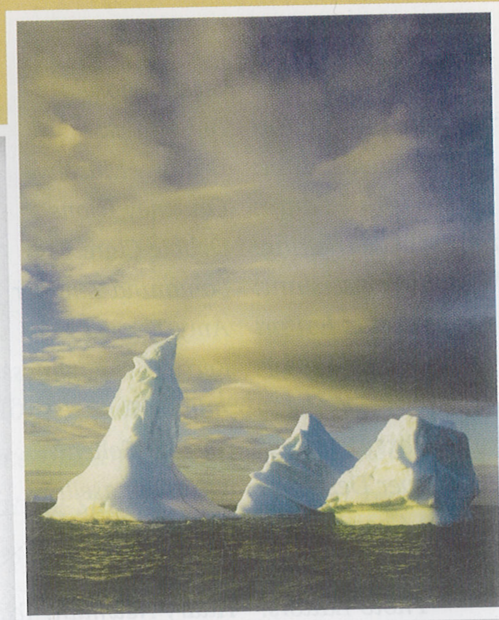

# Earth's Climate

## PAST AND FUTURE

Third Edition

WILLIAM F. RUDDIMAN

W. H. Freeman and Company · New York

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Library of Congress Control Number: 2013937645

ISBN-13: 978-1-4292-5525-7
ISBN-10: 1-4292-5525-0

Printed in the United States of America

Third printing

W. H. Freeman and Company
41 Madison Avenue
New York, NY 10010
Houndmills, Basingstoke RG21 6XS, England
www.whfreeman.com

## Greenhouse Worlds

The first clue that a factor other than distance to the Sun is involved in Earth's habitability comes from comparing it to Venus, another "terrestrial" planet with a similar overall chemical composition (Figure 4-1). Venus is a very hot planet with a mean surface temperature of 460°C, and it is located just 72% as far from the Sun as Earth is.

The average amount of solar radiation sent to each planet varies *inversely* with the square of its distance from the Sun ($1/d^2$). Based on this relationship, Venus receives almost twice (1.93 times) as much solar radiation as Earth does:

$$\frac{Earth}{Venus}\ \frac{(1)^2}{(0.72)^2} = \frac{1}{0.518} = 1.93$$

At first, this calculation might seem to confirm that climate depends entirely on distance from the Sun: because Venus is closer to the Sun, its surface is hotter. In fact, however, this is not the real answer because most of the Sun's radiation never makes it down to Venus's surface. Its upper atmosphere is shrouded in thick sulfuric acid clouds that reflect 80% of the incoming radiation and allow only 20% to reach the surface. In contrast, clouds on Earth reflect just 26% of the incoming radiation, allowing the other 74% to reach its surface.

This large difference in average albedo (the percentage of incoming radiation reflected back to space) between the atmospheres of the two planets almost exactly reverses the relative amounts of solar energy that actually reach their surfaces. Even though Venus receives almost twice as much incoming solar energy at the top of its atmosphere, its higher albedo reduces the amount that reaches its surface to just over half that received on Earth:

$$1.93 \times \frac{0.20}{0.74} = 0.52$$

With less incoming solar radiation, how can Venus be so much hotter? The answer is that Venus has an atmosphere 90 times as dense as that of Earth, and 96% of its atmosphere is composed of carbon dioxide ($CO_2$), a greenhouse gas that is very effective in trapping radiation. Some sunlight does penetrate the thick atmosphere and heat the surface, which causes Venus to emit long wave radiation, just as Earth does. But most of the back radiation never leaves the atmosphere of Venus because the $CO_2$ gas traps it and retains it as internal heat.

In contrast, much less of the energy radiated back from Earth's surface is trapped by water vapor, $CO_2$, and other greenhouse gases (recall Chapter 2).

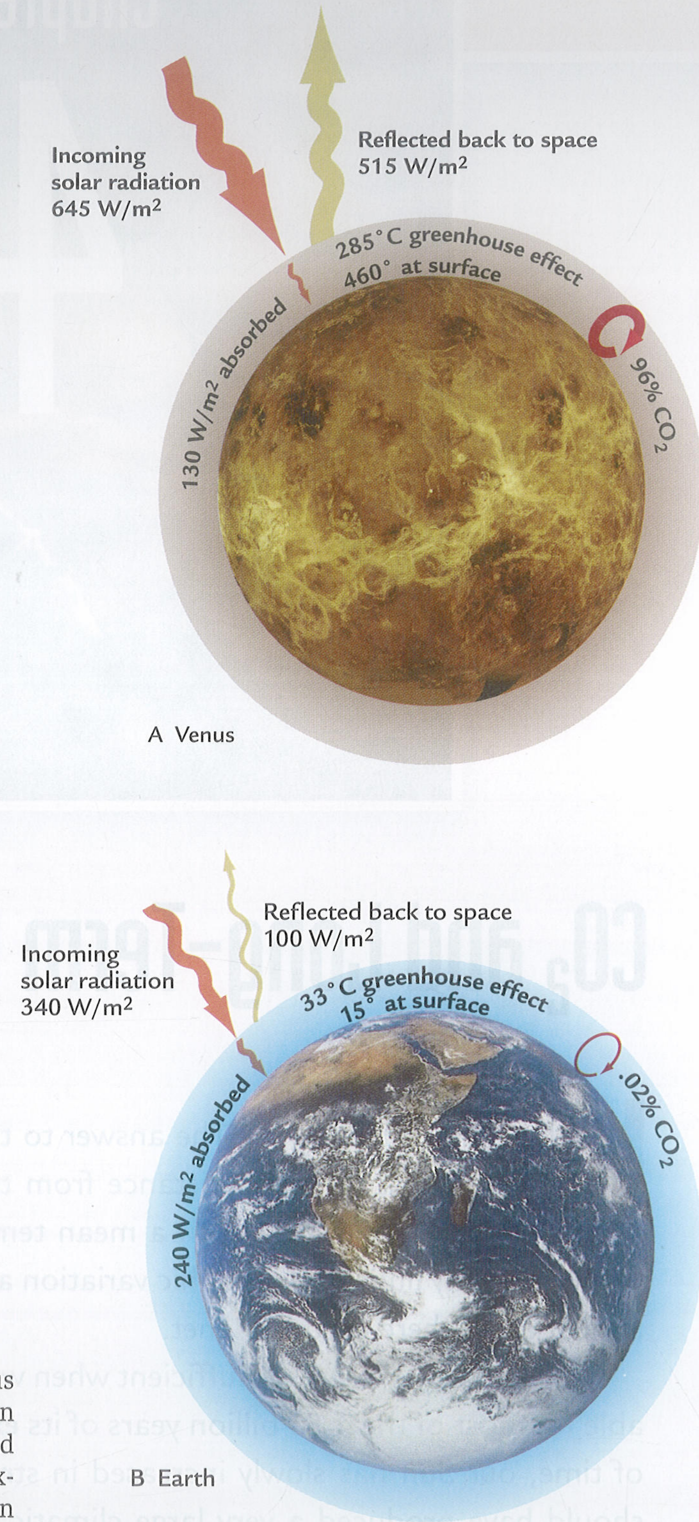



**FIGURE 4-1**
**Why is Venus hot?**
Venus (A) receives almost twice as much solar radiation as Earth (B), but the dense cloud cover on that planet permits less radiation to penetrate to its surface. Yet Venus is much hotter than Earth because its $CO_2$-enriched atmosphere creates a much stronger greenhouse effect that traps much more heat. (NASA.)



**In Summary**, the main reason Venus is so hot compared to Earth is not its closer proximity to the Sun, but its far greater concentrations of heat-trapping greenhouse gases.

Because Venus and Earth both formed as rocky planets in the inner part of our solar system, they contain nearly equal amounts of carbon. Yet the two planets store their carbon in very different reservoirs. Most of Earth's carbon is tied up in its rocks (some of it as coal, oil, and natural gas), while relatively little resides in the atmosphere. Combined with water vapor and other greenhouse gases, the net greenhouse heating of Earth's atmosphere is relatively small—about 32°C (although that difference keeps Earth from freezing solid). In marked contrast, almost all the carbon on Venus resides in its atmosphere as $CO_2$ and produces an enormous net greenhouse warming (285°C), without any significant contribution from water vapor.

This comparison shows how vital greenhouse gases can be to the climate of planets. It also highlights the fact that Earth's comfortably small greenhouse effect is an important factor in its present habitability.

## The Faint Young Sun Paradox

By studying the evolution of stars in the universe, astronomers have recreated the history of our own Sun over the 4.55 billion year existence of our solar system. Throughout this interval, the Sun's interior has been the site of an ongoing nuclear reaction that fuses nuclei of hydrogen (H) together to form helium (He). Models developed by astronomers indicate that this process has caused our Sun to expand and gradually become brighter. These models indicate that the earliest Sun shone 25% to 30% more faintly than today, and that its luminosity, or brightness, then slowly increased to its current strength.

This insight from the field of astronomy creates an intriguing problem for climate scientists. A relatively small decrease in our Sun's present strength would cause all the water on Earth to freeze, despite the warming effect from greenhouse gases. If all our oceans and lakes were to freeze, their bright snow and ice surfaces would reflect more solar radiation, and they would be difficult to melt. One-dimensional numerical climate models that simulate the mean climate of the entire planet (recall Chapter 2) suggest that the combination of a weak Sun and greenhouse gas levels at their present values would have kept Earth completely frozen for the first 3 billion years of its existence (Figure 4-2).

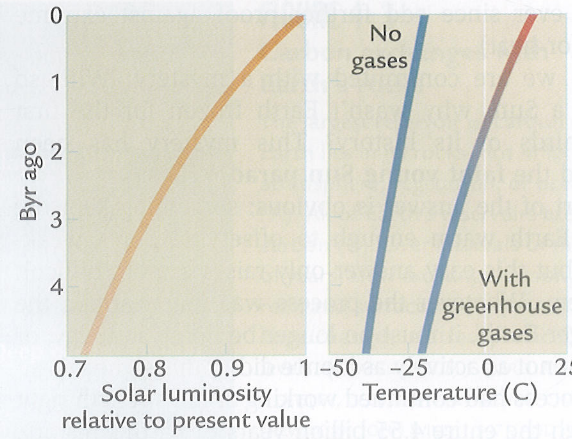



**FIGURE 4-2**
**The faint young Sun paradox**
Astrophysical models of the Sun's evolution indicate it was 25% to 30% weaker early in Earth's history (left). Climate model simulations show that the weaker Sun would have resulted in a completely frozen Earth for more than half of its early history if the atmosphere had the same composition as it does today (right). (ADAPTED FROM D. MERRITTS ET AL., *ENVIRONMENTAL GEOLOGY*, ©1997 BY W. H. FREEMAN AND COMPANY.)

Yet evidence left in Earth's sedimentary deposits shows that Earth was not frozen for its first 3 billion years. Although the first half-billion years of Earth's existence have left no record, evidence of Earth's climatic history gradually becomes more complete after that time and toward the present. Most sedimentary rocks (recall Chapter 3) are made up of particles that were eroded from other rocks, reworked by running water, and transported to a site of deposition. The prevalence of water-deposited sedimentary rocks throughout Earth's early history is direct evidence that Earth was not frozen.

The first evidence of ice-deposited sediments occurs in rocks dated to about 2.3 billion years ago, but these deposits could have been the result of ice sheets in polar regions, similar to those that occur today, and not evidence of a completely frozen planet. As summarized at the end of this chapter, a debate is currently under way as to how close Earth's climate came to a nearly frozen condition during several intervals between 750 and 580 million years ago, but for most of Earth's history the sedimentary evidence leaves no doubt that most of the water on Earth has remained unfrozen.

This conclusion is supported by the continued presence of life on Earth. Primitive life-forms date back to at least 3.5 billion years ago, and their presence on Earth is incompatible with a completely frozen planet at that time. The succession of ever more complex life-forms that have continuously occupied

Earth ever since add further proof against extreme cold (or heat).

So we are confronted with a mystery: With so weak a Sun, why wasn't Earth frozen for the first two-thirds of its history? This mystery has been named the **faint young Sun paradox.**

Part of the answer is obvious: something kept the early Earth warm enough to offset the Sun's weakness, but this easy answer only raises a more difficult problem. Whatever the process was that warmed the younger Earth, it must no longer be doing so today, or at least not as actively as it once did. If this same warming process had continued working at full strength right through the entire 4.55 billion years of Earth's history, it would have combined with the steadily increasing warmth from the strengthening Sun (Figure 4-2) to overheat Earth and make it uninhabitable. Yet that has not happened: somehow Earth has stayed in a moderate temperature range throughout the entire interval when the Sun's brightness was increasing.

The most likely solution to the faint young Sun paradox requires a process that works in the same way a **thermostat** works in a house. When outside temperatures fall in winter, the thermostat detects the cooling and turns on a heat source that keeps the house warm. When temperatures become too hot outside in summer, the thermostat activates a cooling source that keeps the house cool. The thermostat moderates extreme swings in temperature. Such a thermostat must have been at work through Earth's history, warming its climate very early on when it would otherwise have frozen under a weak Sun, and later on cutting back on the extra heat as the Sun strengthened.

One possibility is that greenhouse gases have been part of the mechanism that acts as Earth's thermostat. Our present concentrations of greenhouse gases do not provide enough warming to have counteracted the effects of a weak early Sun, but if these gases were more abundant earlier in Earth's history and subsequently decreased in abundance, that would provide a thermostat-like control.

Our earlier comparison of Earth and Venus lends credibility to this explanation. Earth's carbon is mainly stored in its rocks, while carbon on Venus is mostly in its atmosphere. If carbon can reside in different reservoirs on different planets, why couldn't it move among reservoirs during the history of a single planet? More specifically, could the early Earth have held more carbon in its atmosphere (like Venus), and then transferred it to its rocks later in its history?

## Carbon Exchanges between Rocks and the Atmosphere

To understand how carbon may have shifted among Earth's reservoirs, we can examine the present carbon cycle (Figure 4-3A). Small amounts of carbon exist in the atmosphere, in the surface ocean, and in vegetation, along with a slightly larger reservoir in soils, a much larger reservoir in the deep ocean, and an immensely large reservoir in rocks and sediments. Carbon storage in these reservoirs is measured in billions of tons ("gigatons").

The rates of carbon exchange among these reservoirs vary widely (Figure 4-3B). In general, an inverse relationship exists between the size of a reservoir and the rate at which it exchanges carbon. The smaller reservoirs (the atmosphere, surface ocean, and vegetation) all exchange carbon relatively quickly, while the huge rock reservoir gains and loses carbon much more slowly. Because of the combined effects of small reservoir sizes and rapid exchange rates, carbon can cycle through the surface reservoirs in a few years or decades, but takes much longer to move through the larger and deeper reservoirs.

Because all of these reservoirs exchange carbon with the atmosphere, each has the potential to alter atmospheric $CO_2$ concentrations and affect Earth's climate. The relative importance of each carbon reservoir in Earth's climate history varies according to the time scale under consideration. In this chapter, we are concerned with very gradual climate changes over tens to hundreds of millions of years. Over these very long (tectonic) time scales, the slow carbon exchanges between the rocks and the surface reservoirs are the source of changes in the amount of $CO_2$ in the atmosphere.

### 4-1 Volcanic Input of Carbon from Rocks to the Atmosphere

Carbon cycles constantly but slowly between Earth's interior and its surface. It moves from the deep rock reservoir to the surface mainly as $CO_2$ gas produced during volcanic eruptions and in the activity of hot springs (Figure 4-4).

The present rate of natural carbon input to the atmosphere from the rock reservoir is estimated at approximately 0.15 gigatons of carbon per year (see Figure 4-3B). This value is uncertain by a factor of at least 2 because volcanic explosions are irregular in time and because the amount of $CO_2$ released varies with each eruption. As we will see later, this natural rate of carbon input is roughly balanced by a similar rate of natural removal. This balance between natural input and removal rates helped to keep the size of the "natural" (preindustrial) atmospheric carbon reservoir at ~600 gigatons.

But how likely is it that this balance could have persisted over immensely long intervals of geologic time? We can evaluate this question by a simple thought experiment. Using the reservoir concept



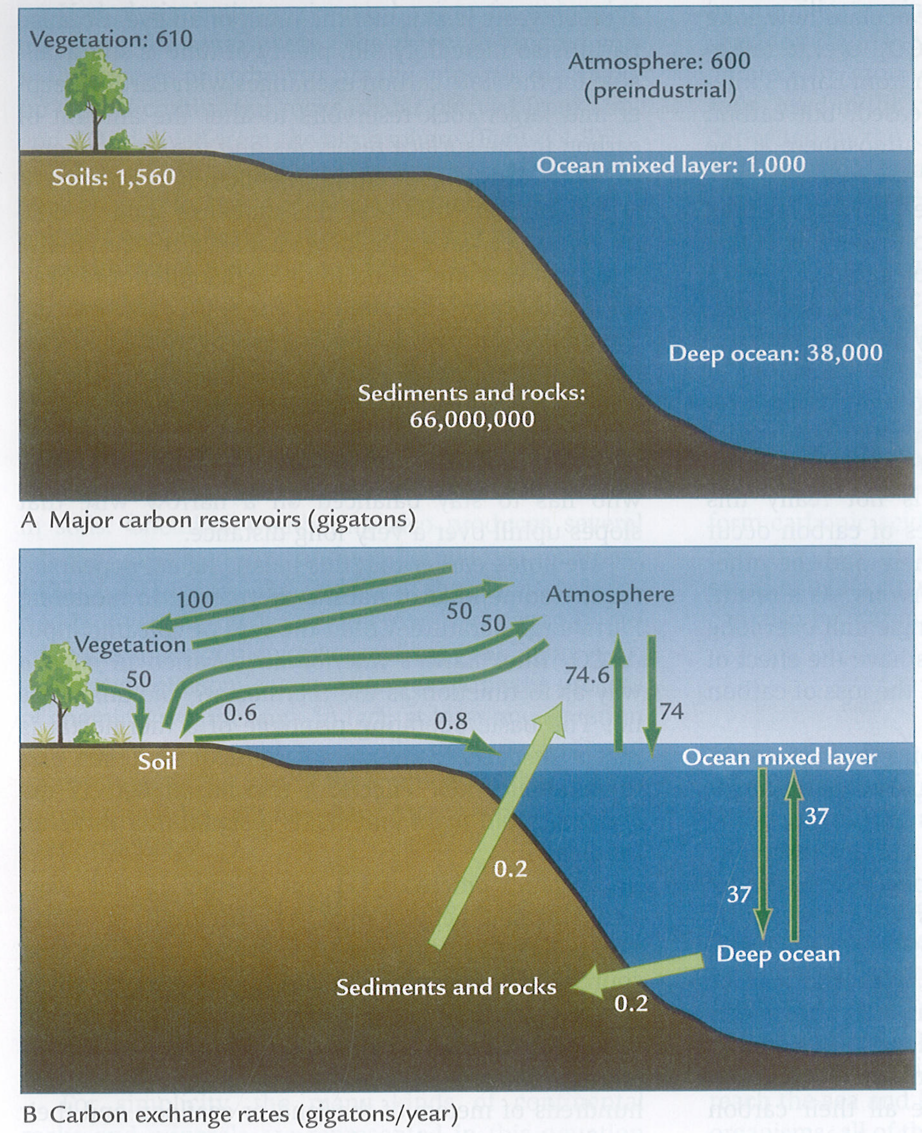



**FIGURE 4-3**
**Carbon exchanges with Earth's rocks**
The largest reservoir of carbon on Earth lies in its rocks, not in its atmosphere, vegetation, or ocean (A). All of Earth's reservoirs exchange carbon (B). Over intervals of millions of years, slow exchanges among the rock and surface reservoirs can cause large changes in atmospheric $CO_2$ levels. (ADAPTED FROM J. HOREL AND J. GEISLER, *GLOBAL ENVIRONMENTAL CHANGE* [NEW YORK: JOHN WILEY, 1997], AND FROM NATIONAL RESEARCH COUNCIL BOARD ON ATMOSPHERIC SCIENCES AND CLIMATE, *CHANGING CLIMATE*, REPORT OF THE CARBON DIOXIDE ASSESSMENT COMMITTEE [WASHINGTON, D.C.: NATIONAL ACADEMY PRESS, 1993].)

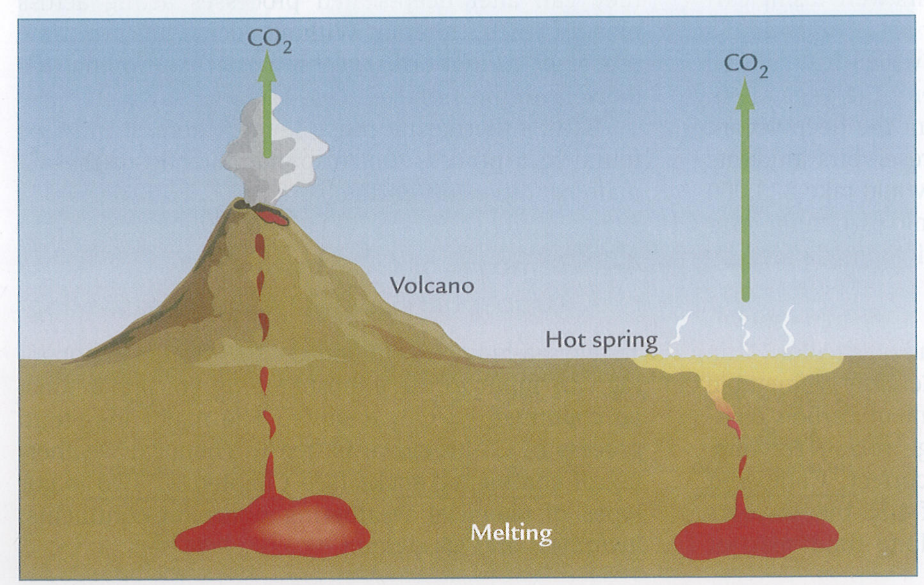



**FIGURE 4-4**
**Input of $CO_2$ from volcanoes**
$CO_2$ enters Earth's atmosphere from deep in its interior through release of gases in volcanoes and at hot springs such as those at Yellowstone National Park in Wyoming.

introduced in Chapter 3, we can calculate how long it would take for the atmospheric $CO_2$ level to fall to zero if all volcanic release of carbon from Earth's interior to the atmosphere abruptly ceased, but carbon continued to be removed from the atmosphere at the same rate as before.

The answer, 4,000 years, is derived by dividing the preindustrial atmospheric carbon reservoir of 600 gigatons by an annual rate of carbon removal of 0.15 gigaton. This number, although far beyond the length of a human lifetime, is remarkably brief in the context of the several billion years of Earth's existence. It tells us that changes in volcanic input persisting over that relatively "small" span of time could have had a drastic effect on the $CO_2$ content of our atmosphere.

In actuality, the atmosphere is not really this vulnerable because rapid exchanges of carbon occur continuously between the atmosphere and the other surface or near-surface carbon reservoirs. As a result, these reservoirs in effect act as a single unit over long intervals, and their rapid exchanges have the effect of slowing and reducing the impact of the loss of carbon from Earth's interior.

In this hypothetical example of a sudden cessation of volcanic $CO_2$ input, the actual scenario might initially develop more like this: As $CO_2$ levels in the atmosphere begin to fall, the other surface reservoirs (vegetation, surface ocean, soils) begin to surrender some of their carbon to the atmosphere, slowing its rate of loss. The combined size of the near-surface reservoirs (atmosphere, vegetation, soil, and surface ocean) is 3,700 gigatons, more than six times larger than the atmospheric reservoir alone. As a result, it would take roughly 24,700 years after volcanism ceased for these reservoirs to lose all their carbon (3,700 gigatons divided by 0.15 gigaton/yr).

Over longer time spans of centuries, the large deep-ocean carbon reservoir would also play a growing role. If all of the surface reservoirs were losing carbon, the deep ocean would deliver some of its ample supply to the surface ocean, from which it would be redistributed among the atmosphere, the vegetation, and the soil. If we take into account the deep ocean, the total size of these combined reservoirs amounts to 41,700 gigatons. In this case, it would take 278,000 years for a total shutdown of volcanic carbon input to deplete them completely (41,700 gigatons divided by 0.15 gigaton/yr).

At this point, it might seem as if we have shown that Earth's surface reservoirs, and particularly the atmosphere, are actually *not* particularly vulnerable to the slow changes in the amount of carbon coming out of (or going into) its large rock reservoirs. But this conclusion would be incorrect. Compared to Earth's unimaginably old age of 4.55 billion years (4,550,000,000 years!), even the long time span of 278,000 years is still just the blink of an eye. Because Earth is so incredibly old, plenty of time is still available for the slow carbon exchanges with Earth's deeper and larger rock reservoirs to alter the amount of carbon in the surface reservoirs and the atmosphere.

With Earth's great antiquity taken into account, it is still amazing that over this immense span of time its volcanoes have somehow managed to keep delivering just enough carbon from Earth's interior to keep the atmosphere from running out of $CO_2$ and freezing the planet, but not so much as to overheat and boil it. Even more amazing is the fact that this balancing act had to be maintained as the faint young Sun was slowly increasing in strength. A crude analogy for this long-term balancing act would be a tightrope walker who has to stay balanced on a narrow wire that slopes uphill over a very long distance.

We noted earlier that this balancing act appears to require some kind of natural thermostat to moderate Earth's temperature. Could the rate of volcanic input of $CO_2$ from Earth's interior have varied in such a way as to function as the thermostat? The answer is no. The basic operating principle of a thermostat is that it first *reacts* to external changes and then *acts* to moderate their effects: a thermostat detects the chill of a cold night and sends a signal that turns on the heat.

Volcanic processes do not operate in this way. The volcanic activity that has occurred on Earth throughout its history has been driven mainly by heat sources located deep in its interior and generally well removed from contact with (and reactions to) the climate system. Climatically driven changes in surface temperature penetrate only the outermost tens to hundreds of meters of the land or seafloor, and their amplitude is greatly reduced compared to those at the surface. As a result, climate changes confined to Earth's surface have no physical mechanism by which they can alter deep-seated processes acting across most of Earth's interior. Without such a link, volcanic processes cannot act as a thermostat controlling $CO_2$ delivery to the surface.

Earth's thermostat must lie elsewhere. It must be found in a process that responds directly to the climate conditions at Earth's surface.

## 4-2 Removal of $CO_2$ from the Atmosphere by Chemical Weathering

To avoid a long-term buildup of $CO_2$ levels, the ongoing $CO_2$ input to the atmosphere by volcanoes must be countered by $CO_2$ removal. The major long-term process of $CO_2$ removal is tied to chemical weathering of continental rocks (see Chapter 3). Two major types of chemical weathering occur on continents: *hydrolysis* and *dissolution*.



Hydrolysis is the main mechanism for removing $CO_2$ from the atmosphere. The three key ingredients in the process of hydrolysis are the minerals that make up typical continental rocks, water derived from rain, and $CO_2$ derived from the atmosphere (Figure 4-5).

Most of the continental crust consists of rocks such as granite, made of **silicate minerals** like quartz and feldspar. Silicate minerals typically are made up of positively charged cations ($Na^{+1}$, $K^{+1}$, $Fe^{+2}$, $Mg^{+2}$, $Al^{+3}$, and $Ca^{+2}$) that are chemically bonded to negatively charged $SiO_4$ (silicate) structures. These silicate minerals are slowly attacked by groundwater containing carbonic acid ($H_2CO_3$) formed by combining atmospheric $CO_2$ with rainwater.

Part of the weathered rock is chemically converted to clay minerals (compounds of Si, Al, O, and H) in soils. Chemical weathering also produces several types of dissolved ions and ion complexes, including $HCO_3^{-1}$, $CO_3^{-2}$, $H_2SiO_4$, and $H^{+1}$. These ions are carried by rivers to the ocean, where most are incorporated in the shells of planktic organisms (see Figure 4-5).

Dozens of chemical equations describe the process of chemical weathering—in fact, at least one equation for each of the many types of silicate minerals found on continents. The part of these processes that is most important to the carbon system can be represented by these reactions:

$$\underset{\text{Rain}}{H_2O} + \underset{\text{From atmosphere}}{CO_2}$$

$$\underset{\substack{\text{Silicate rock}\\\text{(continents)}}}{CaSiO_3} + \underset{\substack{\text{Carbonic acid}\\\text{(soil)}}}{H_2CO_3} \rightarrow \underset{\text{Shells of organisms}}{CaCO_3 + SiO_2} + H_2O$$

For simplicity, the many kinds of continental rocks and minerals are represented in this equation by one silicate mineral, $CaSiO_3$ (wollastonite). Carbon dioxide ($CO_2$) is removed from the atmosphere, incorporated in groundwater to form carbonic acid in soils, used in the chemical weathering of $CaSiO_3$, and deposited in the $CaCO_3$ shells of marine organisms. This reaction is a shorthand summary of the way chemical weathering removes $CO_2$ from the atmosphere and buries it in ocean sediments. This process acts slowly but persistently over long intervals of geologic time and accounts for 80% of the 0.15 gigatons of carbon buried each year in ocean sediments.

It is important to distinguish weathering of silicates by hydrolysis from the action of dissolution, the other kind of weathering. Dissolution is the process that eats away at limestone bedrock and in some areas forms caves. Again, rainwater and $CO_2$ combine in soils to form carbonic acid ($H_2CO_3$) and attack limestone bedrock ($CaCO_3$), and the dissolved ions created by dissolution again flow to the ocean in rivers. Dissolution can also be summarized by these simple reactions:

$$\underset{\text{Rain}}{H_2O} + \underset{\text{From atmosphere}}{CO_2}$$

$$\underset{\substack{\text{Limestone}\\\text{rock}}}{CaCO_3} + \underset{\text{In soils}}{H_2CO_3} \rightarrow \underset{\substack{\text{Shells of}\\\text{organisms}}}{CaCO_3} + \underset{\substack{\text{Returned to}\\\text{atmosphere}}}{H_2O + CO_2}$$

Dissolution of limestone proceeds at much faster rates than hydrolysis of silicates. Similar to hydrolysis, dissolution extracts $CO_2$ from the atmosphere to attack rock. But unlike the weathering of silicate rocks, limestone weathering results in no net removal of $CO_2$ from the atmosphere. In the relatively short interval of time it takes for the dissolved $HCO_3^{-1}$ and $CO_3^{-2}$ ions to reach the sea and become incorporated in the shells of organisms, all of the $CO_2$ is returned to the atmosphere.

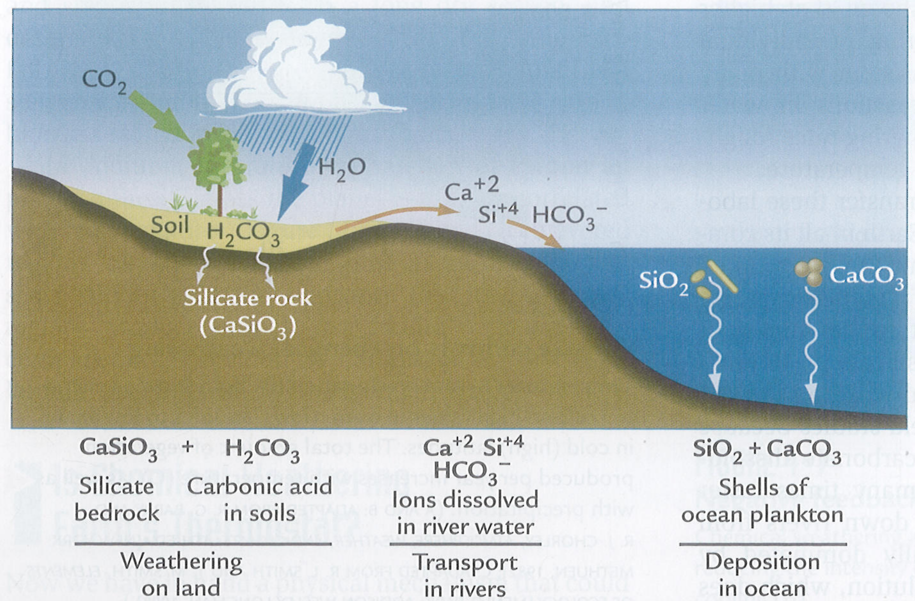



**FIGURE 4-5**
**Chemical weathering removes atmospheric $CO_2$**
Chemical weathering of silica-rich rocks on the continents removes $CO_2$ from the atmosphere, and part of the carbon is later stored in the shells of marine plankton and buried in ocean sediments.

**In Summary**, slow weathering of granite and other silicate rocks on the continents by hydrolysis is the main way that $CO_2$ is pulled out of the atmosphere over very long time scales. In the context of Earth's delicate long-term balancing act, the rate of removal of carbon by chemical weathering must have very nearly balanced the rate of carbon input from volcanoes. If these rates had not been very nearly equal, the system would have gotten out of balance and caused drastic changes in $CO_2$ levels and climate.

The existence of this delicate balance does not imply that either the (volcanic) $CO_2$ input rate or the (weathering) $CO_2$ removal rate remained absolutely constant through time. Yet the fact of Earth's long-term habitability requires that the rates of input and output must have always remained fairly closely balanced even though they varied.

How has this near-perfect balance been possible? As we noted earlier, a thermostat is needed to provide such a balance. In our search for Earth's thermostat within its carbon system, we have ruled out volcanic input of $CO_2$. The other possibility left is chemical weathering. If the rate of chemical weathering is sensitive to climate, it may be able to act as Earth's thermostat.

## Climatic Factors that Control Chemical Weathering

Decades of laboratory experiments and many field studies have shown that rates of chemical weathering are influenced by three environmental factors: temperature, precipitation, and vegetation. These factors all act in a mutually reinforcing way to affect the intensity of chemical weathering.

Laboratory experiments have shown that higher temperatures cause faster weathering of individual silicate minerals. This trend is consistent with many temperature-dependent chemical reactions in water and other aqueous solutions. Weathering rates roughly double for each 10°C increase in temperature.

Unfortunately, it is difficult to transfer these laboratory results to studies of the real Earth in all its complexity. So far, laboratory experiments have examined only a few of the many silicate minerals that are common enough in Earth's crust to be important contributors to the overall rate of silicate weathering on a global scale. Natural chemical weathering rates are also difficult to determine in field studies because of the complicating effects from carbonate dissolution. Because dissolution occurs many times faster than hydrolysis, the ions flowing down rivers from actively eroding terrain are usually dominated by those derived from limestone dissolution, which does not control $CO_2$ levels in Earth's atmosphere, rather than from hydrolysis of silicates, which does control long-term $CO_2$ concentrations. Another problem with field studies is that agriculture and industrial activities have disturbed the natural chemistry of most of Earth's rivers, even in many remote regions.

Still, we can apply the laboratory rule of thumb that says that silicate weathering rates double for each 10°C increase in temperature across the roughly 30°C range of mean annual temperatures found on Earth's surface (Figure 4-6A). Based on this relationship, rates of silicate weathering should increase by a factor of at least 8 (2 × 2 × 2) from the cold polar regions to the hot equatorial latitudes.

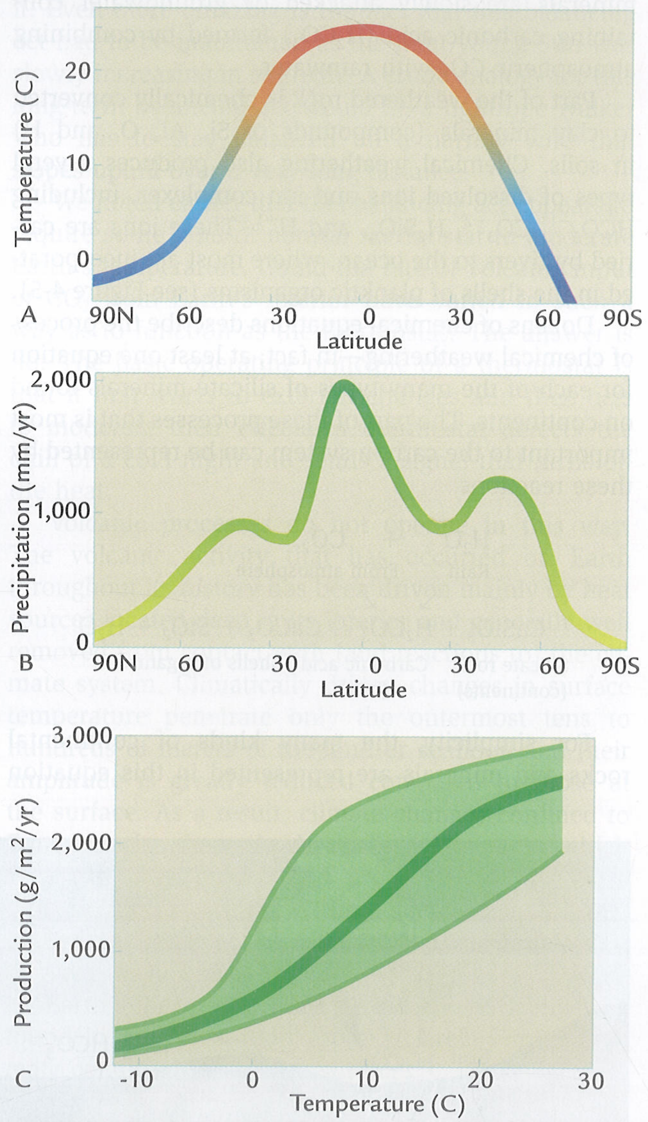



FIGURE 4-6
**Climate controls on chemical weathering**
Temperature (A) and precipitation (B) both show a general trend from high values in warm (low) latitudes to low values in cold (high) latitudes. The total amount of vegetation produced per year increases with temperature (C), as well as with precipitation. (A AND B: ADAPTED FROM R. G. BARRY AND R. J. CHORLEY, *ATMOSPHERE, WEATHER, AND CLIMATE*, 4TH ED. [NEW YORK: METHUEN, 1982]; C: ADAPTED FROM R. L. SMITH AND T. M. SMITH, *ELEMENTS OF ECOLOGY* [MENLO PARK: ADDISON WESLEY LONGMAN, 1998].)



The second major control on weathering is precipitation (Figure 4-6B). Increased rainfall boosts the level of groundwater held in soils, and the water combines with $CO_2$ to form carbonic acid and enhance the weathering process.

Temperature and precipitation are so closely linked in Earth's climate system that it is often difficult to measure their separate contributions to chemical weathering. The heaviest rainfall on Earth occurs in the tropics because warm tropical air holds much more moisture than cool high-latitude air. Polar regions have very little precipitation because the atmosphere holds so little water.

This close relationship breaks down in some regions. For example, lower precipitation in many subtropical regions greatly reduces chemical weathering, even though the relatively warm temperatures in those areas would otherwise favor it. Despite these complications, temperature and precipitation generally act together. A warmer Earth is likely to be a wetter Earth, and both factors tend to act together to intensify chemical weathering.

Vegetation also enhances chemical weathering. Plants extract $CO_2$ from the atmosphere through the process of photosynthesis, and deliver it to soils, where it combines with groundwater to form carbonic acid. Although $H_2CO_3$ is a weak acid, it enhances the rate of chemical breakdown of minerals. Scientists estimate that the presence of vegetation on land can increase the rate of chemical weathering by a factor of 2 to 10 compared to the rates typical of land that lacks vegetation.

Vegetation is closely linked to precipitation and temperature (see Chapter 2). Dense rain forests occur in regions with year-round rainfall, open forest or savannas in areas with a short dry season, grasslands and steppes in places with a long dry season, and deserts or semi-deserts in areas with little or no rainfall. Each step in the direction of greater rainfall is a step toward more vegetation and more total carbon biomass stored in vegetation and soils.

In addition, the rate of production of carbon by photosynthesis across the planet is broadly correlated with temperature (Figure 4-6C). Cold ice-covered regions obviously produce little plant matter, and seasonally or permanently frozen (but ice-free) polar regions produce only sparse tundra vegetation. In comparison, production of carbon in warmer mid-latitude and tropical regions is much greater.

## Is Chemical Weathering Earth's Thermostat?

Now we have in hand a physical mechanism that could act as Earth's thermostat and moderate long-term climate: the **chemical weathering thermostat**. The global rate of chemical weathering is analogous to a thermostat because it reacts to (depends on) the average state of Earth's climate and then alters that state by regulating the rate at which $CO_2$ is removed from the atmosphere.

Consider what would happen if Earth's climate began to warm (Figure 4-7A). Any initial climate change (for any reason) toward a warmer, moister, more heavily vegetated Earth should enhance chemical weathering of silicate minerals, but the faster weathering in this greenhouse world should then speed up the rate of removal of $CO_2$ from the atmosphere. The result should be a slow negative feedback that reduces the $CO_2$ concentration in the atmosphere and moderates the size of the imposed warming.

The opposite sequence should happen if Earth's climate began to cool (Figure 4-7B). Icehouse climates are typically cold, dry, and more sparsely vegetated,

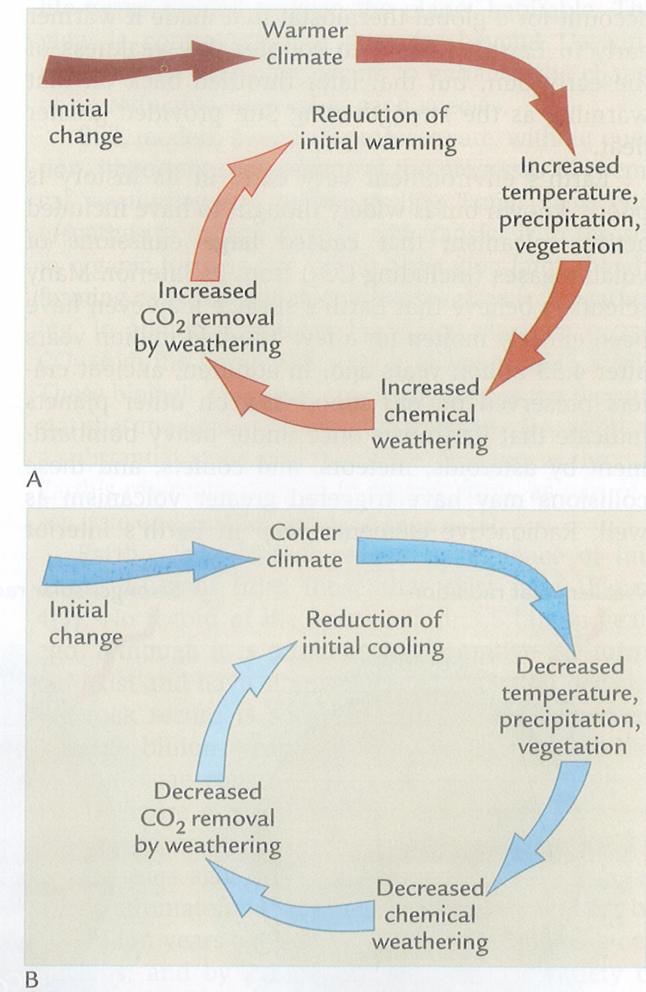



FIGURE 4-7
**Negative feedback from chemical weathering**
Chemical weathering acts as a negative climate feedback by reducing the intensity of an imposed climate warming (A) and cooling (B).

with more extensive snow and ice. An initial climate change toward a colder, drier, less vegetated Earth should reduce chemical weathering and slow the rate of removal of $CO_2$ from the atmosphere. By leaving more $CO_2$ in the atmosphere, slower $CO_2$ removal should reduce the effect of the initial push toward climate cooling.

The functioning of these long-term negative feedbacks does not mean that no climate change occurs at all. Any process that initially acts to warm Earth succeeds in doing so, but by an amount smaller than would have been the case without the negative feedback. Conversely, any process that initially acts to cool Earth succeeds in doing so, but also to a reduced degree. The existence of a climate-dependent negative feedback due to chemical weathering was proposed in 1981 by the geochemist James Walker and his colleagues Paul Hays and James Kastings.

How do we apply this concept to the mystery of the faint young Sun paradox? Recall that we need to account for a global thermostat that made it warmer early in Earth's history to counter the weakness of the early Sun, but that later throttled back on that warming as the strengthening Sun provided greater heat.

Earth's environment very early in its history is poorly known but is widely thought to have included active volcanism that caused large emissions of volatile gases (including $CO_2$) from its interior. Many scientists believe that Earth's surface may even have been entirely molten for a few hundred million years after 4.55 billion years ago. In addition, ancient craters preserved on our moon and on other planets indicate that Earth was once under heavy bombardment by asteroids, meteors, and comets, and these collisions may have triggered greater volcanism as well. Radioactive elements deep in Earth's interior also released heat that could have increased the amount of volcanism. Increased volcanic activity would have delivered more $CO_2$ to the atmosphere and helped to make Earth hotter. As noted earlier, however, it is very unlikely that volcanism is the thermostat responsible for maintaining Earth's moderate climate through all 4.55 billion years of its existence.

Chemical weathering is a more promising explanation. The weakness of the young Sun would have tended to make the early Earth cooler than it is today, and the rate of $CO_2$ removal from the atmosphere by weathering would have been slower because of the lower temperatures. In addition, early continents are thought to have covered a smaller area than they do today. The smaller area of the continents would also have favored slower $CO_2$ removal from the atmosphere by weathering because less rock surface was available to weather. Slower rates of weathering would have left more $CO_2$ in the atmosphere over much of Earth's early history (Figure 4-8A). The warmth produced by this $CO_2$-enriched atmosphere could have countered most of the cooling caused by the smaller amount of incoming solar radiation.

Then, as Earth began to receive more radiation from the brightening Sun, its surface warmed and the rate of chemical weathering gradually increased. Faster chemical weathering began to draw more $CO_2$ out of the atmosphere, and the resulting drop in atmospheric $CO_2$ levels provided a cooling effect that counteracted the gradual increase in solar warming and kept Earth's temperatures moderate (Figure 4-8B). The centerpiece of this explanation is that the slow warming of Earth by the strengthening Sun would have caused changes in weathering rates that moderated changes in climate.

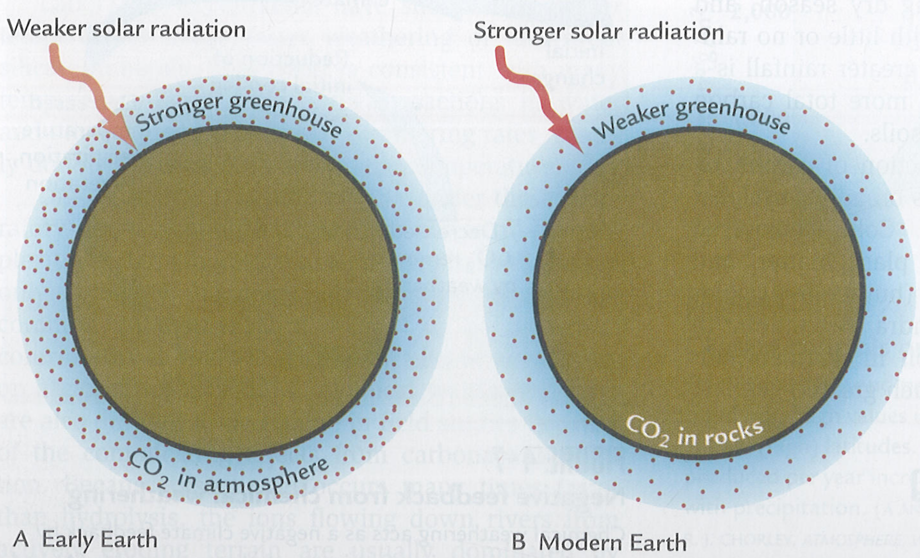



**FIGURE 4-8**
**Earth's thermostat**
A plausible explanation of the faint young Sun paradox is that the weakness of the early Sun was compensated for by a stronger $CO_2$ greenhouse effect in the atmosphere (A). Later, when the Sun strengthened, increased chemical weathering deposited the excess atmospheric greenhouse carbon in rocks, and the weakened greenhouse effect kept Earth's temperatures moderate (B). (ADAPTED FROM W. BROECKER AND T.-H. PENG, *GREENHOUSE PUZZLES* [NEW YORK: ELDIGIO PRESS, 1993].)



**In Summary**, chemical weathering is an excellent candidate for Earth's thermostat. Even though water vapor is a more important greenhouse gas than $CO_2$, it could not have been the source of this thermostat-like action because it amplifies rather than moderates climatic changes (see Chapter 2, Box 2-4).

If chemical weathering is Earth's thermostat, we face still another question: What happened to all the $CO_2$ that once resided in the atmosphere and kept Earth warm? The most likely answer is found by looking at the size of the carbon reservoirs in Figure 4-3: the carbon removed from today's atmosphere by weathering is buried in ocean sediments that eventually turn into rocks. The same process would also have been at work in the past, and over time it would have caused a slow but massive transfer of carbon from the atmosphere to the rocks. If this interpretation is correct, most of Earth's early greenhouse atmosphere lies buried in its rocks instead of concentrated in the atmosphere, as on Venus.

## 4-3 Was Methane Part of the Thermostat?

Decades ago, the astronomer Carl Sagan suggested that higher concentrations of methane ($CH_4$) warmed the early Earth. In the modern atmosphere, methane is a minor trace gas. After being emitted from stagnant carbon-rich wetlands, methane is broken down in a decade or less by chemical interaction with oxygen in the atmosphere. In the early geologic record, however, the absence of rocks with typical red-brown "rust" staining prior to 2.4 billion years ago indicates that Earth's early atmosphere held much less oxygen than it does today. As a result, methane could have stayed in the atmosphere longer, attained higher concentrations, and helped to warm the early Earth.

The subsequent long-term increase in atmospheric oxygen over several billion years would then have reduced the methane content of the atmosphere and weakened its greenhouse effects. Although this explanation provides a long-term cooling trend to counter the warmth from the strengthening Sun, it is not so obvious why methane would have acted like a thermostat by reacting to long-term climate changes. It seems to have acted more as an independent (and coincidentally opposing) climatic factor.

# Is Life the Ultimate Control on Earth's Thermostat?

Although chemical weathering provides a plausible thermostat-like mechanism to moderate Earth's climate, we have also seen that the processes involved are not strictly physical and that biological processes also take a part.

## 4-4 The Gaia Hypothesis

The biologists James Lovelock and Lynn Margulis proposed in the 1980s that life itself has been responsible for regulating Earth's climate. They called their idea the **Gaia hypothesis**, after the ancient Greek Earth goddess. A crude analogy of how their hypothesis works is the way the fur on an animal fluffs out to create an insulated layer and keep the creature warm when the weather turns cold. The animal in effect unconsciously regulates its own environment for its own good. The Gaia hypothesis holds that life regulates climate on Earth for its own good.

An extreme version of the Gaia hypothesis holds that all evolution on Earth has occurred for the greater good of the planet by producing the succession of life-forms needed to keep the planet habitable. This view is controversial: it goes far beyond Darwin's concept that evolution occurs to enhance the chance of reproductive survival of each species.

Still, modern biological processes are, without question, important components of the processes of chemical weathering and carbon cycling. Land plants photosynthesize carbon dioxide and transfer it to the soil in organic form as part of the vegetation litter, thereby forming carbonic acid that enhances chemical weathering. In addition, shell-bearing ocean plankton extract $CO_2$ from the ocean and store it in their $CaCO_3$ shells. These biologic processes are clearly part of the thermostat that moderates Earth's climate today. (In addition, a substantial amount of the carbon that moves through Earth's reservoirs does so in organic form, as part of a separate and smaller subcycle [Box 4-1]).

Earth's long history reveals a sequence of life-forms different from those that exist now (Figure 4-9). No record of life exists before 3.5 billion years ago, although it is possible that primitive life-forms did exist and have simply escaped detection because the rock record is so scarce and poorly preserved. By 3.5 billion years ago, primitive single-celled marine algae capable of photosynthesis had developed (Figure 4-10A). Over the next 3 billion years, slightly more complex organisms evolved: by 2.9 billion years ago, moundlike clumps of marine algae called stromatolites that attached to the seafloor; by 2.5 billion years ago, organisms that contained a cell nucleus; and by 2.1 billion years ago, a variety of multicelled algae.

Most complex forms of life did not arrive until later in Earth's history. Near 540 million years ago, hard shells of many kinds of organisms abruptly appear

# Looking Deeper into Climate Science

Box 4-1

## The Organic Carbon Subcycle

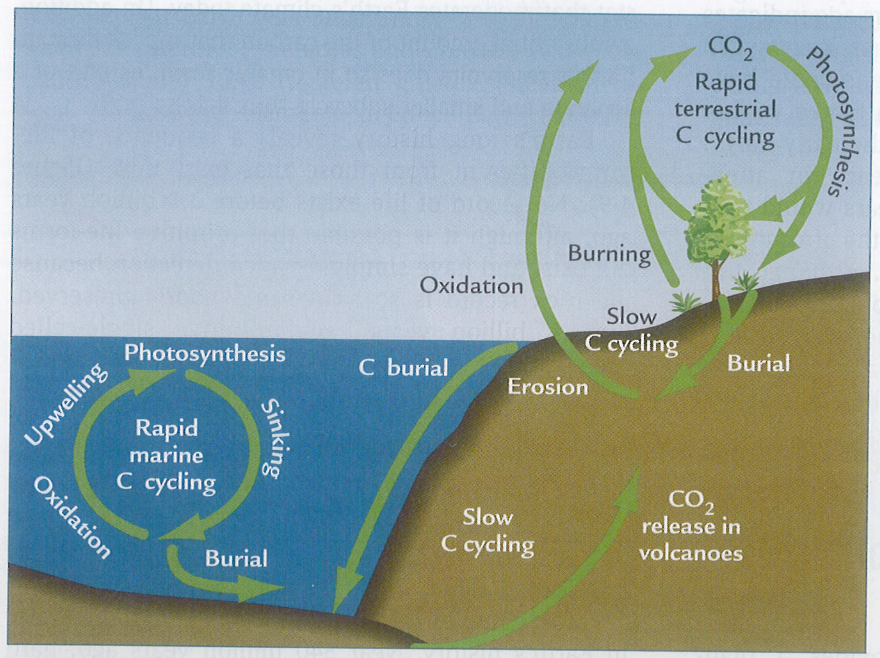
Nearly 20% of the carbon that cycles among Earth's carbon reservoirs today does so in organic form. Photosynthesis is critical to the organic carbon subcycle, mainly because land plants extract $CO_2$ from the atmosphere, and also because ocean plankton extract $CO_2$ from inorganic carbon dissolved in the surface ocean. Most of the organic carbon temporarily stored in land vegetation and ocean plankton is recycled and quickly returned to the ocean-atmosphere system by means of oxidation, which uses available oxygen in water or air to convert organic carbon back to inorganic form.

On land, oxidation consumes organic carbon just after the seasonal fall of leaves or dieback of green vegetation, and after the death of the woody tissue of trees. In the oceans, oxidation slowly consumes organic debris sinking out of the sunlit surface layers where photosynthesis occurs.

Only a small fraction of the organic carbon formed by these processes is buried in the geologic record, and carbon from the land and oceans contributes roughly equal amounts to this total. Burial of organic carbon is favored in water-saturated environments (marine or terrestrial) characterized by (1) low oxygen levels that minimize oxidation, and (2) rapid production of organic matter that consumes the remaining oxygen and allows the rest of the organic debris to escape oxidation. These conditions produce fine-grained carbon-rich muds that eventually turn into mudstones and then into harder rocks called shales.

The carbon buried in sediments and then rocks represents a net loss of $CO_2$ from the interactive carbon reservoirs in the ocean, atmosphere, soil, and vegetation. Once buried, organic carbon stays in the rocks until tectonic processes return it to the surface by slow-acting methods: (1) weathering (and oxidation) of carbon-bearing rocks at Earth's surface, and (2) thermal breakdown of organic carbon in rocks deep in Earth's interior, with release of liberated $CO_2$ through volcanoes.

Because this organic carbon subcycle carries one-fifth of the carbon moving between Earth's rocks and its surface reservoirs, it has the potential to have substantial effects on the global carbon balance and on atmospheric $CO_2$ over long (tectonic-scale) time intervals. Also, under conditions that cause the onset of high productivity and carbon burial in the ocean, large amounts of organic carbon can be quickly extracted from the atmosphere, causing rapid reductions of $CO_2$ levels and rapid climatic cooling.




**The organic carbon subcycle** About 20% of the carbon that shifts between Earth's surface reservoirs (air, water, and vegetation) and its deep rock reservoirs moves in the organic carbon subcycle. Photosynthesis on land and in the surface ocean turns inorganic carbon into organic carbon, most of which is quickly returned to the atmosphere or surface ocean. A small fraction of this organic carbon is buried in continental and oceanic sediments that slowly turn into rock. This carbon is eventually returned to the atmosphere as $CO_2$, either by erosion of continental rocks or by crustal melting and volcanic emissions.



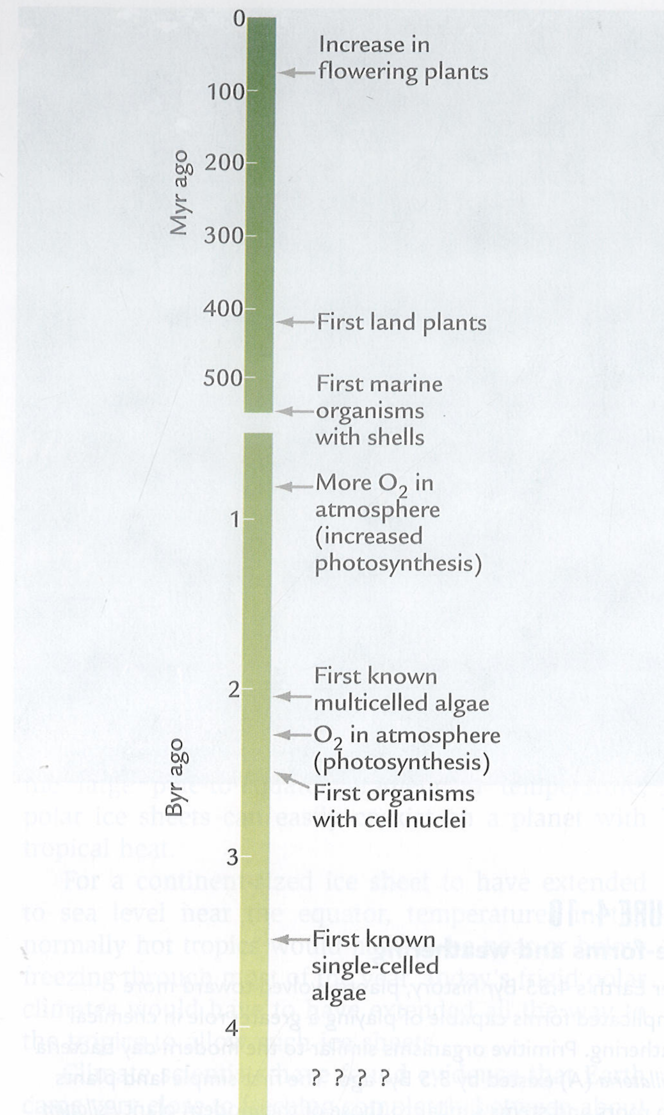



**FIGURE 4-9**
**The Gaia hypothesis**
Over time, life-forms gradually developed in complexity and played a progressively greater role in chemical weathering and its control of Earth's climate. In the extreme form of the Gaia hypothesis, life evolved for the purpose of regulating Earth's climate.

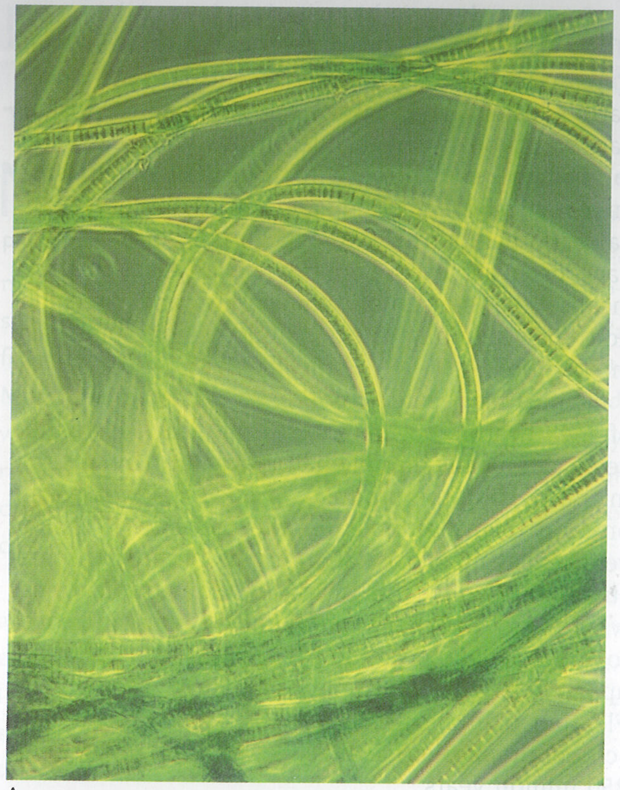
in the fossil record. Before that time, the only fossilized records of life consisted of ghost impressions left imprinted on the surfaces of soft sediment layers. The first primitive land plants did not evolve until near 430 million years ago (Figure 4-10B). These plants had acquired the ability to survive on land because their stems and roots delivered water from the ground. The first treelike plants appeared by 400 million years ago (Figure 4-10C). Trees and grasses are important in modern chemical weathering because they acidify groundwater by adding carbon to soils as litter.

Critics of the Gaia hypothesis point out that many of the active roles played by organisms in the biosphere today are a relatively recent development in Earth's history, and that the role of life in the distant past was probably negligible. In this view, early life-forms were too primitive to have had much effect on chemical weathering, and the delicate climatic balance maintained through Earth's history must have been achieved primarily by physical-chemical means (the effects of temperature and precipitation on weathering rates), rather than by biological intervention.

Critics also note that the very late appearance of shell-bearing oceanic organisms near 540 million years ago means that life had played no obvious role in transferring the products of chemical weathering on land to the seafloor for the preceding 4 billion years. Instead, most $CaCO_3$ in the oceans was presumably deposited in warm shallow tropical seas where concentrations of dissolved ions increased to levels that permitted chemical precipitation, apparently with little or no biological intervention. Floating planktic plants capable of photosynthesis (coccolithophorida) evolved even later, in the last 250 million years.

Supporters of the Gaia hypothesis respond with several counterarguments. First, they claim that critics underestimate the role of primitive life-forms such as algae in the ocean and microbes on land in Earth's earlier history. They point to recent discoveries that modern bacteria with similarities to early primitive life-forms are now thought to play a greater role in the weathering process than has generally been recognized, and they suggest that these organisms must also have been more important than generally thought early in Earth's history, when they were the only life-forms present on land.

One indication that early life-forms were important at a global scale is the first development of an oxygen-rich atmosphere near 2.4 billion years ago, even before the first multicelled algae (see Figure 4-9). Evidence for this important event includes the first appearance of rocks that show red staining (rusting) of iron (Fe) minerals. The appearance of oxidized iron minerals at this time coincides roughly with the disappearance of previously widespread minerals such as FeS (pyrite, or "fool's gold"), which form only under reducing conditions (no oxygen). The only conceivable source of the oxygen that caused the widespread change to oxidized forms of iron is photosynthesis by marine organisms, implying an active global-scale role for these organisms far back in Earth's history. (Also, as noted above, the increase in oxygen would have reduced the amount of methane in the atmosphere.)



A

C

B

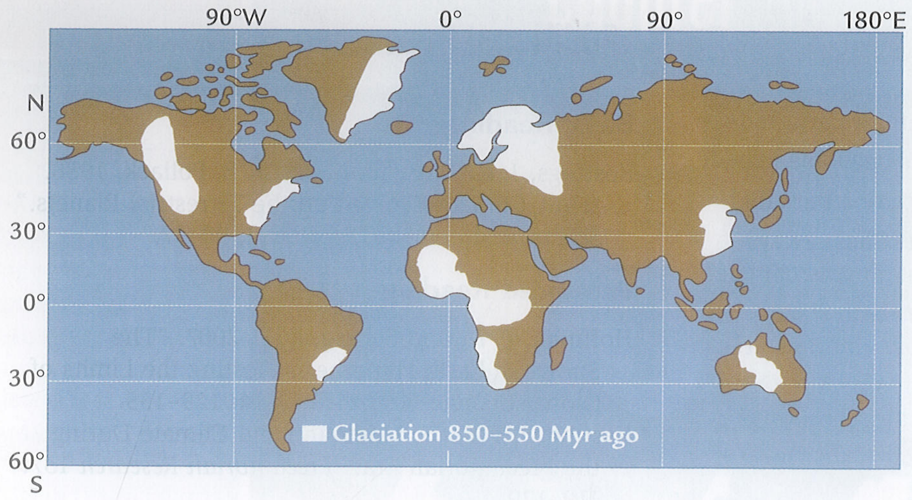
## FIGURE 4-10
**Life-forms and weathering**

Over Earth's 4.55-Byr history, plants evolved toward more complicated forms capable of playing a greater role in chemical weathering. Primitive organisms similar to the modern day bacteria *Oscillatoria* (A) existed by 3.5 Byr ago. The first simple land plants with roots and stems similar to those of the modern plant *Psilotum* (B) appeared by 430 Myr ago. Increasingly complex treelike plants similar to modern tropical cycads (C) appeared by 400 Myr ago and led to the modern diversity of trees and shrubs. (A: SINCLAIR STAMMERS/SCIENCE PHOTO LIBRARY/SCIENCE SOURCE; B: BLICKWINKEL/ALAMY; C: GERALD CUBITT.)

Gaia hypothesis supporters also point out that the general path of biological evolution matches Earth's need for progressively greater chemical weathering through time. The more primitive organisms played a much smaller role in accelerating the process of chemical weathering during a time when it was to Earth's advantage to retain $CO_2$ in its atmosphere to counter the weakness of the faint young Sun. Then, as the Sun strengthened and provided more heat to Earth, more advanced organisms capable of accelerating the weathering process appeared, increased the rates of weathering, and pulled $CO_2$ out of the atmosphere to keep the climate system in approximate balance.

**In Summary**, the Gaia hypothesis is fascinating and still being argued. Scientists generally agree about the "minimum" form of Gaia: the idea that living organisms have played a significant role in the history of physical-chemical processes on Earth, including chemical weathering. Still, the "maximum" claim by proponents of the Gaia hypothesis—that individual life-forms regulate their own evolution for the greater benefit of all life on the planet—is not accepted by most scientists. Somewhere in between lies the answer to the role of life in determining the presence of life on Earth.






## FIGURE 4-11
**Snowball Earth?**

Evidence of several glaciations between 750 and 580 Myr ago exists in rocks on Earth's modern continents. If these glaciated regions were located in the tropics, Earth must have been much colder than today. (ADAPTED FROM L. A. FRAKES, *CLIMATES THROUGH GEOLOGIC TIME* [AMSTERDAM: ELSEVIER, 1979], AND FROM J. G. MEERT AND R. VAN DER VOO, "NEOPROTEROZOIC (1000–540 MYR) GLACIAL INTERVALS: NO MORE SNOWBALL EARTH," *EARTH AND PLANETARY SCIENCE LETTERS* 123 [1994]: 1–13.)

## Was There a Thermostat Malfunction? A Snowball Earth?

Ice sheets occur today at high latitudes, yet they coexist on the same planet with hot tropical regions where a strong overhead Sun heats the land and ocean. With the large pole-to-equator gradient in temperature, polar ice sheets can easily coexist on a planet with tropical heat.

For a continent-sized ice sheet to have extended to sea level near the equator, temperatures in the normally hot tropics would have to be near or below freezing through most of the year. Today's frigid polar climates would have to have extended all the way to the tropics to allow such ice sheets.

Climate scientists have found evidence that Earth came very close to freezing completely between about 750 and 580 million years ago. Sedimentary deposits from glaciers are found on several continents during this interval, providing evidence that ice sheets were present (Figure 4-11). These rocks contain ice-deposited mixtures of coarse boulders and cobbles along with fine silts and clays (see Chapter 3). Because these ancient deposits are difficult to date and correlate accurately, scientists have inferred that as few as two, or as many as four, major glacial eras occurred during this long interval.

A critical question is whether these ice sheets were located at high or low latitudes. For the glacial intervals between 715 and 640 million years ago (but not the ones before or after that interval), the geologic evidence suggests that at least some of the glaciated continents were in the tropics. This conclusion forms the basis for the novel idea that Earth was once nearly frozen—the **snowball Earth hypothesis.**

One obvious factor contributing to this much cooler interval was weaker solar heating from a Sun that was 6% below its modern luminosity (see Figure 4-2). According to the thermostat concept, a cooler Earth would have reduced the rate of chemical weathering, kept $CO_2$ values higher, and moderated global temperature. In this case, however, climate models indicate that $CO_2$ concentrations would have to have been much lower than today to permit ice sheets to exist in tropical latitudes. The thermostat mechanism seems to have malfunctioned, at least for a while.

The reason for the thermostat malfunction remains unresolved. One explanation for the onset of a snowball Earth is that continents were clustered near the equator, where they would initially have been subject to heavy rainfall. Paradoxically, unusually heavy tropical precipitation could have driven unusually strong chemical weathering that greatly reduced $CO_2$ concentrations and chilled the planet.

A debate continues about how cold this world was. Although some scientists feel that Earth was frozen "hard," with sea ice extending right to the equator, evidence of water-deposited sedimentary rocks in several regions points to an incomplete freeze (called by some "slushball Earth"). Climate model simulations generally indicate an Earth with sea ice reaching into middle latitudes, but not as far as the tropics. Because the large amount of solar heat stored in the ocean at low latitudes tends to keep its surface free of ice, model simulations tend to fall short of a hard freeze.

## Key Terms

- greenhouse era (p. 81)
- icehouse era (p. 81)
- faint young Sun paradox (p. 84)
- thermostat (p. 84)
- silicate minerals (p. 87)
- chemical weathering feedback (p. 89)
- Gaia hypothesis (p. 91)
- snowball Earth hypothesis (p. 95)