4

The Habitability of Earth

The Habitability of Earth

LEARNING GOALS

4.1 GEOLOGY AND LIFE
- How is geology crucial to our existence?

4.2 RECONSTRUCTING THE HISTORY OF EARTH AND LIFE
- What can we learn from rocks and fossils?
- How do we learn the age of a rock or fossil?
- What does the geological record show?

4.3 THE HADEAN EARTH AND THE DAWN OF LIFE
- How did Earth get an atmosphere and oceans?
- Could life have existed during Earth's early history?

4.4 GEOLOGY AND HABITABILITY
- What is Earth like on the inside?
- How does plate tectonics shape Earth's surface?
- Why does Earth have a protective magnetic field?

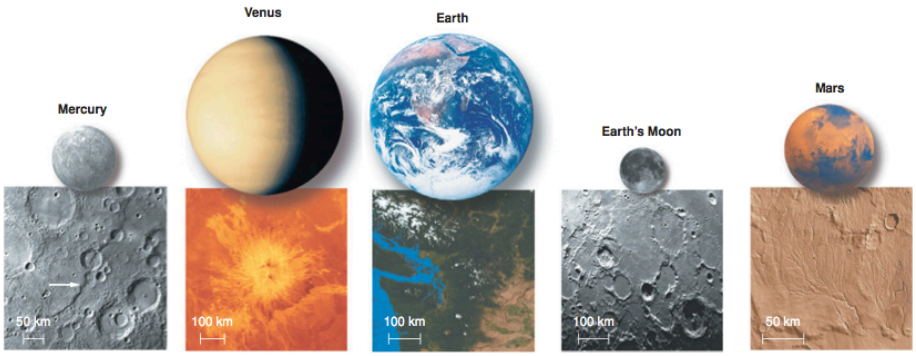
4.5 CLIMATE REGULATION AND CHANGE
- How does the greenhouse effect make Earth habitable?
- What regulates Earth's climate?
- How does Earth's climate change over long periods of time?

THE PROCESS OF SCIENCE IN ACTION

4.6 FORMATION OF THE MOON
- How did the giant impact model win out over competing models?
- Does the giant impact model count as science?

Geology and Geologic History of Earth and Life

Each of these planets (and our moon) has its own unique geology.
The persistence of craters indicates a lack of erosion on the surface.
Venus, Earth, and Mars have volcanoes, through only Earth's remain active.



Heavily cratered Mercury has long steep cliffs (arrow).

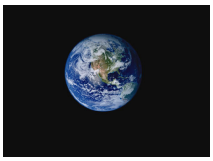
Cloud-penetrating radar revealed this twin- peaked volcano on Venus.

A portion of Earth's surface as it appears without clouds.

The Moon's surface is heavily cratered in most places.

Mars has features that look like dry riverbeds; note the impact craters.

Geology and Geologic History of Earth and Life



Geology is important to life on Earth:
three aspects especially important:

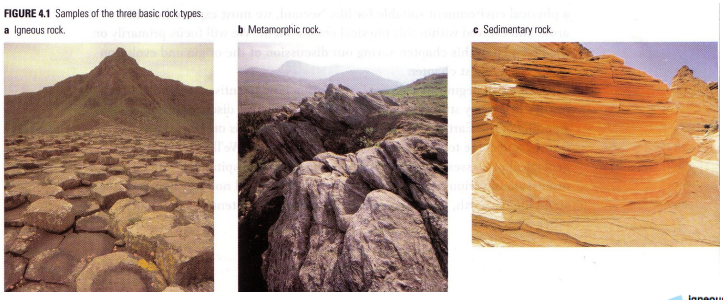
• Volcanic Activity releases gases trapped in Earth's interior, and these gases were the original source of Earth's atmosphere and oceans. In addition, volcanism releases heat and creates chemical environments that helped lead to the origin of life.

•Plate Tectonics recycles rock between the surface and the interior and gradually rearranges the continents. Its most profound relevance to life involves Earth's climate: According to modern understanding, plate tectonics is largely responsible for the long-term climate stability that has allowed life to evolve and thrive for some 4 billion years.

•Earth's Magnetic Field significance is that it shields Earth's atmosphere from the energetic particles of the solar wind (charged particles), and without this shielding, it's likely that a significant portion of our planet's atmosphere would by now have been stripped away into space. By blocking these particles it also stops lethal radiation from causing mutations in our genes.

How to Read Earth's History

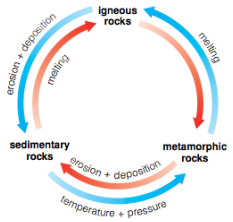
Rocks and Fossils…



Igneous Rock - was once molten and then cooled and solidified

Metamorphic Rock - structurally transformed by high pressure or heat, never molten

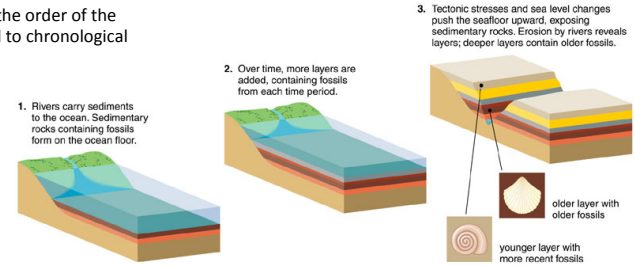
Sedimentary Rock - gradual compression of sediments (sand and silt)



Metamorphic rock could be made from igneous or sedimentary rock transformed by heat and pressure; **rock types tell formation history; rock mineral contents tell composition**

Fossils Created/Survive in Sedimentary Rock

Layer by layer of rock is built up- the order of the strata are assumed to correspond to chronological age of the rocks formation



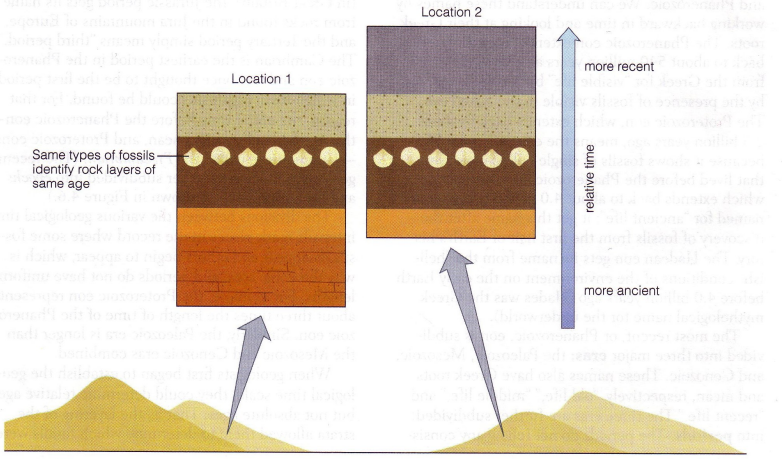
This process is "gentle"

Process deposits minerals in the organic matter and harden it… such matter is "replaced" by minerals

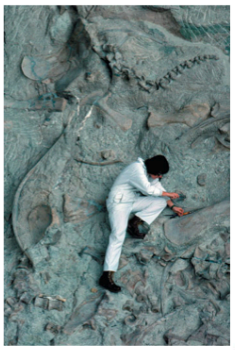
Some mineral rich organic material (bone, teeth, shells) survive mostly intact

Chronology from Sedimentary Strata

FIGURE 4.5 In this diagram, we imagine comparing sedimentary strata at two locations. We find that the fossils found in a particular layer near the top at Location 1 are of the same type as those found in a lower layer at Location 2. We conclude that the two sets of strata represent overlapping time periods, with the strata at Location 1 going farther back in time.



Fossil Gallery



a Dinosaur bones preserved in sandstone in Dinosaur National Monument, which straddles Utah and Colorado.

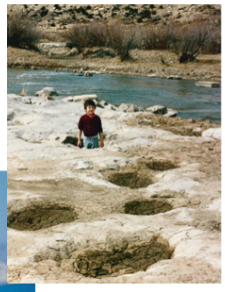
b A 190-million-year-old petrified (stone) tree in Arizona.

c These 200-million-year-old impressions are casts of snail-size, extinct organisms (called ammonites) made when minerals filled the empty space left after the organisms decayed.

e An insect preserved in hardened tree resin (often called *amber*), 45 million years old.

d This 40-million-year-old leaf still retains organic material, including DNA.

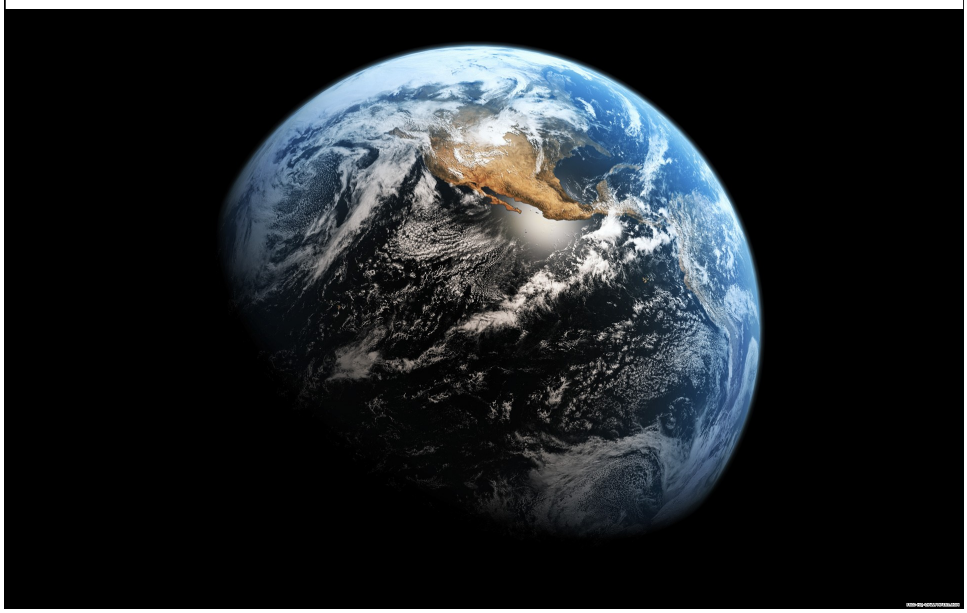
f These tusks belong to a whole 23,000-year-old mammoth discovered in Siberian ice in 1999.



g This boy is standing in a 150-million-year-old dinosaur track in Colorado.

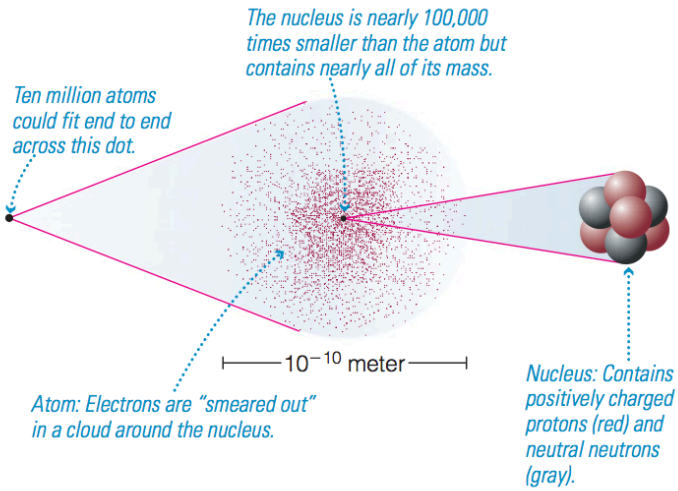
The History of the Earth

- Determining ages
- Formation and Evolution
- Geology and Life



Absolute Ages Measured Using Radiometric Dating

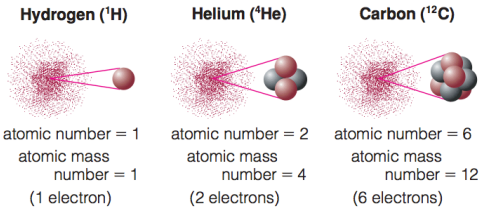
The Atom



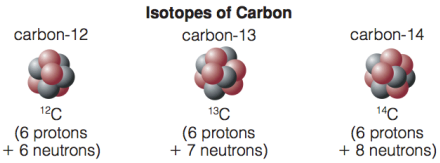
Absolute Ages Measured Using Radiometric Dating

Atomic Number and Isotopes

atomic number = number of protons
atomic mass number = number of protons + neutrons
(A neutral atom has the same number of electrons as protons.)

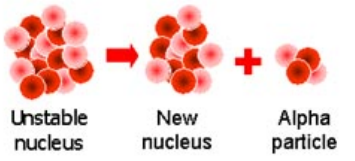


*Different **isotopes** of a given element contain the same number of protons, but different numbers of neutrons.*



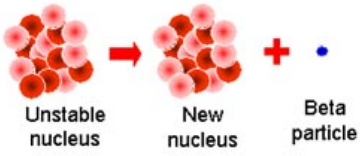
Absolute Ages Measured Using Radiometric Dating

Forms of Radiation



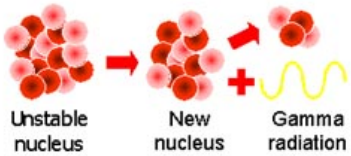
Alpha (α): atom decays into a new atom & emits an alpha particle (2 protons and 2 neutrons: the nucleus of a helium atom)

Daughter has two less protons so is a different element with lower atomic number



Beta (β): atom decays into a new atom by changing a neutron into a proton & electron. The fast moving, high energy electron is called a beta particle

Daughter gains a proton so is a different element with higher atomic number

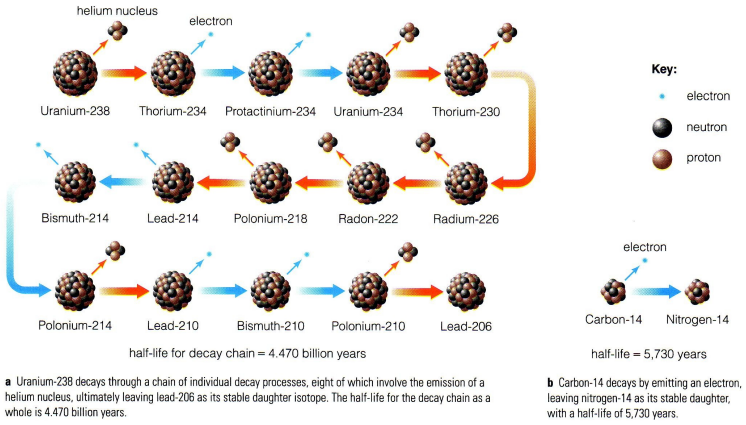


Gamma (γ): after α or β decay, surplus energy is sometimes emitted. This is called gamma radiation & has a very high frequency with short wavelength. The atom is not changed

Daughter element has same number of protons so is the same element with the same atomic number

Absolute Ages Measured Using Radiometric Dating

Radioactive Decay to a Stable Element



a Uranium-238 decays through a chain of individual decay processes, eight of which involve the emission of a helium nucleus, ultimately leaving lead-206 as its stable daughter isotope. The half-life for the decay chain as a whole is 4.470 billion years.

b Carbon-14 decays by emitting an electron, leaving nitrogen-14 as its stable daughter, with a half-life of 5,730 years.

Through a series of radioactive decays, Uranium morphs into Lead!

Each step of the reaction had a (statistically) averaged time duration (in individual decays some take shorter and some are take longer than the average).

The Dating Game- Counting Half Lifes

We assume that all the material was originally pure **Parent Isotope** when the object formed

We then measure the fraction that remains in the Parent Isotope and the fraction that is in the Daughter Isotope. Then using the statistical decay times, called **half-life**, we estimate the time elapsed from formation

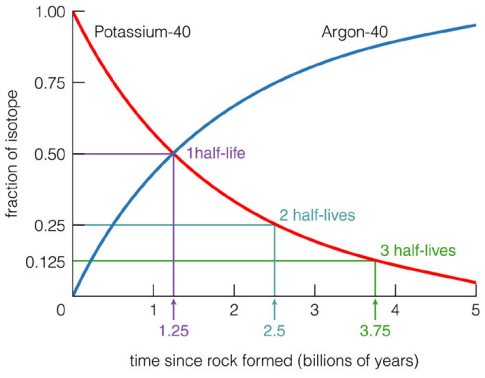
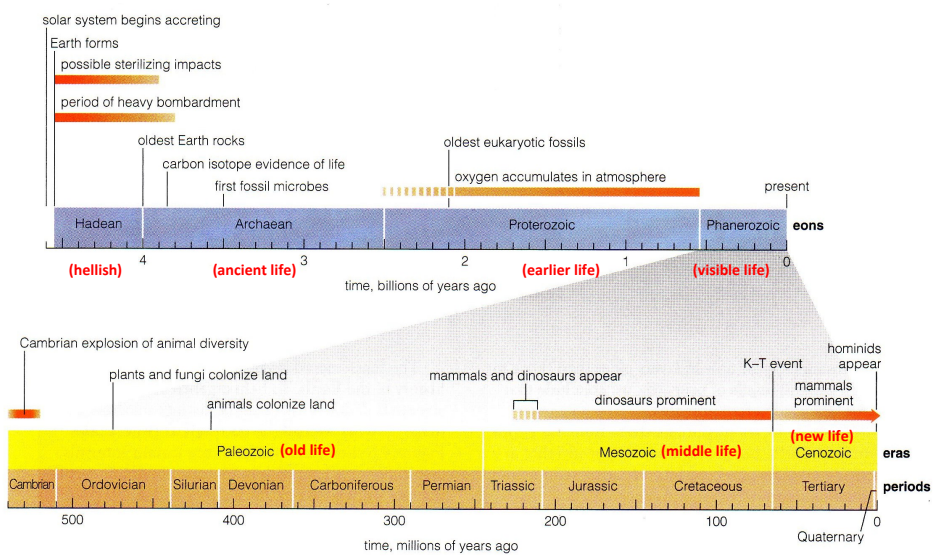


Table 4.1 Selected Isotopes Used for Radiometric Dating of Rocks and Fossils Some of the isotopes decay in several stages of parent–daughter pairs, and only the final daughter product is shown.

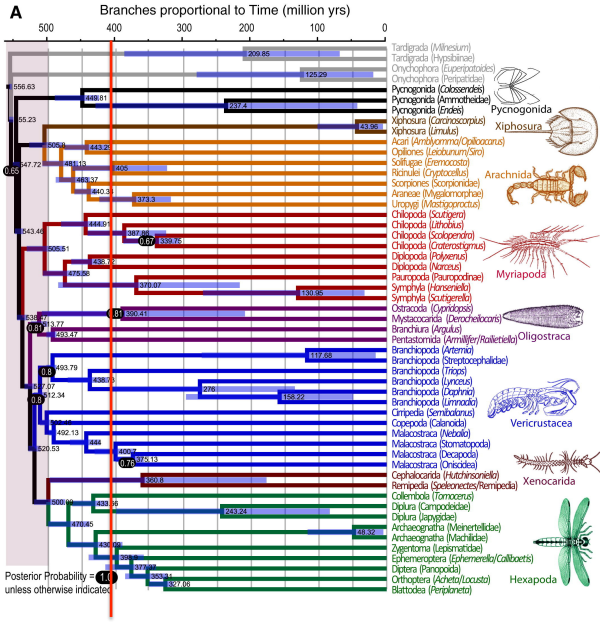
Parent Isotope	Daughter Isotope	Half-Life
Uranium-238	Lead-206	4.470 billion years
Uranium-235	Lead-207	704 million years
Thorium-232	Lead-208	14 billion years
Potassium-40	Argon-40	1.250 billion years
Rubidium-87	Strontium-87	48.8 billion years
Aluminum-26	Magnesium-26	700,000 years
Carbon-14	Nitrogen-14	5,730 years

Eons, Eras, and Periods of Earth's History

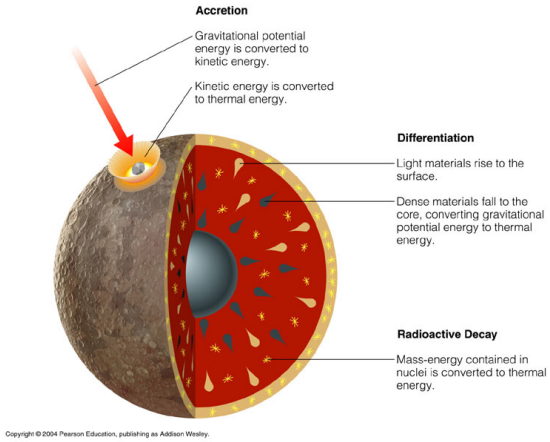


The Cambrian Explosion 550 Million Years Ago

red line at ~400 million years ago indicates when animals colonize on land



Earth Formation: Early Times



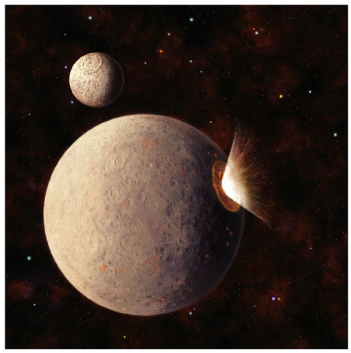
Three majors processes: Accretion, Differentiation, and Radioactive Decay

Earth Formation: Accretion

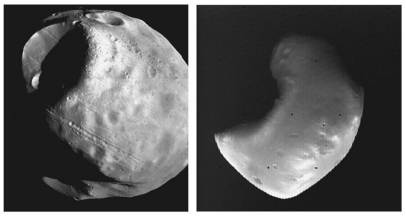
Evidence for an early accretion phase is abundant in the solar system…

This phase was called the period of **heavy bombardment**. It lasted until about 3.8 billion years ago.

Bombardment is still occurring today, it is just that the solar system is pretty well cleaned out now so the frequency of "big" impacts is much reduced.

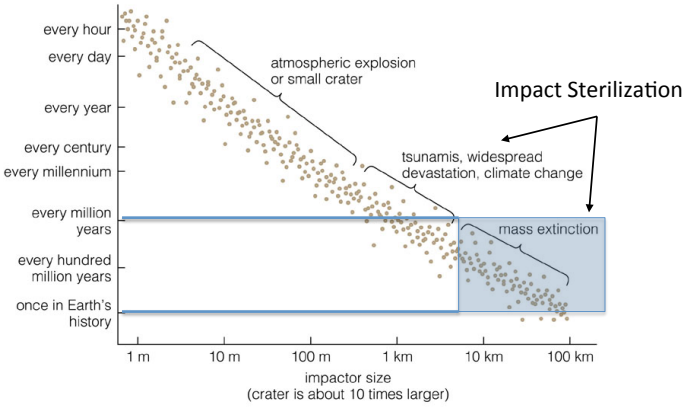


We believe the Earth's moon was formed when a "Mars sized" impactor hit the Earth. The Apollo missions, where the astronauts examined the moon's crust, played an important role in eliminating other hypothesis of the moon's formation.



Earth Formation: Accretion – but how about today?

The frequency of accretion <u>today</u> as a function of "impactor size"



Earth Formation: Atmosphere

Earth did not begin with an atmosphere- too small to hold onto hot gases

<u>Outgassing</u> by volcanoes is the process by which gas is deposited onto the surface of the planet from its interior. This is what built up the atmosphere.

<u>Original Composition</u>

- water
- carbon dioxide
- nitrogen
- sulfur gases

Water condensed and rained to build oceans

Early atmosphere dominated by carbon dioxide; today it is dominated by nitrogen!

Earth Formation: Structure

1. Core
   The core has a solid component and a viscous fluid component; dense metals such as iron and nickel
2. Mantle
   The mantle is composed mostly of silicates (silicon based minerals with oxygen); medium density and molten
3. Crust
   The crust is lowest density rock; this component is recycled and changes due to geological activity

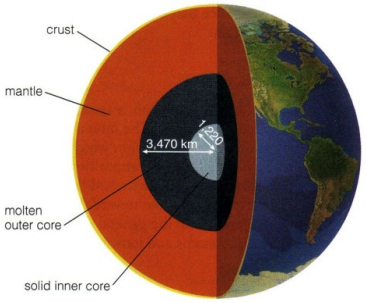
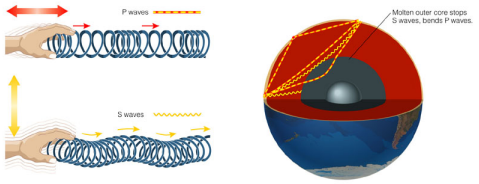


FIGURE 4.10 The basic internal structure of the Earth, as determined from the study of seismic waves. Note that the core is divided into two regions: a solid inner core and a molten outer core.

How do we know….?

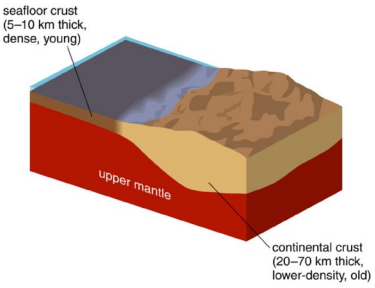
Seismic Waves

When waves cross one medium to another (liquid to solid, high density to low, etc.), the *waves bend and their speed changes*. Provides internal structure and densities (composition).



Earth's Geological Activity

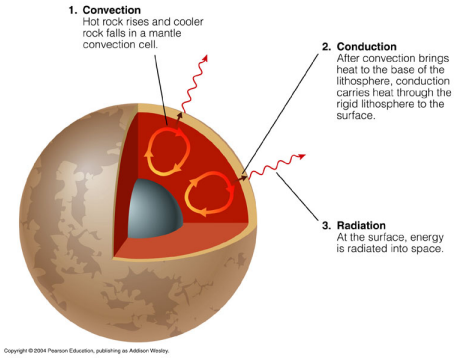
1. Seafloor Crust
   High density igneous rock (basalt), formed from volcanoes along mid-ocean ridges; 5-10 km thick; mostly young- less than 200 million years old
2. Continental Crust
   Lower density, mostly metamorphic and sedimentary rock, parts dates back to the Hadean eon- up to 4 billion years ago; 20-70 km thick; floats on mantle



Mantle Convection

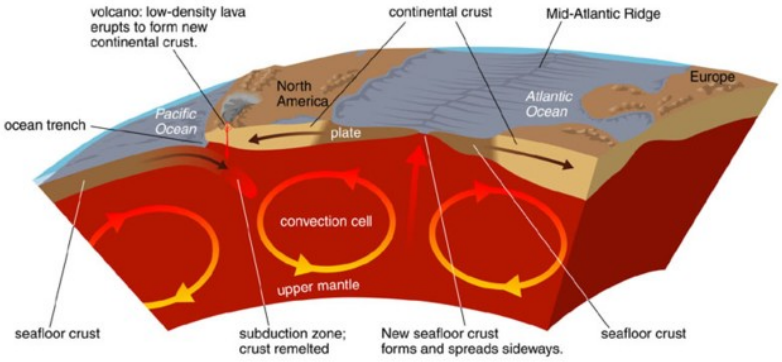
Internal heat (mostly generated by radioactive decay!) drives **convection**, where hot rock rises and cool rock sinks. The convection occurs in convection cells, which deliver hot rock to base of the lithosphere (litho="stone").

This process drives recycling and motion of Earth's crust and keeps Earth geologically active.



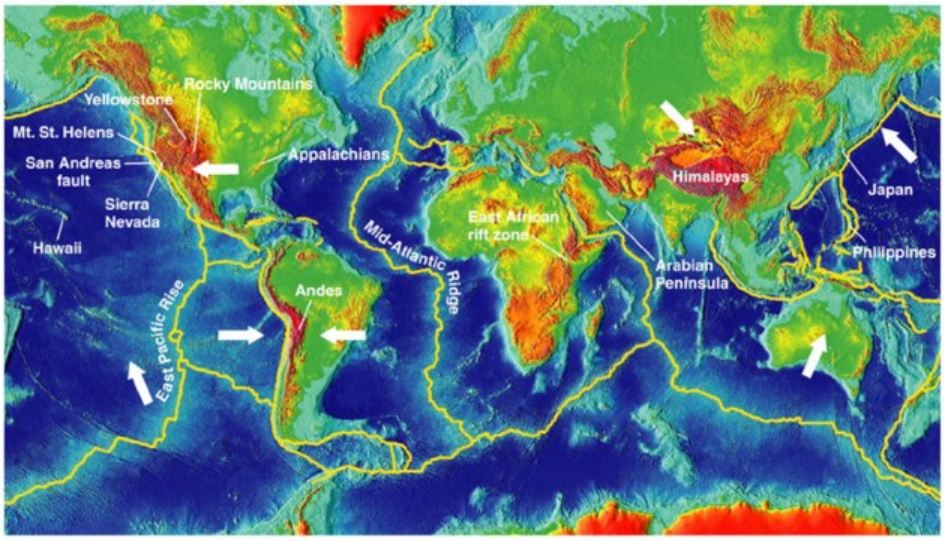
Earth's Crust and Mantel Convection

Competing motions due to convection have broken lithosphere into **plates**. The *process* of these relative plate motions is called **plate tectonics**.
As a result, the plates migrate and Earth experiences **continental drift**.



Continental Drift is the gradual shifting of relative positions of the continents.

Earth's Tectonic Plates



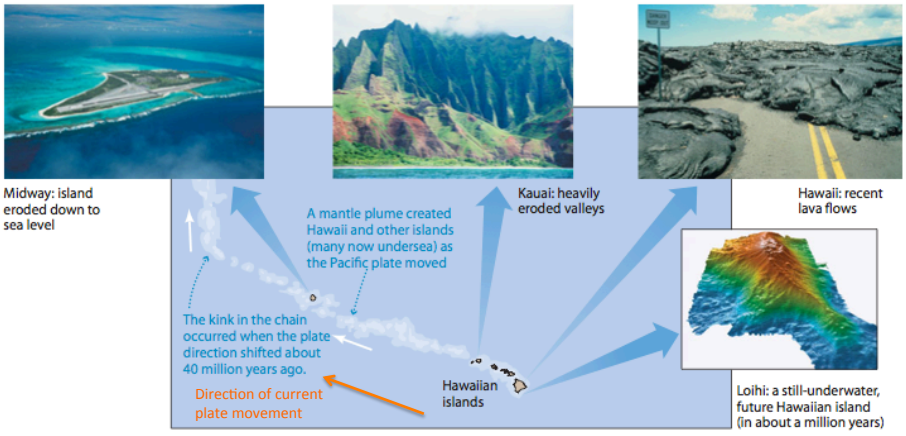
Note the white arrows that show the plate directions. Where plates push together, there are great stresses (subduction), volcanoes, earthquakes, new mountain ranges.

Earth's Tectonic Plates

Mt. Everest is still growing 1.5 inches per year!

Earth's Tectonic Plates

Hawaiian Islands are volcanoes created as the Pacific Plate migrates over a "hot spot" in the Earth's Mantle.



Earth's Tectonic Plates

Continental Drift

By playing the motions backwards and tying together the geological record in sedimentary rocks, we have a model of the history of the Earth's plates.

Note the predictive power – illustrated 150 million yrs future

Note how well South America and Africa (at an angle) fit together. They share similar geology along coasts, further suggesting they may have been joined in the past.

https://www.youtube.com/watch?v=YrruvHNwGq4&spfreload=10
VIDEO: Formation of the Earth 10:24

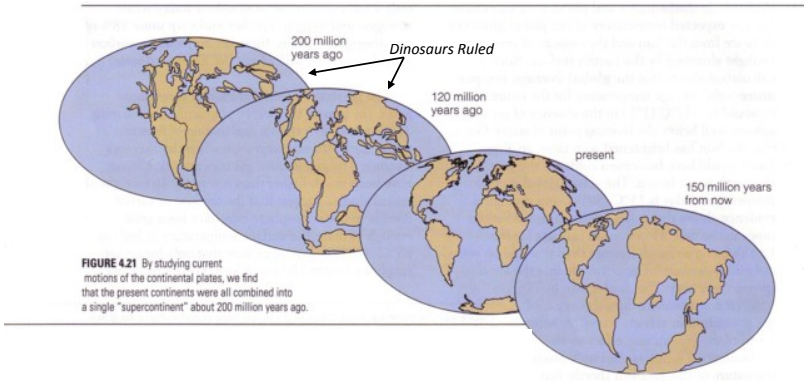
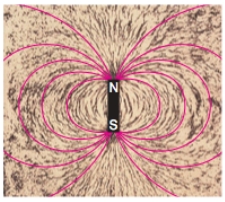
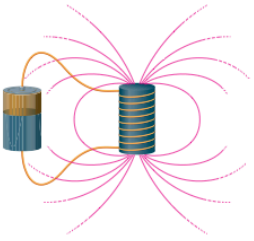


FIGURE 4.21 By studying current motions of the continental plates, we find that the present continents were all combined into a single "supercontinent" about 200 million years ago.

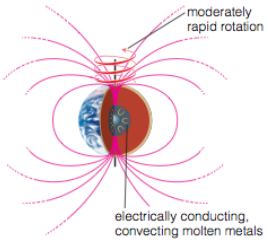
Earth's Magnetic Field



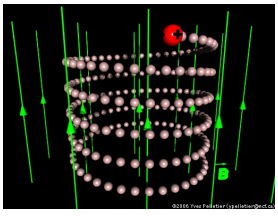
a This photo shows how a bar magnet influences iron filings (small black specks) around it. The *magnetic field lines* (red) represent this influence graphically.



b A similar magnetic field is created by an electromagnet, which is essentially a wire wrapped around a bar and attached to a battery. The field is created by the battery-forced motion of charged particles (electrons) along the wire.



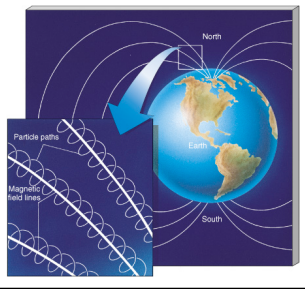
c Earth's magnetic field also arises from the motion of charged particles. The charged particles move within Earth's liquid outer core, which is made of electrically conducting, convecting molten metals.



A charged particle in a magnetic field spirals along the field lines

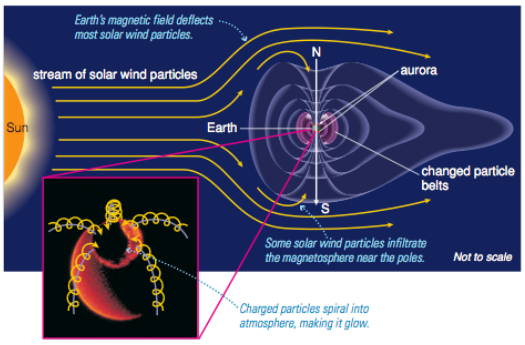
The particle is "trapped"

This is what stops energetic particles from the sun from reaching the Earth's surface, except at the poles



Earth's Magnetic Field

Earth's Invisible Protective "blanket"



a This diagram shows how Earth's invisible magnetosphere (represented in purple) deflects solar wind particles. Some particles accumulate in charged particle belts encircling our planet. The inset is a photo of a ring of auroras around the North Pole; the bright crescent at its left is part of the day side of Earth.

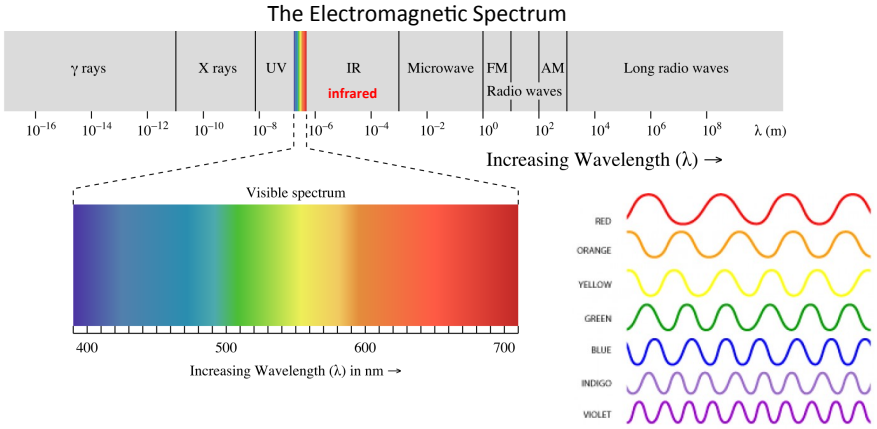
b This photograph shows an aurora in Wapusk National Park, Manitoba, Canada. In a video, you would see these lights dancing about in the sky.

https://www.youtube.com/watch?v=yEYy_nVC4L0
VIDEO: Earth's Magnetism 7:38

Greenhouse Effect

Trapped Infrared Light ➔ Heat

Light is a wave of oscillating electric and magnetic energy
The size of the oscillation is called the wavelength



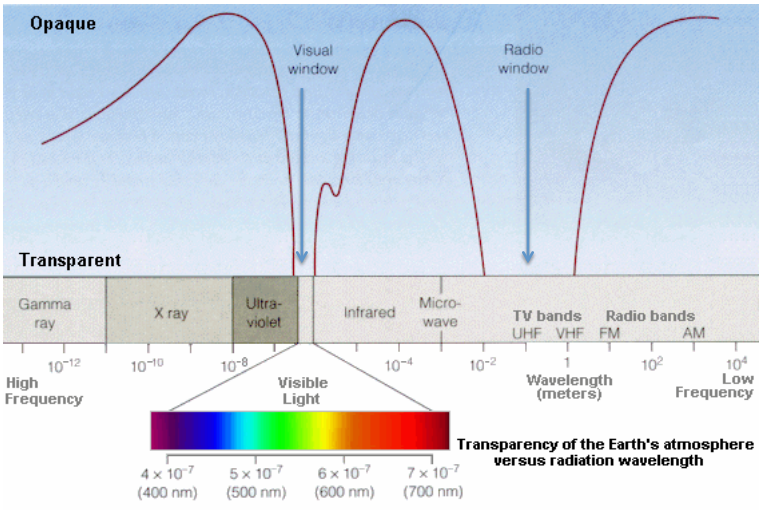
Visible light, which our eye is responsive to, is only one small portion of the **electromagnetic spectrum**. Infrared portion is lower energy, longer wavelength and is important for the Greenhouse Effect.

The energy carried by light is dependent upon its oscillation frequency

Greenhouse Effect

Trapped Infrared Light → Heat

Visible light and Radio wave pass through the atmosphere easily, but infrared light does not, because it is absorbed by certain molecules in the atmosphere



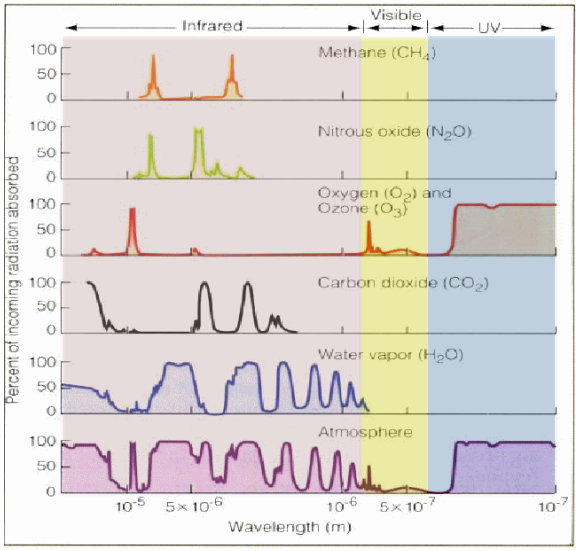
Greenhouse Effect: Greenhouse Gases (absorb infrared light)

Trapped Infrared Light → Heat

In order of the most absorbing to the least:

1. Water Vapor
2. Carbon Dioxide
3. Nitrous Oxide
4. Methane

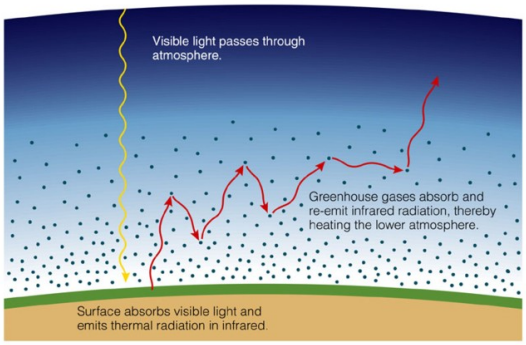
The higher the concentration of the gas, the greater the total absorption

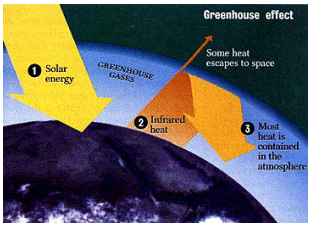


Greenhouse Effect

Trapped Infrared Light → Heat

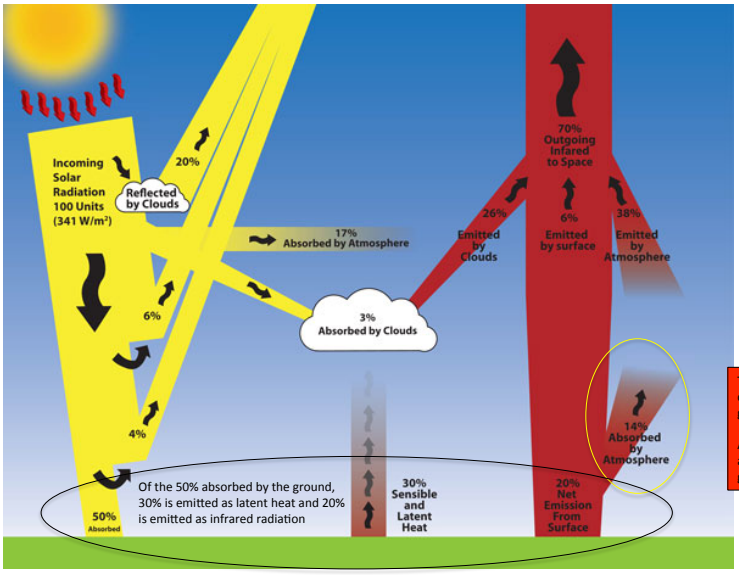
Main Greenhouse Gases:
(1) Water Vapor
(2) Carbon Dioxide





Greenhouse Effect

Trapped Infrared Light → Heat



This 14% will increase if concentration of greenhouse gases increases

Additional absorption by the atmosphere results in a global temperature increase

Greenhouse Effect: Long Baseline Data

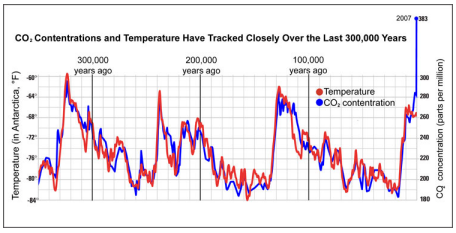
On average, the Earth has been warmer than the estimated mean global temperature of 15 C.

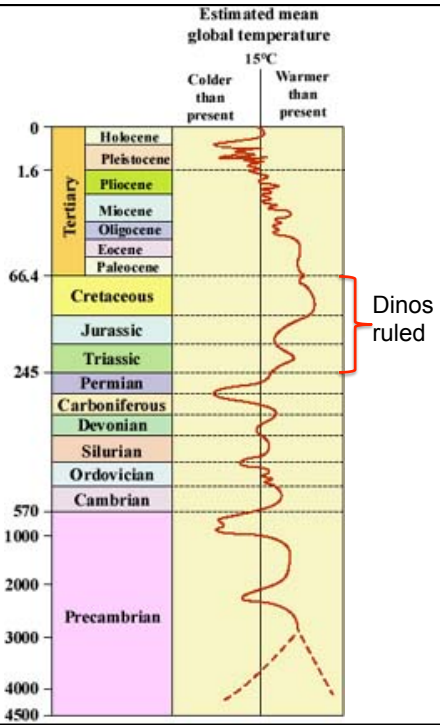
Note how hot it was during the period of the dinosaurs

Note the ice ages during the Tertiary era.

What is driving those oscillations?

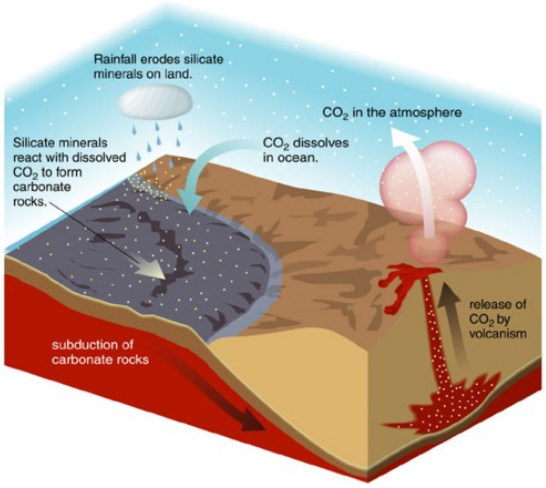
Carbon Dioxide Cycle due to Volcanic Activity?





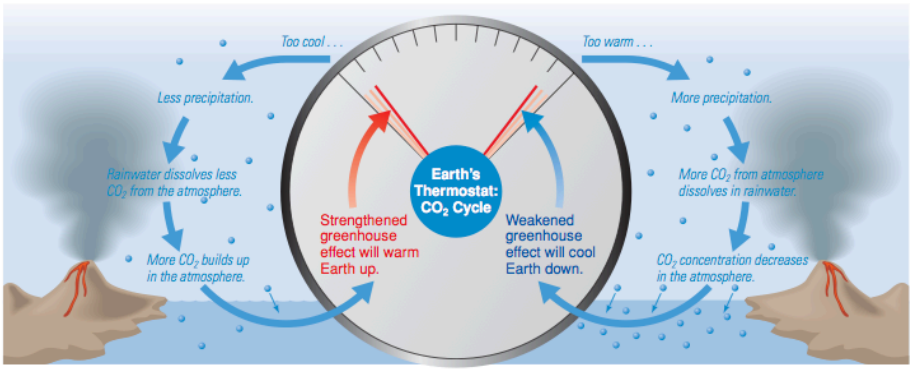
The Carbon Dioxide Cycle

Regulating Earth's Climate



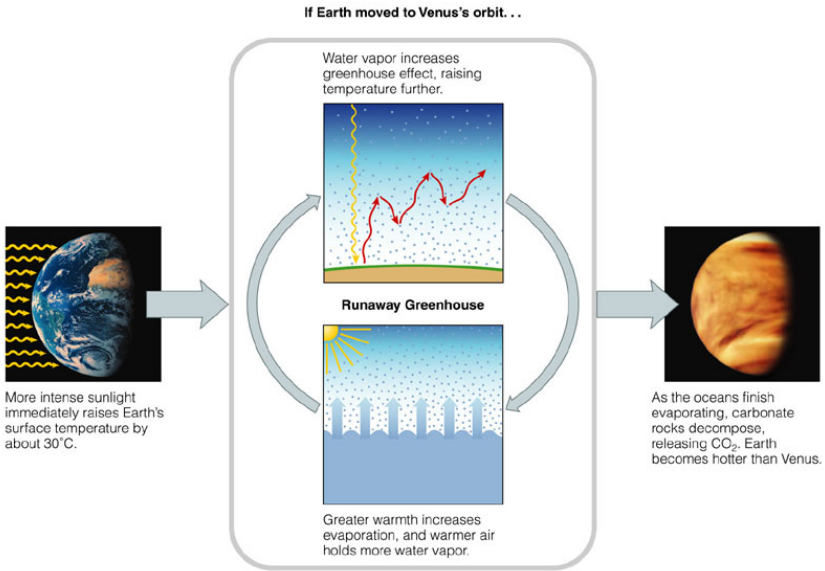
The Carbon Dioxide Cycle

Regulating Earth's Climate

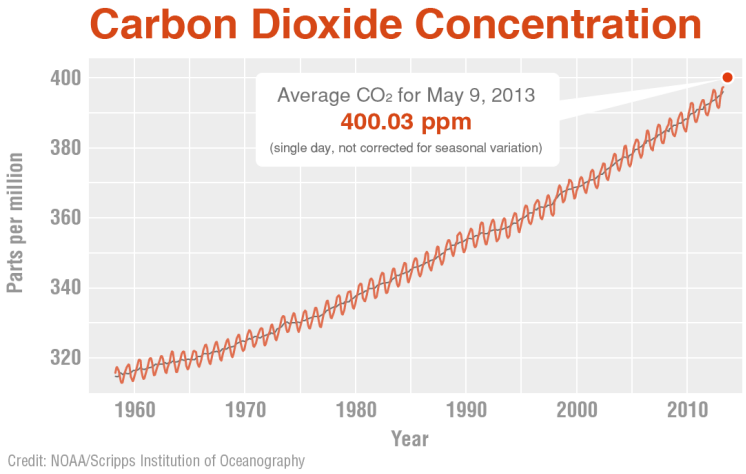


Under stable geological conditions (constant volcanic activity) rain regulates the carbon dioxide concentrations in the atmosphere, so that Earth's temperature oscillates around a mean value. How can this process become unstable?

Runaway Greenhouse Effect: A thought experiment



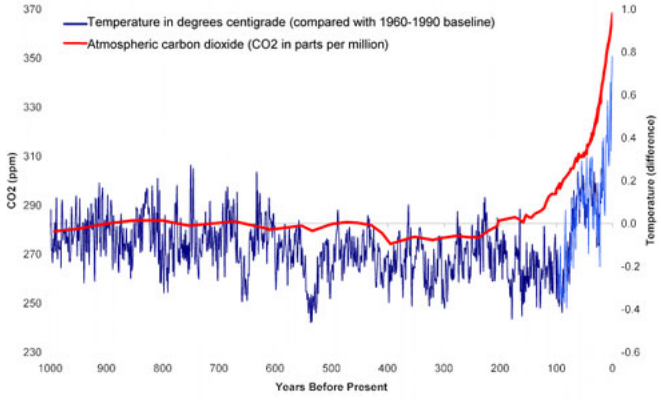
Greenhouse Effect: Recent Data



Recent data of the carbon dioxide concentration in the Earth's atmosphere.

Since 1960, the average concentration has risen by 65 ppm by 2013. Note the seasonal variations.

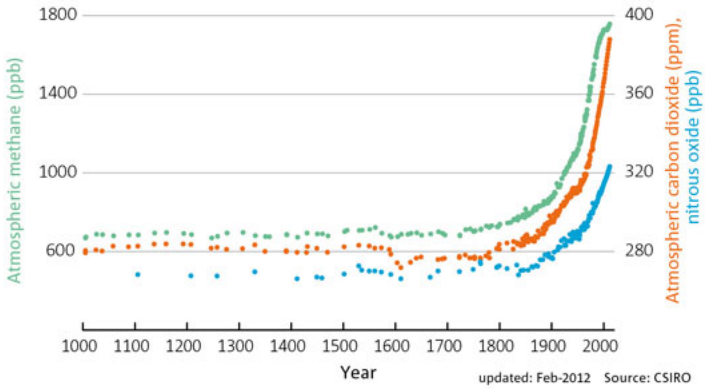
Greenhouse Effect: Recent Data



The industrial revolution began about 100 years ago, and this marks the time of rapid increase in the human generated sources of the atmospheric carbon dioxide concentration and a general rise in the Earth's average temperature by ~ 0.7 degrees Celsius.

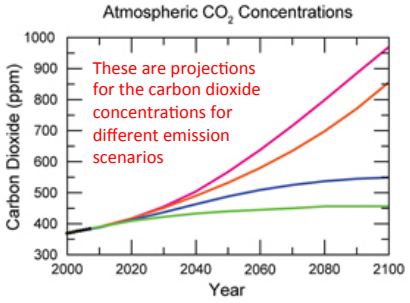
The issue is: at what point does the greenhouse effect "run away", that is, become unstable to an irreversible process in which the oceans begin to evaporate away? This is called the **Runaway Greenhouse Effect**, and it WILL happen to Earth due to the brightening of the sun in about 1.5 to 3 billion years from now no matter what humans do.

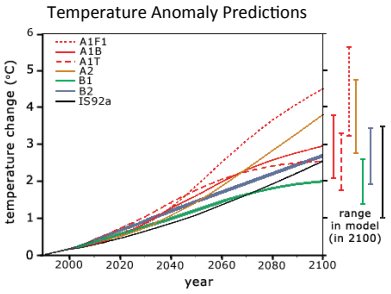
Greenhouse Effect: Recent Data

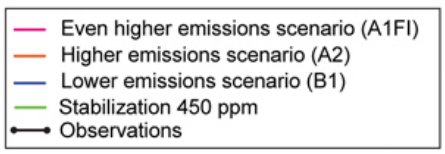


Not only is the carbon dioxide concentrations increasing, but the methane and nitrous oxide greenhouse gas concentrations are also increasing since the industrial revolution began.

Greenhouse Effect: Projections and Model Predictions



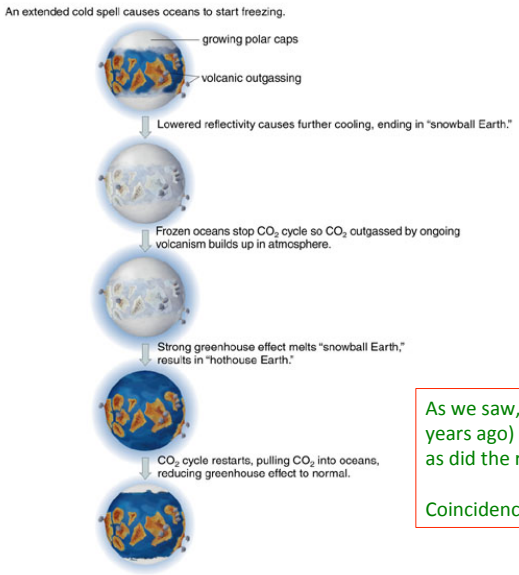




Computer simulation models for each of the projections indicate a continued temperature increase over this century.

If under the "lower emission" scenario (B1), there is still a 1.2 to 2.5 degree predicted increase relative to 1990 temperatures.

The Snowball Earth



Geologists discovered evidence of several long and deep ice ages between 750-580 million years ago and between about 2.4-2.2 billion years ago. Glaciers advanced all the way to the equator.

Ice reflects ~90% of the sunlight hitting it. Further increase in global ice sets up a positive feedback process that cooled Earth even further, called a Runaway Ice Catastrophe, resulting in a Snowball Earth.

As we saw,, the Cambrian Explosion (550 millions years ago) occurred right after one of these periods, as did the rise of oxygen (2.2 billion years ago).

Coincidence?