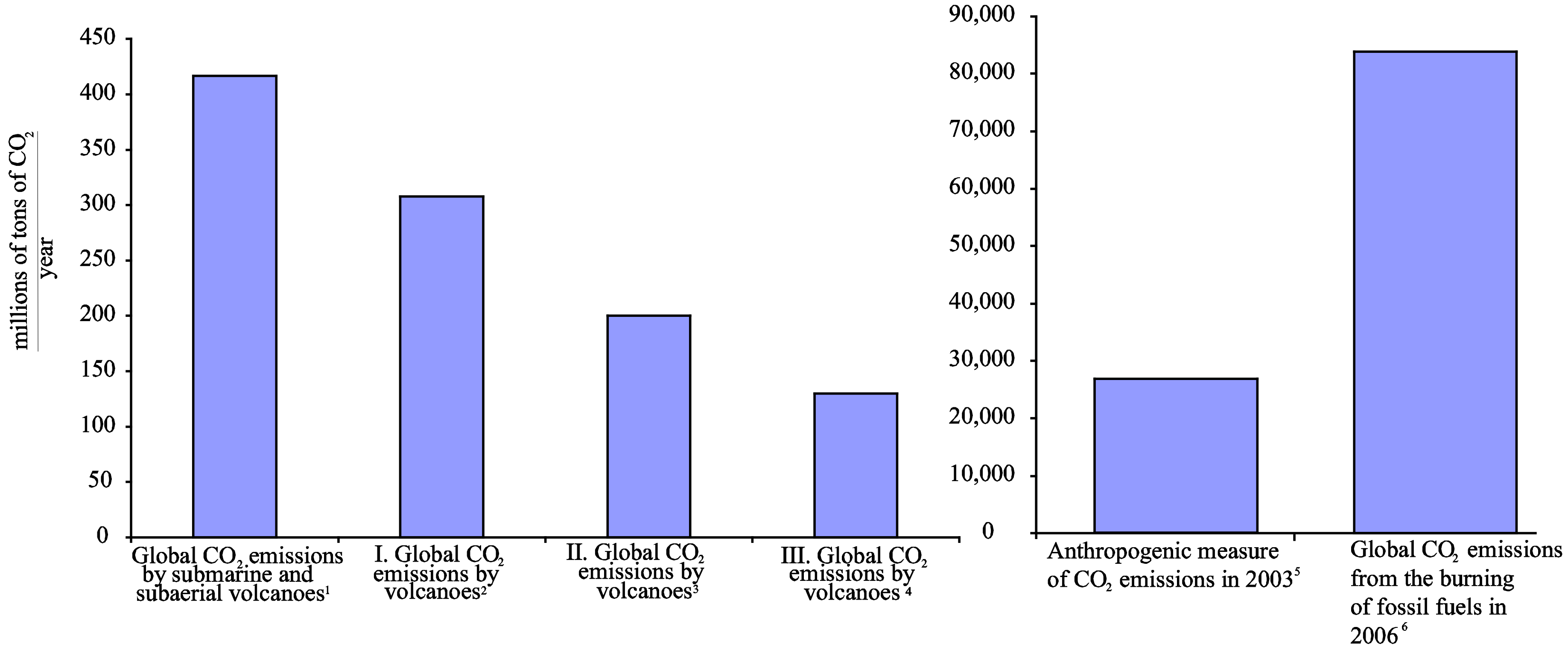
Order of magnitude – The difference between two values by a factor of 10

Volcanogenic – Generated by or stemming from a volcano or volcanic processes

Source of Glossary Definitions

Energy Information Administration, 2008, Greenhouse gases, climate change, and energy: U.S. Department of Energy Brochure DOE/EIA-X012, accessed June 7, 2010, at http://www.eia.doe.gov/bookshelf/brochures/greenhouse/Chapter1.htm.

Millions of Tons of CO_2 Emissions from Volcanic, Anthropogenic, and Burning of Fossil Fuels Sources



[1] Arthur, M.A. 2000, Volcanic contributions to the carbon and sulfur geochemical cycles and global change *in* H. Sigurdsson, and others, eds., Encyclopedia of volcanoes: Academic Press, p 1047.

[2] Brantley, S.L., and Koepenick, K.W., 1995, Measured carbon dioxide emissions from Oldoinyo Lengai, and the skewed distribution of passive volcanic fluxes: Geology, v. 23, no. 10, p. 933-936.

[3] Gerlach, T.M., 1991, Present-day CO_2 emissions from volcanoes: Transactions of the American Geophysical Union (EOS), v. 72, p. 249, and 254-255.

[4] U.S. Geological Survey, 2009, Volcano Hazards Program—Volcanic gases and their effects—Carbon dioxide: U.S. Geological Survey website. (Available at http://volcanoes.usgs.gov/hazards/gas/index.php#CO2.)

[5] Compiled by Earth Policy Institute from Marland, G., Boden, T.A., and Andres, R.J., 2007, Global, regional, and national CO_2 emissions—Trends—A compendium of data on global change: Oak Ridge, Tenn., Carbon Dioxide Information Analysis Center; London, BP, Statistical Review of World Energy, http://www.earthpolicy.org/Indicators/CO2/2008_data.htm#fig3.

[6] Moore, F.C., 2008, Carbon emissions—Carbon dioxide emissions accelerating rapidly: Earth Policy Institute, Eco-Economy Indicators webpage http://www.earthpolicy.org/Indicators/CO2/2008.htm.