Chapter 10:

The trials and tribulations of Mother Earth

Come, where is this young gallant that is so desirous to lie with his mother earth?

As You Like It, Act I. Scene II.

William Shakespeare (1564–1616)

The Oxford Shakespeare, 1914

The Gaia hypothesis

To Shakespeare, "mother earth" was poetry. Bruno, an Animist, placed a living spirit in the Earth as well as in many normally inanimate objects. There is a modern scientific middle ground, the Gaia hypothesis of James Lovelock and Lynn Margulis. Does the Earth act as a single large biological organism? That is, does life on Earth act as a consortium of organisms for the benefit of all?

The hypothesis smells of the Natural Theology of William Paley on one end. That is, each organism has a role assigned by the Creator for the good of all. On the other end, the weak form of the hypothesis, that terrestrial life has not yet produced instability that led to its undoing, is a restatement of the weak anthropic principle. Our ancestors had to survive to breed for us to be here to observe. Yet the strong form of the Gaia hypothesis as proposed by Lovelock and Margulis is science and not mysticism.

Working together. Real consortia of organisms exist including right within our cells. Margulis, in her day job, studied such consortia. There are more microbes in our gut than people on the Earth. Most of them are beneficial. We would starve without them. The benefit is two way. The microbes extract energy from the food and break it down to a form we can use in the process. Margulis has shown that termites need microbes in their guts to digest wood. Cows have microbes in their guts that eat grass. The cow in turn digests some of the microbes while providing a home for the rest.

Biologists in general call mutual benefit “symbiosis.” It is quite common in nature. Numerous examples exist of symbiosis between large organisms. The squirrel buries acorns to eat later. The few that do not get eaten are unintentionally planted away from the parent tree. They germinate often in open soil where it is easy for the squirrel to dig. This is group selection in that the genes in the eaten acorns benefit from the traits that make them attractive to squirrels for planting. Jays do the same with acorns in California where there are no native tree squirrels near sea level in the Bay Area. You have probably seen a lot of examples on TV, like tickbirds eating parasites off a water buffalo’s hide to the benefit of both species (Figure 1).

Figure 1: Two tick birds rest of the shoulders of a water buffalo. Both species benefit. The water buffalo has fewer ticks after the birds have eaten. Photo by George Thompson.

Margulis found a more intriguing form called endosymbiosis (Greek for inside together life) within the Eukaryote cell. The descendents of once free-living Bacteria make their homes as organelles within the cell walls. There was endosymbiosis early in eukaryotic evolution.

I begin with an example that is controversial because it occurred so long ago that subsequent evolution has wiped out most of the evidence. Vestiges of once free-living spirochetes (one of their relatives causes syphilis) aid in our cell division. These organelles are also the flagella that propel Eukaryote microbes. Margulis liked to point out the close link between flagellation and sex in her lectures.

 **(Lichens on rock face)** The mitochondria and the chloroplasts in Eukaryote cells are more easily traced to their free-living Bacteria relatives. Both types of organelles are very important to the Eukaryote hosts. Modern mitochondria produce useful energy from oxygen and food. Chloroplasts convert sunlight into useful energy. Lichens are examples of more geologically recent endosymbiosis where a fungus harbors photosynthetic algae. (The partners have not yet started to exchange genes so their association is not strictly endosymbiosis in some formal definitions.) Such associations have evolved independently several times.

The capture of mitochondria and chloroplasts occurred long enough ago that the origin is unclear. They may have been parasites that evolved to be less virulent and finally useful, they may have been captured and put to use in the cell, or they may have been organisms that evolved a way to avoid being digested once they were engulfed by another microbe. The ancestral bacteria for mitochondria used a form of photosynthesis that does not produce free oxygen. The original mitochondria may have provided energy to their Eukaryote hosts by photosynthesis like modern chloroplasts do with oxygen-producing photosynthesis.

Endosymbiosis has evolved so that mitochondria and chloroplasts cannot live outside their host cells. The fate of mitochondria in a rat is the fate of the rat. Natural selection acts both on the host and the mitochondria to make the association more fit. Faulty mitochondria cause countless human diseases; natural selection eliminates the unfortunate victims. Around 75% of the traceable genes in our nucleus came originally from the mitochondria.

The organelles benefit relative to their free-living relatives. Take, for example, chloroplasts in an oak leaf. They must go wherever the oak puts its leaf, but the oak puts them in a good place where there is lots of sunlight. It supplies them with nutrients and water. It keeps some of them alive in the winter (in cool climates) to make more when it sets leaves in the spring. The free-living cyanobacteria, relatives of the chloroplasts, have to make do without this help on the ground.

Close symbiosis also occurs in microbial mats. The film on unbrushed teeth is an example. The mats self-organize so that one microbe can use the waste products of another. The symbiosis is complex enough that, like the mitochondria and us, many of the mat organisms could not survive without it.

Natural selection and competition occurs on the level of symbiotic ecosystems as well as genes, individuals and species. Selection may involve large animals and plants. For example, Darwin discussed the displacement of one ecosystem by another but did not include it in his struggle for existence. He considered grass and cattle. The cattle eat the grass and the grass is highly evolved so that grazing does not cause excessive damage. However, seeds from nearby forests fall unto the field and spout. These plants do not tolerate grazing and quickly succumb to the cows. Similarly, the predators on the cattle (in a wild situation) make quick work of forest animals that stray into the field. Overall, the cattle and their predators prevent the forest ecosystem from displacing the grass ecosystem.

Feedback and control. Surely symbiotic consortia exist, but the Gaia hypothesis implies that the whole biosphere acts as one. On a micro-ecological level, organisms do act to their own benefit and the detriment of other organisms. Nature is not a song in the *Lion King*; it is a struggle of existence. The law of the jungle does not mean a utopia. The water buffalo gets cleared of ticks; the tickbird gets lunch, but the tick is lunch. The bird does not try to improve the ticks; it eats both sick and healthy ones. It will starve if there is a dearth of ticks. The water buffalo will starve if there is a dearth of grass. There is feedback including natural selection, but it is to the demise of individual organisms. Neither was feedback in the end a boon to the countless species that have become extinct. The early worm got caught.

Gaia is limited; in its scientific form, local consortia only provide an analogy that got Margulis and Lovelock thinking. They implied that biology keeps the Earth as a whole clement and otherwise habitable. There are limits to this. Lush conditions do not now exist on Mars and Venus. The recent (over the last 20,000 years) mass extinction on Earth resulted from evolution becoming unstable, with our own species overly fit. We attribute the Cretaceous-Paleogene extinction to an asteroid impact in the next chapter. But some of the other mass extinctions may owe to climate and/or evolution becoming unstable. I discuss them below.

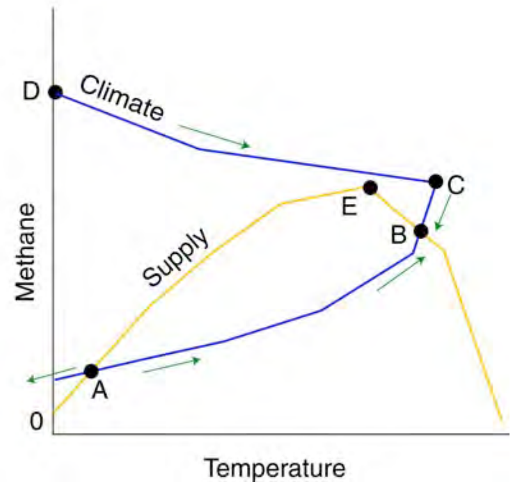


Figure 2: The temperature and the methane concentration track the climate curve. The equilibrium at point A is unstable. The equilibrium at point B is stable.

It has been surprisingly hard to document global Gaian feedbacks, as opposed to contrived examples and selection at the level of ecosystems. Kelvin Zahnle of Ames NASA shared this one with me. It is like a supply and demand graph in beginning economics. See Primary on economics at end of chapter. On the Archean Earth, methane was a significant greenhouse gas. At a given level of carbon dioxide, the (globally averaged) temperature is a function of the amount of methane in the air. Figure 2 is somewhat more complicated than a supply and demand diagram because temperature is a function of methane concentration while methane production (supply) is a function of temperature. At low methane concentrations, the temperature (climate curve) increases with methane concentration. It reaches a maximum temperature (C) at some methane concentration. Above this concentration, methane forms a haze in the air. This, like dust from volcanic eruptions, cools the climate. The biological production of methane and the concentration in the air in equilibrium with it (supply curve) increase with temperature at low temperatures. There is a maximum methane production at temperature-concentration point E. Methane production goes to zero at very high temperatures where no life can survive.

The temperature and methane concentration at any given time lie on the climate curve (by assumption to maintain simplicity). If we start the climate between the crossing point A and point 0, there is less methane production than is needed to maintain the climate. The temperature decreases toward point 0 where the frozen surface produces no methane. If we start between crossing points A and B the methane production is more than is needed to maintain the climate. Methane builds up and the temperature increases to point B. At point B, methane production and climate are in equilibrium. If we start between points D and B, there is too little methane production to maintain the climate. Methane decreases increasing the temperature until stable point B is reached. From the diagram, we see that both stable and unstable equilibrium exist. The equilibrium at B is stable. If we start anywhere between D and A, we end up at that point. The equilibrium at A is unstable. If we start even slightly off it we end up at either 0 or B.

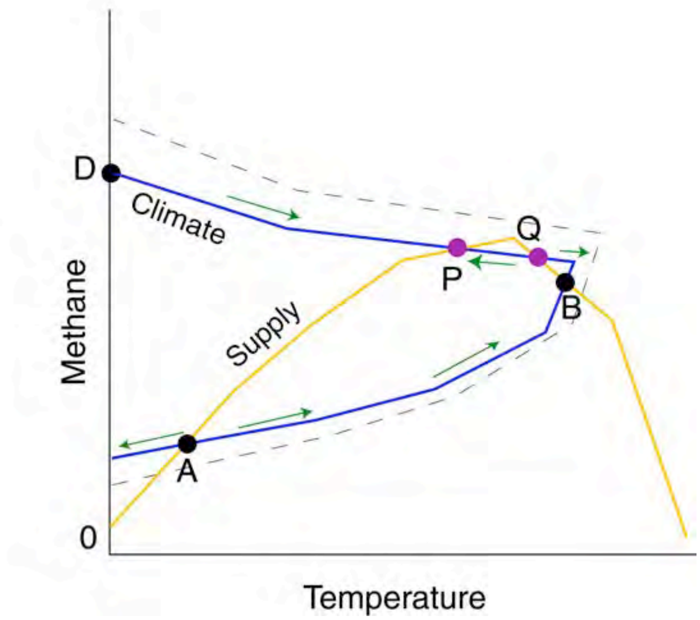


Figure 3: The previous figure at a lower CO_2 concentration provides simple jumps between equilibria. The climate curve intersects the supply curve at four points. Points A and B are the unstable and stable points on the previous figure. Point Q is unstable while point P is stable. A large perturbation might cause the system to jump between the stable points. An gradual increase in CO_2 will bring the climate curve to the one in the previous figure dashed line. The stable point P will no longer exist and the system at P will jump to B.

In analogy with economics, several stable and unstable equilibria can exist (Figure 3). We can make things exceedingly complicated. (There is a Nobel Prize for economics so the field is not simple.) We could have the curves intersect four (or even more) times rather than twice. Then we have two stable and two unstable equilibria. We could add more axes, like one for CO_2 concentration in the air. In that case, we can have four crossings for some values of CO_2 and 2 crossings for others. At the transition value, the equilibrium jumps across the diagram.

Figure 4: The brachiopod *Lingula* shows that evolution sometimes produces stasis in an organism that is already “fit.” These organisms inhabit mud on the seafloor, an environment that has changed little over time. The modern green specimen resembles the 500-million-year-old fossil on the left of the inset. Yet evolution did produce close relatives that differ including the white modern specimens and the ancient specimen on the right of the inset. Photo by author. Inset from Sedgwick and McCoy, 1855.

Paleontologists make use of this property with evolution. Punctuated equilibria exist for the form of an organism. Mivart was a proponent, while Darwin was not. Typically an organism evolves slowly. It is already fit for its niche. Natural selection works to maintain stasis. Sometimes it evolves rapidly jumping from one equilibrium niche to another.

I discuss specific events in Earth history and examine their stability in the remainder of this chapter.

Starting life in the dark

May never glorious sun reflex his beams
Upon the country where you make abode;
But darkness and the gloomy shade of death
Environ you

First Part of King Henry the Sixth, Act V. Scene IV.
William Shakespeare (1564–1616)
The Oxford Shakespeare, 1914

Our daily experience hinders thinking about the earliest life of the Earth. Shakespeare could not imagine life in the dark. Neither could most biologists until the discovery in the 1980s that the tree of life begins with non-photosynthetic organisms (Chapter 9). Our distant ancestors lived in the dark, probably as microbes in cracks in rocks. We know some about this environment on the Earth from extant organisms. We know very little about its fossil life. Traditional geology considered the deposits within cracks in rocks to be unimportant, unless they contained economic minerals. Paleontologists eschewed these cracks in their search for fossils and still find them difficult to study.

Serpentine: Rocks for lunch. I return to serpentine as a prime habitable environment on rocky planets. It was likely to have been the most bountiful subsurface environment on the early Earth. It is a significant environment on the modern Earth.

Figure 5: Uplift several hundred million years ago and erosion by glaciers during the Ice Age expose the upper mantle in the foreground and the base of the oceanic crust (grey rocks on skyline). Mantle rock is magnesium-iron silicate $(Mg,Fe)_2SiO_4$. It has weathered somewhat and the ferrous iron near the surface has reacted with oxygen from the air. This rust makes the rock to be tan. (Petrologists call the rock dunite; the Scottish word for the color is "dun," which is also used for trout flies with this color.) Given time, circulating ground water will react with this rock forming serpentine. Only a few plants have colonized the surface. Lewis Hills, Newfoundland. Photo by the author.

We have already seen that serpentine with the aid of boron in solution facilitates the abiotic production of ribose (a building block of DNA) in Chapter 4 and a widespread seafloor environment in Chapter 8. The ferrous iron in serpentine reacts with water to form hydrogen H_2 (as discussed in chapter 8). On the modern Earth, hydrogen in seawater reacts with oxygen, feeding microbes. As discussed below, the oxygen that makes 21% of our air is the product of photosynthesis. It was not available before photosynthesis evolved. Note that there are other modest sources of hydrogen including ferrous iron reacting with water in basalt. Energetic particles from radioactive decay also separate some water into hydrogen and oxygen.

On the early Earth, microbes reacted hydrogen with carbon dioxide to gain energy. Biologists do not know if this was the first energy source, but it became an important one. Carbon dioxide was readily available, as it was a common component of volcanic gases from the midoceanic ridge and arc volcanoes. I have already discussed the effects of CO_2 in the atmosphere on climate (Chapter 7).

Thermodynamics and studies of modern microbes give biologists a good idea of the likely biological reactions. For simplicity, one reaction methanogenesis makes methane

$$4H_2 + CO_2 \rightarrow CH_4 + H_2O$$

hydrogen (in solution) + carbon dioxide (in solution) → methane (in solution) + water

An alterative reaction acetogenesis (acetic acid is a simple carbohydrate and here a proxy for organic matter in general, see Chapter 4) makes organic matter but yields somewhat less energy. In terms of simplified empirical formulas, it is

$$2H_2 + CO_2 \rightarrow H_2O + CH_2O$$

hydrogen (in solution) + carbon dioxide (in solution) → water + organic matter (carbohydrate in cell)

Both methanogen and acetogen microbes thrive on the modern Earth where CO_2 and H_2-rich waters mix. Interestingly, the key enzyme that catalyzes methanogenesis contains a nickel atom. Nickel is common in serpentine but rare in most terrestrial rocks. This is yet another hint that early life lived within serpentine.

Thermophile methogens exist. They and their low-temperature relatives draw down the limiting reactant to trace levels in a closed environment. Conversely, the coexistence of H_2 and CO_2 in quantity thus indicates sterility. This situation prevailed, for example, in a borehole into serpentine containing rocks within the San Andreas Fault where fluid temperature where about 135°C.

Ancient hydrogen-using microbes depended on abiotic sources, including rocks and volcanoes. These sources on the early Earth were quite limited compared with those from modern photosynthesis. The amount of carbon dioxide that became organic carbon per time "primary productivity" was less than 1 hundred thousandth that of modern productivity. Some modern methanogens use hydrogen that is metabolic byproduct of organic matter produced by photosynthesis.

Using energy: ATP and small change. Evolution has covered many of the tracks on how the earliest pre-cellular and cellular life converted chemical energy into useful products within the cell. Microbes are able to "eat" a variety of chemicals. They need to make a myriad of chemicals within their cells.

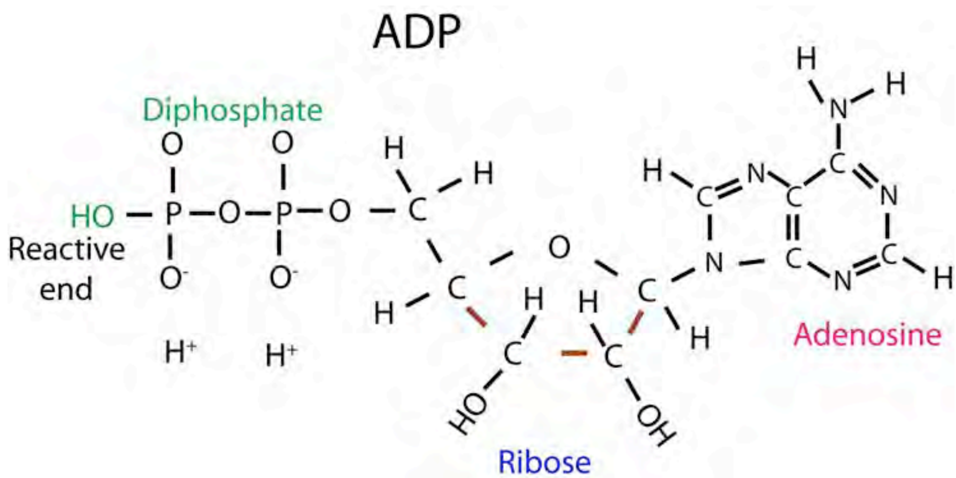


Figure 6: Bond diagram of ADP. The building blocks are ribose, adenosine, and 2 phosphate ions. The compound acts as an acid, releasing 2 H^+ groups.

One lifestyle would be to couple each and every energy-producing reaction from whatever the microbe eats to every energy-consuming reaction it needs to persist. This approach probably occurred early on apparently but proved wanting. Biologists have found no organisms that act in this way. Rather all cellular life uses ATP (adenosine triphosphate) as a common energy currency. It makes ATP from ADP (adenosine diphosphate) in the energy-producing reaction and then uses converts ATP back to ADT to drive an energy-consuming reaction.

The reactions are conceptually simple. Adding another phosphate group to ADP makes ATP. Removing the phosphate, reverses the process. Highly evolved catalysts in the cell recycle the ATP and ADP efficiently. The mitochondria in Eukaryote cells (including us) make almost all of our ATP, making them necessary endosymbionts.

A selective advantage of using ATP is that the energy producing biochemistry could tune itself to make only one product. Methanogens do this near the theoretical thermodynamic limit. The energy using biochemistry can tune to use ATP. Once evolved, ATP use was locked in. (It is not optimal when we eat sugar; we get only 40% of the theoretical energy as useful product.) A mutation that changes ATP to something else would modify lethally many of the chemicals in the cell.

In analogy, standard money makes commerce more efficient. Both you and a fast food outlet would find it inconvenient to barter a cow for 3 goats, 1 ten-speed bike, 8 chickens, a sandwich, French fries, and a soft drink. The merchant would not appreciate even having to take and make change in the 200 or so currencies in use today.

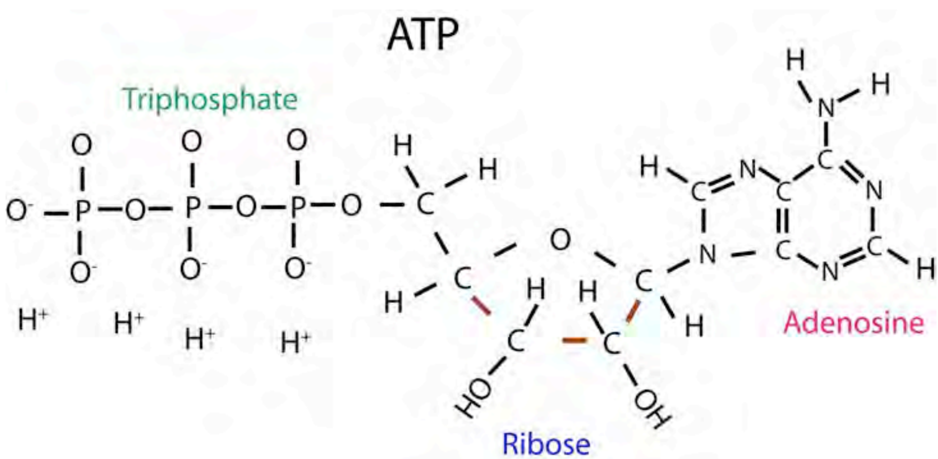


Figure 7: Bond diagram of ATP. The building blocks are ribose, adenosine, and 3 phosphate groups. The compound acts as an acid, releasing 4 H^+ ions. The additional phosphate stores energy in a retrievable form.

Returning to ATP and ADP, terrestrial life, like a *Lego* set, reutilizes basic building blocks. These molecules contain ribose and the base adenosine, blocks for making DNA and RNA. Cells can use ATP directly to make DNA.

Photosynthesis and the short-term carbon cycle

The Earth's surface now teems with life that depends on the photosynthetic primary producers of traditional ecology. Green plants and marine plankton taken in carbon dioxide and make organic matter and "free" oxygen,

$CO_2 + H_2O + \text{photons} \rightarrow CH_2O + O_2$ Carbon dioxide (in air or water) + water + visible light → organic matter (carbohydrates in cell) + oxygen (in air or water)

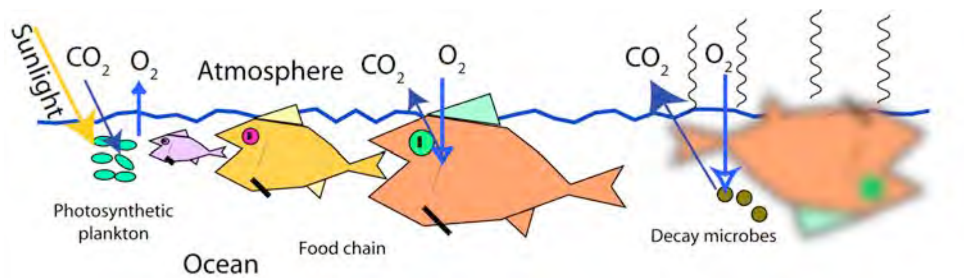


Figure 7: The short-term carbon cycle in the ocean. Plankton capture the energy of sunlight to make organic matter and oxygen from CO_2. Animals eat the plankton and each other. Respiration reacts organic matter and oxygen to make CO_2. Decay microbes have the same effect. CO_2 and O_2 exchange between air and water.

Animals regain some of the energy from the light (by making ATP) from the reverse of this reaction when they eat. Fungi and the microbes of decay and rot do the same thing. Some organisms, like yeast in a wine vat, take the reaction only part way, in that case sugar to ethanol. I discuss the sequence of events that led to modern photosynthesis and the somewhat unstable effects they had on the global environment.

Living at the surface. Photosynthesis faced a chicken and egg problem on the early Earth. Sunlight is lethal to many life forms. Its ultraviolet (UV) photons contain enough energy to break apart molecules. This causes us to sunburn. Barber shops and doctors offices once used ultraviolet lamps to sterilize equipment. Ultraviolet light was a more serious hazard on the early Earth. Ozone O_3 in the upper atmosphere (stratosphere, above 8 to 18 km elevation) now absorbs much of the incoming UV. The ozone, however, comes from molecular oxygen O_2 in the air that was hit by the UV radiation. This oxygen is the product of photosynthesis. The shield did not exist before life evolved this ability.

Strong selective pressures unrelated to photosynthesis favored microbes that tolerated surface conditions. First, the sea surface mixes with the air providing a food source from chemical disequilibria. The ancient air contained hydrogen from arc volcanoes and carbon dioxide, prime food for methanogens. It contained disequilibrium products of the photolysis (disruption by UV photons) of methane, including carbon monoxide, which is lethal to us but good food for some microbes.

Microbes at the sea surface had the first crack at the bounty but endured the greatest hazard from UV. The intensity of UV and visible light decreases gradually with depth. Green and blue light penetrate deeper than UV and red light. The continuous variation of conditions with depth drove selection. A microbe that could tolerate slightly shallower depths had an advantage.

Getting started with photosynthesis. The photosynthetic biochemistry in modern life is too complex to have originated as a single mutation. For example, the modern enzyme called rubisco contains 1000s atoms; it is involved with the subtask of managing the CO_2 used in photosynthesis. Like DNA, it uses a 5-carbon sugar as a building block. Rather photosynthesis evolved from traits useful for other proposes. Overall, photosynthesis controls and greatly promotes the reactions that photolysis does uninvited within cells exposed to sunlight.

An attractive possibility is that photosynthesis developed from light detection by motile microbes. Almost any complex organic compound is a pigment in the sense that it absorbs some visible wavelengths more than others. The pigments in our retina are similar to the pigments used in photosynthesis. Though complex and cloaked by time, microbes evolved to take advantage of reactions that were occurring anyway.

Light detection is useful in the deep sea as it is at the surface. Black smoker fluids vent at around 350°C. Microbes benefit by getting close to but not into the bountiful fluid. The vent fluid is not quite hot enough to produce visible (red) heat that we can see. It does produce infrared light with wavelengths just longer that visible red. There are vent-loving shrimp with highly evolved "eyes" on their backs for detecting infrared.

Then how did the ability to detect light become one to harvest it? I go back to the acetogen reaction where organic matter forms from hydrogen and carbon dioxide. This reaction proceeds and yields energy if the reactants are present in reasonable amounts and the microbe has suitable catalysts. It proceeds rapidly in some modern photosynthetic microbes. This trait (photocatalysis) could evolve gradually in an acetogenic microbe with some light detection ability. It went from getting a slight help from light in making organic matter to where it was dependent on the light to efficiently make organic matter. The biochemistry proved useful for other modes of photosynthesis that do not require hydrogen.

Photosynthesis without oxygen production. Oxygen-producing photosynthesis accomplishes two tasks for an organism. First it makes organic matter. For that task, it need merely rid itself of oxygen atoms that come in with the CO_2 or H_2O molecules. Second the organic matter is a store of energy. Like us, the photosynthetic organism can "eat" some of its organic matter by running the reaction backwards. Hydrogen-using photosynthesis does the first task but not the second. The back reaction consumes energy.

Free oxygen is toxic to many microbes. These organisms are now exiled to anaerobic environments in the subsurface and within other organisms where they are pathogens and symbionts. They dominated the early Earth before there was free oxygen. Extant photosynthetic microbes retain biochemical pathways that dispose of oxygen without freeing it. I discuss two of them that involve common elements on the Earth.

First, you may have seen or smelled the mess when someone tried to kill the algae in a small pond with copper sulfate $CuSO_4$. This compound is indeed toxic to pond algae and much of it does die. It is not toxic to many of the microbes that rot the dead algae. These organisms run the photosynthetic reaction backwards using up the free oxygen in the pond. Any fish still alive then die adding to the rot.

The pond does not become sterile once the oxygen in gone. Anaerobic microbes react the sulfate with organic matter to make ATP.

$$2CH_2O + SO_4^{--} \rightarrow 2CO_2 + S^{--} + 2H_2O$$

organic matter (in rot) + sulfate (ion in water) → carbon dioxide (in solution in water) + sulfide (ion in water) + water

Much of the sulfide combines with the water to form hydrogen sulfide gas.

$2H_2O + S^{--} \rightarrow H_2S + 2OH^-$

water + sulfide (ion in water) → hydrogen sulfide gas + hydroxyl (ion in water)

In small quantities, hydrogen sulfide has a potent unpleasant smell, like its source in rotten eggs. In larger quantities, it is lethal to humans. Again toxicity is in the eye of the beholder. Photosynthetic microbes make new organic matter from the output of the decay organisms,

$2CO_2 + S^{--} + 2H_2O + \text{photons} \rightarrow 2CH_2O + SO_4^{--}$

carbon dioxide (in solution in water) + sulfide ion (in water) + water + light → organic matter (in cell) + sulfate ion (in water)

The pond is a system with a closed cycle of carbon and sulfur. Biologists call it a sulfuretum. It occurs naturally, for example, in stagnant dense salt water beneath fresh water in fjords and deep within thick microbial mats in shallow seawater.

Second if you hike, you have probably seen rusty water around rock outcrops. Ferrous iron is soluble in water. Organisms react it will oxygen from the air to make ferric iron

$4Fe^{++} + 10H_2O + O_2 \rightarrow 4Fe(OH)_3 + 8H^+$

ferrous ion (in solution) + water + oxygen (in solution) → ferric hydroxide (rust) + hydrogen ion (in solution)

This reaction also occurs underground whenever surface waters or seawater circulates through rocks. Over time, deeply weathered rock and soil becomes red on the modern Earth as its ferrous iron rusts. You are probably familiar with red soils if you live in a region where glaciers have not recently removed the surface rocks.

The ferrous iron remained in solution on the early Earth because there was no free oxygen to rust it. It was a voluminous oxygen sink for photosynthesis

$$CO_2 + 4Fe^{++} + 11H_2O + \text{photons} \rightarrow CH_2O + 4Fe(OH)_3 + 8H^+$$

carbon dioxide (in solution in water) + ferrous ion (in water) + water + light → organic matter (in cell) + ferric hydroxide (rust) + hydrogen ion (in water)

Extant microbes make organic matter by this reaction. Rot microbes run the reaction in reverse to gain energy. As with a sulfuretum, both iron and carbon have a complete cycle.

Oxygen-producing photosynthesis. We breathe oxygen produced by photosynthesis and eat the plants that made the oxygen. However, oxygen was not present on the early Earth before microbes made it. Trace amounts produced by photolysis and radiolysis reacted with ferrous iron to rust rocks.

Why then did oxygen-producing photosynthesis evolve. First, photosynthesis needs an oxygen sink. Sulfate and ferric iron-producing photosynthesis grind to a halt once the sulfide and ferrous iron are exhausted. Second, oxygen is toxic to many organisms. A microbe that can tolerate it in quantity eliminates some of its competition. As an analogy, wine yeast kill competitors when they make ethanol, an ingredient in many antiseptics.

In this case, evolution has not covered all of its tracks. The oxygen-making "photosystem" within one-celled cyanobacteria formed from the fusion of two simpler photosystems from the fusion of two microbes. Cyanobacteria probably arose on land where there is a dearth of ferrous iron and sulfide in well-drained fresh water and soils. Later some descendents of the first cyanobacteria probably evolved in sulfide-rich marine waters. They use copper, which is now rare in seawater but was common in a sulfide-rich ocean. As noted above, chloroplasts in green plants are the descendents of endosymbiont cyanobacteria.

Rubisco is a good example were evolution locked in a serviceable but non-optimal trait. Much of biochemistry of a plant depends on it. Rubisco cannot be changed a lot without killing the cell. It evolved when the concentration of CO_2 was much higher than the current levels in the atmosphere. However, many organisms, including maize and pineapple, have evolved molecular mechanisms to endure a dearth of CO_2.

Overall photosynthesis in plants is inefficient. It makes poor use of green light; plants are green. Genetic engineering to greatly improve or replace the current biochemistry is exceedingly dangerous. The improved organism could out compete plants and marine plankton if it got loose.

Oxygen atmosphere

Evolution of oxygen-producing photosynthesis caused a major crisis for life and climate. As already noted, oxygen is a toxic. Too much of it not good even for us and it is lethal for many anaerobic microbes. In addition, the greenhouse gas methane cannot coexist in quantity with free oxygen in the atmosphere.

I discuss the timing before discussing the problems that oxygen caused. The build-up of free oxygen may not have immediately followed the evolution of oxygen-producing photosynthesis. The short-term carbon cycle works with oxygen being a trace constituent of the atmosphere and the ocean as well as with it being a major one. That is, the short-term cycle produces equal amounts of organic matter and oxygen. Molecular paleontologists distinguish between evidence for oxygen-producing organisms from that for oxygen in the air.

Primer on the long-term carbon cycle. In addition to the short-term cycle of photosynthesis and decay, carbon has a long-term cycle involving the crust and mantle on scales of millions to billions of years. This cycle played a major role in the build up of oxygen in our air. Tectonics determines its rate (Chapter 8). The cycle is vigorous on the modern Earth. It has slowed to a snail’s pace on Mars. I start with sources and then go to sinks.

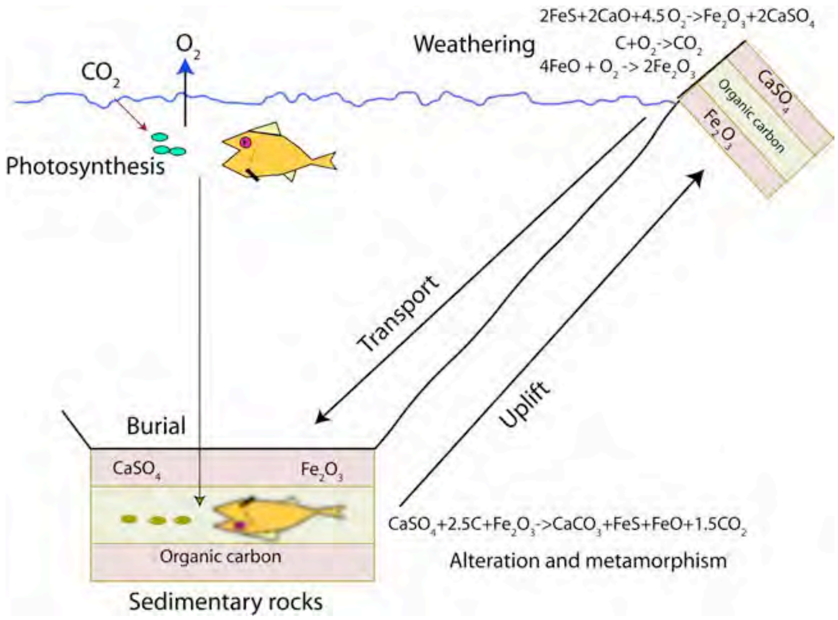


Figure 8: Long-term carbon and oxygen cycle. Photosynthesis produces organic matter and oxygen from CO_2. Dead organisms sink to the seafloor where they are buried within sedimentary rocks. Sulfate (represented as $CaSO_4$) and ferric iron from weathering accumulate in the sediments. Microbial alteration and metamorphism react the organic matter with the sulfate and the ferric iron to form carbonate, sulfide (represented as FeS), ferrous iron, and CO_2. The sediments and metamorphic rocks formed from them are uplift and exposed to erosion. Weathering produce ferric iron, CO_2, and sulfate that enter surface environments and eventual are transported to the ocean. Only a few simple reactions are given and pyrite FeS_2 is omitted for brevity.

The crustal cycle involves the erosion and deposition of sedimentary rocks, the rock cycle studied by Hutton. I start with carbonates, such as limestone (calcium carbonate $CaCO_3$), that dissolve in rainwater. Streams carry the water to the ocean. There is also reduced carbon of organic origin in sediments. This includes coal, oil, and natural gas. However, most of the material is distributed within rocks like shale (mud turned to rock at a depth of a few kilometers in the Earth). This carbon oxidizes at outcrops with the help of microbes. It enters the surface cycle as carbon dioxide in the air.

The carbon atoms mix from carbonate and organic sources mix in the air and in the water. Each one goes through rapid cycle of photosynthesis and decay about 200 times before it gets buried again in a few ten thousands of years. About 20% of the buried carbon is organic and 80% carbonate. The eroded rocks have about the same ratio. The process just moves carbon from one place to another. There is no net change in the amount of oxygen in the air or net composition of carbon in sediments.

Tectonics carries some of the buried carbon down to depth of several kilometers and temperatures of several hundred degrees Celsius, where carbonates are unstable. The carbonate reacts with silica to form calcium silicates and CO_2:

$CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2$

Calcium carbonate (limestone) + silicon dioxide (quartz in rock) → calcium silicate (in rock) + carbon dioxide (gas or in solution)

Chapter 7 includes discussion of the effect of this reaction on climate. The resulting metamorphic rock is a type of marble.

Common igneous rocks like basalt, as well as marble, contain calcium silicate as a component. These rocks weather at the surface. This reverses the reaction in two steps

$CaSiO_3 + H_2O \rightarrow Ca^{++} + 2OH^{-} + SiO_2$

Calcium silicate (in rock) + water → calcium ion (in water) + silicon dioxide (in water)

Silicon dioxide is not very soluble in water, about 10 parts per million. Diatoms remove it to make shells. It would have precipitated abiotically on the early Earth. The calcium ion enters the ocean. There it has the net effect of removing CO_2

$Ca^{++} + 2OH^- + CO_2 \rightarrow CaCO_3 + H_2O$

Calcium ion (in water) + hydroxyl ion (in water) + carbon dioxide (in water) → calcium carbonate (limestone) + water

Magnesium silicate $MgSiO_3$ is a component of many igneous rocks along with olivine Mg_2SiO_4, which forms serpentine. Magnesium carbonate $MgCO_3$ is a component of natural carbonate sediments. It behaves analogously to these calcium reactions.

We need to consider the involvement of sulfide and ferrous iron in eroded rocks in the cycle. We have already seen that rock rusts at outcrops. The net effect of oxygen producing photosynthesis and rusting is the same as ferric-iron-producing photosynthesis. Atmospheric oxygen also reacts with sulfide in rocks. An idealized reaction is (here only sulfur is oxidized because ferrous iron oxidation was considered above)

$FeS + 2O_2 + H_2O \rightarrow FeO + H_2SO_4$

Iron sulfide in rocks + oxygen (in water) + water → ferrous oxide (in solution) + sulfuric acid (in solution)

This produces sulfate and has the net effect of sulfate-producing photosynthesis. Microbes get energy from this reaction. The reaction occurs where mining has exhumed lots of sulfide. The effluent is acid mine drainage. It is toxic to common stream life but not to specialized organisms.

Sulfate in solution and as calcium sulfate ($CaSO_4$ used to make plaster) are buried within sedimentary rocks. So is ferric iron from rusted rocks. Microbes gain energy by reacting these substances with organic matter. The reactions proceed abiotically during metamorphism. The net effect is that buried organic carbon reacts with sulfate and ferric iron.

The mantle cycle is similar to the crustal cycle except that it is sluggish. Processes at the midoceanic ridge have a major effect. Carbon dioxide degases from freezing basaltic lava. Hot black smoker fluids carry it into the ocean. A few kilometers away from the axis, warm about 50°C fluids, carry seawater downward into the basalt. Calcium ion in the basalt reacts to form carbonate. The circulation carries additional calcium back into the ocean. Overall the ridge axis is a net sink of CO_2 from the ocean and a net source of calcium to surface environments. About half of the calcium we find in sediments came form this source. Geochemists figured this out by noting that there is far more calcium in an average sedimentary rock than could come from eroding any reasonable source mixture of igneous rocks.

Seafloor spreading then carries the oceanic crust to a subduction zone. In the meantime, the seafloor accumulates carbonate and organic carbon containing sediments. The sediments get subducted carrying the carbonate and the basalts down to great depth. Much of the carbon returns to the surface at arc volcanoes. It is unclear whether plate tectonics are currently a net source or sink of carbon to surface environments.

Rock sinks for oxygen. It is tempting to view the build up of oxygen in the air as the result of the burial of organic carbon. This is true on an intermediate-term scale of millions of years. Over longer time scales, atmospheric oxygen has many enemies and a few friends. These processes have left wide tracks in the rock record. The oxygen that we breathe in the air is a small entry in the total global ledger.

Figure 9: Rock rusts in a soil profile exposed by digging in coastal central California. Cedars area. Photo by author.

Geochemists know that there is little ferric iron and much ferrous iron in the igneous rocks like basalt that come from the Earth's mantle. The sulfur is mainly in its reduced form sulfide. Sediments contain much oxidized iron and sulfur, the equivalent of several global present atmospheres worth of oxygen. There is much ferric iron in crustal rocks that have formed by melting material that was once near the surface. Red granite is an example. We also see buried organic carbon in sediments, but there is about twice has much buried oxygen as buried organic carbon. We really do not know the long-term flux from subduction of sediments. Both organic carbon and ferric iron in sediments return to the mantle.

Hydrothermal activity at the mid-oceanic ridge axis was an oxygen sink once sulfate-producing photosynthesis evolved and sulfate was present in seawater. At present, sulfate-bearing seawater enters hydrothermal systems. The sulfate reacts with ferrous iron to form sulfide and magnetite at temperatures above 200°C.

$SO_4^{--} + 12FeO \rightarrow 4Fe_3O_4 + S^{--}$

Sulfate ion (in water) + ferrous iron (in rock) → magnetite (in rock) + sulfide ion (in water)

Part of the sulfide comes out of hydrothermal vents and part forms iron sulfide in the rocks

$S^{--} + FeO + H_2O \rightarrow FeS + 2OH^{--}$

Sulfide ion (in water) + ferrous iron in rock + water → iron sulfide (in rock) + hydroxyl ion (in water)

At the high temperature deep in the circulation, the reaction goes to the left. The sulfide removed from the rock vents through the black smokers.

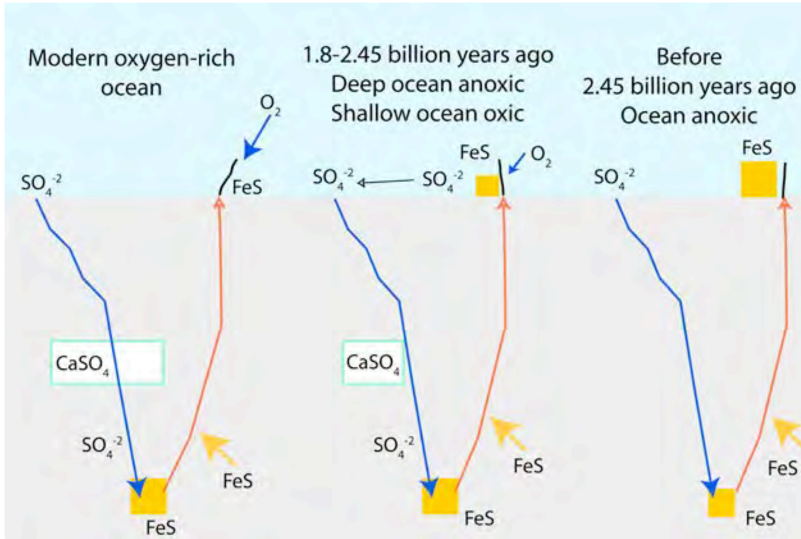


Figure 10: (left) Cold water carries sulfate into ridge-axis hydrothermal systems. On the modern Earth, most of the sulfate precipitates has anhydrite, which dissolves and returns to the ocean once the rock cools. The remaining sulfate continues downward into the hot part of the system were it reacts with the rock to form iron sulfide. The amount of sulfide produces (equivalently the sulfate consumed) is independent of the concentrateion of sulfate in the downgoing water. The hot water dissolves sulfide from the rock and carries to the surface where it reacts with oxygen in the seawater. (middle) Between 1.8 and 2.45 billion years ago, the surface ocean was oxic. Anhydyrite formation limited the amount of sulfide produced from seawater sulfate. There was not enough oxygen in the seawater to oxidize the sulfide vented to the seafloor. This oxygen sink kept the deep ocean anoxic. (right) Before 2.45 billion years ago, the ocean was anoxic. Sulfate entering hydrothermal systems reacted to form sulfide. Sulfide vented to the seafloor did not get oxidized.

The circulation is a significant oxygen sink but not a major sulfur source or sink to surface environments. If we define the sulfate that heads down into the circulation to be 1 unit for simplicity, 1/10 of a unit becomes sulfide and stays in the rock. An additional 1/10 unit of sulfide comes from the rock. Sulfides precipitate near the vent when the hot water mixes with cool seawater. The rest 9/10 of the downwelling sulfate forms calcium sulfate (anhydrite, $CaSO_4$) at temperatures around 150°C in the downwelling fluid.

$Ca^{++} + SO_4^{--} \rightarrow CaSO_4$

calcium ion (in water and from basalt) + sulfate (in water) → calcium sulfate (in rock)

The calcium sulfate dissolves and returns to the ocean when the rock cools as it moves away from the ridge axes. It is neither an oxygen sink nor a sulfur sink. In the modern ocean, the sulfide deposits oxidize by reacting with dissolved oxygen in the seawater. This removes oxygen from the ocean and ultimately from the air.

Methane and excess oxygen. I have already commented on the excess oxygen relative to organic matter in crustal and sediment reservoirs. One could attribute this to subduction of organic carbon bearing sediments. I have already discussed methane as a climate buffer. It is also a potent net oxygen source.

As discussed in Chapter 7, methane is not cold trapped at the top of the troposphere. Instead in ascends to where photolysis decomposes it,

CH_4 + photons → C + $2H_2$

Methane (gas) + UV light → carbon (really complicated organic haze) + hydrogen (gas)

The hydrogen gas then escapes from the atmosphere. The haze settles to the surface and enters the biological cycle. Eventually biological reactions cause the carbon to enter methane. The hydrogen in the methane ultimately comes from water. The net effect is

C + $2H_2O$ → CH_4 + O_2

Carbon (haze) + water → methane (gas) + oxygen (gas)

The process proceeds without free oxygen as making ferric iron from ferrous iron or sulfate from sulfide are oxygen sinks.

In fact, the escape of methane to space ended when free oxygen became present in the air in more than trace quantities. Methane and oxygen react rapidly. If there are large comparable quantities of both, a spark will set of a violent explosion. (You have been taught not to look for gas leaks with a match.) Microbes eat the mixture when it is present in trace quantities. Photolysis in the air reduces whichever gas is limiting to minute quantities. That is, methane photolysis and hydrogen escape got the atmosphere to the edge of having free oxygen but could not have caused the free oxygen itself.

Oxygen events in Earth history. To reiterate, the rock cycle is a major oxygen sink. The hard-rock crust of the Earth and the sedimentary mass have been oxidized through geological time. The process became important has soon as there was ferric iron and sulfate-producing photosynthesis. The escape of hydrogen to space allowed the amount of oxidation to exceed the amount of organic matter buried in sediments.

Hydrothermal circulation removes oxygen within sulfate the ocean and hence oxygen from the surface system. This process did not become important until there was significant sulfate in the ocean. The flux of sulfur and oxygen reached its present level once the sulfate level in the ocean was 1/10 the present. Additional sulfate in seawater formed calcium sulfate that later re-dissolved.

Oxidation of sulfides vented on the seafloor directly removes oxygen from the ocean. The sink did not exist until there was dissolved oxygen in the ocean. The flux reached its maximum present level when all of the vented sulfide oxidized.

Classically, geologists examined ancient sedimentary rocks to see when oxygen built up in the air and the ocean. They see evidence that there was little oxygen on the early Earth. Minerals like pyrite (fool's gold FeS_2) and pitchblend (uranium oxide UO_2) that quickly oxidize at the modern surface occur within sediments. These minerals are not common in sediments younger than 2.5 billion years. Younger sediments show evidence of oxidation. Sandstones younger than that age are frequently red from ferric oxide (Fe_2O_3). For example, 200 million year old red sandstones outcrop in the Connecticut Valley and New Jersey. They provide the building blocks for brownstone houses in New York City.

Figure 11: 1.9 billion year old iron formation accumulated on the seafloor where deep ferrous iron bearing waters mixed with shallow oxygen-bearing waters. Upper Peninsula of Michigan. (photo by the author)

Geologists also see evidence that the early ocean was reduced. The transition from reduced at 2.5 billion years to oxidized at 1.85 has an important economic consequence.

During this time the deep ocean was reduced and ferrous iron (FeO) was soluble. The shallow ocean had some dissolved oxygen. As occurs now, the deep water upwelled to the surface. There the ferrous iron encountered oxygen and microbes oxidized ferrous iron to insoluble magnetite (Fe_3O_4) and ferric iron (Fe_2O_3). These minerals settled to the seafloor forming sedimentary iron formation. It is now the major source of iron ore for commerce. Deposits exist in the Upper Peninsula of Michigan, Canada, and Australia. Much of your car came from these mines.

Evidence from isotopes. This is where the discussion would have ended in 1960 or 2000. The results seemed reasonable, but doubts remained. A minority of geologists contended that there was significant oxygen in the air by the time of a decent rock record at 3.5 billion years and that the sedimentary pyrite and iron formations reflected widespread though local conditions. Improved equipment and the penchant to measure recently quantified the advent of atmospheric oxygen.

I retreat in historical time to the 1950s and 1960s. Recalling chemistry in Chapters 4 and 7, the number of protons in an atom determines what element it is and most of its chemistry. Atoms of the same element can have different numbers of neutrons; or in chemical terms, an element can have different isotopes. Carbon has two stable isotopes. They are ^{12}C (6 protons and 6 neutrons) and ^{13}C (6 protons and 7 neutrons). About 1% of natural carbon is ^{13}C and 99% ^{12}C. This ratio, however, is not constant in nature as the chemical properties of the isotopes differ slightly. To compact notation, geochemists express relative changes as parts per thousand. They define

$$\delta^{13}C \equiv 1000 \times [^{13}C/^{12}C_{sample} - ^{13}C/^{12}C_{standard}] / ^{13}C/^{12}C_{standard}$$

The standard is arbitrary by convention. In the case of carbon, it is a belemnite (a cephalopod, relative of squid) fossil made of carbonate from the eastern United States. The organism lived in the ocean, which has not changed a lot over time; hence marine sedimentary carbonates in general have values near the standard, that is, $\delta^{13}C$ is near 0.

Photosynthetic microbes prefer ^{12}C; $\delta^{13}C$ is about –25. This is also true of land plants except that some grasses like maize (including popcorn) do not fractionate isotopes. Sedimentary organic carbon scatters around this value. Methanogens produce methane with $\delta^{13}C$ around –50. This lets geochemists distinguish biogenic from abiogenic methane.

To the first order, the carbon isotope cycle as behaves as a closed system. The mantle $\delta^{13}C$ value of the ultimate source of sedimentary carbon is about –6. A mixture of 80% of the carbon as carbonate and 20% as organic has this average value.

Geochemists measure carbon isotopes in both ancient carbonates and ancient organic-rich sediments. They see carbon isotope fractionation from the mantle value in all their samples. There are well-preserved rocks by 3.5 billion years. The oldest sediments from the Issua area of Greenland are 3.8 billion years old. These rocks show carbon isotope fractionation. However, they were once heated to around 800°C at depth in the Earth. It is conceivable that an abiotic process fractionated the carbon isotopes in these rocks.

Overall, one sees evidence of life with photosynthesis in any terrestrial rock wherever one might expect evidence to be preserved. The carbon isotopes are little help in telling whether the photosynthesis produced free oxygen rather than ferric iron or sulfate.

The isotopes of sulfur provide further evidence. Sulfur has 4 stable isotopes. The common isotope is ^{32}S (95%, 16 protons, 16 neutrons); ^{34}S (4.23%, 16 protons, 18 neutrons) is fairly common. There are two rare isotopes, ^{33}S (0.75%, 16 protons and 17 neutrons) and ^{36}S (0.02%, 16 protons, 20 neutrons). The standard is sulfur from a meteorite. The earth's mantle and basalts derived from it also have this value. This is yet more evidence that the Earth accreted from material with the composition of meteorites.

Until recently, geochemists measured only the ratio $^{34}S/^{32}S$ and used $\delta^{34}S$ notation. A large fractionation occurs when microbes reduce sulfate from seawater by reacting it with organic matter in sediments. The microbes preferentially take in the lighter isotope ^{32}S; $\delta^{34}S$ is thus negative in the sedimentary sulfide and positive in the sulfate that remains in the water. The difference in $\delta^{34}S$ between sulfate and sulfide can be up to 70 per mil. Significant fractionation occurs in sedimentary sulfide and sulfates throughout the last 3.5 billion years of Earth history when there are good samples. The effect is easy to measure. In fact, it is large enough that it posed a puzzle before isotopes were understood. My mother's 1920s chemistry book warned to measure the atomic weight of sulfur before using it. Modern chemists do this measurement to check the accuracy of their laboratory techniques.

Until about 2000, geochemists did not routinely measure the rare isotopes ^{33}S and ^{36}S. They expected that their fractionation would depend on the mass difference. That is, $\delta^{33}S$ would be 1/2 $\delta^{34}S$ and $\delta^{36}S$ twice $\delta^{34}S$. Careful measurements showed that this relationship does not in fact occur. Samples of sediments deposited before 2.45 million years ago show scatter about the expected correlation, that is, mass independent fractionation. Mass independent fractionation is small for samples dated between 2.45 and 2.2 billion years and tiny but still measurable for younger samples.

How did mass independent fractionation occur before 2.45 billion years ago? Biologists and geochemists have excluded some of the likely suspects. They have studied various organisms that use sulfur. Mass independent fractionation is tiny, but tags the type of organism. It is also tiny in hydrothermal, volcanic, and metamorphic processes.

We need to look at the sky. Volcanoes today put sulfur into the air, mainly as hydrogen sulfide H_2S and sulfur dioxide SO_2. Biology produces various volatile sulfur compounds. Dimethyl sulfide $(CH_3)_2S$ is the most common in the modern atmosphere. Marine plankton produce it.

Photolysis from UV light decomposes these sulfur compounds. The absorption lines are slightly different for molecules with different sulfur isotopes. There are lots of molecules with the common isotope ^{32}S and the next most common isotope ^{34}S. Photons with the correct wavelength for photolysis are absorbed high in the atmosphere. The UV light at lower elevations lacks them. The other two rare isotopes ^{33}S and ^{36}S do not occur within enough molecules to have this effect. Photons with the correct wavelength continue down into the lower atmosphere where photolysis preferentially affects the rare isotopes.

Photolysis does not affect the total amount of say ^{33}S in the air, but it does produce a group of molecules that is enriched in it and a group that is depleted. On the present Earth, both molecules react with the abundant oxygen in the air. The sulfur comes down oxidized as sulfate, for example, as sulfuric acid H_2SO_4 (the ingredient of acid rain). The sulfate mixes into the ocean, a huge reservoir. This recombines the ^{33}S-rich and ^{33}S-poor fractions, leaving no record. This recombination did not occur before there was oxygen in the air. Even a few parts per million of the gas suffices to convert the sulfur in sulfate. The transition, 2.45 billion years ago marks the rise of significant oxygen in the atmosphere. It also marks the advent of oxygen in the upper 100 meters (or so) of the ocean that mixes with the air. It is tempting to associate this transition with the time that sulfate in the ocean reached 1/10 the modern level and further increases in sulfate did not increase the flux of it into the seafloor.

The deep ocean probably remained anoxic for some time. The end of common sedimentary iron formations at 1.85 billion years ago may mark when the deep ocean became oxic. There is some evidence of this from iron isotopes. Iron has four stable isotopes with masses of 54, 56, 57, and 58. A transition in the preserved fractionation of these isotopes does occur at that time, but the modern system and the biology are not yet well enough understood to extrapolate.

Snowball Earth: Trial by ice

The advent of atmospheric oxygen was a somewhat unstable evolutionary event on the Earth. The concentration of the gas built up slowly. Some organisms, like our distant microbial ancestors, evolved the ability to efficiently oxidize organic matter. Other organisms evolved the ability to tolerate it. These include open ocean hydrogen-using photosynthetic organisms. In this case, the hydrogen is a product of photosynthesis and decay rather than hydrothermal vents. Other organisms evolved to avoid oxygen. Their descendants inhibit the subsurface and even our guts. They can infest a puncture wound.

Oxygen gas had a profound effect on the climate. Methane is a powerful greenhouse gas. The trace amount from natural swamps, rice and cattle farming, and garbage has a significant effect at present. Methane was a minor component of the atmosphere on the early Earth. Its concentration dropped to trace levels once oxygen was present.

Ancient sediments preserve an excellent record of this event. Glacial deposits do not occur before 2.45 billion years ago. The exception is the 2.9 billion year old Pongola sequence in southern Africa. Interesting limited sulfur isotope data indicate that this may be a brief period when the air contained oxygen. Glacial deposits become common after 2.45 billion years ago. The Huronian sequence in north of Lake Huron in Canada and in adjacent Michigan is a well-studied example.

Evidence from a limited rock record indicates that these glaciers like the modern ice age were regional events at high to middle latitudes. Open water and photosynthesis persisted near the equator. The ice covered some niches for life but created others.

Glaciers in the rock record. Scientists are intrigued by the last major glacial epochs in the Precambrian. Deposits occur worldwide. There are two major episodes named after localities in southern Australia. The Sturtian event occurred between about 710 and 680 million years ago. The Marinoan event occurred between 605 and 585 million years ago. There were also slightly younger events including the glacial deposits near Boston that caused confusion in the early debates on continental drift.

Widespread glaciation in Australia, southern Africa, and Death Valley, California, as well as northwestern Canada and Norway did not surprise modern geologists. There as been a lot of time for continental drift since then. The deposits could well have formed near the poles and some of the localities since moved to hot desert regions.

Dawn Sumner, then an undergraduate working with Joe Kirshvink and Bruce Runnegar, examined deposits in Australia. They measured the direction of magnetization in sedimentary rocks containing the glacial interval, the same method used to study continental drift. They were wary; sedimentary rocks can be magnetized well after their time off deposition. In that case, the direction of magnetization would provide no information about the glaciation.

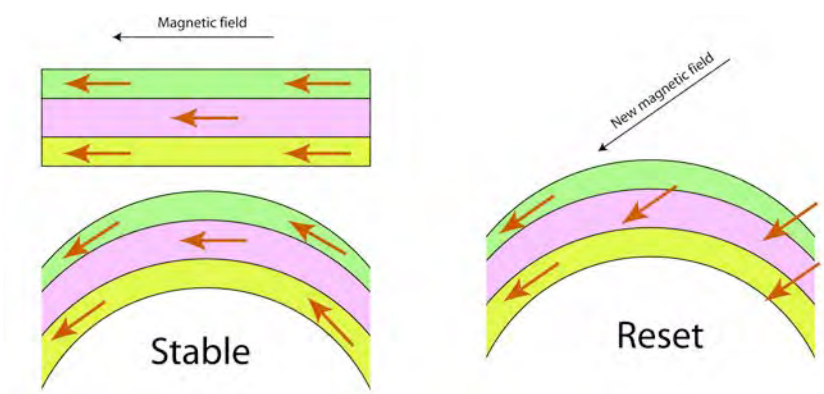


Figure 12: (Top left) layers of sedimentary rocks accumulate at the surface at the equator. The direction of magnetism with the rock (red arrows) aligns with the horizontal direction of the Earth's magnetic field. (Bottom left) Later folding deforms the layers. A stable direction of magnetism folds with the rocks. (Right) If the rocks were magnetized after folding the direction of magnetism in the rock would align with the direction of the Earth's magnetic field after the folding. The magnetic direction is parallel to the beds only on the left side of the fold.

Their rocks, however, were sediments deposited on an unstable slope. Piles of sediment had slumped before being covered with later flat-lying subsequent deposits. If the sediments were magnetized later than the slumping, the direction of magnetization would be the same in all the beds. If they were magnetized before slumping, the direction of magnetization would have folded with the beds. They showed that the latter case occurred. The rocks were magnetized at the time of deposition. The magnetization and the glaciers were near the Equator. Subsequent work has confirmed this result. Was the entire Earth covered by ice?

Did the ocean and the continents freeze over? Late Precambrian rocks are too rare to establish that ice covered the Earth. Geologists thus focus on indirect evidence. Geological attention has focused on "cap" carbonates immediately above the glacial deposits. They indicate the return of the conditions we expect from the tropics. Carbon isotopes provide unexpected evidence. The composition $\delta^{13}C$ of the carbonates is that of a mantle source. One interpretation is that the ocean froze over. Carbon dioxide from volcanoes build up in the air until the greenhouse became hot enough for ice to melt. Most of the photosynthetic organisms had died off during thee ice age. The cap carbonate represents aboitic deposits that took in CO_2 with the volcanic composition because there was no sink in organic carbon. The climate may have been quite hot, like 80°C until the excess CO_2 ended up in carbonates.

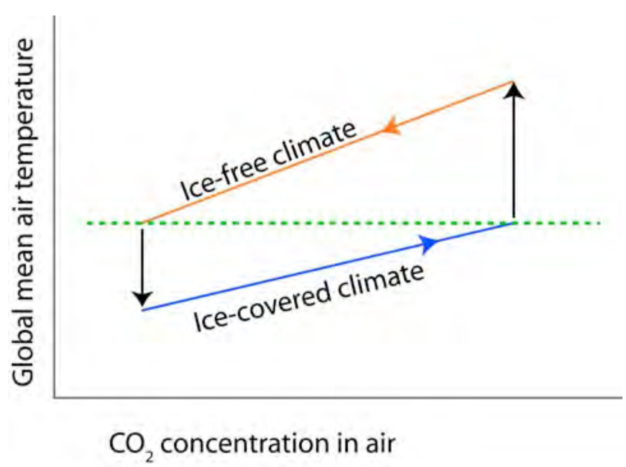


Figure 13: The Snowball Earth climate cycle has an ice-free and ice-covered branch. An ice-free climate consumes CO_2 lowering the global temperature. The temperature becomes cold enough that global freezing occurs and the planet becomes ice covered. CO_2 builds up in the air until melting occurs. The climate then jumps to being ice-free. A loop takes tens of million years. The extent of local and seasonal ice-free water during the cold part of the cycle and the maximum temperature just after deglaciation are unknown.

Primer on climatic belts: Grab the brass ring. Meteorologists have good enough understanding of the climate on the modern Earth that they can extrapolate generalities into the deep past including Snowball Earth. I present a phenomenological discussion. I begin with what may seem a digression: the climate near mountains.

As discussed immediately below prevailing winds exist over much of the world. On the west coast of the United States, winds blow from west to east. (By convection, the west wind comes from the west and blows to the east.) The west sides of the Sierra Nevada and other ranges along the coast are wet. The climates in Nevada, eastern California, eastern Oregon, and eastern Washington are dry.

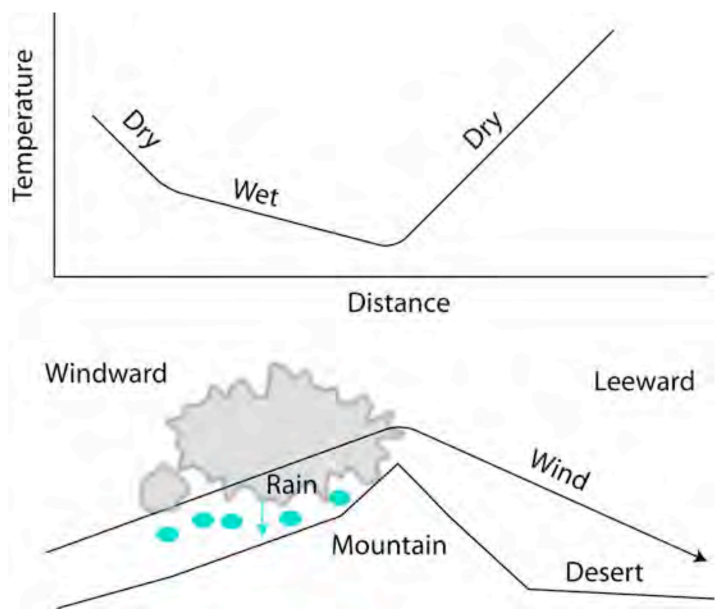


Figure 14: Prevailing winds carry air over a mountain range. The rising air cools, becoming saturated with water. Precipitation falls on the windward side. The air on the leeward side is hot and dry.

Air ascends as it blows over the mountains. As discussed in Chapter 7, ascending air cools by about 10 K per kilometer. It eventually becomes cold enough that water vapor condenses as clouds and precipitation falls to the ground. The air then ascends along a "wet" adiabat (about 6.5 K per kilometer) where it is saturated with water. Once over the mountain, the air descends heating up by 10 K per kilometer. The descending air is hotter (at a given elevation) then it was on the windward side of the mountain. This heat to do this comes from the latent heat of the water vapor that condensed and became rain. In general, precipitation occurs beneath ascending air. This air on its descent is hot and dry.

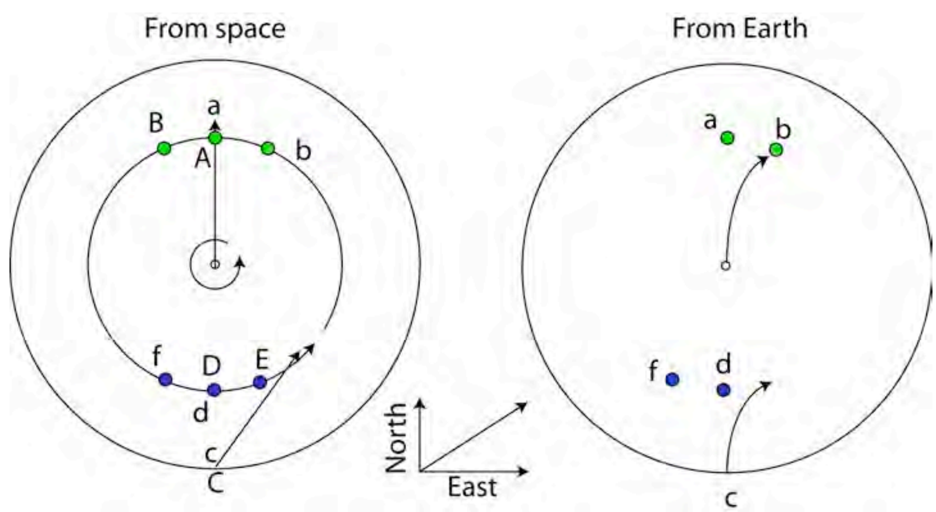


Figure 15: Turntable model of wind circulation looking down on North Pole. (left) A projectile (representing an air mass) starts from the pole due south toward point a on the turntable and point A in "fixed" space. While the projectile moves south the turntable rotates so that point a on the turntable is at point B in space and point b on the turntable is at point A in space. (right) The projectile arrives at point b. An observer on the Earth sees the air mass curve clockwise. (left) An observer at the edge of the turntable (point C in space) attempts to aim due north at point d on the Earth and point D in space. The rotation of the turntable adds to the launch velocity (inset) and the projectile heads east of point E in space. The turntable rotates while the projectile moves. (right) An observer on the Earth sees the air mass curve clockwise.

I now apply the effects of ascending air and descending air to the global climate. For the snowball Earth, we are concerned with areas of intense precipitation and dry areas with net evaporation. As Torrcelli inferred, temperature differences in the air power the winds. The tropics receive more sunlight that the Polar Regions and are hence hotter. The hot air at the equator rises and the cold air at the pole sinks. If the Earth did not rotate, the cold air from the poles would flow all the way to the equator. The rotation of the Earth makes actual climate more complicated.

I discuss the physics using the analogy of carousels in amusement parks. At some parks, one can get a free ride by grabbing a brass ring and throwing it through the mouth of a picture of a clown. The rotation of the carousel makes this task difficult. The ring once thrown appears to curve to the riders but to move straight to bystanders. You can also observe this effect by playing catch on a merry-go-round in a children's park.

The atmosphere behaves somewhat like the ring projectile in that it is only weakly coupled to the ground. I start with a projectile released at the pole of the carousel, representing cold air headed south from the pole. A viewer from space sees that the projectile moves in a straight line. An observer on the carousel rotates beneath the projectile and sees it curve clockwise. The wind represented by the projectile approaches from the north and east.

The observer now throws a projectile from the edge of the carousel, representing air flowing northward from mid-latitudes. The motion of the carousel adds to the velocity imparted by the observer. An observer from space sees that the path is well to the right of the intended direction. The carousel again rotates under the of the projectile, but the velocity of the carousel at the edge is greater than the velocity near the center. The observer sees the projectile curve clockwise. The wind represented by the projectile approaches from the south and west.

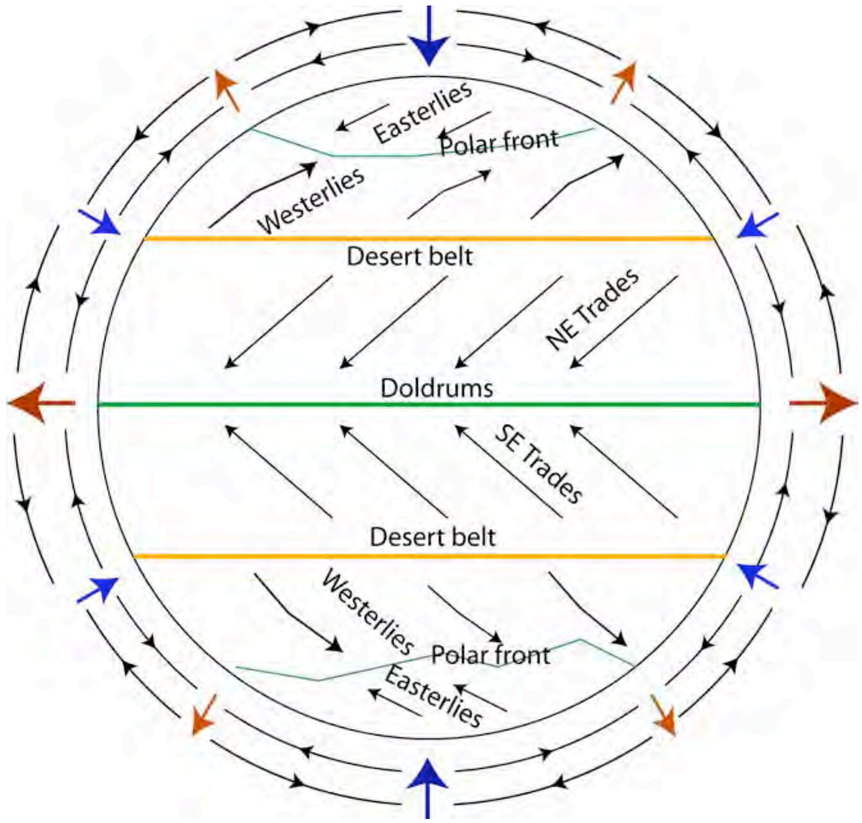


Figure 16: Climate belts viewed from above the equator. Trade winds move toward the equator and easterlies from the poles. Westerlies move north from the desert belt. The region of circulation (troposphere) is about 18-km thick near the equator and 8-km thick at high latitudes. Equatorial doldrums and desert regions of up-flowing and down-following air have weak surface winds. Sailing ships crossing them risked becoming becalmed. Ships headed to the New World from Europe were frequently becalmed in the desert belts. The crews jettisoned horses that died of starvation giving rise to the term "horse latitudes." The pole front is a region of storms where ships are unlikely to get seriously becalmed. Not to scale.

Meteorologists call the perturbation of wind and ocean current directions by the Earth's rotations the Coriolis effect. It is strong enough on the Earth that air cannot flow directly the pole to the equator. Rather zones of upwelling and downwelling divide each hemisphere into 3 wind belts. Starting with the equator, hot air rises. Cooler air from each side moves toward the equator, warming as it does so. This air picks up moisture when it passes over the ocean. The Coriolis effect deflects the air so that it produces a wind from the northeast. This flow is quite regular over the ocean basins, hence the name "trade winds" from the era of sail-driven ships.

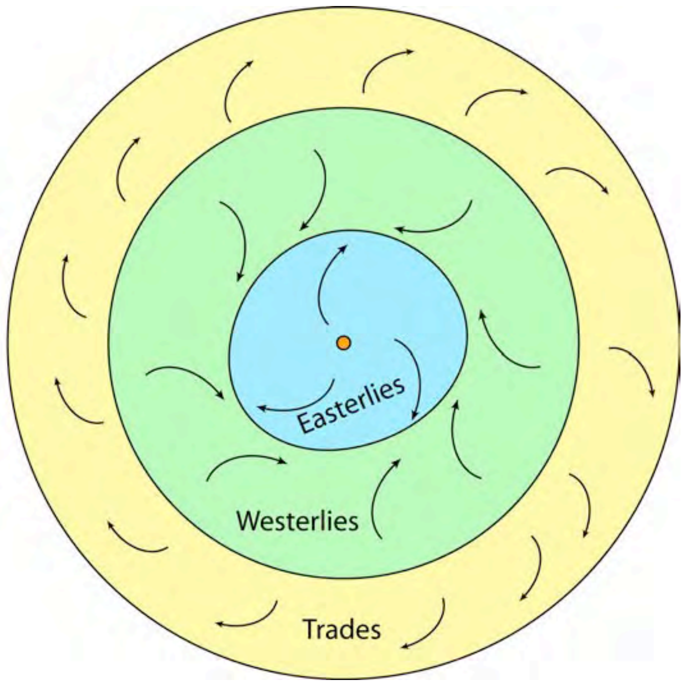


Figure 17: Climate belts view looking down from the North Pole. The easterlies and westerlies represent prevailing averages of irregular winds.

Rain falls from the air rising at the equator. Hence equatorial climate is wet with tropical rain forests. The ascending air is quite dry by the time it reaches the top the troposphere (the part of the atmosphere with weather up to 18 kilometer elevation). This cold trap prevents water from reaching the upper atmosphere (Chapter 7). The air moves northward and cools, radiating heat to space. The Big Island of Hawaii and Maui are good places to see this return flow in action. The climate is dry above about 1500 meters elevation.

Figure 18: Trade winds drive air through the pass between Mona Loa in the foreground and Mona Kea in the background. The cloud-covered windward side is wet and the leeward side is dry. The viewpoint is within the northward-moving return flow for the trade winds. The mountains above the level of the trade-wind clouds are dry. Photo by author.

The cooled dry air descends around in the subtropics (30° latitude). The effect produces the desert belts of the world, including the Sahara north of the equator and the Kalahari south of the equator in Africa. The descending air feeds the trade winds completing the cycle.

Climate away from the tropics is erratic, but belts capture the general effect. In the northern hemisphere, air flows north from the tropical desert belts, warming and picking up moisture. The Coriolis effect deflects this air into mid-latitude westerlies. They are the prevailing winds of much of the continental United States. This air rises in mid-latitude low-pressure systems, producing precipitation. The lows and their associated highs move around so that the rain and snow and dry intervals alternate at a given place.

The cold air from the poles deflects into polar easterlies. It warms as it comes south. The boundary between westerlies and easterlies is the polar front. That is, the fronts on weather maps. The polar front is often poorly defined and moves around. Like the tropical deserts, polar regions of downwelling air are dry.

Some physics of ice ages. The above discussion of basic meteorology indicates that it is quite difficult to completely freeze the ocean especially along coasts in desert regions where there is net evaporation. Ice itself is an effective greenhouse. You may have seen the base of ice piles melting on cold days. Old lake and sea ice is transparent. Light can penetrate several meters maintaining photosynthesis.

Scientists know enough about the physics of the latest ice ages to extrapolate. A cold climate is clearly necessary for snow to accumulate into a glacier. It is not sufficient. For example, parts of Alaska and Siberia were not ice covered in the last ice age. More snow must fall than later evaporates or melts and flows away.

Figure 19: The terminus of Nelchina Glacier, Alaska. The melting ice releases ground up rock that will soon chemically weather. This black material and the exposed rock absorb sunlight while the white ice surface reflects it. Note that much of the mountain range is bare rock. Summer solstice. Photo by author.

On the modern Earth, much of the melting of glaciers and semi-permanent snowfields occurs in the few hottest days in the summer. Ice accumulates if the last winter's snow does not all melt. Subtle astronomical effects now modulate this seasonality. Summers are warmer when the tilt of the Earth's axis is larger and the Sun is nearer the Earth in the northern summer. Right now the Earth is moving toward glacial conditions. The tilt of the axis is decreasing; the Tropics of Cancer and Capricorn move by about a kilometer per century toward the Equator. The Sun is already farther away from the Earth in the northern summer than it is in the winter. It is a simple, though cumbersome, calculation to use Newton's laws to hindcast the position of the Earth's orbit and the tilt of the Earth's axis. Glaciations over the last several hundred thousand years do in fact occur at the expected times.

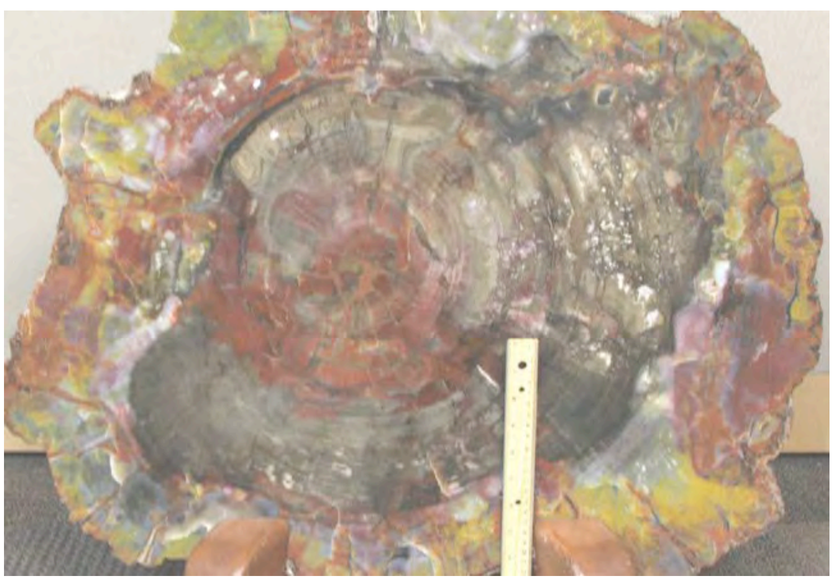


Figure 20: The annual rings in a petrified log indicate as seasonal climate with a summer growing season. Photo by author.

The effect of albedo, sunlight reflecting from ice back into space is quite important. The process is somewhat unstable. More ice implies colder climate, more reflected light, and still more ice. Glaciation also depresses the concentration of carbon dioxide on the Earth's atmosphere. The rocks ground up by glaciers readily react to form carbonates, sucking CO_2 from the air. Yet glaciation was not completely unstable in the last ice ages. Glaciers covered some mountainous regions, but stopped at about the Ohio and Missouri Rivers in the United States and in Northern France in Europe.

Figure 21: The desert near Mina Nevada is in the lee of the Sierra Nevada. The region was wet during the Ice Age and a small lake occupied the lowest part of this valley. The valley had net evaporation and glaciers did not form in the mountains in the background.

Then how did glaciation reach the equator in Snowball Earth? As noted above, both the amount of snow and whether it melts are important. Deserts like the Sahara and Nevada received more precipitation during the recent ice age than now, but they were still zones of net evaporation. Snow could not accumulate there. Snow can conceivably accumulate near the equator where there is intense precipitation. In that case, equatorial glaciers do not imply that ice covered the entire Earth.

A biological Gaian control on modern glaciation or Snowball Earth is not evident. A climatic one is at least feasible. Once established, the ice caps received little snow. They acted like the poles in the simple diagrams as source of cold surface winds. Like the poles in the diagrams, they were areas of dry descending air. The interior of modern Antarctica, for example, is dry, but a zone of slow net ice accumulation. In many places the ice at the bottom of the sheet formed from snow that fell hundreds of thousand years ago.

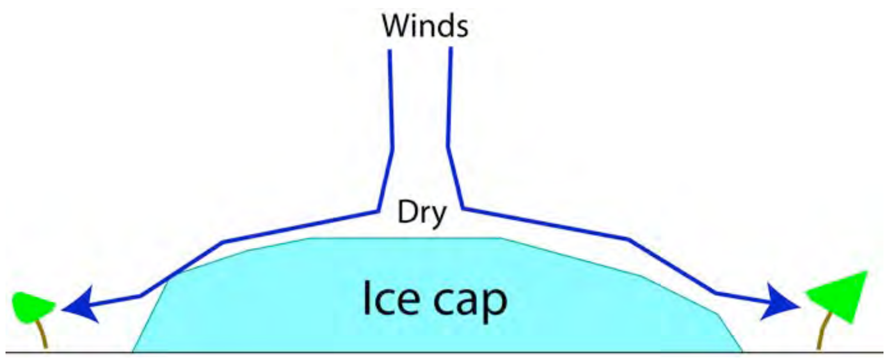


Figure 22: The interior of an icecap is high and cold. Air settles from the top of the troposphere and flows outward. Like the desert belts the region of downflow is dry. The interior of the icecap receives little snow. This effect strongly affects the climate of Antarctica. It occurs in the winter in the Alps. The cold winds cause the southeast of France to be unpleasantly blustery that time of year. The interiors of Canada and Siberia have low elevation but are potent sources of cold air in the northern winter.

This decrease in snow decreased the movement rate of the glacial ice and the rate of erosion. This in turn diminished the CO_2 sink. Glacial retreat began about 20,000 years ago when the alignment of the Earth's axis an orbit became unfavorable for ice accumulation. General climate models exist for computing the effects of varying CO_2 in the air. They are not yet flexible enough, nor fast enough to provide good information on ice-age climate.

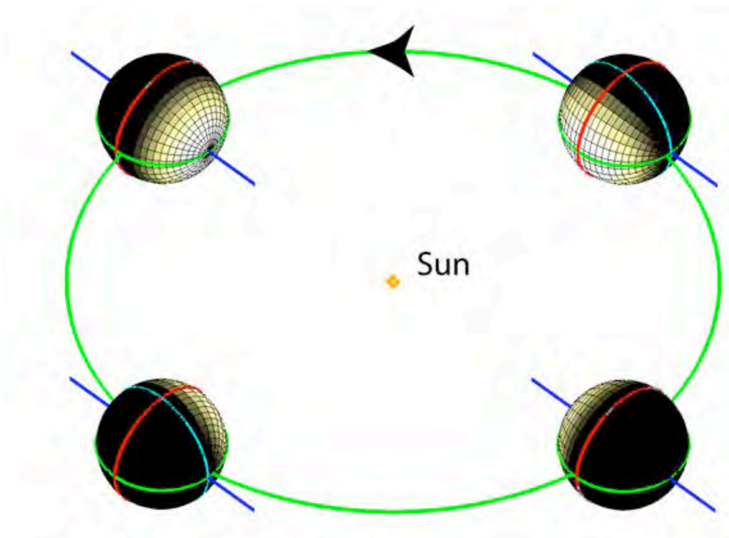


Figure 23: Planet with its rotation axis in its orbital plane. The sun is directly overhead in the polar summers. This planet has warm poles and intense seasons.

Scientists have also examined the tilt of the Earth's axis as a cause for Snowball Earth. The situation is exportable to other planets, even though it appears wanting for the Earth. If the Earth's axis were in the plane of the earth's orbit, the Sun would be directly overhead 24-7 during the polar summer. This would tend to melt ice quickly. In fact, the equator where the Sun is overhead at noon on the equinoxes actually gets less sunlight annually than do the poles.

However, orbital astronomy indicates that this situation is unlikely for the Earth. Tidal forces couple the Moon's orbit to Earth's equatorial bulge and hence to the tilt of its axes. (This is one of the forces that drives procession of equinoxes; see Chapter 3). Astronomers have found no away to tilt the Earth's axis to near the plane of its orbit and then back again to it present condition. The tilt of Mars' axis does change a lot. This process significantly affects its climate.

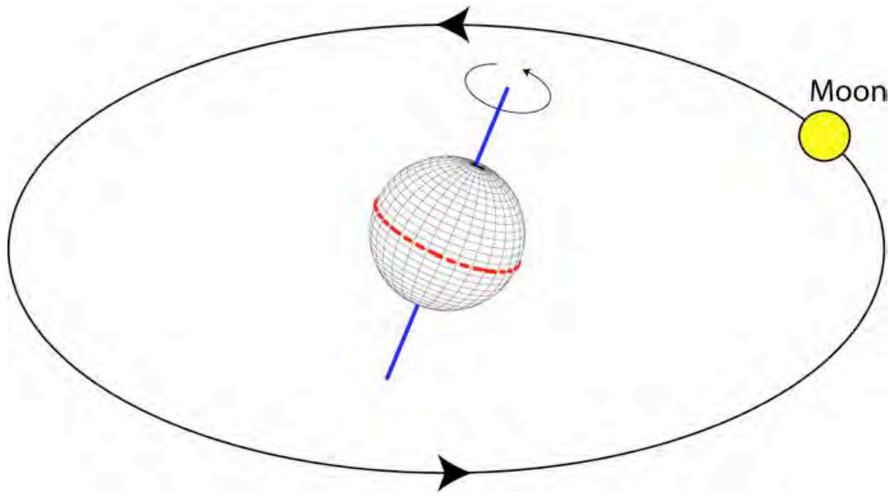


Figure 23: Tides couple the orbital plane of the Moon to the rotational axis of the Earth. The Moon's orbit acts like a flywheel or gyroscope, stabilizing the tilt of the Earth's axes. Astronomers use sophisticated orbital mechanics and heavy mathematics to study this effect.

There has been speculation that the Earth is "special" because it has a large moon that stabilized the tilt of the Earth's axis. There would be marked climate swings on a moonless planet as its axis tilted back and forth. However, the changes occur over millions of years, time of evolution to act and biota to move about. The argument could even be reversed making a moonless planet favorable for intelligent life. Variable conditions often favor a thoughtful rather than a programmed response.

The gist: Living is hard but life is tough

The Gaia concept is useful shorthand for saying that stable equilibria exist on the Earth. However, we do not understand the biology and physics of any real global example. The concept is not yet exportable to astrobiology beyond saying that a long-term stable environment is possible, as on the Earth.

In fact, life has globally fouled its nest several times in the Earth's history. It initially depended on internal sources of energy from the Earth's interior. It evolved the ability harvest the bounty of sunlight early in the Earth's history. Thereafter, life had energy to plow back into weathering of surface rocks. Extensive chemical weathering in the geological record is hence a weak biosignature.

Photosynthesis utilized adaptations for other purposes that are somewhat lost in the mist of time. Its byproducts had profound effects on the surface environment. Methane is a potent greenhouse gas, the one candidate that I identified as a potentially stable Gaian control. The advent of oxygen-producing photosynthesis was destabilizing. It brought ice ages. It rendered the Earth's surface unfit for anaerobic organisms. The Snowball Earth episode may have even endangered photosynthesis by covering the Earth with ice.

I have discussed only some of the tribulations in this chapter. I discuss trials of life by asteroid impacts in the next chapter. I discuss the origin of complex multicellular life in chapter 14 and the current trial of our stewardship of the environment.

Finally, it is easy to come up with arguments that the Earth is special in this or that way because its life passed its tests. We cannot expect anything else, as we need to be here to observe. This anthropic effect limits what we can export off the Earth's surface.

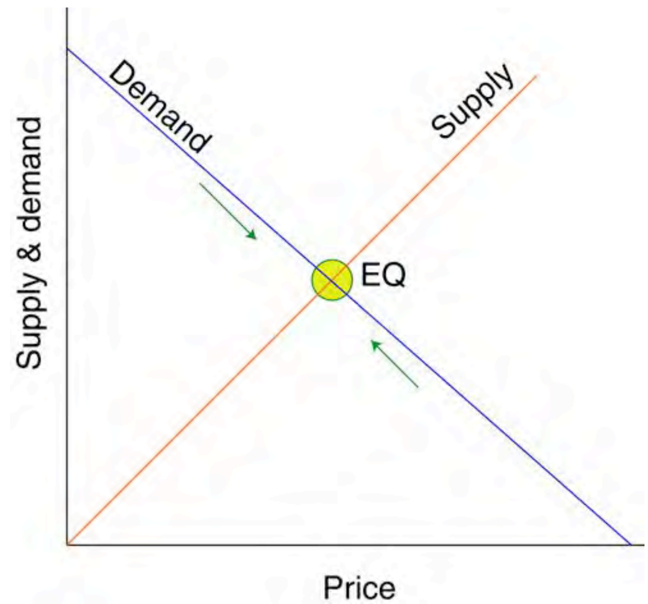
Primer on Economics

Darwin drew heavily from the *laissez faire* theory of economics that was prevalent at his time. After he published *The Origin of Species*, social Darwinists considered the plight of the poor to be a beneficial form of natural selection.

The basic theory from Adam Smith involves supply and demand. The supply of a commodity increases as the price goes up. The demand decreases with increasing price. There is an equilibrium price where supply equals demand. The theory assumes that there are a large number of independent producers, a large number of independent buyers, and that supply, demand, and price can adjust quickly. These assumptions may have been applicable to small merchants in England in 1800, but they are not applicable in general. *Laissez faire* economics proved unstable in the late 1800s when large suppliers achieved monopolies. Even where competition persisted, the sluggish response of supply and demand to price led to boom-bust economic cycles.

Sluggish response applies particularly to supply. There are real entry barriers and it takes a long time to produce many commodities like redwood trees from scratch. Sluggish response usually occurs with the supply of specialized labor. For example, monolingual unlettered Afghan goatherds can do nothing quickly about the demand for brain surgeons at the Mayo Clinic. Conversely, the learned doctors at the clinic are probably unwilling and certainly unable to herd goats.

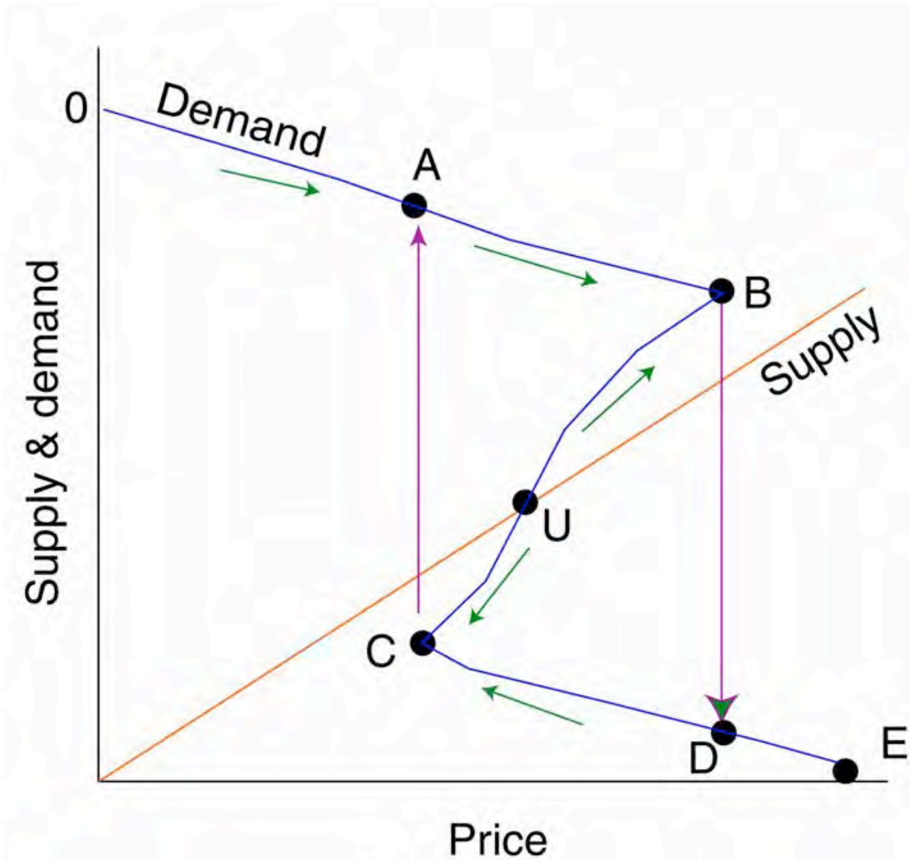
An interesting microeconomic example of boom-bust occurred in western Michigan in my youth. Much of the land is sandy and not particularly fertile. Small farmers returning from World War II went to work in local factories. They did not have time to farm, but they planted Christmas trees, which were in great demand and took little day-to-day attention. In the late 1950s, I was in the Boy Scouts. The Christmas trees had matured all at about the same time creating a glut. It did not pay many of the tree farmers to harvest and ship them. The local scouts got them for cheap if we cut them ourselves.



For an example somewhat analogous to my Gaia examples, I use cashews. These (thought-experiment) cashews grow wild in the jungle and some are ripe at all times. It takes considerable effort to gather them and some are easier to gather than others. There is some stockpile at all times, but the (instantaneous) supply adjusts to the current price. The demand is fickle and depends on the price. No one really needs cashews; there is no demand at very high prices. There is a finite demand even if they are free. The producers can only gradually change the price. They have stockpiles and gradually raise prices when their stock dwindles and lower them when it grows. The instantaneous supply changes slowly since the collectors find out the current price only when they return from the jungle with their nuts. All this leads to the simple case were the consumption and price track the demand curve.

If the price is lower than the equilibrium, the demand is high and the supply is low. The producers see their stockpiles dwindle and raise the price, which increases the supply. The price increase decreases consumption. The demand and price track to the equilibrium point. If the price is higher than the equilibrium, supply exceeds demand. The producers see their stockpiles increase. They drop the price and cut supply. This again tracks the price along the demand curve to the equilibrium.

The situation is more complicated if they buyers are very fickle. Between points 0 and B, the buyers consider cashews to be a mark of frugality. However, if the price rises above point B, they are extravagant and there is little demand. If we start the price on the frugal branch between points 0 and B, the examples works like before and the price tracks the demand curve to point EQ. If we start on the extravagant branch between points E and C, stockpiles build up and the price tracks to point C. Then cashews become a mark of frugality and the demand suddenly jumps to point A and then tracks to point EQ. The branch between points B and C also tracks to point C and then jumps to point A. For those with some mathematics, the French mathematician René Thom used diagrams like this in his catastrophe theory.



A second form of this diagram exists where there is no stable equilibrium. The supply and demand curves intersect at point U. If we start between points U and C, the price tracks to point C and then jumps to point A when cashews become frugal. When we start between points U and B, the curve tracks to point B where cashews become extravagant and jump to point D. Thereafter, the price tracks endlessly from points D to C and a jump to point A and from A to B with a jump to point D. The curve between C and B never gets reoccupied.

Exercises

For the sports minded, an athletic team is an example with both cooperation and competition to make and stay on the roster. If you have played on a children's or K-12 team, you will be able to document the tension between competition within the team and cooperation. Was anything done to specifically cut down on competition within the team? Did your experience differ with the sport or the level?

You can get an idea on how fast rocks weather by looking at building stones exposed to the elements and at rocks in stonewalls. Note where you see rust.

You can measure the importance of the latent heat of melting ice and of vaporizing water with a sauce plan. Fill the bottom of the pan with ice cubes that have been allowed warm up to the freezing point so that a film of water is on them. Put the burner on low-medium. Time how long it takes for the ice to melt. (A)__________

Time how long it takes from melting to when boiling starts (B)____________

Measure the depth of water with ruler. It is best not to let the pan boil dry. Measure how long it takes for half the water to boil and then multiple by 2 and record ____________(C)

It is 100°C between freezing and boiling. To get the temperature change that has heat equal to the latent heat of melting compute

$100 \times A \div B$ $100 \times$ _____ $\div$ _______ = _____ gives the number of degrees Celsius

The analogous quantity for boiling is

100 × C ÷ B   100 × _____ ÷ _______ = _____ gives the number of degrees Celsius.