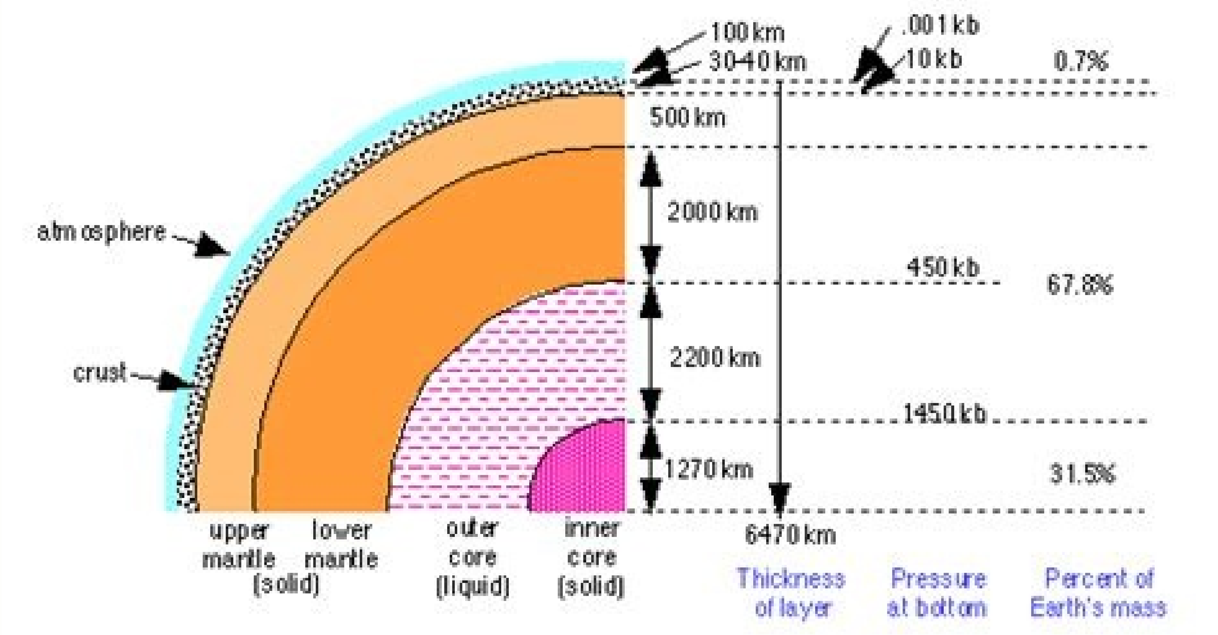
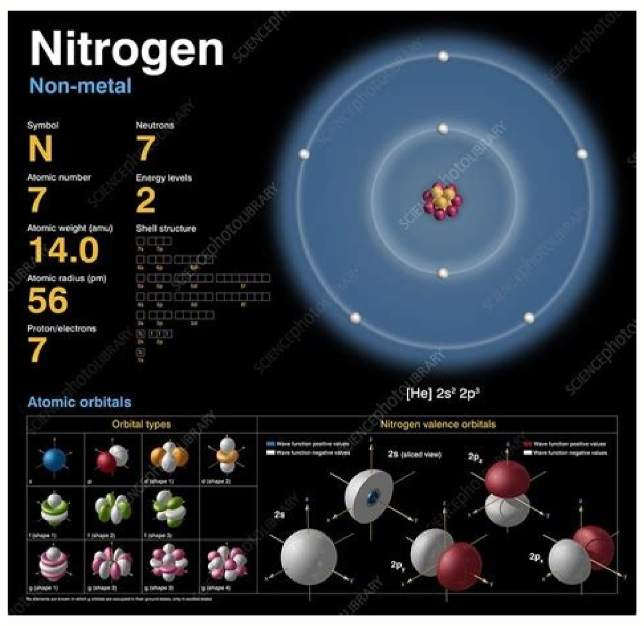
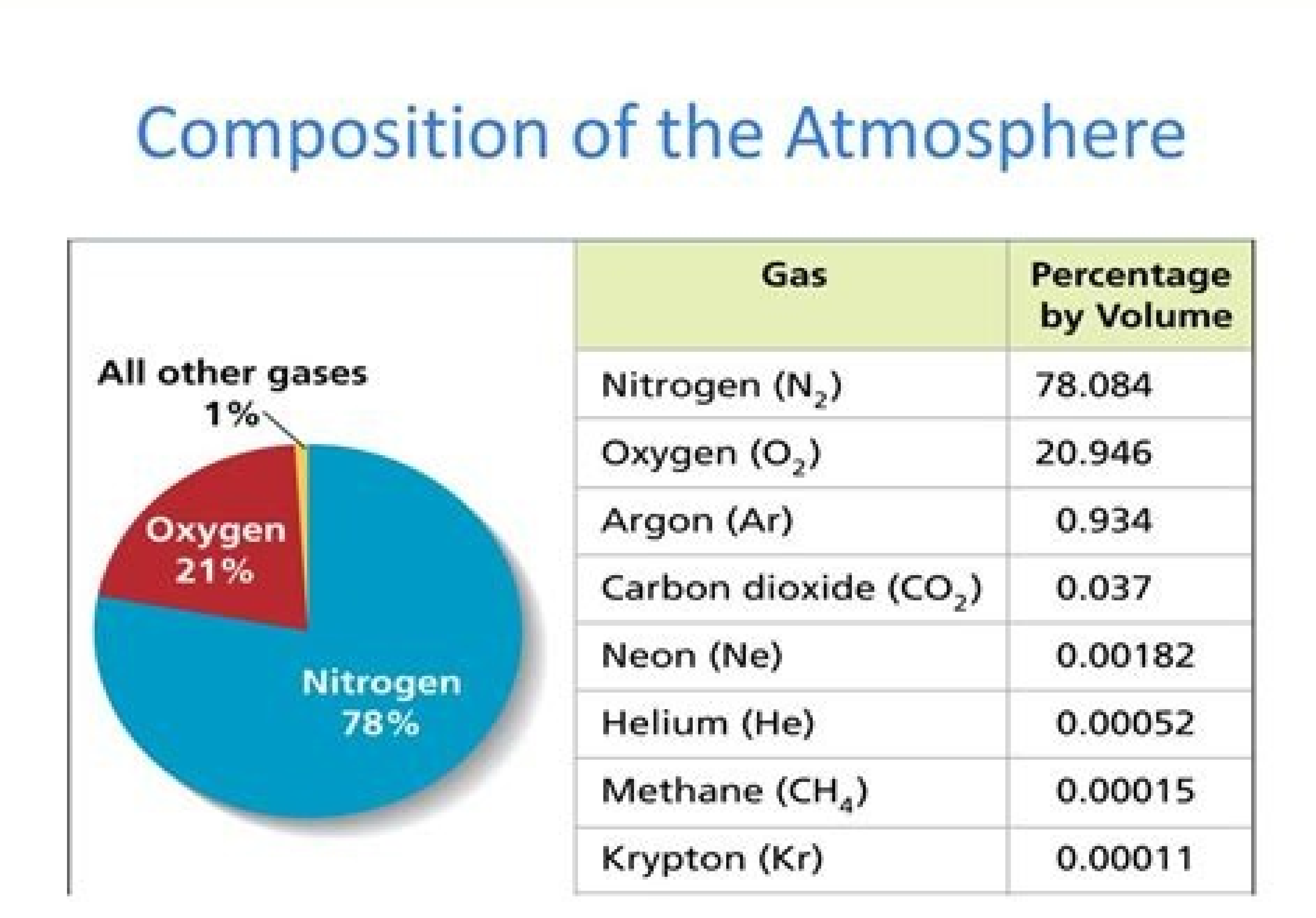
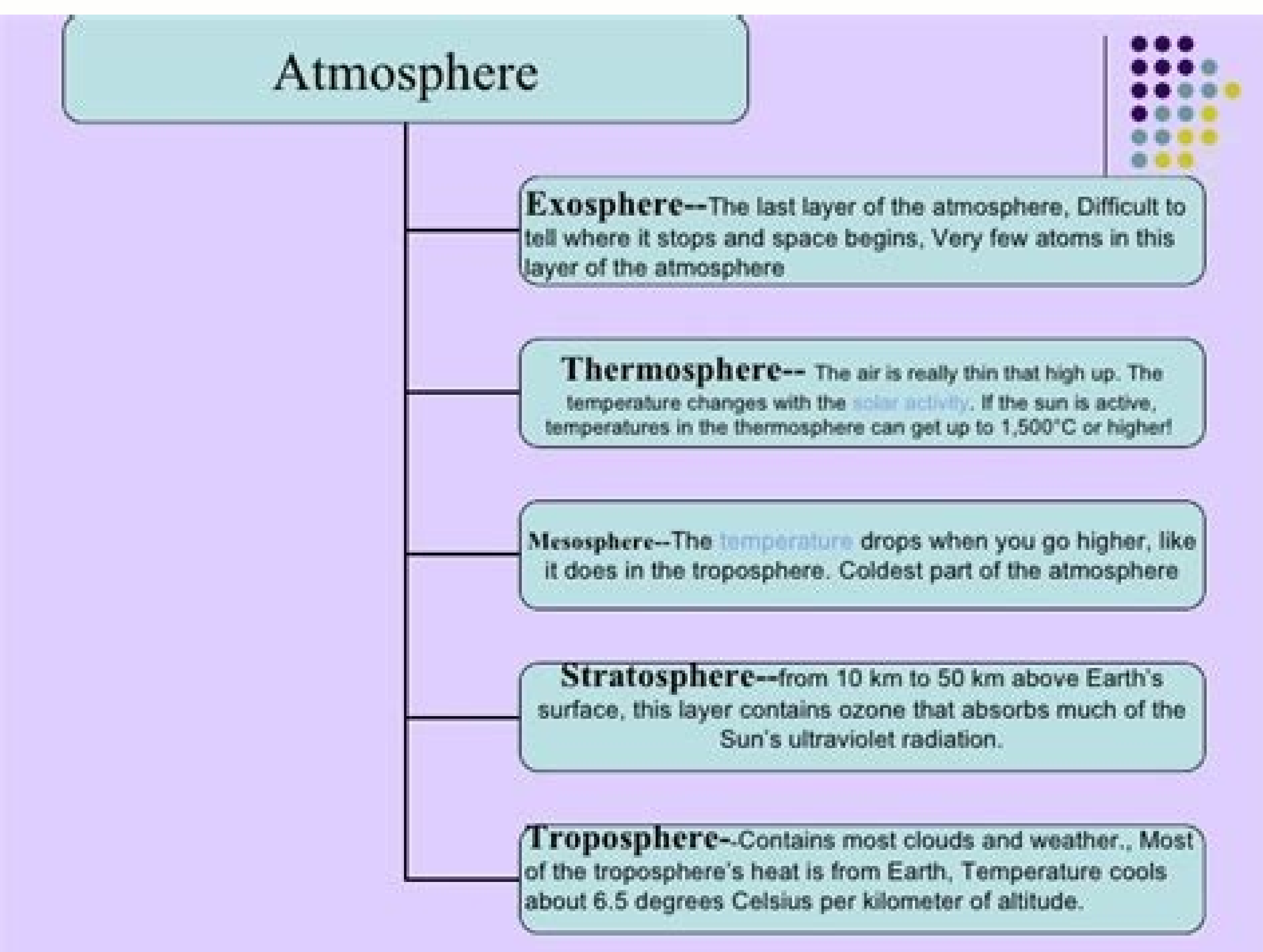
The atmosphere chemical composition and structure worksheet







Gas	Percentage by Volume
Nitrogen (N_2)	78.084
Oxygen (O_2)	20.946
Argon (Ar)	0.934
Carbon dioxide (CO_2)	0.037
Neon (Ne)	0.00182
Helium (He)	0.00052
Methane (CH_4)	0.00015
Krypton (Kr)	0.00011



Atmosphere and Oceans by Anne E. Egger, Ph.D. The fact that the moon's surface is covered with meteorite impact craters is obvious to us today. Though the moon is not far from us, impact craters are few and far between on Earth. As it turns out, Earth has received just as many incoming meteorites as the moon, but the presence of the atmosphere has determined the fate of many of them. Small meteorites burn up in the atmosphere before ever reaching Earth. Those that do hit the surface and create an impact crater are lost to us in a different way – the craters are quickly eroded by weather generated in the atmosphere, and the evidence is washed away. The moon, on the other hand, has no atmosphere, and thus every meteor aimed at the moon hits it, and the craters have remained essentially unchanged for 4 billion years (Figure 1). Figure 1: Craters on the far side of the moon (L) and Manicouagan crater in Quebec (R). Image courtesy of NASA. The early Greeks considered "air" to be one of four elementary substances; along with earth, fire, and water, air was viewed as a fundamental component of the universe. By the early 1800s, however, scientists such as John Dalton recognized that the atmosphere was in fact composed of several chemically distinct gases, which he was able to separate and determine the relative amounts of within the lower atmosphere. He was easily able to discover the major components of the atmosphere: nitrogen, oxygen, and a small amount of something incombustible, later shown to be argon. The development of the spectrometer in the 1920s allowed scientists to find gases that existed in much smaller concentrations in the atmosphere, such as ozone and carbon dioxide. The concentrations of these gases, while small, varied widely from place to place. In fact, atmospheric gases are often divided up into the major, constant components and the highly variable components, as shown in Table 1 and Table 2: Nitrogen (N2) 78.08% Oxygen (O2) 20.95% Argon (Ar) 0.93% Neon, Helium, Krypton 0.0001% Table 1: Constant Components. Proportions remain the same over time and location. Carbon dioxide (CO2) 0.038% Water vapor (H2O) 0-4% Methane (CH4) trace Sulfur dioxide (SO2) trace Ozone (O3) trace Nitrogen oxides (NO, NO2, N2O) trace Table 2: Variable Components. Amounts vary over time and location. Although both nitrogen and oxygen are essential to human life on the planet, they have little effect on weather and other atmospheric processes. The variable components, which make up far less than 1 percent of the atmosphere, have a much greater influence on both short-term weather and long-term climate. For example, variations in water vapor in the atmosphere are familiar to us as relative humidity. Water vapor, CO2, CH4, N2O, and SO2 all have an important property: They absorb heat emitted by Earth and thus warm the atmosphere, creating what we call the "greenhouse effect." Without these so-called greenhouse gases, the Earth's surface would be about 30 degrees Celsius cooler – too cold for life to exist as we know it. Though the greenhouse effect is sometimes portrayed as a bad thing, trace amounts of gases like CO2 warm our planet's atmosphere enough to sustain life. Global warming, on the other hand, is a separate process that can be caused by increased amounts of greenhouse gases in the atmosphere. In addition to gases, the atmosphere also contains particulate matter such as dust, volcanic ash, rain, and snow. These are, of course, highly variable and are generally less persistent than gas concentrations, but they can sometimes remain in the atmosphere for relatively long periods of time. Volcanic ash from the 1991 eruption of Mt. Pinatubo in the Philippines, for example, darkened skies around the globe for over a year. Though the major components of the atmosphere vary little today, they have changed dramatically over Earth's history, about 4.6 billion years. The early atmosphere was hardly the life-sustaining blanket of air that it is today; most geologists believe that the main constituents then were nitrogen gas and carbon dioxide, but no free oxygen. In fact, there is no evidence for free oxygen in the atmosphere until about 2 billion years ago, when photosynthesizing bacteria evolved and began taking in atmospheric carbon dioxide and releasing oxygen. The amount of oxygen in the atmosphere has risen steadily from 0 percent 2 billion years ago to about 21 percent today. Comprehension Checkpoint Nitrogen and oxygen, which make up more than 99% of Earth's atmosphere, have a bigger influence on climate than other components of the atmosphere. Recently, we have continuous satellite monitoring of the atmosphere and Doppler radar to tell us whether or not we will experience rain anytime soon; however, atmospheric measurements used to be few and far between. Today, measurements such as temperature and pressure not only help us predict the weather, but also help us look at long-term changes in global climate (see our Temperature module). The first atmospheric scientists were less concerned with weather prediction, however, and more interested in the composition and structure of the atmosphere. The two most important instruments for taking measurements in Earth's atmosphere were developed hundreds of years ago: Galileo is credited with inventing the thermometer in 1593, and Evangelista Torricelli invented the barometer in 1643. With these two instruments, temperature and pressure could be recorded at any time at any place. Of course, the earliest pressure and temperature measurements were taken at Earth's surface. It was a hundred years before the thermometer and barometer went aloft. While many people are familiar with Ben Franklin's kite and key experiment that tested lightning for the presence of electricity, few realize that kites were the main vehicle for obtaining atmospheric measurements above Earth's surface. Throughout the 18th and 19th centuries, kite-mounted instruments collected pressure, temperature, and humidity readings; unfortunately, scientists could only reach up to an altitude of about 3 km with this technique. Figure 2: Scientist launches a radiosonde. Instruments for collecting data are in the white and orange box. image © NASA Jet Propulsion Laboratory Unmanned balloons were able to take measurements at higher altitudes than kites, but because they were simply released with no passengers and no strings attached, they had to be retrieved in order to obtain the data that had been collected. This changed with the development of the radiosonde, an unmanned balloon capable of achieving high altitudes, in the early 1930s. The radiosonde included a radio transmitter among its many instruments, allowing data to be transmitted as it was being collected so that the balloons no longer needed to be retrieved. A radiosonde network was developed in the United States in 1937, and continues to this day under the auspices of the National Weather Service. Comprehension Checkpoint What was an advantage of the radiosonde over earlier data collection instruments? Through examination of measurements collected by radiosonde and aircraft (and later by rockets), scientists became aware that the atmosphere is not uniform. Many people had long recognized that temperature decreased with altitude – if you've ever hiked up a tall mountain, you might learn to bring a jacket to wear at the top even when it is warm at the base – but it wasn't until the early 1900s that radiosondes revealed a layer, about 18 km above the surface, where temperature abruptly changed and began to increase with altitude. The discovery of this reversal led to division of the atmosphere into layers based on how temperature varies with altitude. Figure 3: This graph shows how temperature varies with altitude in earth's atmosphere. Note Mt. Everest for reference. The lowermost 12 to 18 km of the atmosphere, called the troposphere, is where all weather occurs – clouds form and precipitation falls, wind blows, humidity varies from place to place, and the atmosphere interacts with the surface below. Within the troposphere, temperature decreases with altitude at a rate of about 6.5° C per kilometer. At 8,856 m high, Mt. Everest still reaches less than halfway through the troposphere. Assuming a sea level temperature of 26° C (80° F), that means the temperature on the summit of Everest would be around -31° C (-24° F)! In fact, temperatures at Everest's summit average -36° C, whereas temperatures in New Delhi (in nearby India), at an elevation of 233 m, average about 28° C (82.4° F). At the uppermost boundary of the troposphere, air temperature reaches about -100° C and then begins to increase with altitude. This layer of increasing temperature is called the stratosphere. The cause of the temperature reversal is a layer of concentrated ozone. Ozone's ability to absorb incoming ultraviolet (UV) radiation from the sun had been recognized in 1881, but the existence of the ozone layer at an altitude of 20 to 50 km was not postulated until the 1920s. By absorbing UV rays, the ozone layer both warms the air around it and protects us on the surface from the harmful short-wavelength radiation that can cause skin cancer. It is important to recognize the difference between the ozone layer in the stratosphere and ozone present in trace amounts in the troposphere. Stratospheric ozone is produced when energy from the sun breaks apart O2 gas molecules into O atoms; these O atoms then bond with other O2 molecules to form O3, ozone. This process was first described in 1930 by Sydney Chapman, a geophysicist who synthesized many of the known facts about the ozone layer. Tropospheric ozone, on the other hand, is a pollutant produced when emissions from fossil-fuel burning interact with sunlight. Above the stratosphere, temperature begins to drop again in the next layer of the atmosphere called the mesosphere, as seen in the previous figure. This temperature decrease results from the rapidly decreasing density of the air at this altitude. Finally, at the outer reaches of Earth's atmosphere, the intense, unfiltered radiation from the sun causes molecules like O2 and N2 to break apart into ions. The release of energy from these reactions actually causes the temperature to rise again in the thermosphere, the outermost layer. The thermosphere extends to about 500 km above Earth's surface, still a few hundred kilometers below the altitude of most orbiting satellites. Comprehension Checkpoint All weather, including clouds, wind, and precipitation, occurs in the Figure 4: The graph on the left shows how pressure changes with altitude in Earth's atmosphere. The mountain profile shown in the lower left represents Mt. Everest, the point of highest elevation on Earth's surface. The image on the right is a representation of the density of gas molecules in the atmosphere, with the layers of the atmosphere labeled. Atmospheric pressure can be imagined as the weight of the overlying column of air. Unlike temperature, pressure decreases exponentially with altitude. Traces of the atmosphere can be detected as far as 500 km above Earth's surface, but 80 percent of the atmosphere's mass is contained within the 18 km closest to the surface. Atmospheric pressure is generally measured in millibars (mb); this unit of measurement is equivalent to 1 gram per centimeter squared (1 g/cm2). Other units are occasionally used, such as bars, atmospheres, or millimeters of mercury. The correspondence between these units is shown in the table below. bars millibars atmospheres millimeters of mercury 1.013 bar = 1013 mb = 1 atm = 760 mm Hg Table 3: Correspondence of atmospheric measurement units. At sea level, pressure ranges from about 960 to 1,050 mb, with an average of 1,013 mb. At the top of Mt. Everest, pressure is as low as 300 mb. Because gas pressure is related to density, this low pressure means that there are approximately one-third as many gas molecules inhaled per breath on top of Mt. Everest as at sea level – which is why climbers experience ever more severe shortness of breath the higher they go, as less oxygen is inhaled with every breath. Though other planets host atmospheres, the presence of free oxygen and water vapor makes our atmosphere unique as far as we know. These components both encouraged and protected life on Earth as it developed, not only by providing oxygen for respiration, but by shielding organisms from harmful UV rays and by incinerating small meteors before they hit the surface. Additionally, the composition and structure of this unique resource are important keys to understanding circulation in the atmosphere, biogeochemical cycling of nutrients, short-term local weather patterns, and long-term global climate changes. Earth's atmosphere contains many components that can be measured in different ways. This module describes these different components and shows how temperature and pressure change with altitude. The scientific developments that led to an understanding of these concepts are discussed. Key Concepts Earth's atmosphere is made up of a combination of gases. The major components of nitrogen, oxygen, and argon remain constant over time and space, while trace components like CO2 and water vapor vary considerably over both space and time. The atmosphere is divided into the thermosphere, mesosphere, stratosphere, and troposphere, and the boundaries between these layers are defined by changes in temperature gradients. Pressure decreases exponentially with altitude in the atmosphere. Our knowledge about the atmosphere has developed based on data from a variety of sources, including direct measurements from balloons and aircraft as well as remote measurements from satellites. Anne E. Egger, Ph.D. "Composition of Earth's Atmosphere" Visionlearning Vol. EAS-2 (5), 2003. Top Page 2 Plate Tectonics by Anne E. Egger, Ph.D. The deepest places on Earth are in South Africa, where mining companies have excavated 3.5 km into Earth to extract gold. No one has seen deeper into Earth than the South African miners because the heat and pressure felt at these depths prevents humans from going much deeper. Yet Earth's radius is 6,370 km – how do we begin to know what lies below this thin skin of the Earth when we cannot see it? Isaac Newton was one of the first scientists to theorize about the structure of Earth. Based on his studies of the force of gravity, Newton calculated the average density of Earth and found it to be more than twice the density of the rocks near the surface. From these results, Newton realized that the interior of Earth had to be much denser than the surface rocks. His findings excluded the possibility of a cavernous, fiery underworld inhabited by the dead, but still left many questions unanswered. Where does the denser material begin? How does the composition differ from surface rocks? Volcanic vents like Shiprock occasionally bring up pieces of Earth from as deep as 150 km, but these rocks are rare, and we have little hope of taking Jules Verne's Journey to the Center of the Earth. Instead, much of our knowledge about the internal structure of the Earth comes from remote observations – specifically, from observations of earthquakes. Earthquakes can be extremely destructive for humans, but they provide a wealth of information about Earth's interior. This is because every earthquake sends out an array of seismic waves in all directions, similar to the way that throwing a stone into a pond sends out waves through the water. Observing the behavior of these seismic waves as they travel through the Earth gives us insight into the materials the waves move through. Comprehension Checkpoint Our knowledge about the internal structure of Earth comes mainly from An earthquake occurs when rocks in a fault zone suddenly slip past each other, releasing stress that has built up over time. The slippage releases seismic energy, which is dissipated through two kinds of waves, P-waves and S-waves. The distinction between these two waves is easy to picture with a stretched-out Slinky®. If you push on one end, a compression wave passes through the Slinky® parallel to its length (see P-waves video). If instead you move one end up and down rapidly, a "ripple" wave moves through the Slinky® (see S-waves video). The compression waves are P-waves, and the ripple waves are S-waves. Illustration of a P-wave/compression wave. Illustration of a S-wave/ripple wave. Both kinds of waves can reflect off of boundaries between different materials: They can also refract, or bend, when they cross a boundary into a different material. But the two types of waves behave differently depending on the composition of the material they are passing through. One of the biggest differences is that S-waves cannot travel through liquids whereas P-waves can. We feel the arrival of the P- and S-waves at a given location as a ground-shaking earthquake. If Earth were the same composition all the way through its interior, seismic waves would radiate outward from their source (an earthquake) and behave exactly as other waves behave – taking longer to travel further and dying out in velocity and strength with distance, a process called attenuation. (See Figure 1.) Figure 1: Seismic waves in an Earth of the same composition. Given Newton's observations, if we assume Earth's density increases evenly with depth because of the overlying pressure, wave velocity will also increase with depth and the waves will continuously refract, traveling along curved paths back towards the surface. Figure 1 shows the kind of pattern we would expect to see in this case. By the early 1900s, when seismographs were installed worldwide, it quickly became clear that Earth could not possibly be so simple. Andrija Mohorovičić was a Croatian scientist who recognized the importance of establishing a network of seismometers. Though his scientific career had begun in meteorology, he shifted his research pursuits to seismology around 1900, and installed several of the most advanced seismometers around central Europe in 1908. His timing was fortuitous, as a large earthquake occurred in the Kupa Valley in October 1909, which Mohorovičić felt at his home in Zagreb, Croatia. He made careful observations of the arrivals of P- and S-waves at his newly-installed stations, and noticed that the P-waves that measured more than 200 km away from an earthquake's epicenter arrived with higher velocities than those within a 200 km radius. Although these results ran counter to the concept of attenuation, they could be explained if the waves that arrived with faster velocities traveled through a medium that allowed them to speed up, having encountered a structural boundary at a greater depth. This recognition allowed Mohorovičić to define the first major boundary within Earth's interior – the boundary between the crust, which forms the surface of Earth, and a denser layer below, called the mantle (Mohorovičić, 1910). Seismic waves travel faster in the mantle than they do in the crust because it is composed of denser material. Thus, stations farther away from the source of an earthquake received waves that had made part of their journey through the denser rocks of the mantle. The waves that reached the closer stations stayed within the crust the entire time. Although the official name of the crust-mantle boundary is the Mohorovičić discontinuity, in honor of its discoverer, it is usually called the Moho (see the interactive animation below). Interactive Animation: Moho Another observation made by seismologists was the fact that P-waves die out about 105 degrees away from an earthquake, and then reappear about 140 degrees away, arriving much later than expected. This region that lacks P-waves is called the P-wave shadow zone (Figure 2). S-waves, on the other hand, die out completely around 105 degrees from the earthquake (Figure 2). Remember that S-waves are unable to travel through liquids. The S-wave shadow zone indicates that there is a liquid layer deep within Earth that stops all S-waves but not the P-waves. Figure 2: The P-wave and S-wave shadow zones. In 1914, Beno Gutenberg, a German seismologist, used these shadow zones to calculate the size of another layer inside of the Earth, called its core. He defined a sharp core-mantle boundary at a depth of 2,900 km, where P-waves were refracted and slowed and S-waves were stopped. Comprehension Checkpoint Scientists figured out that there is a liquid layer deep within Earth by observing On the basis of these and other observations, geophysicists have created a cross-section of Earth (Figure 3). The early seismological studies previously discussed led to definitions of compositional boundaries; for example, imagine oil floating on top of water – they are two different materials, so there is a compositional boundary between them. Later studies highlighted mechanical boundaries, which are defined on the basis of how materials act, not on their composition. Water and oil have the same mechanical properties – they are both liquids. On the other hand, water and ice have the same composition, but water is a fluid with far different mechanical properties than solid ice. Figure 3: Compositional and mechanical layers of Earth's structure. There are two major types of crust: crust that makes up the ocean floors and crust that makes up the continents. Oceanic crust is composed entirely of basalt extruded at mid-ocean ridges, resulting in a thin (~ 5 km), relatively dense (~3.0 g/cm3) crust. Continental crust, on the other hand, is made primarily of less dense rocks such as granite (~2.7 g/cm3). It is much thicker than oceanic crust, ranging from 15 to 70 km. At the base of the crust is the Moho, below which is the mantle, which contains rocks made of a denser material called peridotite (~3.4 g/cm3). This compositional change is predicted by the behavior of seismic waves and it is confirmed in the few samples of rocks from the mantle that we do have. At the core-mantle boundary, composition changes again. Seismic waves suggest this material is of a very high density (10-13 g/cm3), which can only correspond to a composition of metals rather than rock. The presence of a magnetic field around Earth also indicates a molten metallic core. Unlike the crust and the mantle, we don't have any samples of the core to look at, and thus there is some controversy about its exact composition. Most scientists, however, believe that iron is the main constituent. These compositional layers are shown in Figure 3. Comprehension Checkpoint What are two types of crust? The compositional divisions of Earth were understood decades before the development of the theory of plate tectonics – the idea that Earth's surface consists of large plates that move (see our Plate Tectonics I module). By the 1970s, however, geologists began to realize that the plates had to be thicker than just the crust, or they would break apart as they moved. In fact, plates consist of the crust acting together with the uppermost part of the mantle; this rigid layer is called the lithosphere and it ranges in thickness from about 10 to 200 km. Rigid lithospheric plates "float" on a layer called the asthenosphere that flows like a very viscous fluid, like Silly Putty®. It is important to note that although the asthenosphere can flow, it is not a liquid, and thus both S- and P-waves can travel through it. At a depth of around 660 km, the pressure becomes so great that the mantle can no longer flow, and this solid part of the mantle is called the mesosphere. The lithospheric mantle, asthenosphere, and mesosphere all share the same composition (that of peridotite), but their mechanical properties are significantly different. Geologists often refer to the asthenosphere as the jelly in between two pieces of bread: the lithosphere and mesosphere. The core is also subdivided into an inner and outer core. The outer core is liquid molten metal (and able to stop S-waves), while the inner core is solid. Because the pressure is even higher in the inner core, the core is solid even though its temperature is higher than that of the mantle, it is possible for the core to remain a liquid at much higher the pressures than peridotite.) The distinction between the inner and outer core was made in 1936 by Inge Lehmann, a Danish seismologist, after improvements in seismographs in the 1920s made it possible to "see" previously undetectable seismic waves within the P-wave shadow zone. These faint waves indicated that they had been refracted again within the core when they hit the boundary between the inner and outer core. The mechanical layers of Earth are also shown in Figure 3, in comparison to the compositional layers. Our picture of the interior of Earth becomes clearer as imaging techniques improve. Seismic tomography is a relatively new technique that uses seismic waves to measure very slight temperature variations throughout the mantle. Because waves move faster through cold material and slower through hot material, the images they receive help scientists "see" the process of convection in the mantle (see our Plates, Plate Boundaries, and Driving Forces module). These and other images offer a virtual journey into the center of Earth. Earth's interior structure is composed of layers that vary by composition and behavior. Using principles of physics like gravity and wave motion, this module explains how scientists have determined Earth's deep structure. Different types of seismic waves are discussed. The module details both compositional and mechanical layers of Earth. Key Concepts Our knowledge about the structure of Earth's interior comes from studying how different types of seismic waves, created by earthquakes, travel through Earth. Earth is composed of multiple layers, which can be defined either by composition or by mechanical properties. The crust, mantle, and core are defined by differences in composition. The lithosphere, asthenosphere, mesosphere, and outer and inner cores are defined by differences in mechanical properties. HS-C3.2, HS-ESS2.A2, HS-PS4.A4 Anne E. Egger, Ph.D. "Earth Structure" Visionlearning Vol. EAS (1), 2003. Top Page 3 Earth Cycles by John Arthur Harrison, Ph.D. N2 Nitrogen (N) is an essential component of DNA, RNA, and proteins, the building blocks of life. All organisms require nitrogen to live and grow. Although the majority of the air we breathe is N2, most of the nitrogen in the atmosphere is unavailable for use by organisms. This is because the strong triple bond between the N atoms in N2 molecules makes it relatively inert, or unreactive, whereas organisms need reactive nitrogen to be able to incorporate it into cells. In order for plants and animals to be able to use nitrogen, N2 gas must first be converted to more a chemically available form such as ammonium (NH4+), nitrate (NO3-), or organic nitrogen (e.g., urea, which has the formula (NH2)2CO). The inert nature of N2 means that biologically available nitrogen is often in short supply in natural ecosystems, limiting plant growth and biomass accumulation. Nitrogen is an incredibly versatile element, existing in both inorganic and organic forms as well as many different oxidation states. The movement of nitrogen between the atmosphere, biosphere, and geosphere in different forms is called the nitrogen cycle (Figure 1), one of the major biogeochemical cycles. Similar to the carbon cycle, the nitrogen cycle consists of various reservoirs of nitrogen and processes by which those reservoirs exchange nitrogen (note the arrows). (See The Carbon Cycle module for more information.) Figure 1: The nitrogen cycle. Yellow arrows indicate human sources of nitrogen to the environment. Red arrows indicate processes in which microorganisms participate in the transformation of nitrogen. Blue arrows indicate physical forces acting on nitrogen. And green arrows indicate natural processes affecting the form and fate of nitrogen that do not involve microbes. Five main processes cycle nitrogen through the biosphere, atmosphere, and geosphere: nitrogen fixation, nitrogen uptake through organismal growth, nitrogen mineralization through decay, nitrification, and denitrification. Microorganisms, particularly bacteria, play major roles in all of the principal nitrogen transformations. Because these processes are microbially mediated, or controlled by microorganisms, these nitrogen transformations tend to occur faster than geological processes like plate motion, a very slow, purely physical process that is a part of the carbon cycle. Instead, rates are affected by environmental factors that influence microbial activity, such as temperature, moisture, and resource availability. Comprehension Checkpoint Processes within the nitrogen cycle progress at a ___ rate than geological processes like plate motion. Figure 2: Part of a clover root system bearing naturally occurring nodules of Rhizobium, bacteria that can transform atmospheric nitrogen through the process of nitrogen fixation. Each nodule is about 2-3 mm long. Image courtesy of . image © The Microbial World Nitrogen fixation is the process wherein N2 is converted to ammonium, or NH4+. This is the only way that organisms can attain nitrogen directly from the atmosphere; the few that can do this are called nitrogen-fixing organisms. Certain bacteria, including those among the genus Rhizobium, are able to fix nitrogen (or convert it to ammonium) through metabolic processes, analogous to the way mammals convert oxygen to CO2 when they breathe. Nitrogen-fixing bacteria often form symbiotic relationships with host plants. This symbiosis is well-known to occur in the legume family of plants (e.g., beans, peas, and clover). In this relationship, nitrogen-fixing bacteria inhabit legume root nodules (Figure 2) and receive carbohydrates and a favorable environment from their host plant in exchange for some of the nitrogen they fix. There are also nitrogen-fixing bacteria that exist without plant hosts, known as free-living nitrogen fixers. In aquatic environments, blue-green algae (really a bacteria called cyanobacteria) are an important free-living nitrogen fixer. In addition to nitrogen-fixing bacteria, high-energy natural events such as lightning, forest fires, and even hot lava flows can cause the fixation of smaller, but significant, amounts of nitrogen. The high energy of these natural phenomena can break the triple bonds of N2 molecules, thereby making individual N atoms available for chemical transformation. Within the last century, humans have become as important a source of fixed nitrogen as all natural sources combined. Burning fossil fuels, using synthetic nitrogen fertilizers, and cultivating legumes all fix nitrogen. Through these activities, humans have more than doubled the amount of fixed nitrogen that is pumped into the biosphere every year (Figure 3), the consequences of which are discussed below. Figure 3: Recent increases in anthropogenic N fixation in relation to "natural" N fixation. Modified from Vitousek, P. M., and Matson, P. A. (1993). Agriculture, the global nitrogen cycle, and trace gas flux. The Biogeochemistry of Global Change: Radiative Trace Gases. R. S. Oremland. New York, Chapman and Hall: 193-208. NH4+ → Organic N The ammonium (NH4+) produced by nitrogen-fixing bacteria is usually quickly taken up by a host plant, the bacteria itself, or another soil organism and incorporated into proteins and other organic nitrogen compounds, like DNA. When organisms nearer the top of the food chain (like us!) eat, we are taking up nitrogen that has been fixed initially by nitrogen-fixing bacteria. Organic N → NH4+ After nitrogen is incorporated into organic matter, it is often converted back into inorganic nitrogen by a process called nitrogen mineralization, otherwise known as decay. When organisms die, decomposers (such as bacteria and fungi) consume the organic matter and lead to the process of decomposition. During this process, a significant amount of the nitrogen contained within the dead organism is converted to ammonium. Once in the form of ammonium, nitrogen is available for use by plants or for further transformation into nitrate (NO3-) through the process called nitrification. NH4+ → NO3- Some of the ammonium produced by decomposition is converted to nitrate (NO3-) via a process called nitrification. The bacteria that carry out this reaction gain energy from it. Nitrification requires the presence of oxygen, so nitrification can happen only in oxygen-rich environments like circulating or flowing waters and the surface layers of soils and sediments. The process of nitrification has some important consequences. Ammonium ions (NH4+) are positively charged and therefore stick (are sorbed) to negatively charged clay particles and soil organic matter. The positive charge prevents ammonium nitrogen from being washed out of the soil (or leached) by rainfall. In contrast, the negatively charged nitrate ion is not held by soil particles and so can be washed out of the soil, leading to decreased soil fertility and nitrate enrichment of downstream surface and groundwater. NO3- → N2+ N2O Through denitrification, oxidized forms of nitrogen such as nitrate (NO3-) and nitrite (NO2-) are converted to dinitrogen (N2) and, to a lesser extent, nitrous oxide gas (NO2). Denitrification is an anaerobic process that is carried out by denitrifying bacteria, which convert nitrate to dinitrogen in the following sequence: NO3- → NO2- → NO → N2O → N2. Nitric oxide and nitrous oxide are gases that have environmental impacts. Nitric oxide (NO) contributes to smog, and nitrous oxide (N2O) is an important greenhouse gas, thereby contributing to global climate change. Once converted to dinitrogen, nitrogen is unlikely to be reconverted to a biologically available form because it is a gas and is rapidly lost to the atmosphere. Denitrification is the only nitrogen transformation that removes nitrogen from ecosystems (essentially irreversibly), and it roughly balances the amount of nitrogen fixed by the nitrogen fixers described above. Comprehension Checkpoint Which process returns nitrogen gas to the atmosphere? Early in the 20th century, a German scientist named Fritz Haber figured out how to short-circuit the nitrogen cycle by fixing nitrogen chemically at high temperatures and pressures, creating fertilizers that could be added directly to soil. This technology spread rapidly over the 20th century, and, along with the advent of new crop varieties, the use of synthetic nitrogen fertilizers led to an enormous boom in agricultural productivity. This agricultural productivity has helped us to feed a rapidly growing world population, but the increase in nitrogen fixation has had some negative consequences as well. While the consequences are perhaps not as obvious as an increase in global temperatures (see our Data Analysis and Interpretation module) or a hole in the ozone layer (see The Practice of Science module), they are just as serious and potentially harmful for humans and other organisms. Why? Not all of the nitrogen fertilizer applied to agricultural fields stays to nourish crops. Some is washed off of agricultural fields by rain or irrigation water, where it leaches into surface water or groundwater and can accumulate. In groundwater that is used as a drinking water source, excess nitrogen can lead to cancer in humans and respiratory distress in infants. The US Environmental Protection Agency has established a standard for nitrogen in drinking water of 10 mg per liter nitrate-N. Unfortunately, many systems (particularly in agricultural areas) already exceed this level. By comparison, nitrate levels in waters that have not been altered by human activity are rarely greater than 1 mg/L. In surface waters, added nitrogen can lead to nutrient over-enrichment, particularly in coastal waters receiving the inflow from polluted rivers. This nutrient over-enrichment, also called eutrophication, has been blamed for increased frequencies of coastal fish-kill events, increased frequencies of harmful algal blooms, and species shifts within coastal ecosystems. Reactive nitrogen (like NO3- and NH4+) present in surface waters and soils, can also enter the atmosphere as the smog-component nitric oxide (NO) which is a component of smog, and also as the greenhouse gas nitrous oxide (N2O). Eventually, this atmospheric nitrogen can be blown into nitrogen-sensitive terrestrial environments, causing long-term changes. For example, nitrogen oxides comprise a significant portion of the acidity in acid rain, which has been blamed for forest death and decline in parts of Europe and the northeastern United States. Increases in atmospheric nitrogen deposition have also been blamed for more subtle shifts in dominant species and ecosystem function in some forest and grassland ecosystems. For example, on nitrogen-poor serpentine soils of northern Californian grasslands, plant communities have historically been limited to native species that can survive without a lot of nitrogen. There is now some evidence that elevated levels of atmospheric N input from nearby industrial and agricultural development have allowed invasion of these ecosystems by non-native plants. As noted earlier, NO is also a major factor in the formation of smog, which is known to cause respiratory illnesses like asthma in both children and adults. Currently, much research is devoted to understanding the effects of nitrogen enrichment in the air, groundwater, and surface water. Scientists are also exploring alternative agricultural practices that will sustain high productivity while decreasing the negative impacts caused by fertilizer use. These studies not only help us quantify how humans have altered the natural world, but increase our understanding of the processes involved in the nitrogen cycle as a whole. Although the majority of the air we breathe is N2, molecular nitrogen cannot be used directly to sustain life. This module provides an overview of the nitrogen cycle, one of the major biogeochemical cycles. The five main processes in the cycle are described. The module explores human impact on the nitrogen cycle, resulting in not only increased agricultural production but also smog, acid rain, climate change, and ecosystem upsets. Key Concepts The nitrogen cycle is the set of biogeochemical processes by which nitrogen undergoes chemical reactions, changes form, and moves through difference reservoirs on Earth, including living organisms. Nitrogen is required for all organisms to live and grow because it is the essential component of DNA, RNA, and protein. However, most organisms cannot use atmospheric nitrogen, the largest reservoir. The five processes in the nitrogen cycle – fixation, uptake, mineralization, nitrification, and denitrification – are all driven by microorganisms. Humans influence the global nitrogen cycle primarily through the use of nitrogen-based fertilizers. HS-C5.2, HS-ESS2.A1, HS-ESS3.C1, HS-LS1.C3 John Arthur Harrison, Ph.D. "The Nitrogen Cycle" Visionlearning Vol. EAS-2 (4), 2003. Top Page 4 Earth Cycles by John Arthur Harrison, Ph.D. Carbon is the fourth most abundant element in the universe, and is absolutely essential to life on Earth. In fact, carbon constitutes the very definition of life, as its presence or absence helps define whether a molecule is considered to be organic or inorganic. Every organism on Earth needs carbon either for structure, energy, or, as is the case of humans, for both. Discounting water, you are about half carbon. Additionally, carbon is found in forms as diverse as the gas carbon dioxide (CO2), and in solids like limestone (CaCO3), wood, plastic, diamonds, and graphite. The movement of carbon, in its many forms, between the atmosphere, oceans, biosphere, and geosphere is described by the carbon cycle, illustrated in Figure 1. This cycle consists of several storage carbon reservoirs and the processes by which the carbon moves between reservoirs. Carbon reservoirs include the atmosphere, the oceans, vegetation, rocks, and soil; these are shown in black text along with their approximate carbon capacities in Figure 1. The purple numbers and arrows in Figure 1 show the fluxes between these reservoirs, or the amount of carbon that moves in and out of the reservoirs per year. If more carbon enters a pool than leaves it, that pool is considered a net carbon sink. If more carbon leaves a pool than enters it, that pool is considered net carbon source. Figure 1: A cartoon of the global carbon cycle. Pools (in black) are gigatons (1Gt = 1x109 Tons) of carbon, and fluxes (in purple) are Gt carbon per year. Illustration courtesy NASA Earth Science Enterprise. image © NASA The global carbon cycle, one of the major biogeochemical cycles, can be divided into geological and biological components. The geological carbon cycle operates on a timescale of millions of years, whereas the biological carbon cycle operates on a timescale of days to thousands of years. The geological component of the carbon cycle is where it interacts with the rock cycle in the processes of weathering and dissolution, precipitation of minerals, burial and subduction, and volcanic eruptions (see The Rock Cycle module for information). In the atmosphere, carbonic acid forms by a reaction with atmospheric carbon dioxide (CO2) and water. As this weakly acidic water reaches the surface as rain, it reacts with minerals at Earth's surface, slowly dissolving them into their component ions through the process of chemical weathering. These component ions are carried in surface waters like streams and rivers eventually to the ocean, where they precipitate out as minerals like calcite (CaCO3). Through continued deposition and burial, this calcite sediment forms the rock called limestone. This cycle continues as seafloor spreading pushes the seafloor under continental margins in the process of subduction. As seafloor carbon is pushed deeper into the Earth by tectonic forces, it heats up, eventually melts, and can rise back up to the surface, where it is released as CO2 and returned to the atmosphere. This return to the atmosphere can occur violently through volcanic eruptions, or more gradually in seeps, vents, and CO2-rich hotsprings. Tectonic uplift can also expose previously buried limestone. One example of this occurs in the Himalayas where some of the world's highest peaks are formed of material that was once at the bottom of the ocean. Weathering, subduction, and volcanism control atmospheric carbon dioxide concentrations over time periods of hundreds of millions of years. Comprehension Checkpoint Carbonic acid reaches the Earth's surface by way of Biology plays an important role in the movement of carbon between land, ocean, and atmosphere through the processes of photosynthesis and respiration. Virtually all multicellular life on Earth depends on the production of sugars from sunlight and carbon dioxide (photosynthesis) and the metabolic breakdown (respiration) of those sugars to produce the energy needed for movement, growth, and reproduction. Plants take in carbon dioxide (CO2) from the atmosphere during photosynthesis, and release CO2 back into the atmosphere during respiration through the following chemical reactions: Respiration: C6H12O6 (organic matter) + 6O2 → 6CO2 + 6 H2O + energy Photosynthesis: energy (sunlight) + 6CO2 + H2O → C6H12O6 + 6O2 Through photosynthesis, green plants use solar energy to turn atmospheric carbon dioxide into carbohydrates (sugars). Plants and animals use these carbohydrates (and other products derived from them) through a process called respiration, the reverse of photosynthesis. Respiration releases the energy contained in sugars for use in metabolism and changes carbohydrate "fuel" back into carbon dioxide, which is in turn released back to the atmosphere. The amount of carbon taken up by photosynthesis and released back to the atmosphere by respiration each year is about 1,000 times greater than the amount of carbon that moves through the geological cycle on an annual basis. On land, the major exchange of carbon with the atmosphere results from photosynthesis and respiration. During daytime in the growing season, leaves absorb sunlight and take up carbon dioxide from the atmosphere. At the same time plants, animals, and soil microbes consume the carbon in organic matter and return carbon dioxide to the atmosphere. Photosynthesis stops at night when the sun cannot provide the driving energy for the reaction, though respiration continues. This kind of imbalance between these two processes is reflected in seasonal changes in the atmospheric CO2 concentrations. During winter in the northern hemisphere, photosynthesis ceases when many plants lose their leaves, but respiration continues. This condition leads to an increase in atmospheric CO2 concentrations during the northern hemisphere winter. With the onset of spring, however, photosynthesis resumes and atmospheric CO2 concentrations are reduced. This cycle is reflected in the monthly means (the light blue line) of atmospheric carbon dioxide concentrations shown in Figure 2. Figure 2: The "Keeling Curve," a long-term record of atmospheric CO2 concentration measured at the Mauna Loa Observatory (Keeling et al.). Although the annual oscillations represent natural, seasonal variations, the long-term increase means that concentrations are higher than they have been in 400,000 years (see text and Figure 3). Graphic courtesy of NASA's Earth Observatory. image © NASA In the oceans, phytoplankton (microscopic marine plants that form the base of the marine food chain) use carbon to make shells of calcium carbonate (CaCO3). The shells settle to the bottom of the ocean when phytoplankton die and are buried in the sediments. The shells of phytoplankton and other creatures can become compressed over time as they are buried and are often eventually transformed into limestone. Additionally, under certain geological conditions, organic matter can be buried and over time form deposits of the carbon-containing fuels coal and oil. It is the non-calcium containing organic matter that is transformed into fossil fuel. Both limestone formation and fossil fuel formation are biologically controlled processes and represent long-term sinks for atmospheric CO2. Comprehension Checkpoint The major biological exchange of carbon with the atmosphere is from Recently, scientists have studied both short- and long-term measurements of atmospheric CO2 levels. Charles Keeling, an oceanographer at the Scripps Institute of Oceanography, is responsible for creating the longest continuous record of atmospheric CO2 concentrations, taken at the Mauna Loa observatory in Hawaii. His data (now widely known as the "Keeling curve," shown in Figure 2) revealed that human activities are significantly altering the natural carbon cycle. Since the onset of the industrial revolution about 150 years ago, human activities such as the burning of fossil fuels and deforestation have accelerated, and both have contributed to a long-term rise in atmospheric CO2. Burning oil and coal releases carbon into the atmosphere far more rapidly than it is being removed, and this imbalance causes atmospheric carbon dioxide concentrations to increase. In addition, by clearing forests, we reduce the ability of photosynthesis to remove CO2 from the atmosphere, also resulting in a net increase. Because of these human activities, atmospheric carbon dioxide concentrations are higher today than they have been over the last half-million years or longer. Because CO2 increases the atmosphere's ability to hold heat, it has been called a "greenhouse gas." Scientists believe that the increase in CO2 is already causing important changes in the global climate. Many attribute the observed 0.6 degree C increase in global average temperature over the past century mainly to increases in atmospheric CO2. Without substantive changes in global patterns of fossil fuel consumption and deforestation, warming trends are likely to continue. The best scientific estimate is that global mean temperature will increase between 1.4 and 5.8 degrees C over the next century as a result of increases in atmospheric CO2 and other greenhouse gases. This kind of increase in global temperature would cause a significant rise in average sea-level (0.09-0.88 meters), exposing low-lying coastal cities or cities located by tidal rivers, such as New Orleans, Portland, Washington, and Philadelphia, to increasingly frequent and severe floods. Glacial retreat and species range shifts are also likely to result from global warming, and it remains to be seen whether relatively immobile species such as trees can shift their ranges fast enough to keep pace with warming. Even without the changes in climate, however, increased concentrations of CO2 could have an important impact on patterns of plant growth worldwide. Because some species of plants respond more favorably to increases in CO2 than others, scientists believe we may see pronounced shifts in plant species as a result of increasing atmospheric CO2 concentrations, even without any change in temperature. For example, under elevated CO2 conditions, shrubs are thought to respond more favorably than certain grass species due to their slightly different photosynthetic pathway. Because of this competitive inequality, some scientists have hypothesized that grasslands will be invaded by CO2-responsive grass species or shrubby species as CO2 increases. Figure 3: CO2 over the past 140,000 years as seen in an ice core and in the modern Mauna Loa record. The red line represents predicted concentrations. Figure courtesy of : Rebecca Dorsey, University of Oregon. Comprehension Checkpoint Carbon dioxide is considered a greenhouse gas because In an attempt to understand whether recently observed changes in the global carbon cycle are a new phenomenon, or have instead occurred throughout geologic history, scientists have devoted considerable effort to developing methods for understanding Earth's past atmosphere and climate. These techniques include analysis of gas bubbles trapped in ice, tree rings, and ocean and lake floor sediments for clues about past climates and atmospheres. Together, these techniques suggest that over the past 20 million years, the Earth's climate has oscillated between relatively warm and relatively cold conditions called interglacial and glacial periods. During interglacial periods, atmospheric CO2 concentrations were relatively high, and during glacial periods, CO2 concentrations were relatively low. We are currently in an interglacial warm period, and human activities are pushing CO2 concentrations higher than they have been for hundreds of thousands of years (Figure 3). Understanding and mitigating negative impacts of atmospheric CO2 enrichment constitute two of the most central challenges that environmental scientists and policy makers currently face. In order to address this issue, the scientific community has formed the Intergovernmental Panel on Climate Change (IPCC), an international, interdisciplinary consortium comprised of thousands of climate experts collaborating to produce consensus reports on climate change science. Many nations have agreed to conditions specified by the Kyoto Protocol, a multilateral treaty aimed at averting the negative impacts associated with human-induced climate change. The United States, which is currently responsible for approximately one quarter of global CO2 emissions, has so far declined to participate in the Kyoto Protocol. Carbon, the fourth most abundant element in the universe, moves between the atmosphere, oceans, biosphere, and geosphere in what is called the carbon cycle. This module provides an overview of the global carbon cycle, one of the major biogeochemical cycles. The module explains geological and biological components of the cycle. Major sources and sinks of carbon are discussed, as well as the impact of human activities on global carbon levels. Key Concepts The presence of carbon determines whether something is organic or inorganic; all living things require carbon to live. Carbon cycles through the ecosystem in various ways, from photosynthesis and respiration to weathering and other geologic processes. Many factors, such as seasons and human activities, influence the concentration of carbon in the global atmosphere. HS-C1.5, HS-C5.2, HS-C7.2, HS-ESS2.A1, HS-ESS2.A3, HS-ESS2.D3, HS-LS2.B3 John Arthur Harrison, Ph.D. "The Carbon Cycle" Visionlearning Vol. EAS-2 (3), 2003. Top Page 5 Earth Cycles by Anne E. Egger, Ph.D. We all see changes in the landscape around us, but your view of how fast things change is probably determined by where you live. If you live near the coast, you see daily, monthly, and yearly changes in the shape of the coastline. Deep in the interior of continents, change is less evident – rivers may flood and change course only every 100 years or so. If you live near an active fault zone or volcano, you experience infrequent but catastrophic events like earthquakes and eruptions. Throughout human history, different groups of people have held to a wide variety of beliefs to explain these changes. Early Greeks ascribed earthquakes to the god Poseidon expressing his wrath, an explanation that accounted for their unpredictability. The Navajo view processes on the surface as interactions between opposite but complementary entities: the sky and the Earth. Most 17th century European Christians believed that the Earth was essentially unchanged from the time of creation. When naturalists found fossils of marine creatures high in the Alps, many devout believers interpreted the Old Testament literally and suggested that the perched fossils were a result of the biblical Noah's flood. In the mid-1700s, a Scottish physician named James Hutton began to challenge the literal interpretation of the Bible by making detailed observations of rivers near his home. Every year, these rivers would flood, depositing a thin layer of sediment in the floodplain. It would take many millions of years, reasoned Hutton, to deposit a hundred meters of sediment in this fashion, not just the few weeks allowed by the Biblical flood. Hutton called this the principle of uniformitarianism: Processes that occur today are the same ones that occurred in the past to create the landscape and rocks as we see them now. By comparison, the strict biblical interpretation, common at the time, suggested that the processes that had created the landscape were complete and no longer at work. Figure 1: This image shows how James Hutton first envisioned the rock cycle. Hutton argued that in order for uniformitarianism to work over very long periods of time, Earth materials had to be constantly recycled. If there were no recycling, mountains would erode (or continents would decay, in Hutton's terms), the sediments would be transported to the sea, and eventually the surface of the Earth would be perfectly flat and covered with a thin layer of water. Instead, those sediments once deposited in the sea must be frequently lifted back up to form new mountain ranges. Recycling was a radical departure from the prevailing notion of a largely unchanging Earth. As shown in Figure 1, Hutton first conceived of the rock cycle as a process driven by Earth's internal heat engine. Heat caused sediments deposited in basins to be converted to rock, heat caused the uplift of mountain ranges, and heat contributed in part to the weathering of rock. While many of Hutton's ideas about the rock cycle were either vague (such as "conversion to rock") or inaccurate (such as heat causing decay), he made the important first step of putting diverse processes together into a simple, coherent theory. Hutton's ideas were not immediately embraced by the scientific community, largely because he was reluctant to publish. He was a far better thinker than writer – once he did get into print in 1788, few people were able to make sense of his highly technical and confusing writing (to learn more about Hutton and see a sample of his writing, visit the Resources for this module). His ideas became far more accessible after his death with the publication of John Playfair's "Illustrations of the Huttonian Theory of the Earth" (1802) and Charles Lyell's "Principles of Geology" (1830). By that time, the scientific revolution in Europe had led to widespread acceptance of the once-radical concept that the Earth was constantly changing. A far more complete understanding of the rock cycle developed with the emergence of plate tectonics theory in the 1960s (see our Plate Tectonics I module). Our modern concept of the rock cycle is fundamentally different from Hutton's in a few important aspects: We now largely understand that plate tectonic activity determines how, where, and why uplift occurs, and we know that heat is generated in the interior of the Earth through radioactive decay and moved out to the Earth's surface through convection. Together, uniformitarianism, plate tectonics, and the rock cycle provide a powerful lens for looking at the Earth, allowing scientists to look back into Earth history and make predictions about the future. Comprehension Checkpoint If Earth's materials were not recycled then The rock cycle consists of a series of constant processes through which Earth materials change from one form to another over time. As within the water cycle and the carbon cycle, some processes in the rock cycle occur over millions of years and others occur much more rapidly. There is no real beginning or end to the rock cycle, but it is convenient to begin exploring it with magma. You may want to open the rock cycle schematic in Figure 2 and follow along in the sketch; click on the diagram to open it in a new window. Figure 2: A schematic sketch of the rock cycle. In this sketch, boxes represent Earth materials and arrows represent the processes that transform those materials. The processes are named in bold next to the arrows. The two major sources of energy for the rock cycle are also shown; the sun provides energy for surface processes such as weathering, erosion, and transport, and the Earth's internal heat provides energy for processes like subduction, melting, and metamorphism. The complexity of the diagram reflects a real complexity in the rock cycle. Notice that there are many possibilities at any step along the way. Magma, or molten rock, forms only at certain locations within the Earth, mostly along plate boundaries. (It is a common misconception that the entire interior of the Earth is molten, but this is not the case. See our Earth Structure module for a more complete explanation.) When magma is allowed to cool, it crystallizes, much the same way that ice crystals develop when water is cooled. We see this process occurring in places like Iceland, where magma erupts out of a volcano and cools on the surface of the Earth, forming a rock called basalt on the flanks of the volcano (Figure 3). But most magma never makes it to the surface and it cools within Earth's crust. Deep in the crust below Iceland's surface, the magma that doesn't erupt cools to form gabbro. Rocks that form from cooled magma are called igneous rocks; intrusive igneous rocks if they cool below the surface (like gabbro), extrusive igneous rocks if they cool above (like basalt). Figure 3: This picture shows a basaltic eruption of Pu'u O'o, on the flanks of the Kilauea volcano in Hawaii. The red material is molten lava, which turns black as it cools and crystallizes. Rocks like basalt are immediately exposed to the atmosphere and weather. Rocks that form below the Earth's surface, like gabbro, must be uplifted and all of the overlying material must be removed through erosion in order for them to be exposed. In either case, as soon as rocks are exposed at the Earth's surface, the weathering process begins. Physical and chemical reactions caused by interaction with air, water, and biological organisms cause the rocks to break down. Once rocks are broken down, wind, moving water, and glaciers carry pieces of the rocks away through a process called erosion. Moving water is the most common agent of erosion – the muddy Mississippi, the Amazon, the Hudson, the Rio Grande, all of these rivers carry tons of sediment weathered and eroded from the mountains of their headwaters to the ocean every year. The sediment carried by these rivers is deposited and continually buried in floodplains and deltas. In fact, the US Army Corps of Engineers is kept busy dredging the sediments out of the Mississippi in order to keep shipping lanes open (see Figure 4). Figure 4: Photograph from space of the Mississippi Delta. The brown color shows the river sediments and where they are being deposited in the Gulf of Mexico. image © NASA Comprehension Checkpoint Erosion is caused primarily by Under natural conditions, the pressure created by the weight of the younger deposits compacts the older, buried sediments. As groundwater moves through these sediments, minerals like calcite and silica precipitate out of the water and coat the sediment grains. These precipitants fill in the pore spaces between grains and act as cement, gluing individual grains together. The compaction and cementation of sediments creates sedimentary rocks like sandstone and shale, which are forming right now in places like the very bottom of the Mississippi delta. Because deposition of sediments often happens in seasonal or annual cycles, we often see layers preserved in sedimentary rocks when they are exposed (Figure 5). In order for us to see sedimentary rocks, however, they need to be uplifted and exposed by erosion. Most uplift happens along plate boundaries where two plates are moving towards each other and causing compression. As a result, we see sedimentary rocks that contain fossils of marine organisms (and therefore must have been deposited on the ocean floor) exposed high up in the Himalaya Mountains – this is where the Indian plate is running into the Eurasian plate. Figure 5: The Grand Canyon is famous for its exposures of great thicknesses of sedimentary rocks. image © Anne Egger Comprehension Checkpoint Most uplift happens If sedimentary rocks or intrusive igneous rocks are not brought to the Earth's surface by uplift and erosion, they may experience even deeper burial and be exposed to high temperatures and pressures. As a result, the rocks begin to change. Rocks that have changed below Earth's surface due to exposure to heat, pressure, and hot fluids are called metamorphic rocks. Geologists often refer to metamorphic rocks as "cooked" because they change in much the same way that cake batter changes into a cake when heat is added. Cake batter and cake contain the same ingredients, but they have very different textures, just like sandstone, a sedimentary rock, and quartzite, its metamorphic equivalent. In sandstone, individual sand grains are easily visible and often can even be rubbed off; in quartzite, the edges of the sand grains are no longer visible, and it is a difficult rock to break with a hammer, much less rubbing pieces off with your hands. Some of the processes within the rock cycle, like volcanic eruptions, happen very rapidly, while others happen very slowly, like the uplift of mountain ranges and weathering of igneous rocks. Importantly, there are multiple pathways through the rock cycle. Any kind of rock can be uplifted and exposed to weathering and erosion; any kind of rock can be buried and metamorphosed. As Hutton correctly theorized, these processes have been occurring for millions and billions of years to create the Earth as we see it: a dynamic planet. Comprehension Checkpoint All processes in the rock cycle take millions of years. The rock cycle is not just theoretical; we can see all of these processes occurring at many different locations and at many different scales all over the world. As an example, the Cascade Range in North America illustrates many aspects of the rock cycle within a relatively small area, as shown in Figure 6. Figure 6: Cross-section through the Cascade Range in Washington state. Image modified from the Cascade Volcano Observatory, USGS. The Cascade Range in the northwestern United States is located near a convergent plate boundary, where the Juan de Fuca plate, which consists mostly of basalt saturated with ocean water is being subducted, or pulled underneath, the North American plate. As the plate descends deeper into the Earth, heat and pressure increase and the basalt is metamorphosed into a very dense rock called eclogite. All of the ocean water that had been contained within the basalt is released into the overlying rocks, but it is no longer cold ocean water. It too has been heated and contains high concentrations of dissolved minerals, making it highly reactive, or volatile. These volatile fluids lower the melting temperature of the rocks, causing magma to form below the surface of the North American plate near the plate boundary. Some of that magma erupts out of volcanoes like Mt. St. Helens, cooling to form a rock called andesite, and some cools beneath the surface, forming a similar rock called diorite. Storms coming off of the Pacific Ocean cause heavy rainfall in the Cascades, weathering and eroding the andesite. Small streams carry the weathered pieces of the andesite to large rivers like the Columbia and eventually to the Pacific Ocean, where the sediments are deposited. Continual deposition of sediments near the deep oceanic trench results in the formation of sedimentary rocks like sandstone. Eventually, some sandstone is carried down into the subduction zone, and the cycle begins again (see the Experiment! section in the Resources for this module). The rock cycle is inextricably linked not only to plate tectonics, but to other Earth cycles as well. Weathering, erosion, deposition, and cementation of sediments all require the presence of water, which moves in and out of contact with rocks through the hydrologic cycle; thus weathering happens much more slowly in a dry climate like the desert southwest than in the rainforest (see our module The Hydrologic Cycle for more information). Burial of organic sediments takes carbon out of the atmosphere, part of the long-term geological component of the carbon cycle (see our module The Carbon Cycle module); many scientists today are exploring ways we might be able to take advantage of this process and bury additional carbon dioxide produced by the burning of fossil fuels (see News & Events in Resources). The uplift of mountain ranges dramatically affects global and local climate by blocking prevailing winds and inducing precipitation. The interactions between all of these cycles produce the wide variety of dynamic landscapes we see around the globe. Earth's materials are in constant flux. Some processes that shape the Earth happen quickly; others take millions of years. This module describes the rock cycle, including the historical development of the concept. The relationship between uniformitarianism, the rock cycle, and plate tectonics is explored in general and through the specific example of the Cascade Range in the Pacific Northwest. Key Concepts The rock cycle is the set of processes by which Earth materials change from one form to another over time. The concept of uniformitarianism, which says that the same Earth processes at work today have occurred throughout geologic time, helped develop the idea of the rock cycle in the 1700s. Processes in the rock cycle occur at many different rates. The rock cycle is driven by interactions between plate tectonics and the hydrologic cycle. HS-C5.2, HS-C7.1, HS-ESS2.A3 Anne E. Egger, Ph.D. "The Rock Cycle" Visionlearning Vol. EAS-2 (7), 2005. Top Page 6 Earth Cycles by Anne E. Egger, Ph.D. As recently as 12,000 years ago, you could walk from Alaska to Siberia without having to don a wetsuit. At that time, glaciers and ice sheets covered North America down to the Great Lakes and Cape Cod, though coastal areas generally remained ice-free. These extensive ice sheets occurred at a time when sea level was very low, exposing land where water now fills the Bering Strait. In fact, throughout Earth's history, times of extensive glaciers correlate with low sea level and times when only minor ice sheets exist (like today) correlate with high sea levels. These correlations are due to the fact that the amount of water on Earth is constant, and is divided up between reservoirs in the oceans, in the air, and on the land. In addition, Earth's water is constantly cycling through these reservoirs in a process called the hydrologic cycle. Both of these facts together lead us to the conclusion that more water stored in ice sheets means less water in the oceans. Earth is the only planet in our solar system with extensive liquid water – other planets are too hot or too cold, too big or too small. Though Mars appears to have had water on its surface in the past and may still harbor liquid water deep below its surface, our oceans, rivers, and rain are unique as far as we know, and they are life-sustaining. Understanding the processes and reservoirs of the hydrologic cycle is fundamental to dealing with many issues, including pollution and global climate change. As early as 800 BCE, Homer wrote in the Iliad of the ocean "from whose deeps every river and sea, every spring and well flows," suggesting the interconnectedness of all of Earth's water. It wasn't until the 17th century, however, that the poetic notion of a finite water cycle was demonstrated in the Seine River basin by two French physicists, Edmé Mariotte and Pierre Perrault, who independently determined that the snowpack in the river's headwaters was more than sufficient to account for the river's discharge. These two studies marked the beginning of hydrology, the science of water, and also the hydrologic cycle. The hydrologic cycle can be thought of as a series of reservoirs, or storage areas, and a set of processes that cause water to move between those reservoirs (see Figure 1). The largest reservoir by far is the oceans, which hold about 97% of Earth's water. The remaining 3% is the freshwater so important to our survival, but about 78% of that is stored in ice in Antarctica and Greenland. About 21% of freshwater on Earth is groundwater, stored in sediments and rocks below the surface of Earth. The freshwater that we see in rivers, streams, lakes, and rain is less than 1% of the freshwater on Earth and less than 0.1% of all the water on Earth. Figure 1: The hydrologic cycle. Arrows indicate volume of water that moves from reservoir to reservoir. Comprehension Checkpoint More freshwater is stored in ice than is found in all other freshwater sources combined. Water moves constantly between these reservoirs through the processes of evaporation, condensation and precipitation, surface and underground flow, and others. The driving force for the hydrologic cycle is the sun, which provides the energy needed for evaporation just as the flame of a gas stove provides the energy necessary to boil water and create steam. Water changes from a liquid state to a gaseous state as it evaporates from the oceans, lakes, streams, and soil (see our Water: Properties and Behavior module for a further explanation). Because the oceans are the largest reservoir of liquid water, that is where most evaporation occurs. The amount of water vapor in the air varies widely over time and from place to place; we feel these variations as humidity. The presence of water vapor in the atmosphere is one of the things that makes Earth livable for us. In 1859, Irish naturalist John Tyndall began studying the thermal properties of the gases in Earth's atmosphere. He found that some gases, like carbon dioxide (CO2) and water vapor, trap heat in the atmosphere (a property commonly called the greenhouse effect), while other gases like nitrogen (N2) and argon (Ar) allow heat to escape to space. The presence of water vapor in the atmosphere helps keep surface air temperatures on Earth in a range from about -40° C to 55° C. Temperatures on planets without water vapor in the atmosphere, like Mars, stay as low as -100° C. Once water vapor is in the air, it circulates within the atmosphere. When an air package rises and cools, the water vapor condenses back to liquid water around particulates like dust, called condensation nuclei. Initially these condensation droplets are much smaller than raindrops and are not heavy enough to fall as precipitation. These tiny water droplets create clouds. As the droplets continue to circulate within the clouds, they collide and form larger droplets, which eventually become heavy enough to fall as rain, snow, or hail. Though the amount of precipitation varies widely over Earth's surface, evaporation and precipitation are globally balanced. In other words, if evaporation increases, precipitation also increases; rising global temperature is one factor that can cause a worldwide increase in evaporation from the world's oceans, leading to higher overall precipitation. Since oceans cover around 70% of Earth's surface, most precipitation falls right back into the ocean and the cycle begins again. A portion of precipitation falls on land, however, and it takes one of several paths through the hydrologic cycle. Some water is taken up by soil and plants, some runs off into streams and lakes, some percolates into the groundwater reservoir, and some falls on glaciers and accumulates as glacial ice. Comprehension Checkpoint What drives the hydrologic cycle? The amount of precipitation that soaks into the soil depends on several factors: the amount and intensity of the precipitation, the prior condition of the soil, the slope of the landscape, and the presence of vegetation. These factors can interact in sometimes surprising ways – a very intense rainfall onto very dry soil, typical of the desert southwest, often will not soak into the ground at all, creating flash-flood conditions. Water that does soak in becomes available to plants through soil moisture and groundwater (see Figure 2). Plants take up water through their root systems, which mostly draw water from soil moisture; the water is then pulled up through all parts of the plant and evaporates from the surface of the leaves, a process called transpiration. Water that soaks into the soil can also continue to percolate down through the soil profile below the water table into groundwater reservoirs, called aquifers. Aquifers are often mistakenly visualized as great underground lakes; in reality, groundwater saturates the pore spaces within sediments or rocks (see Figure 2). Figure 2: Groundwater exists below the water table, which divides unsaturated soil, rock, and sediments from saturated. Water that doesn't soak into the soil collects and moves across the surface as runoff, eventually flowing into streams and rivers to get back to the ocean. Precipitation that falls as snow in glacial regions takes a somewhat different journey through the water cycle, accumulating at the head of glaciers and causing them to flow slowly down valleys. Comprehension Checkpoint Flash-flooding can result from intense rainfall The properties of water and the hydrologic cycle are largely responsible for the circulation patterns we see in the atmosphere and the oceans on Earth. Atmospheric and oceanic circulation are two of the major factors that determine the distribution of climatic zones over the Earth. Changes in the cycle or circulation can result in major climatic shifts. For example, if average global temperatures continue to increase as they have in recent decades, water that is currently trapped as ice in the polar ice sheets will melt, causing a rise in sea level. Water also expands as it gets warmer, further exacerbating sea level rise. Many heavily populated coastal areas like New Orleans, Miami, and Bangladesh will be inundated by a mere 1.5 meter increase in sea level (see Figure 3). Additionally, the acceleration of the hydrologic cycle (higher temperatures mean more evaporation and thus more precipitation) may result in more severe weather and extreme conditions. Some scientists believe that the increased frequency and severity of El Niño events in recent decades is due to the acceleration of the hydrologic cycle induced by global warming. Figure 3: Areas in red would be flooded with a 1.5 m rise in sea level; areas in blue would be flooded by a 3.5 m rise in sea level. Image has been modified from the original from the US Environmental Protection Agency (EPA). Even more immediately, the finitude of Earth's freshwater resources is becoming more and more apparent. Groundwater can take thousands or millions of years to recharge naturally, and we are using these resources far faster than they are being replenished. The water table in the Ogallala Aquifer, which underlies 175,000 square miles of the US from Texas to South Dakota, is dropping at a rate of 10-60 cm per year due to extraction for irrigation. Surface waters around the world are largely contaminated by human and animal waste, most noticeably in countries like India and China, where untreated rivers provide the drinking and washing water for nearly 2 billion people. Although legislation like the Clean Water Act in the United States and water conservation practices such as the use of low-flow toilets and showerheads in parts of the world has begun to address these issues, the problems will only grow as world population increases. Every spring and well, every river and sea does indeed flow from the same source, and changes affect not just one river or lake, but the whole hydrologic cycle. Powered by the sun, water constantly cycles through the Earth and its atmosphere. This module discusses the hydrologic cycle, including the various water reservoirs in the oceans, in the air, and on the land. The module addresses connections between the hydrologic cycle, climate, and the impacts humans have had on the cycle. Key Concepts Though the amount of water on Earth remains constant, it is regularly cycling through the ecosystem through various processes. Earth's water supply is stored in a variety of ways, from ice sheets to oceans to underground reservoirs. Like other processes occurring on Earth, the hydrologic cycle is affected by global warming and, as a result, influences climate and weather patterns. HS-C5.2, HS-C6.1, HS-ESS2.C1 Anne E. Egger, Ph.D. "The Hydrologic Cycle" Visionlearning Vol. EAS-2 (2), 2003. Top Page 7 Earth Cycles by Heather MacNeill Falconer, M.A./M.S. For centuries, alchemists around the world searched tirelessly for the philosopher's stone – a substance rumored to have the ability to turn base metals, like lead, into gold (Figure 1). Like the Holy Grail, stories claimed that this stone was also able to cure illness, prolong life, and even create the user's clone. The German alchemist Hennig Brand was one such pursuer of the philosopher's stone. So much so that he completely depleted his first wife's significant inheritance in his pursuits, and used his second wife's dowry to do the same! Figure 1: The Alchemist in Search of the Philosopher's Stone, painting by Joseph Wright of Derby. image © Wikimedia Commons In 1669, Brand was conducting an experiment using concentrated urine and sand when he came across something unique. After boiling his mixture down, Brand was left with a white, waxy substance that continued to glow in the dark after it had cooled. At first, he thought that he had discovered the famed stone, but soon discovered this was not the case. What Brand had discovered was phosphorus – one of the most important elements to life on Earth. Like carbon, oxygen, hydrogen, and nitrogen, phosphorus is a limiting nutrient for all forms of life, which means that the potential for an organism's growth is limited by the availability of this vital nutrient. It forms part of the structure of DNA and RNA, is needed for energy transport in cells, provides structure to cellular membranes, and assists in giving bones and teeth their rigidity. In short, without phosphorus, we simply could not exist. And yet, for something so crucial, it is one of the most difficult elements for living things to access in nature. Prior to the 1800s, very little was known about phosphorus or how it moved through the environment. Early chemists like Robert Boyle knew that the element was highly flammable and would phosphoresce, or glow, when exposed to oxygen. In fact, in 1680 Boyle took advantage of this flammability and developed the first matchstick by using phosphorus to ignite wooden sticks dipped in sulfur. But, like other elements, phosphorus' contribution to the growth and health of organisms remained a mystery. For almost a century, scientists believed Sir Francis Bacon's hypothesis that water was the "principle of vegetation" – the essential nutrient for plant growth (Tindall & Krunkel, 1998). This idea was supported by experiments conducted by notable scientists like Jan Baptiste van Helmont, John Evelyn, and Robert Boyle. For example, in 1629, the Flemish alchemist van Helmont put Bacon's theory to test with his famous willow tree experiment. Van Helmont's experiment involved the growth of a willow tree in what he thought was a controlled environment. In his own words, I took an Earthen vessel, in which I put 200 pounds of Earth that hadbeen [sic] dried in a Furnace, which I moystened with Rainwater, and I implanted therein the Trunk or Stem of a Willow Tree, weighing five pounds; and at length, five years being finished, the Tree sprung from thence, did weigh 169 pounds, and about three ounces: But I moystened the Earthen Vessel with Rain-water, or distilled water (alwayes when there was need) and it was large, and implanted into the Earth, and least the dust that flew about should be co-mingled with the Earth, I covered the lip or mouth of the Vessel with an Iron-Plate covered with Tin, and easily passable with many holes. I computed not the weight of the leaves that fell off in the four Autumnes. At length, I again dried the Earth of the Vessell, and there were found the same two hundred pounds, wanting about two ounces. Therefore 164 pounds of Wood, Barks, and Roots, arose out of water onely. (van Helmont, 1662) We now know that there were flaws in van Helmont's experiment, including his use of soil in an application meant to show that water alone was what nourished plants. However, his contributions to our knowledge of the role of elements in plant nutrition were significant. The willow tree experiment alone marked the beginning of experimental plant physiology, and is both one of the first quantitative experiments in biology and one of the first written accounts of the use of the scientific method (Hershey, 2003; Morton, 1981). During the 17th century, however, a German chemist named Johann Glauber argued that soil, not water, was the sole source of nourishment for plants. This sparked a debate that continued in various forms into the 18th century. In 1775, Frances Home concluded that both arguments were correct. Home theorized that not one but many factors influence a plant's growth – a conclusion that would open up new research in various fields. In 1838, a competition was held by The Academy of Sciences in Göttingen, Germany (Tindall & Krunkel, 1998). The Academy asked members of the scientific community to determine whether the inorganic elements found in the ashes of plants are present in the living plant, and whether there was any evidence of these inorganic elements being necessary for plant growth and survival. Justus von Liebig, a German chemist, won the contest with his treatise Organic Chemistry and its Applications to Agriculture and Physiology (von Liebig, 1838). Von Liebig explained that certain elements, like Carbon (C), Hydrogen (H), and Phosphorus (P), are vital to the growth and sustainability of plants. His work drew clear connections between crop yield and the amount of fertilizer offered during the growing season, and identified a hierarchy of minerals in these interactions. One of the most important moments in von Liebig's work is a discussion of the "Law of Minimum." The Law of Minimum states that the growth and yield of a plant are limited by the nutrient in least abundance, regardless of which nutrient that might be. This law is often referred to as Liebig's Law of Minimum, though it is understood now that the discovery actually belongs to Karl Sprengel, a German agronomist working at the same time. Because macronutrients like carbon, oxygen, hydrogen, and nitrogen are readily available in Earth's atmosphere, more often than not the limiting nutrient for plant growth in natural ecosystems is phosphorus. Comprehension Checkpoint According to the Law of Minimum Like many of Earth's cycles, the phosphorus cycle involves movement through biological and geological systems, and this movement is driven by various chemical transformations. Unlike carbon or nitrogen, however, phosphorus moves only through the lithosphere, biosphere, and hydrosphere. It is one of the only biogeochemical cycles that does not involve a gaseous stage, meaning that it does not become part of Earth's atmosphere in any significant way. Figure 2: Phosphates are a biological molecule that play an important role in the structure and function of living things. They contain at least one phosphorus atom bound to four oxygen atoms, but will bond with other atoms (like hydrogen) to create a wide variety of compounds necessary for life. As Brand discovered, elemental phosphorus is a highly reactive substance. Simply exposing it to air will stimulate a chemical reaction with oxygen. This means that in nature the element is typically found as a phosphate (PO4-3). Phosphates, in their most basic form, contain one phosphorus atom bound to four oxygen atoms, with one of those oxygen atoms being bonded to another atom, like hydrogen (Figure 2). A very common phosphate found in nature, for example, is HPO4-2. There are a wide variety of combinations that take place with this simple PO4-3 anion: bonding with carbon, nitrogen, and hydrogen to create the energy storage compound ATP, for example, or with calcium (and occasionally hydrogen) to create calcium phosphate (Figure 3). DNA, our genetic blueprint, relies on phosphate groups to provide the backbone to its double-helix structure (see our DNA II: The Structure of DNA module for more information), and cell membranes rely on phospholipids to give them structure (see our Membranes I: Introduction to Biological Membranes module). Figure 3: Adenosine Tri-Phosphate (ATP) is responsible for the transport of chemical energy within cells for metabolism, and calcium phosphate is a primary component of milk, bones, and teeth. In the environment, phosphates can be found in both organic and inorganic forms. Organic phosphates are mainly created through biological processes and include a bonded carbon, such as in plant or animal tissues. Inorganic phosphates on the other hand, are not associated with carbon. They are produced through natural processes like chemical weathering of phosphorous-containing rocks, or man-made processes like the chemical manufacturing of fertilizers. While animals are able to use either of these forms, plants are able to use only the inorganic form. Comprehension Checkpoint Phosphorous is most often found The phosphorus cycle is similar to other elemental cycles and is often described in an overly-simplified way: As Earth's tectonic plates shift, volcanic action, earthquakes, and movement at plate boundaries expose buried sediments and rock to the surface of the planet (to learn more, read our Plates, Plate Boundaries, and Driving Forces and The Rock Cycle: Uniformitarianism and Recycling modules). When exposed to elements like wind and water, mechanical and chemical weathering of these rocks take place. These transformations release phosphates that have been bound in these reservoirs to the environment, where they become available in soil and water. After passing through biological systems via the food chain, phosphorus is eventually returned to the soil and then into aquatic systems, where it ultimately becomes sediment and can move back into the geological part of the cycle (Figure 4). Figure 4: A simplified drawing of the phosphorus cycle. Phosphorus moves in multiple directions through a series of smaller processes. Like all of Earth's cycles, there is no start or finish to the phosphorus cycle, and certainly no single direction of movement. Earth's cycles are complex webs where resources move in multiple directions. In fact, it might be even easier to think of the phosphorus cycle as being a process made up of a series of smaller processes that may or may not ever interact – processes that take place over a time frame as short as weeks and as long as millennia. To get a better sense of the movement of phosphorus through the lithosphere, biosphere, and hydrosphere, it helps to view it in terms of its movement on a shorter time-scale and through a specific ecosystem. During the months of September and October 1967, scientists T.R. Cleugh and B.W. Hauser began a helicopter survey on 463 lakes in the Precambrian Shield in northwestern Ontario, Canada (Figure 5). Lakes were numbered in the order they were sampled, and data on maximum depth, visibility, dissolved solids, and conductivity were recorded to create lake profiles (Cleugh & Hauser, 1971). This was the first step in what would become one of the most well-known examples of extreme science: the creation of the Experimental Lakes Area (ELA), a project run by the Freshwater Institute to manipulate whole-lake ecosystems. Figure 5: Map of the Precambrian Shield The Experimental Lakes Project had its beginnings in 1965 when the US and Canadian governments were asked by the International Joint Commission (IJC), a commission that helps Canada and the US prevent disputes over boundary waters, to devote resources to understanding pollution in the lower Great Lakes/St. Lawrence Plain. This unique region – spanning the southern part of Ontario to areas of central New York, Vermont, Pennsylvania, and Ohio – had been transformed during the early 20th century from forests rich in oak, hemlock, and mixed-conifers to land primarily devoted to agriculture. Housing developments throughout the region also increased significantly over this time. The water bodies of interest to the IJC were beginning to show effects of eutrophication – a condition of excessive plant and algae growth that can kill fish and other wildlife in the water – and little to no information existed on the causes or controls. As a result, the Experimental Lakes Area was created to study these questions. It consisted of isolated, pristine land containing 58 lakes and watersheds, free from cultural or industrial influence, where researchers could actively manipulate whole ecosystems. The first experiments involved researchers directly controlling nutrient influxes to isolate the factors that might influence eutrophication in the water bodies. One of the experiments – that on Lake 227 – was conducted over the course of 44 years. It and a shorter experiment in Lake 226 were the first of their kind to clearly identify phosphorus as a driving factor in eutrophication. Comprehension Checkpoint Excessive algae growth Lake 227 is small by most lake standards and offered limnologist David W. Schindler and his research team an ideal subject on which to test their ideas about eutrophication. In June 1969, Schindler and his team began to intentionally fertilize Lake 227 on a weekly basis, using a fertilizer with a 12:1 ratio by weight of nitrogen to phosphorus (Schindler, 2008). At the time, they were interested in testing a hypothesis popular in North America that the supply of carbon could limit the growth of phytoplankton in lakes. They chose Lake 227 specifically because it had a low concentration of dissolved inorganic carbon (Schindler, 2009). For the first five years of the experiment, the researchers added phosphorus and nitrogen to the lake to ensure phytoplankton had adequate amounts for growth and sustainability, but limited access to carbon. Figure 6: The data from Schindler's research shows a clear connection between the amount of phosphorus added to the lakes and the algal growth. image © David W. Schindler After nutrient-loading Lake 227 for the first time, Schindler and his team noticed that algae growth increased significantly (or "bloomed") despite the low concentration of carbon. Further, they saw that the blooms had a direct correlation to the amount of phosphorus they added to the water (Figure 6). While Schindler began to suspect phosphorous as the culprit, he needed further evidence. Importantly, the soap and detergent industry, whose products contained phosphorous, worked to take the focus off of the phosphorus-containing products by arguing that nitrogen was as influential in aquatic systems as phosphorus. So, the team began to test the effects of nitrogen separately by adding nitrogen and carbon to Lake 226. Figure 7: An aerial photograph of Lake 226 taken in August 1973. The plastic curtain dividing the lake at the narrows allowed Schindler's team to nutrient load each half of the lake with different amounts of phosphates. The northern basin, shown on the bottom half of the photo, became eutrophic in response to the excess phosphorus. image © David W. Schindler Lake 226, shaped like an hourglass, had two basins that could be isolated from one another at the narrows with a heavy nylon curtain (Figure 7). Schindler's group added nitrogen and carbon to both of the basins, but in the north basin they also added phosphorus. Again, algal blooms were in direct relation to the amount of phosphorus added – the south basin remained pristine, while the north basin bloomed within weeks (Schindler, 1977). Schindler's research began to show clearly that phosphorus, and not carbon or nitrogen, is the nutrient that has the greatest effect on plant growth in aquatic ecosystems. As Schindler notes in his personal recount of the history of the ELA, the aerial photograph of the two basins shown in Figure 7 had more impact on policy makers than hours of testimony based on scientific data, helping to convince them that controlling phosphorus was the key to controlling eutrophication problems in lakes. (Schindler, 2009) The reason for phosphorus's impact is simple. Along with carbon, nitrogen, oxygen, and potassium, phosphorus is a macronutrient that determines whether an organism will grow and survive, or wither and die. Without it, living beings cannot grow, reproduce, move, or do much of anything. But because other macronutrients are readily available, more often than not the limiting nutrient for plant growth in natural ecosystems is phosphorus. This is partly because the largest reservoir of phosphorus is locked up in sedimentary rock and unavailable, and partly because its chemistry in the environment limits its availability. Comprehension Checkpoint In the Experimental Lakes Project, which element was found to cause excessive algae growth? Since humans began to walk the Earth, we have interacted with – and influenced – many natural processes, and the phosphorus cycle is no exception. Because phosphates are quite limited in soil naturally, modern agricultural practices frequently involve the application of fertilizers heavy in inorganic phosphates. When phosphorus is added to an ecosystem through non-natural or excessive means – run-off from farms (both fertilizers and animal excrement), sewerage, or phosphate-containing detergents – the sudden increase in nutrient availability can have a dramatic effect on plant growth. Soil has a saturation point with respect to how much phosphate it can hold, and plants have a limit as to how fast they can take it up, so the application of too much phosphate results in both leaching into the water supply and run-off into lakes, streams, and oceans. Since aquatic ecosystems have very low phosphate concentrations naturally, whenever phosphate enters the water column, phytoplankton like algae quickly consume it. As Schindler and his team showed with the ELA, if the influx of phosphate steadily continues for a period of time, the algae and other aquatic phytoplankton are able to reproduce so quickly and efficiently that they literally form a mat on the surface of the water, blocking out light for other plants and organisms living below (Figure 8). This reduces the ability of bottom-dwelling plants to photosynthesize, reducing the amount of oxygen being released into the water. Figure 8: Myvatn Lake - a shallow eutrophic lake in northern Iceland. image © Israel Hervas Bengochea/Shutterstock As the algae die, they fall to the bottom where they are decomposed by bacteria – a process that uses a large amount of dissolved oxygen. As this dissolved oxygen is depleted, fish and other organisms living in the water body slowly suffocate and die. Though we have learned better and made many efforts to change, the effects of these practices still linger. The over-application of fertilizers with high concentrations of phosphate is still a problem, and bodies of water in places with heavy agricultural communities suffer the greatest. Fortunately, as we learn more about the impacts our actions have on our environment, we can consciously make choices that will benefit rather than harm our surroundings. The body of research on phosphorus conducted at the Experimental Lakes Area was a seminal contribution to environmental science. While the phosphorous cycle can be simplified, as we did above, to a cycle that includes a geological component and a biological component, the cycle is actually far more detailed than this. All living organisms need phosphorous to survive and grow. This module describes forms that phosphorous takes in nature and how the element cycles through the natural world. A historical journey highlights how we came to understand this vital element. The Experimental Lakes Project shows the harmful effects of too much phosphorous on the environment as a result of human activities. Key Concepts The phosphorus cycle is the set of biogeochemical processes by which phosphorus undergoes chemical reactions, changes form, and moves through different reservoirs on Earth, including living organisms. The phosphorus cycle is the only biogeochemical process that does not include a significant gaseous phase. Phosphorus is required for all organisms to live and grow because it is an essential component of ATP, the structural framework holding DNA and RNA together, cellular membranes, and other critical compounds. Agricultural runoff, over-fertilization, and sewage all increase the amount of phosphate available to plants and can cause significant ecological damage. HS-C5.2, HS-ESS2.A1, HS-ESS3.C1, HS-LS1.C3 Cleugh, T. R., & Hauser, B. W. (1971). Results of the initial survey of the Experimental Lakes Area, northwestern Ontario. J. Fish. Res. Board Can., 28, 129-137. Hershey, D. (2003). Misconceptions about Helmont's Willow Experiment. Plant Science Bulletin, Fall (49.3). Morton, A. G. (1981). History of Botanical Science, Academic Press, London, ISBN 0-12-508480-3, 474. Schindler, D. W., Hecky, R. E., Findlay, D. L., Stainton, M. P., Parker B. R., Paterson, M. J.,...& Kasian, S. E. (2008). Eutrophication of lakes cannot be controlled by reducing nitrogen input: Results of a 37-year whole-ecosystem experiment. PNAS, 105(32), 11254–11258. Schindler, D. W. (1977). Evolution of phosphorus limitation in lakes: Natural mechanisms compensate for deficiencies of nitrogen and carbon in eutrophied lakes. 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