Chapter 2

Earth Systems

Chapter Summary

Chapter 2 establishes the concept of systems and of Earth as a series of interconnected systems, geosphere, atmosphere, hydrosphere, and biosphere operating from the atomic to the planetary scale. According to the nebular hypothesis, the Earth system originated rocky materials accumulated gravitationally through collisions out of a nebula of gas and dust as the solar system formed.

Earth's overall interior structure is a series of spherical shells. These layers formed after accretion of a relatively homogeneous planet was completed when the heat generated by collisions during accretion, gravitational settling of denser materials and radioactive decay of unstable elements caused large parts of the Earth to become molten. These molten materials differentiated based on density and chemical compatibility, creating the dense iron/nickel core, moderately dense rocky mantle and thin, least dense/chemically incompatible crust. The crust itself is divided into two parts with an extremely thin basaltic oceanic crust covering over half the planet, while the thicker, less dense granitic crust of the continents covers the rest. Details of the Earth's interior density, structure, and mobility are determined by the differential velocity and refraction of seismic waves.

Earth's current atmosphere is the third our planet has possessed. The first atmosphere of nebular gases gathered during planetary accretion was lost to space. The second atmosphere, dominated by H_2O, CO_2, CH_4, SO_2, and N_2, was released from the cooling Earth's interior via volcanic outgassing. Condensation and precipitation of this water created the ocean and hydrosphere. Removal of atmospheric CO_2 by dissolution in the oceans and photosynthetic consumption by early life moved most of Earth's carbon from the ocean to the crust and created the third and current atmosphere dominated by N_2 and O_2. Life could not have formed in the absence of the ocean in which to dissolve CO_2 and the present atmosphere could not have formed without the presence of life on Earth. Life has played a key role in atmospheric evolution just as the changing composition of the atmosphere has determined how life has evolved.

The various reservoirs in Earth's hydrosphere are interconnected by the water cycle, a highly efficient mechanism for transferring energy, water, and other materials through the Earth system. Most water on Earth rests in the salt water ocean while most fresh water is stored in glacial ice in Greenland and Antarctica. Less than 1% of Earth's fresh water exists in the atmosphere, rivers, lakes, and ground water, which supply most human water demand.

Life has evolved via Darwinian natural selection since the first cyanobacteria appear in the rock record 3.5 billion years ago. Our understanding of the history of life and Earth history have grown together through the work of distinguished scientists and their study of traces of life called fossils. While species have evolved and gone extinct since the origin of life, particularly difficult periods in Earth history have resulted in mass extinctions of large parts of the biosphere such as the extinction of the dinosaurs 65 million years ago and the accelerated rate of extinction occurring today due to human-induced environmental changes.

Earth history is measured using relative and absolute dating techniques. Relative dating places sedimentary and other rock types in order of their construction and has been used to build a geologic time scale reflecting major transitions in the fossil record. Fossil evidence recording the evolution of organisms over time is a key tool used to construct and correlate the sedimentary rock record from across the planet, necessary as no single location contains a full record of Earth history. Absolute dating using radiometric decay of unstable atomic nuclei allows for attachment of absolute dates to the geologic time scale. These techniques indicate that human existence is limited to a small fraction of Earth history and that many of the resources we consume take far longer to create than the lifetime of our species, making them effectively non-renewable on human time scales.

Chapter Outline

I. Defining Systems

II. Origin of the Earth/Moon System

- a. Earth Accretion and Differentiation – Nebular Hypothesis
- b. Origin of the Geosphere
  - i. Earth's Internal Composition
  - ii. Earth's Layered Structure
- c. Origin and Evolution of the Atmosphere
  - i. First Atmosphere – Nebular Gases
  - ii. Second Atmosphere – Volcanic Gases
    1. Oceanic Interaction – Carbon Deposited in Geosphere
    2. Biosphere Interaction – Photosynthesis Releases O_2
  - iii. Third Atmosphere – Consequence of Life
  - iv. Atmospheric Structure

d. Origin of the Hydrosphere
    i. Source of Earth's Water
    ii. Water Reservoirs in the Earth System
    iii. Global Ocean
    iv. Cryosphere – Glaciers and Ice Sheets
    v. The Water Cycle
e. Origin of the Biosphere
    i. Origin of Life
    ii. Fossil Record.
    iii. Evolution of Life – A Historical Perspective
    iv. Extinctions

III. Geologic Time
    a. Relative Dating
    b. Geologic Time Scale
    c. Absolute Dating
    d. Rates of Geologic Processes

Chapter Learning Objectives

After studying this chapter, students will be able to:

- describe the parts, origin, operation, and evolution of the four dominant Earth systems.
- define and differentiate the movement of matter and energy through the reservoirs of the Earth system with the importance of rate and proportion of material in flux between reservoirs assessed via residence times.
- describe the formation of Earth and its internal differentiated and layered structure as a terrestrial planet formed via the nebular hypothesis.
- describe the compositional, density, and dynamic characteristics of the Earth's primary layers including inner and outer core, lower, transitional and upper mantle, oceanic and continental crust, asthenosphere, and lithosphere.
- describe the evolution of Earth's atmosphere over geologic time.
- describe the role of volcanic outgassing, ocean formation, and development of photosynthetic life in determining the composition of the atmosphere and crust.
- describe the thermal and compositional structure of the modern atmosphere.

- describe the origin of the hydrosphere within the context of the nebular hypothesis and early atmospheric development.
- describe the reservoirs and connections within the hydrosphere that make up the water cycle.
- identify the key components and scale of the cryosphere.
- explain the evolution of life over Earth history by identifying key scientists and their discoveries.
- identify and distinguish between relative and absolute dating methods and how they can be used to determine ages of Earth materials and rates of Earth processes.
- recognize the short duration of human existence on Earth relative to Earth history and the rate of formation of many natural resources, making them non-renewable on human time scales.

End of Chapter Questions

Questions for Review

1. In Earth system science it is important to identify *reservoirs* and *residence times* for materials. What are these, and why are they important to understand?

Reservoirs represent pools or boxes within the system that contain the material under study. They have finite borders across which materials pass to other reservoirs via Earth system processes in discrete amounts called fluxes. Residence time is the length of time it takes the amount of material in the reservoir to be added (or removed) via a given process or flux.

For example, the atmosphere, woody vegetation in the biosphere, and rocks such as coal and limestone all represent reservoirs for carbon in various forms (CO_2 *in the atmosphere, organic carbon in vegetation, and organic carbon and calcium carbonate (*$CaCO_3$*) in rocks). The amount of carbon in these reservoirs is vastly different with the vast majority found in rocks. The residence time gives a measure of the AVERAGE time required to replace or deplete the material in the reservoir and is indicative of how sensitive that reservoir is to perturbations in fluxes between the reservoirs. Burning fossil fuels, for example, has an infinitesimally small effect on the reservoir of carbon stored in rocks. Compared* *to the much smaller carbon reservoir in the atmosphere, however, the same carbon released as CO_2 by burning fossil fuels has a large effect. Human activity has increased the size of this reservoir by 1/3 over the last two centuries! Woody vegetation in the biosphere and atmosphere also has large effects on each other as roughly 20% of the atmospheric carbon content crosses between these reservoirs in any given year. The NET effect of this transfer is smaller than that of fossil fuel consumption, however, because nearly as much carbon crosses between atmosphere and biosphere as plants grow in spring and summer as is lost back to the atmosphere in fall and winter. Knowledge of residence times indicates how small changes in either the flux of carbon from fossil fuels or in the balance between biosphere/atmosphere by deforestation, biomass burning, or reforestation efforts can have a major effect on the size of the reservoir of atmospheric carbon.*

2. The Earth is largely a closed system with respect to matter. What about with respect to energy? Provide examples with your answer.

Earth receives a very small net increase of mass in the form of meteoroids and comets from space relative to its mass. The loss of mass from giant impacts is even smaller, making Earth a nearly closed system with respect to matter.

Earth transfers significant amounts of energy across its surface, with 99% of the surface energy flux arriving from the Sun compared to internal geothermal sources. This large input of light energy is balanced over the long term by release of infrared radiation based on the Earth's average surface temperature (15 ^{O}C). Changes in solar radiation, should they occur, would immediately reverberate through the Earth system, causing a change in temperature to reflect the new energy flow. This makes Earth an open system with respect to solar radiation and energy in general. Fortunately for life, Earth's sun appears to release nearly constant levels of radiation on the timescale of centuries and millennia, keeping the Earth's climate reasonably stable. Changes in the *greenhouse effect caused by changing the composition of Earth's atmosphere via human activity or natural causes change the atmosphere's ability to retain heat, resulting in short-term imbalances in the overall planetary energy budget. In the long-term, storage of more incoming radiation by greenhouse gases raises the temperature of the atmosphere, resulting in greater infrared emissions to space, thereby restoring balance in the system.*

3. Small irregularities in the early interstellar nebula led to local clusters of mass. The pull of gravity at a location is directly related to how much mass is present. How does this lead to a self-reinforcing process that leads to the formation of entire planets?

Newton's law of gravity states that the strength of the gravitational force is proportional to the product of the masses being attracted divided by the square of the distance between them.

$$F_g \sim \frac{(mass_1)(mass_2)}{distance^2}$$

Most collisions between matter in a nebula occur at high enough speed that the particles bounce off each other as gravity is too weak to hold them together. Clustering of matter in clumps, however, greatly increases the force of gravity locally as the distance between particles declines, allowing the material to cluster in ever-smaller volumes. As more matter falls into the growing cluster, the overall mass increases, raising the force of gravity thereby allowing the cluster to withstand the high-speed impacts, which would tend to cause the material to fly apart. Once a protoplanetary cluster reaches about 1 km in size, the positive feedback created allows for rapid planetary growth over a few hundred thousand years.

4. The earth is divided generally into the core, mantle, and crust. What is the essential difference in materials (composition) that defines the core as very distinct from the mantle and crust?

The core is composed of an alloy of iron and nickel with up to 10% of a lighter element such as oxygen, sulfur, or hydrogen. The mantle and crust are composed of rocky materials composed of silicate minerals dominated by silicon, oxygen, and aluminum with only a few percent of metallic elements such as iron. The lower density of the silicates accounts for their presence above the metals of the core.

5. The crust and mantle are both made of rocky material but are compositionally distinct. However, the upper mantle and the crust are understood to be part of one layer called the *lithosphere*. What is this layer, and how is it defined?

The lithosphere is the solid brittle layer of crustal and upper mantle rock lying above the weak pliable rock of the asthenosphere. The rigid rocks of the lithosphere have the ability to break and move along faults creating earthquakes and other seismic activity. The ability to flow in asthenospheric rocks prevents such seismic activity as the rock simply deforms plastically. Earth's plates consist of lithospheric rock floating and moving on the plastic asthenosphere.

6. Water can exist in three phases of matter: a solid, liquid, or gas. Why is Earth's distance from the Sun relevant to these phases of water and life on this planet?

Earth's average distance of 150,000,000 km from the Sun gives Earth surface temperatures that allow water on Earth to exist as a solid, liquid, and gas at many points on Earth's surface. This combination of states allows for water to act as a medium for chemical reactions and transport of materials and energy through the Earth system. Without this ability, living cells would be unable to exchange *nutrients and wastes with their environment, preventing life as we know from existing on Earth's surface.*

7. Thinking about the water cycle, describe how the interaction of the hydrosphere and the atmosphere is critical to all life on land.

The hydrosphere and atmosphere interact both through the evaporation and precipitation of water as well as through provision of a sink for atmospheric components. Without the ocean, there would have been no large sink for atmospheric CO_2 *via inorganic dissolution or consumption by photosynthesis by marine phytoplankton. Without this sink, the atmosphere would be dominated by* CO_2 *causing a runaway greenhouse effect, making Earth too hot for liquid water or life as seen on Venus. The water cycle is also critical for life on land as it provides the precipitation needed to fill soils, rivers, lakes, and groundwater with water, without which land organisms cannot survive. Water flowing across the land weathers and erodes minerals on Earth's land surface, fertilizing the ocean with these nutrients and increasing marine biological productivity.*

8. The stratosphere is located immediately above the troposphere in our atmosphere. According to the temperature profile shown in Figure 2.11, explain why the stratosphere should be relatively stable with respect to vertical air motion compared with the troposphere.

The atmosphere is transparent to most wavelengths of incoming solar radiation. This causes absorption of solar radiation mostly to occur at Earth's surface. Release of infrared radiation from this warmed surface then heats the atmosphere from below, causing the troposphere to be warmest at the Earth's surface and to cool as one increases in elevation. Since air parcels in the atmosphere sort themselves by density, less-dense warm air tends to rise while more-dense cold air sinks to replace it. The warm air at the Earth's surface *underlies cold air and is thus unstable, causing it to rise, creating rapid vertical convection and mixing in the troposphere.*

The stratosphere, however, contains the ozone layer, which absorbs incoming ultraviolet radiation, converting it to heat. This localized source of heat causes the temperature to rise as one increases in elevation in the stratosphere. With low-density warmer air over higher density cooler air, the stratosphere is stable and has little ability to convect vertically.

9. There is ample evidence of past and present interaction of the biosphere and atmosphere in shaping atmospheric composition. Why was the activity of the biosphere over 2 billion years ago so crucial in the development of an atmosphere conducive to modern life on Earth today?

Without the evolution of photosynthetic living organisms, Earth's atmosphere would be far different than it is today. While much of the CO_2 released from volcanic eruptions would have dissolved inorganically in the oceans, living organisms greatly speed this process and helped to ensure Earth did not enter a runaway greenhouse which would have evaporated away the oceans and made the planet more like Venus. The presence of CO_2 as only a trace gas in the atmosphere is a direct consequence of life. In addition, the production of oxygen as a by-product of photosynthesis accounts for the 21% of oxygen found in the atmosphere today. The release of this free oxygen initially was used to oxidize iron and other reduced metals dissolved in the ocean, creating the banded iron formations found in rocks ~2 billion years old. Only after these materials were depleted from the ocean could free oxygen accumulate in the atmosphere, creating the oxidized Earth surface we see today. Without this oxygen serving as an electron sink, multi-cellular complex life forms such as most plants and animals would not be possible due to the energetic metabolic requirements involved. In addition, until free oxygen accumulated in the atmosphere, the ozone layer could not form. Without the ozone layer to shield Earth's surface *from ultraviolet radiation, even single-cell organisms would have remained restricted to water and been unable to colonize the land surface.*

10. Life exists in many forms today on Earth, but when examining the earliest life on the planet, we must define what life is. What is the definition of life by biological standards, and what key aspect of that definition is helpful in understanding the interaction of Earth systems?

Life is any organized discrete body that consumes energy to grow and maintain itself through homeostatic processes, possesses the ability to reproduce its own form and ultimately ceases to function and returns its constituent elements to the surrounding environment. A chemist would add that living organisms use energy to create internal order (decreased entropy) at the expense of creating greater external disorder (increased entropy) in their environment. The organization of matter against chemical gradients, i.e., locally decreasing entropy by creating long-term chemical disequilibrium, makes life's role unique in the Earth system where entropy increases via inorganic processes as chemical equilibrium is established.

11. What is the difference between *relative* and *absolute* geologic ages? Because it is not usually possible to get an absolute geologic age for each and every rock formation, why is it important to use both techniques together?

Relative geologic ages indicate the order in which events happened, whereas absolute ages indicate the actual timing of events. Absolute ages are better than relative ages because one can still order the events based on the dates. Unfortunately, absolute dates can only be obtained from certain rocks under specific circumstances. Relative geologic ages are thus important as their ordering can constrain when undated rocks form or events occur based on where they fall relative to rocks which can be dated absolutely. Similarly, if one knows *the order of 3 siblings in a family and the birthdates of 1 or more of these people, this narrows down the possible ages for the unknown siblings and their parents. Geologists use relative and absolute dating in the same way.*

12. Why are fossils so crucial to the determination of reliable relative geological ages, and how are they used to construct a composite history of large regions of the Earth?

No place on Earth contains a full, uninterrupted geological record of sedimentation because crustal movements, changes in sea level, erosion, etc. cause the landscape to change, either preventing sedimentation or removing previously deposited sediments and sedimentary rocks by erosion, subduction, or metamorphosis. Fossils, particularly widely dispersed trace fossils of organisms existing for a narrow period of time, allow geologists to correlate different rock layers from various parts of the world, as the fossils indicate that the rocks are of the same age. This allows for reconstruction of both the history of life, under the premises of Darwin's theory of evolution, and of the rock record in various parts of the world over time.

13. What is meant by a *half-life*, and how is this concept used to provide absolute geologic ages?

Half-life refers to the length of time required for half of a given amount of an unstable radioactive isotope to decay. As more and more of the original radioactive material breaks down, there is less material to decay, causing the rate of decay to decline exponentially, though the half-life itself remains the same for a particular isotope. In rocks that contain radioactive isotopes and their daughter elements in a closed structure where no material can leave or enter, the gradual shift in the proportion of parent and daughter isotopes over time allows one to calculate the fraction of material that has decayed. The number of half-

lives since the material began to decay can then be determined revealing the age of the rock. This technique only works where the material in question has not had its isotopic composition altered and when it contained sufficient quantities of a radioactive isotope to survive the period of decay with enough material remaining for accurate detection and measurement.

14. Are fish that are high on the food chain (mostly predators) or fish that are low on the food chain (mostly prey) likely to have higher mercury concentrations in their bodies? Why?

Predatory fish high on the food chain are more likely to contain high concentrations of mercury or other heavy metals and pesticides due to bioaccumulation than organisms lower on the food chain such as grazers. At each step up the food chain the metal content of the lower levels is concentrated in the tissues of the higher organisms by the accumulation and storage of the metals from many individual prey organisms. The greater the number of levels in the food chain, the greater will be the bioaccumulation of mercury.

15. If there were no life on Earth, do you think there would be an active nitrogen cycle? Why or why not?

Without microbial activity, most nitrogen on Earth would end up as relatively inert N_2*, which makes up the bulk of our current atmosphere. High-energy lightning bolts can create amino acids and other compounds involving nitrogen, but these are not generated in large amounts. Biological activity in many ecosystems is ultimately limited by availability of nitrogen in forms other than* N_2 *such as* NO_3^- *and* NH_4^+*. Today human activities such as the industrial production of fertilizer cause more nitrogen fixation than the rest of the biosphere combined. So, without life, Earth would have a far more limited nitrogen cycle than we see today.*

16. Why is the fact that the Earth has an actively circulating, liquid outer core so crucial to life on the planet?

Earth's actively circulating liquid iron/nickel outer core produces Earth's dipole magnetic field. Movements of the molten iron create a far stronger magnetic field than the remnant magnetism generated by static solid magnetic minerals stored in cooled rocks. This powerful dynamo shields Earth's surface from most incoming high-energy radiation, thereby protecting life on Earth's surface from having its DNA destroyed. Without this shield, life could not live on Earth's exposed surface. Lack of strong magnetic fields render the surfaces of most other planets and moons in the solar system unable to support life, though life might exist beneath the surface under favorable conditions.

Critical Thinking/Discussion

1. The richness and complexity of processes on Earth is best understood by identifying and examining the interaction of *systems*:

a) System *scale* and *limits* must be defined before we can understand system interaction. Why? Provide relevant examples to illustrate your answer.

All systems, other than possibly the entire universe, interact in some fashion with their environment. As such, one must determine the scale and limits or boundaries of a system to have a meaningful discussion of its properties and status. The scale and limits will depend on the type of questions one is seeking to answer as illustrated by small-scale and large-scale examples below.

A lake can be defined as the body of water within a particular basin. In looking at the food chain of plankton and fish within the lake, this definition would seem to completely contain the ecosystem. However, one must also consider the movement of water, energy, and nutrients in and out of the lake at its atmospheric and rock or sediment limits. Without solar energy to drive *photosynthesis the ecosystem would shut down, hence the energy input must also be accounted for in the system even if we chose not to extend our system out 150,000,000 kilometers to the sun. Similarly, changes in water level in the lake or addition of nutrients from in-flowing streams or sediments must also be taken into account to determine how the plankton grow, etc. While distant weathering and precipitation in the mountains ultimately are the origin for these inputs, inclusion of these locations may not be particularly helpful in understanding the system of the lake, even though the input/output components of each must be accounted for.*

Earth itself provides a second example. At the present time very little matter is exchanged between Earth and the space environment around it. While meteoroids do slowly add mass to Earth and major impacts and human rockets occasionally remove material, by and large the top of Earth's atmosphere represents a fairly solid limit to matter in understanding Earth systems. In terms of energy, however, incoming solar radiation is a major factor influencing the Earth's surface conditions and systems. Solar radiation drives the hydrologic cycle and atmospheric circulation almost exclusively. The rock cycle, however, is primarily driven by Earth's internal circulation arising from radioactive decay. The speed of the rock cycle, in turn, determines the atmospheric concentration of CO_2 *via volcanic outgassing, determining the strength of the greenhouse effect and thereby affecting the hydrologic cycle, atmospheric circulation, and the outgoing infrared budget of the Earth system.*

b) Consider a car moving down the highway. Is this an open or closed system? With respect to matter or energy? Or with respect to which matter? Provide at least two examples each of how this moving car is an open and closed system.

A car is a closed system with respect to matter when its occupants are sealed inside and no material is being moved in and out via the doors. It is an open system with respect to matter, however, when one considers the operation of the *internal combustion engine. Burning of gasoline in the engine involves taking in oxygen from the atmosphere outside the car and releasing water vapor and carbon dioxide in return. The car's gas tank ultimately becomes "empty" of fuel because of being an open system as the car loses the mass of its fuel.*

With respect to energy, a car is a closed system given that the chemical energy contained within its fuel is converted to kinetic energy and heat during combustion. If the heat from the engine were to be completely contained in the cabin of the vehicle and there were no friction on the tires or surface of the car we would have a fully closed system. More accurately, a car is an open system for energy because excess heat from combustion and from friction is lost to the environment around the car. That is the purpose of the radiator.

A car is also an open system for energy when one considers the role of sunlight in warming the interior of a sealed car on a hot summer day. Like Earth, sunlight passes through the glass of the windows to be absorbed by the car's interior. This energy is converted to heat, which then warms in the air in the car until the outside temperature of the vehicle rises enough that the whole car loses as much infrared heat to the environment as the Sun adds to the car.

2. From many lines of evidence, it is clear that the biosphere has interacted with the atmosphere and the hydrosphere to create the compositions of all of these systems that we see today. It can be argued that the current state of the Earth system has evolved to accommodate life, driven significantly *by* the actions of life. Make this argument, citing at least three examples from the text or from other systems you have studied.

The Earth that we see today clearly is the product of living organisms as evidenced by the fact that we have an atmosphere that is 21% free oxygen, chemically incompatible with the minerals at Earth's surface. Without continuous new production by photosynthesis, the current supply of oxygen would be *depleted by rock weathering in 20 million years. Photosynthesis by living organisms has created the atmosphere we see today.*

Life has also altered the state of the atmosphere by fixing large quantities of atmospheric carbon dioxide into organic matter and calcite shells often stored in the form of limestone. Most of Earth's carbon is stored in the crust rather than the atmosphere because of the photosynthetic and shell-building activities of life. This control on CO_2 in the atmosphere in turn plays a large role in keeping the planetary temperature from getting too warm or too cold for life. As temperatures increase, photosynthetic organisms consume more CO_2, causing a decrease in the greenhouse effect, cooling the Earth by a negative feedback. When temperatures cool too much, photosynthesis slows withdrawal of CO_2 from the atmosphere and respiration and on-going volcanic activity raise CO_2 back up to warm the planet.

Another manner in which life has altered the Earth system relates to iron in the ocean and crust. Iron is a critical micronutrient for living cells. During the Archean when the atmosphere was still anoxic, huge quantities of ferrous (Fe^{+2}) iron were dissolved in the oceans from black smokers at mid-ocean ridges. This reduced iron was gradually consumed by oxygen released photosynthetically by cyanobacteria, allowing for deposition of banded iron formations as the coastal ocean began to experience both aerobic and anaerobic conditions. Under today's oxidizing atmosphere created by life, the ocean's iron supply often limits biological activity because fresh iron supplies must come from limited volcanic activity and dust blown into the ocean from the continents.

3. The biosphere has grown and contracted through time—it has not had a stable history. Describe the interaction of evolution, speciation (the emergence of new species), and extinction in the context of other changing Earth systems in shaping the ongoing dynamic balance that is the history and current state of life on Earth.

From its earliest origins, life has responded to and altered the conditions of the environment around it. Growth of cyanobacteria and expansion of photosynthesis changed Earth from a CO_2, N_2-rich chemically reducing atmosphere to an oxidizing one dominated by N_2 and O_2. This conversion of the biogeochemical environment, effectively "poisoning" the microbial world by free oxygen forced life to adapt and evolve to the new conditions. New species of organisms arose which could live and thrive in the new aerobic environment…ultimately creating the animals and plants we see today. Those whose environments faded either retreated to refuges, such as the anaerobic environment of swamps and sediments or went extinct. This same process of adaptation to changing environmental conditions, either by migration, adaptation, speciation, or extinction continues today even if on less dramatic scales. As human-dominated ecosystems have exploded across the Earth surface, we see other organisms adapting to the new conditions by altering their ranges or habits to avoid extinction. We even see rapid speciation of viruses and microbes that now consume our wastes or infest our agricultural systems if not our own bodies. As human activities alter the Earth's radiative balance and climate, we may be seeing the same type of speciation that the fossil record indicates has occurred when climate changed at various points in the last half billion years. Life will survive human civilization and its excesses…but it may give us a very different world than what we see today, just as the world of today is so very different from the one the dinosaurs left 65,000,000 years ago after Earth's ecosystems were shattered by a large comet or asteroid.

4. Humans are relative newcomers to the Earth system. Given this, and our tremendous success as a species on this planet, why is understanding the history of Earth's systems prior to our emergence as a species so crucial to shaping our own future actions and decisions?

Humans armed with modern technology and a population over 6 billion need to understand the history and functioning of Earth systems because our collective *impact on these systems have now reached a planetary scale and threaten our survival as a species. In the course of the last few centuries we have consumed a significant fraction of the accessible mineral and fossil energy resources, which required millions of years or more to generate. We are extracting ground and surface water in unsustainable ways causing long-standing water bodies to shrink or disappear. We dominate most terrestrial and marine ecosystems in terms of our extraction of food and fiber. Production of fertilizer and heavy metals now exceed the natural biogeochemical cycles of nitrogen, phosphorus, mercury, lead, and others. The trace gas chemistry of the atmosphere has been sufficiently modified by our emissions of CO_2, CH_4, N_2O, and chlorofluorocarbons such that we depleted the ozone layer and altered the heat budget of the atmosphere and Earth in detectable ways. Environmental change is now causing extinction rates to spike in what could be the sixth mass extinction event of the last 540,000,000 years. We no longer have the luxury of assuming that the Earth systems' natural processes can absorb our impacts without fundamentally altering their functioning, in ways that we often cannot anticipate or adapt to. Only by understanding how these systems functioned before our growth to a planetary force can we have any hope to predict outcomes before they arrive and alter our behavior to avoid undesirable consequences of our activities. Failure to do so runs the risk of not only degrading the quality of human existence but of inviting us to join those species consigned to the oblivion of extinction.*

Web Resources

Multiple Topics

http://www.windows.ucar.edu/

Nebular Hypothesis

http://csep10.phys.utk.edu/astr161/lect/solarsys/nebular.html

Atmospheric Formation

http://www.globalchange.umich.edu/globalchange1/current/lectures/samson/evolution_atm/

Hydrologic Cycle

http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/hyd/smry.rxml

http://earthobservatory.nasa.gov/Features/Water/water_2.php

Snowball Earth Hypothesis

http://www.snowballearth.org/

Geologic Time Scale

http://www.geosociety.org/science/timescale/