Chapter 20:
The Atmosphere and Climate Change

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Remains of a Viking settlement in Greenland from the Medieval Warm Period.

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Overview

- Origin of the Global Warming Issue
- Twentieth-Century Methods to Reconstruct Past Temperatures
- How the Atmosphere Works
- How Earth’s Atmosphere, Oceans, and Land Affect Climate
- The Greenhouse Effect
- The Major Greenhouse Gases
- Greenhouse Gases and Climate
- The Oceans and Climate Change
- Forecasting Climate Change Using Computer Simulation
- Climate Change and Feedback Loops

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Origin of the Global Warming Issue

- The present-day discussion about global warming is complex and confusing
- Global warming has become highly contentious
- Global warming has turned into a debate that is often far removed from evidence based on science
- Medievel Warm Period (MWP) 500-1500
- Little Ice-Age 1400-1700

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Fundamental Questions about Global Warming

- What is the origin of rapid warming in the geologic record?
- Is the present rapid warming unprecedented or at least so rare that many living things will not be able to respond successfully to it?
- To what extent, have people caused it?
- What are likely to be the effects on people?
- What are likely to be the effects on all life on Earth?
- How can we make forecasts about it and other kinds of climate change?
- What can we do to minimize potential negative effects?

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Historical Background of the Origin of the Global Warming Issue

- Possibility that burning fossil fuels might warm the climate is not a new idea
  - First suggested early in the 19th century
  - Not much attention given to this possibility, however, until the first decades of the 20th century
- Guy Stewart Callendar (1938) studied 19th-century measurements of atmospheric carbon dioxide concentration and found they were considerably lower than measurements made then in the 20th century

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Historical Background of the Origin of the Global Warming Issue

- Callendar suggested the difference could be attributed to the amount of CO_2 added to the atmosphere from the burning of fossil fuels since the beginning of the Industrial Revolution
  - Highly controversial concept
  - Callendar was attacked by his scientific colleagues
  - Most believed that 19th-century scientists were incompetent and the earlier measurements were inaccurate
- Few people in the first half of the 20th century took seriously the idea that human beings could be changing the environment at a global level

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Historical Background of the Origin of the Global Warming Issue

- Callendar's calculations of increasing CO_2 in the atmosphere reevaluated
  - The beginning of the environmental movement in the second half of the 20th century
  - The worldwide spread of DDT caused scientists to realize that people could be having global effects on the environment

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Historical Background of the Origin of the Global Warming Issue

- Also during 19th century
  - Scientists began to understand that climate changed greatly over long periods
  - There were times of continental glaciations
  - Evidence—debris at the edges of existing glaciers which looked the same as those deposited at lower elevations
- Cycles were apparent
  - 100,000 year cycles divided into 20,000–40,000 year periods

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Historical Background of the Origin of the Global Warming Issue

- The International Geophysical Year (1957-58)
  - Atmospheric observatory established near the top of Mauna Loa volcano (11,500 ft)
    - Measuring the concentration of carbon dioxide and discovered that it was increasing annually
    - It was proposed that the increase in atmospheric carbon dioxide was indeed warming the Earth

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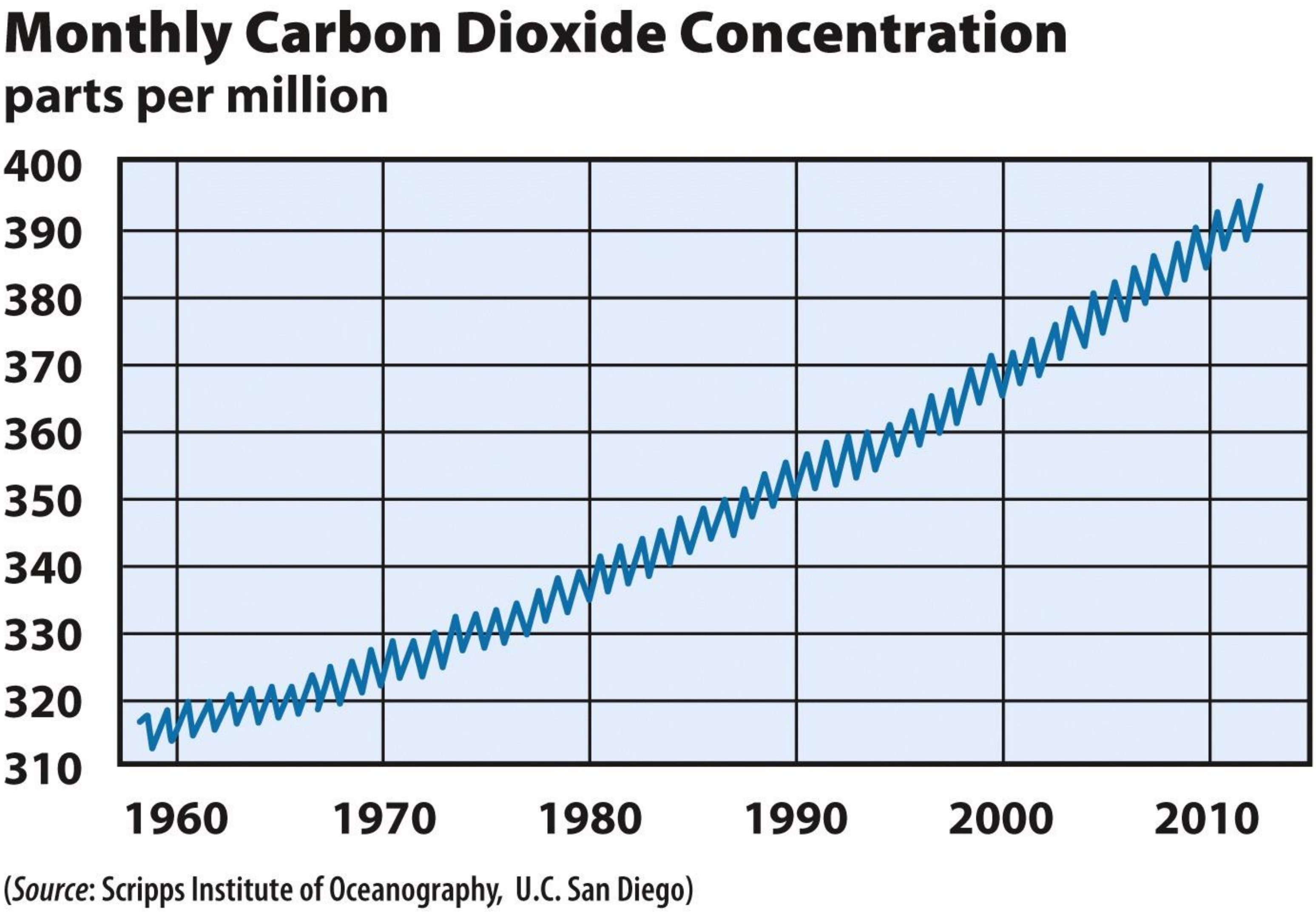

Carbon dioxide concentrations in the air above Mauna Loa, Hawaii

Seems that CO2 has warmed the earth !

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The NOAA Observatory on Mauna Loa, where these measurements were made.

11500 ft above sea-level. Collecting data from 1950s. Free from photosynthesis, respiration of living beings, no industrial exposures etc.

NOAA- National Oceanic Atmospheric Administration

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Twentieth-Century Methods to Reconstruct Past Temperatures

- Hadley Meteorological Centre in Britain has tried to plot temperature of earth
- Instrumental records
  - Climate measurements began in 1860s
  - Data from pre 19th century is
    - Estimates
    - Extrapolated
    - Interpolated
  - We have very accurate data since 1960
    - Improved instrumentation

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Twentieth-Century Methods to Reconstruct Past Temperatures

- Historical Records
  - Go back a few centuries
  - Mostly qualitative
    - Books, newspapers, journal articles, personal journals, ships' logs, travelers' diaries, and farmers' logs
- Proxy records
  - Proxy data—not strictly climatic, but provides insight into climate
    - Tree rings, sediments, ice cores, fossil pollen, corals, and carbon-14 (^{14}C)

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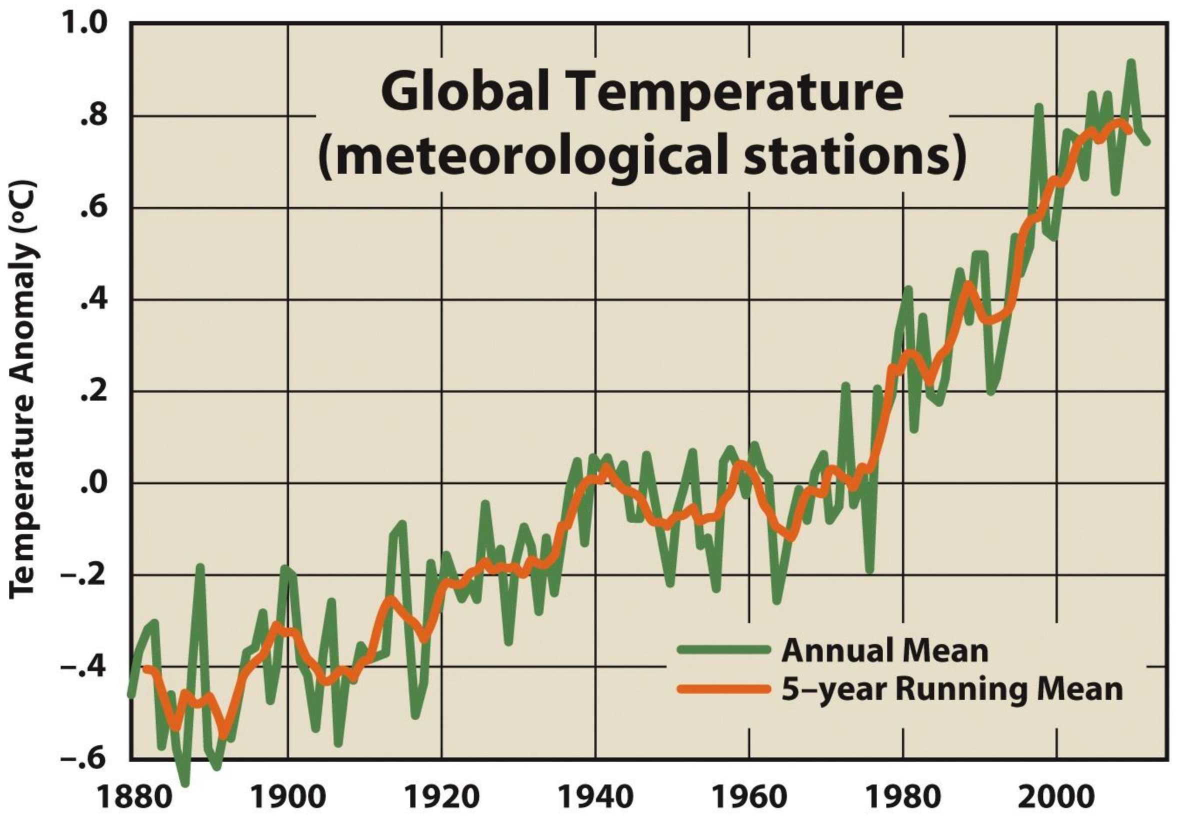

(*Source:* Global Temperature. NASA, 2012, GISS Surface temperature analysis. Http://data.giss.nasa.gov)

FIGURE 20.3 The temperature difference between the average at the end of the 19th century and the years between 1880 and today. This graph shows the difference between calculated annual mean world surface temperatures for each year (are green) and the 5-year running mean (red). Temperature departure refers to changes in mean global temperature from some standard, such as 1951–1980.

Climatologists studying climate change prefer, in general, to look at the difference between temperatures at one time compared to another, rather than the actual temperature, for a variety of technical reasons.

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FIGURE 20.4 Argentiere glacier in the French Alps. (Top): Etching made between 1850 and 1860 when the glacier was near its greatest extent, and

(Bottom): a modern photograph of the glacier taken from a similar vantage point in 1966.

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Proxy Climate Records

- Sediment
  - Biological material (ex: pollen) is deposited on the land and stored for extended periods in lake, bog and pond sediments
  - Pollen is useful
    - Quantity of pollen is an indicator of relative abundance of each plant species
    - Pollen can be dated
    - Can be used to construct a climate history

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FIGURE 20.5 Scientist examining a sediment core taken by drilling into the seafloor.

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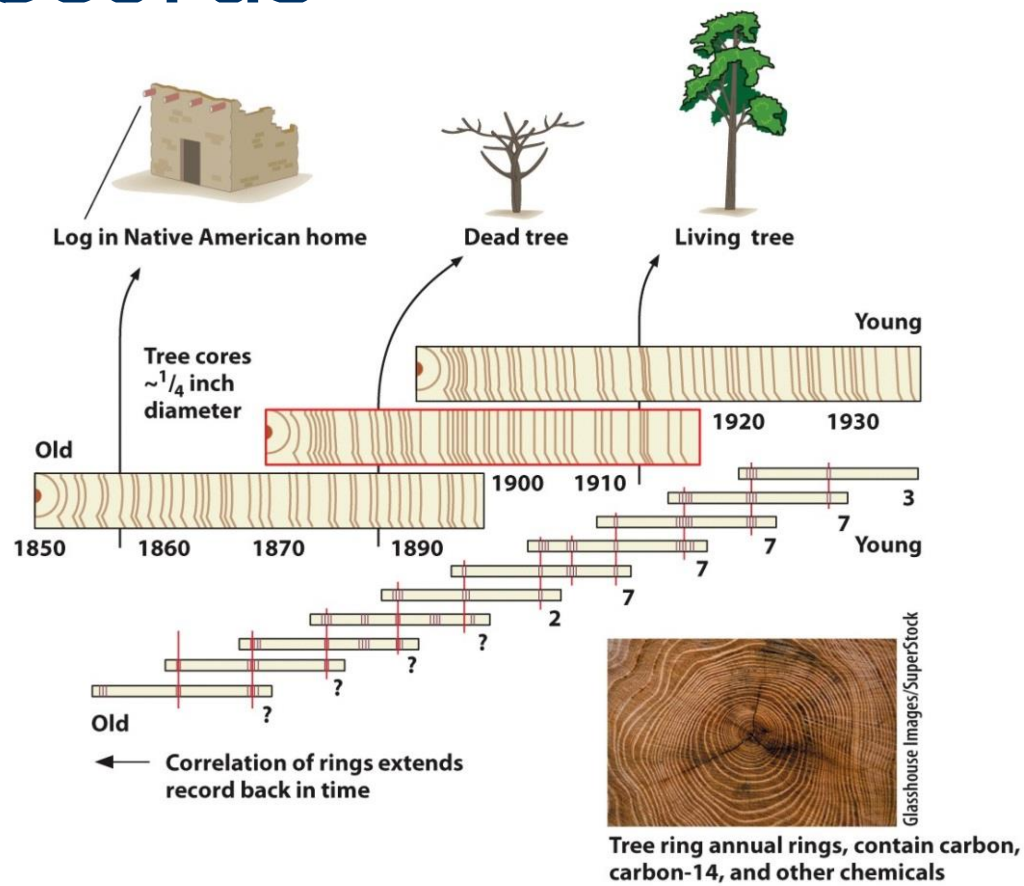
Proxy Climate Records

- Tree rings dendrochronology
  - Many trees create one growth ring per year
    - Width, density and ionic composition of the ring are indicative of climate
    - Tree Ring Lab in Arizona (1937)
    - Forest History & Archeologist



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Tree rings are useful for local and regional climate reconstructions where trees are primarily affected by temperature and rainfall, often in very sunny climates.

Isotopic signature.
An **isotopic** signature (also **isotopic** fingerprint) is a ratio of non-radiogenic 'stable **isotopes**', stable radiogenic **isotopes**, or unstable radioactive **isotopes** of particular elements in an investigated material.

Tree ring annual rings, contain carbon, carbon-14, and other chemicals

Dendrochronology, the study of tree growth rings, can be used as an indicator of past climate. The spacing (relative volume of wood) of rings and the isotopic content ($_{14}C$, for example) of wood can provide information about past rainfall and solar activity.

Proxy Climate Records

- Ice cores
  - Polar ice and mountain glaciers have ice records that go back 100s or 1000s of year
  - Oldest is 800,000 years

  Ice cores have small bubbles of air
    - Can measure carbon dioxide and methane levels from the time the ice was created
    - The temp of the atmosphere in various glacial layers can be estimated by analysis of stable isotopes of Oxygen & Hydrogen that correlate with temp.
- Two important gases being measured in ice cores are
- (CO_2) and methane (CH_4).

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FIGURE 20.7 Scientist examining an ice core from a glacier. The core was stored in a freezer so that ice bubbles could be extracted from it to provide data about the atmosphere in the past (CO_2, dust, lead, etc.).

Proxy Climate Records

- **Coral** (tiny, soft-bodies organism, divided into colonies and the at the base, hard substance made of limestone skeletons of marine polyps)
  - Coral exoskeleton made of calcium carbonate
    - Carbonate contains isotopes of oxygen
    - Used to determine temperature of water in which the coral grew
- The growth of corals has been dated directly with a variety of dating
oral growth, thereby revealing the
able time periods.

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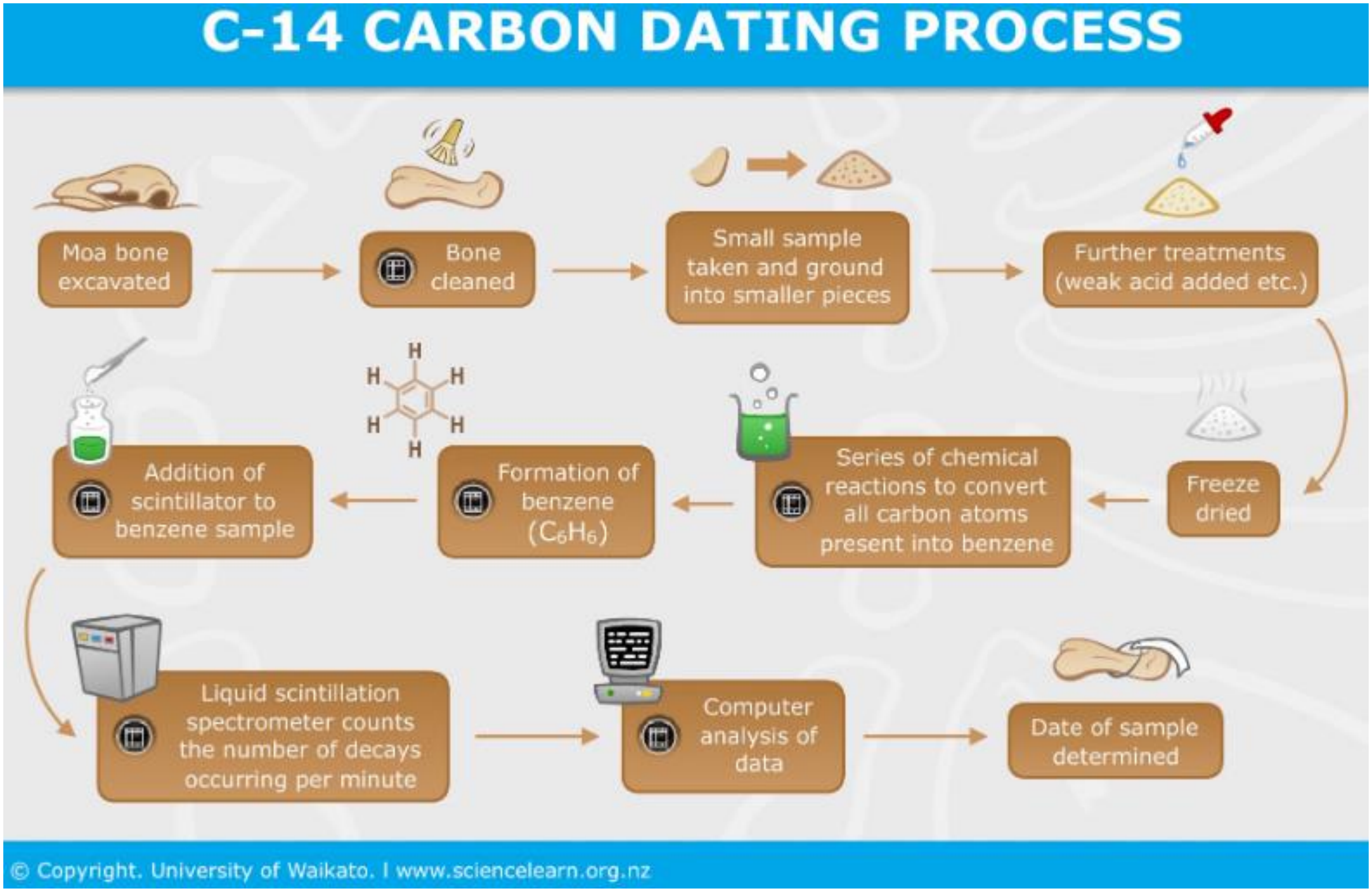
C-14 CARBON DATING PROCESS
Moa bone excavated
Bone cleaned
Small sample taken and ground into smaller pieces
Further treatments (weak acid added etc.)
Freeze dried
Series of chemical reactions to convert all carbon atoms present into benzene
Formation of benzene (C_6H_6)
Addition of scintillator to benzene sample
Liquid scintillation spectrometer counts the number of decays occurring per minute
Computer analysis of data
Date of sample determined
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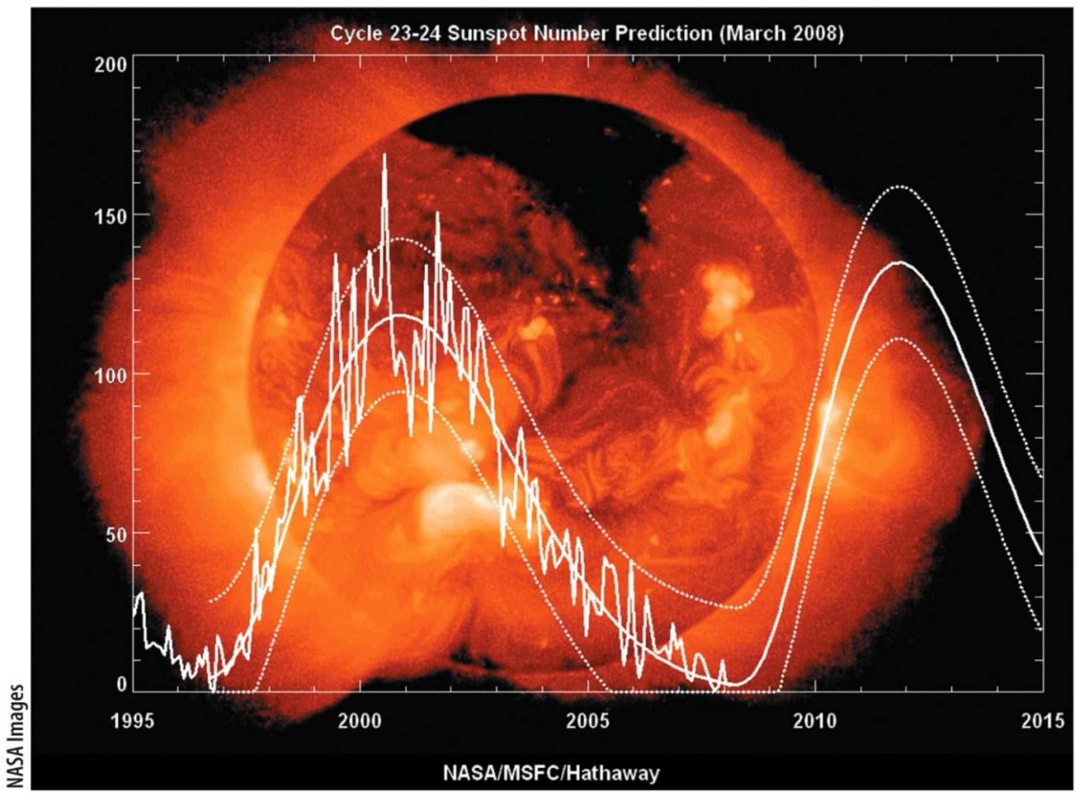
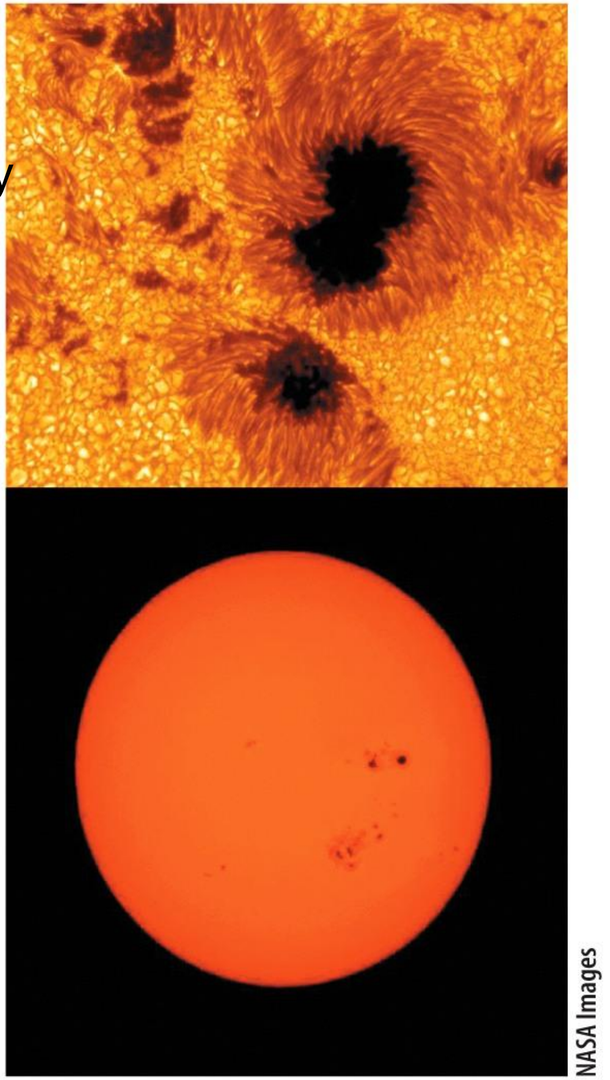
FIGURE 20.8 (a) Sunspot cycle with number of sunspots per year, from 1995 to 2009 and (b) photos of sunspots in 2003. The large sunspots are about 150,000 km across (for comparison, Earth's diameter is about 12,750 km).

The sunspots are the dark areas; each is surrounded by an orange ring and then a hot gold color. Notice the great variety in the number of sunspots from year to year in the 11-year cycle (over 150 in 2001 and very few in 2008 and 2009). Sunspots (Darker relative cooler) 3800K; Photosphere: 5800K





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Carbon 14 and sunspots

- Radioactive carbon 14 (14C) is produced in the upper atmosphere by the collision of cosmic rays and nitrogen 14 (14N).
- Cosmic rays come from outer space; those the Earth receives are predominantly from the sun.
- The abundance of cosmic rays varies with the number of sunspots, so-called because they appear as dark areas on the sun.
- As sunspot activity increases, more energy from the sun reaches Earth. There is an associated solar wind, which produces ionized particles consisting mostly of protons and electrons, emanating from the sun.
- The radioactive 14C is taken up by photosynthetic organisms—green plants, algae, and some bacteria—and stored in them.
- The record of 14C in the atmosphere has been correlated with tree ring chronology. Each ring of wood of known age contains carbon, and the amount of 14C can be measured.

- **Sunspots** are darker than the surrounding areas because they are expending less energy and have a lower temperature.

- **Sunspots** often have poles ("polarity") like the south and north poles of magnets.

- **Sunspots** are **formed** continuously as the Sun's magnetic field actively moves through the Sun.

How the Atmosphere Works

- Weather
  - What's happening now in the atmosphere near the earth's surface
    - Temperature, pressure, cloudiness, precipitation, winds
- Climate is the average weather
  - Usually refers to long periods of time
  - Classified mainly by latitude and wet/dry

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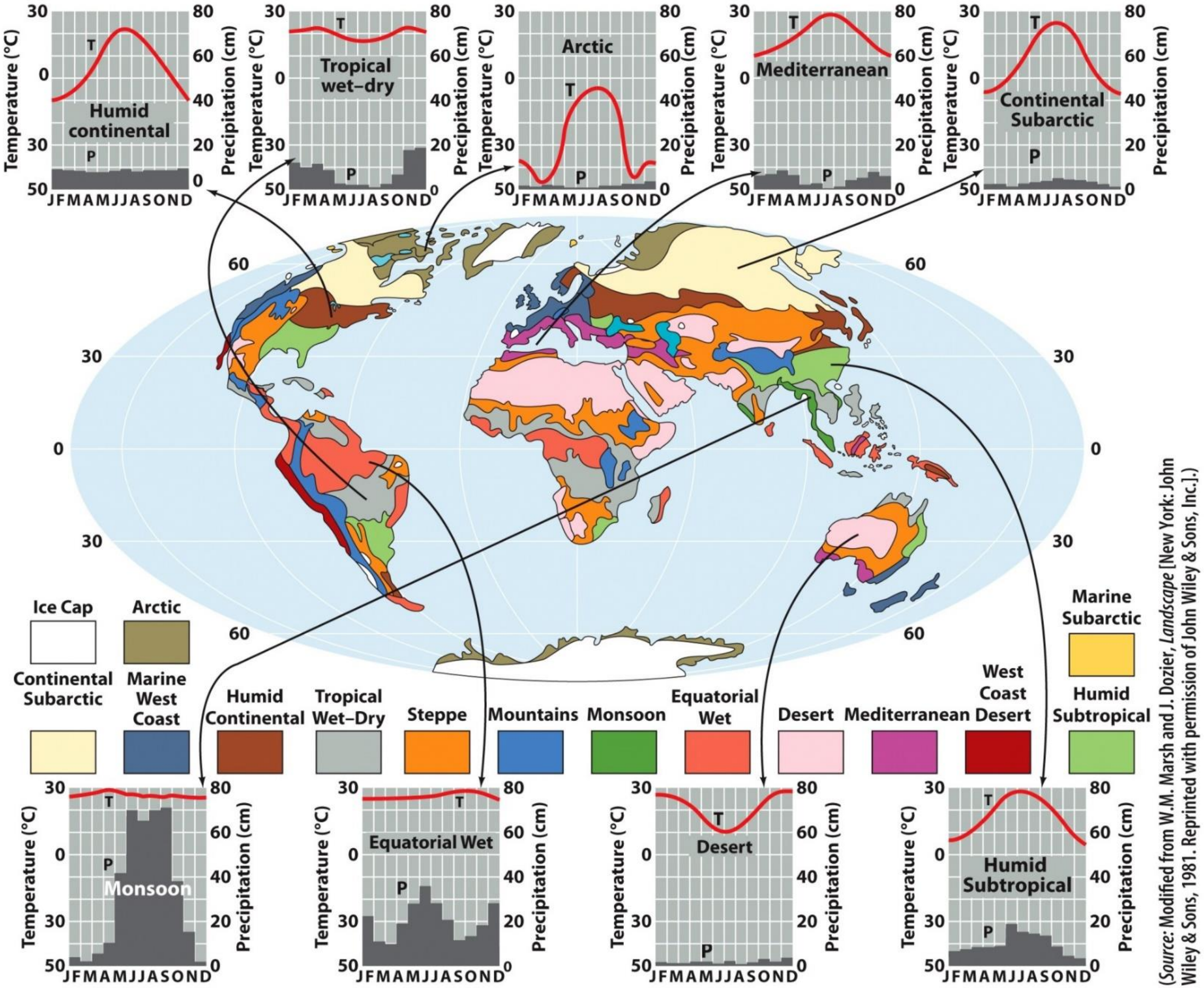

The climates of the world and some of the major climate types in terms of characteristic precipitation and temperature conditions.

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The Atmosphere

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- Thin layer of gases that envelops Earth
  - Held near the surface by gravitation and pushed upward by thermal energy
- Comprised of
  - Nitrogen (78%)
  - Oxygen (21%)
  - Argon (0.9%)
  - Carbon dioxide (0.03%)
  - Water vapor
  - Trace amounts of other gases/pollutants
- Methane (0.00017%), ozone, hydrogen sulfide, carbon monoxide, oxides of nitrogen and sulfur, and a number of small hydrocarbons, as well as synthetic chemicals, such as chlorofluorocarbons (CFCs)
- A dynamic system, i.e, ever-changing

The Climate is Always Changing

- A vast, chemically active system
- Fueled by sunlight and affected by high-energy compounds emitted by living things (for example, oxygen, methane and carbon dioxide)
- Fueled also by our industrial and agricultural activities
- Reservoir for complex chemical reactions, changing from day to night and with the chemical elements available

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Structure of the Atmosphere

- Made up of several vertical layers
- Troposphere—bottom layer ground up to 10–20 km,
    - Where weather occurs
    - Temperature decreases with elevation
- From an average of about 15°C at the surface to -60°C at 12 km
    - At the top is tropopause—acts as a lid -60°C (remaining water vapor condenses)
- Stratosphere—above the troposphere elevation of approximately 40 km, with a max concentration of ozone above the equator at about 25–30 km
    - Stratospheric ozone layer just above the tropopause
    - Protects against UV radiation
- Stratospheric ozone (O_3) protects life in the lower atmosphere from receiving harmful doses of ultraviolet radiation

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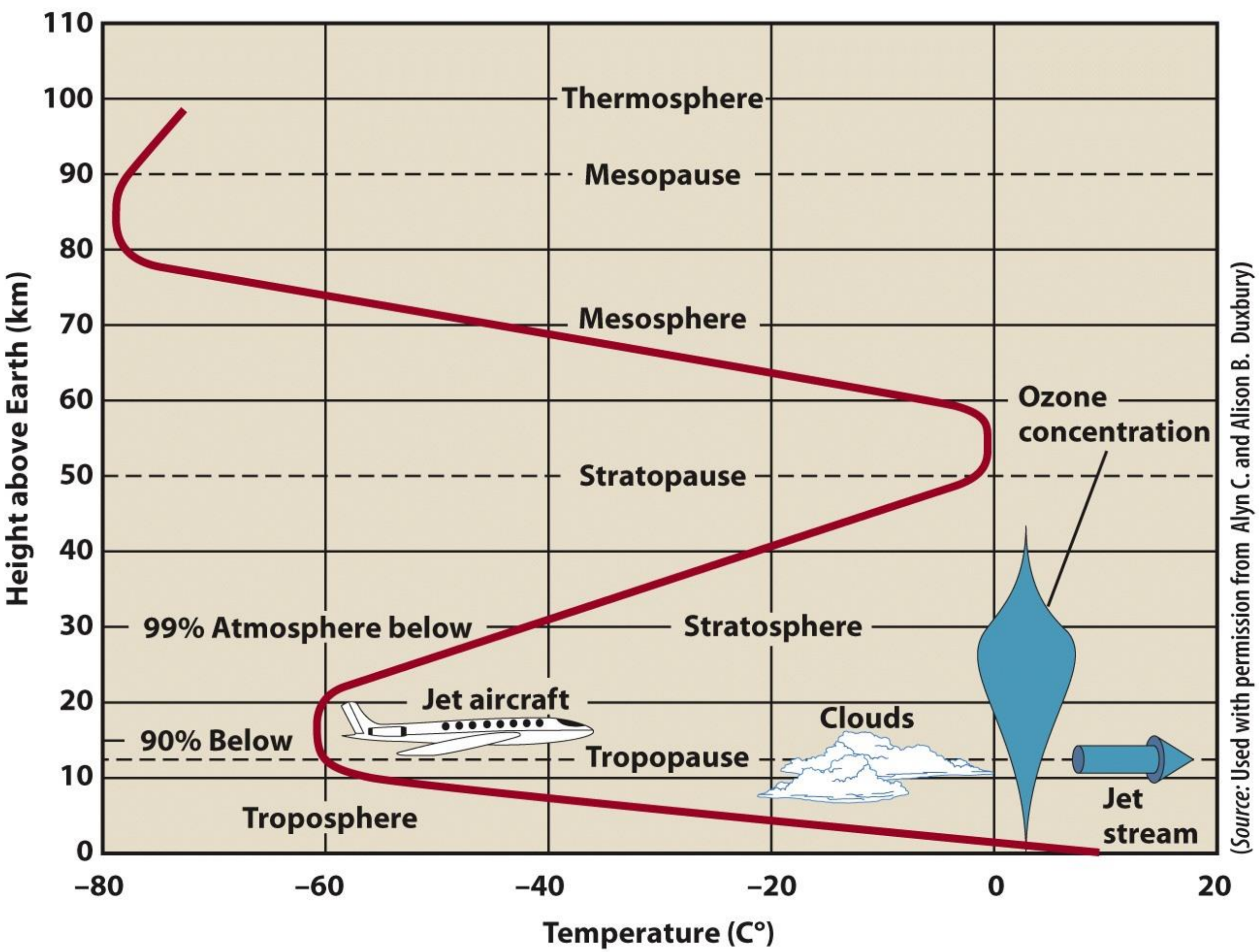

FIGURE 20.10 An idealized diagram of the structure of the atmosphere showing temperature profile and the ozone layer of the atmosphere to an altitude of 110 km.

Note that 99% of the atmosphere (by weight) is below 30 km, the ozone layer is thickest at about 25–30 km, and the weather occurs below about 11 km—about the elevation of the jet stream.

Atmospheric Processes

- Processes generally defined by pressure, temperature and water vapor content
  - Pressure is force per unit area
    - Caused by the weight of overlying atmospheric gases on those below
    - Pressure Decreases with altitude
    - Low-pressure systems usually bring clouds (air rises & cools and condensing of water vapors occurs)
    - High-pressure systems usually bring clear skies (air moves downwards and gets warms – clear & sunny vision)

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Atmospheric Processes

- Temperature is the relative hotness or coldness of materials
  - Measure of thermal energy
- Water vapor content is how much water is in the gaseous form
  - Varies from 1% to 4%

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Atmospheric Processes

- Atmosphere moves due to
  - Earth’s rotation
  - Differential heating
- Produces global patterns of prevailing winds and latitudinal belts of high and low pressure

- The atmosphere moves because of Earth’s rotation and the differential heating of Earth’s surface and atmosphere.

- These produce global patterns that include prevailing winds and latitudinal belts of low and high air pressure from the equator to the poles. Three cells of atmospheric circulation (Hadley cells) are present in each hemisphere.

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Hadley cells

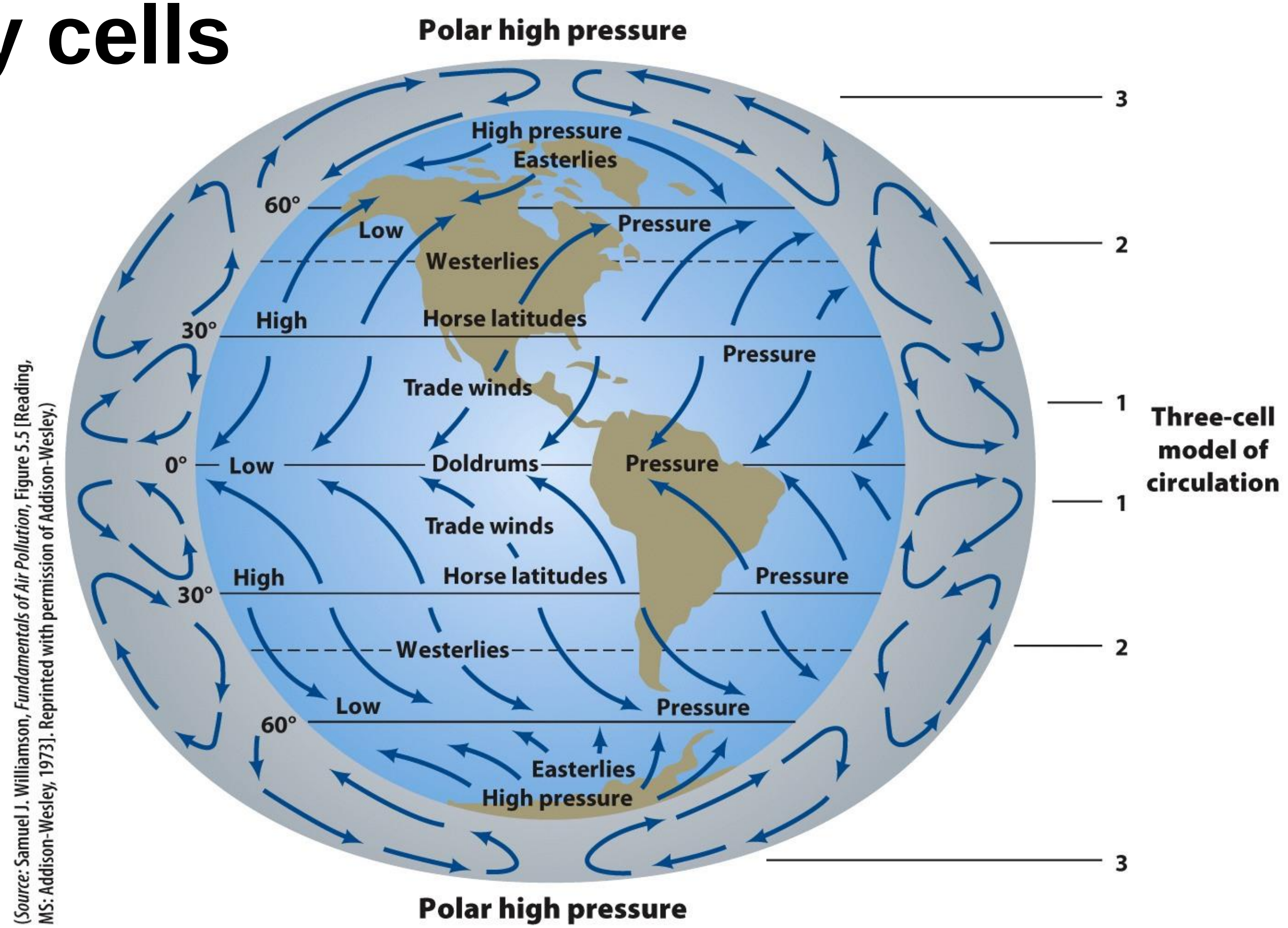

FIGURE 20.11 Generalized circulation of the atmosphere. The heating of the surface of the Earth is uneven, producing pressure differences (warm air is less dense than cooler air). There is rising warm air at the equator and sinking cool air at the poles. With rotation of Earth, three cells of circulating air are formed in each hemisphere (called **Hadley cells** after George Hadley who first proposed a model of atmospheric circulation in 1735).

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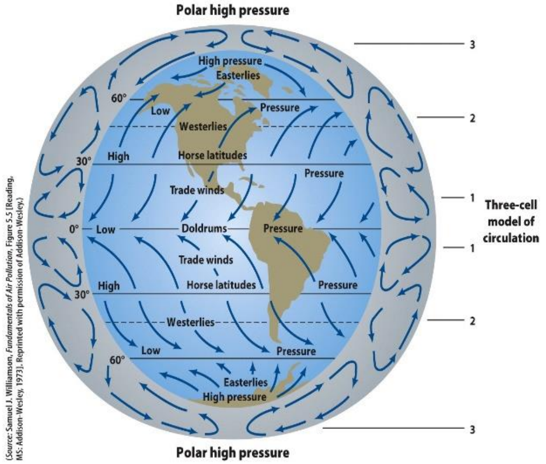
The belts of low air pressure develop at the equator, where the air is warmed most of the time during the day by the sun. The heated air rises, creating an area of low pressure and a cloudy and rainy climate (cell 1).



This air then moves to higher latitudes (toward the poles) because it is cooler at higher elevations and because sunlight is less intense at the higher latitudes.

By the time the air that was heated at the equator reaches about 30° latitude, it has cooled enough to become heavier, and it descends, creating a region of high pressure with its characteristic sunny skies and low rainfall and forming a latitude belt where many of the world’s deserts are found.

Then, the air that descended at 30° latitude moves poleward along the surface, warms, and rises again, creating another region of generally low pressure around 50° to 60° (cell 2) latitude and once again becoming a region of clouds and precipitation.

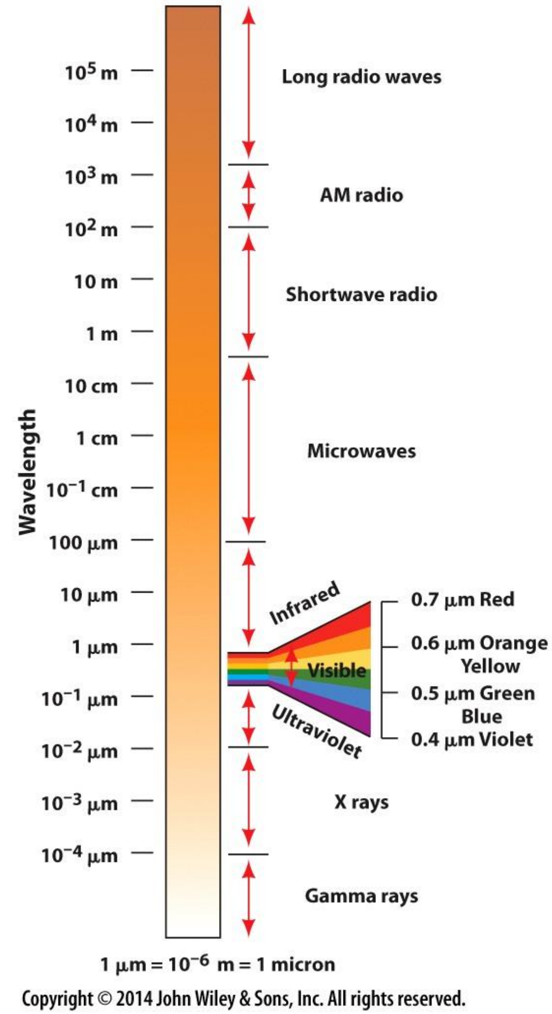
Atmospheric orientation in cell 3, moves air toward the poles at higher elevation and toward the equator along the surface. Sinking cool air at the poles produces the polar high-pressure zones at both poles.

At the most basic level, warm air rises at the equator and moves toward the poles, where it sinks after going through (cell 2); its return flow is along the surface of Earth toward the equator.

What Makes the Earth Warm?

- Almost all the energy from the sun
- Sunlight comes in a wide range of electromagnetic radiation
  - Long to short wavelengths
  - Most of the radiation that reaches the Earth is in the infrared and visible wavelengths
- Earth, much cooler, radiates energy mostly in the longer far-infrared wavelengths

The hotter the surface of any object, the shorter the dominant wavelengths. That's why a hot flame is blue and a cooler flame is red



Kinds of electromagnetic radiation the Earth receives.

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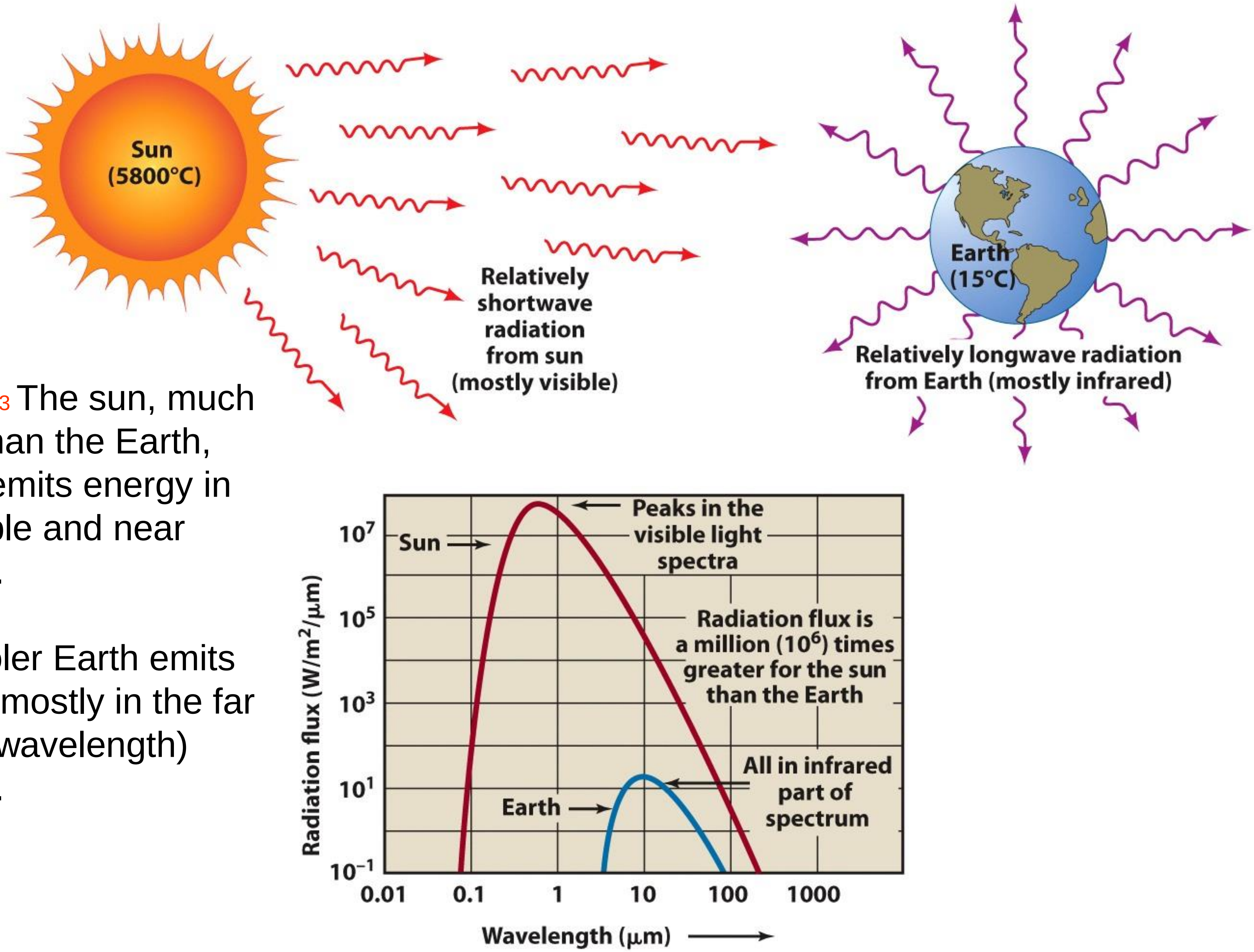

FIGURE 20.13 The sun, much hotter than the Earth, mostly emits energy in the visible and near infrared.

The cooler Earth emits energy, mostly in the far (longer wavelength) infrared.

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What Makes the Earth Warm?

- Under typical conditions Earth's atmosphere
  - Reflects ~30% of the electromagnetic energy that comes in from the sun
  - Absorbs ~25%
  - The remaining ~45% gets to the surface
    - Radiates back to the atmosphere or into outer space

As the surface warms up, it radiates more energy back to the atmosphere, which absorbs some of it. The warmed atmosphere radiates some of its energy upward into outer space and some downward to Earth's surface.

Most of the sun's radiation that reaches Earth is in the visible and near-infrared wavelengths while Earth, much cooler, radiates energy mostly in the longer far-infrared wavelengths

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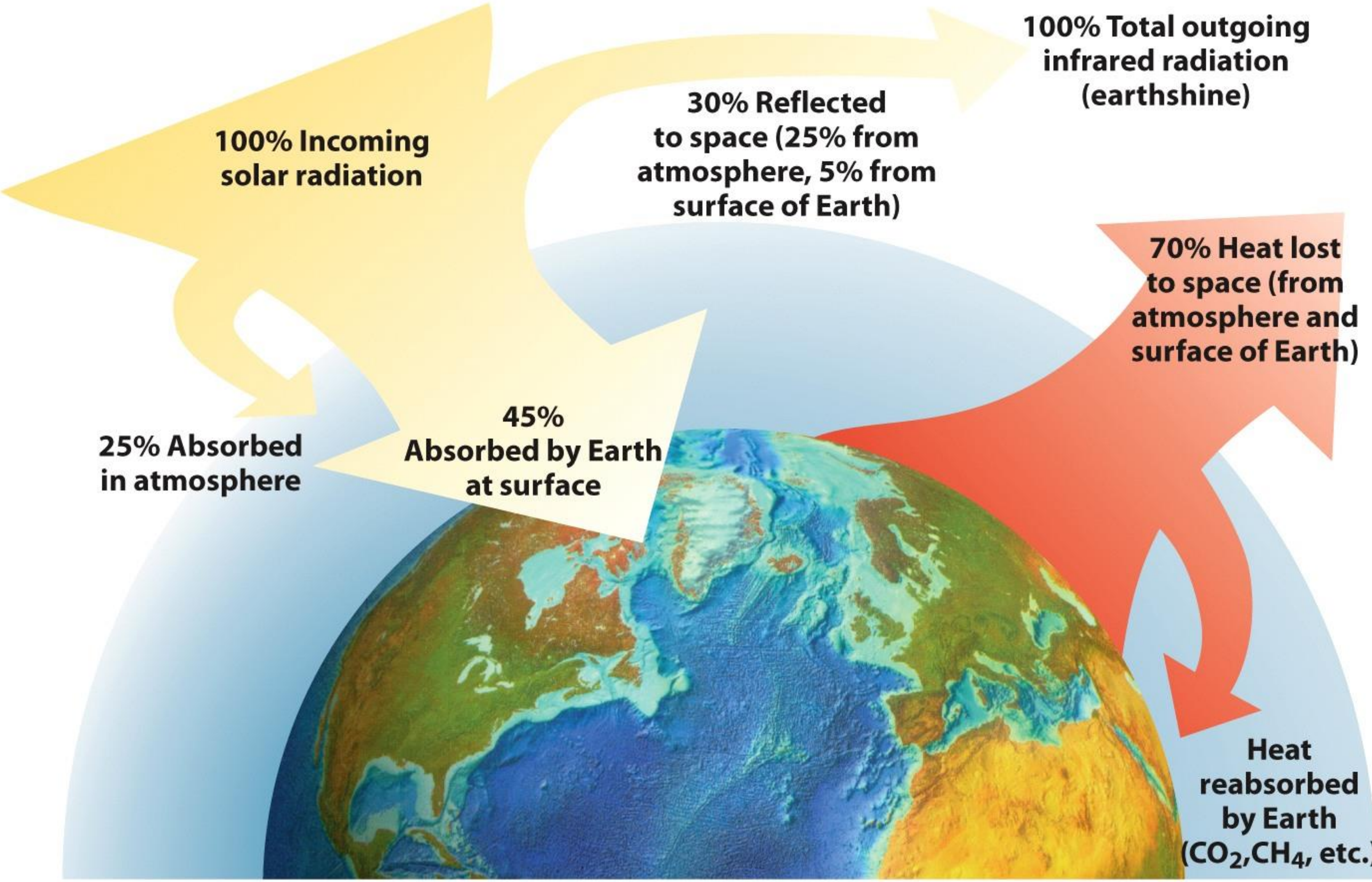

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FIGURE 20.14 Earth's energy budget.

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Causes of Climate Change

- Milankovitch cycles
  - Explain why climate changes
  - Earth is like a wobbling top following an elliptical orbit around the sun
- Three cycles
  - Cycle 1—26,000 years
    - Earth does not keep its poles at a constant angle in relation to the sun
    - Wobble around the pole makes a complete cycle in 26,000 years
  - Cycle 2—tilt of wobble also varies over a period of 41,000 years
  - Cycle 3—100,000 years
    - Elliptical orbit around the sun also changes
    - Sometimes it is a more extreme ellipse; other times it is closer to a circle and this occurs over 100,000 years

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Causes of Climate Change

- Three cycles
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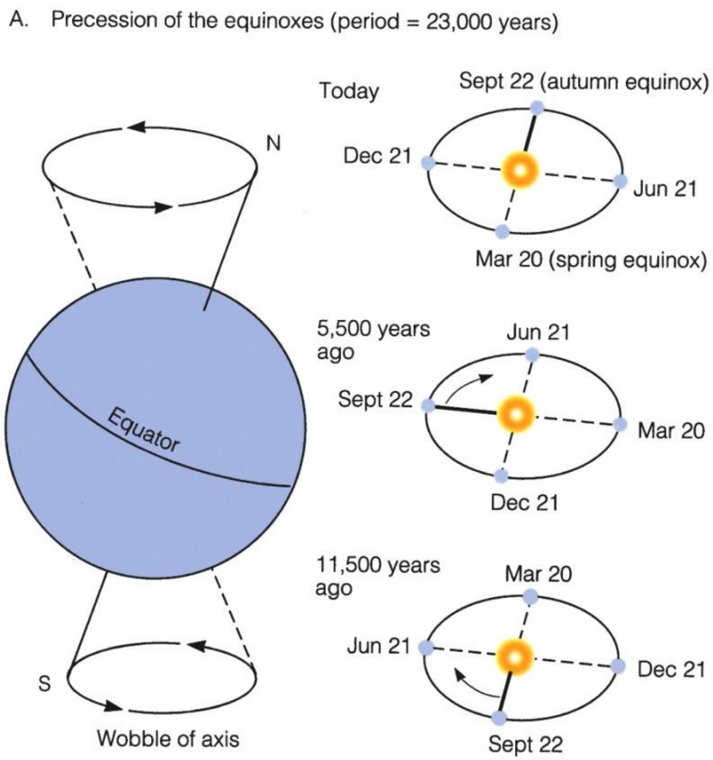

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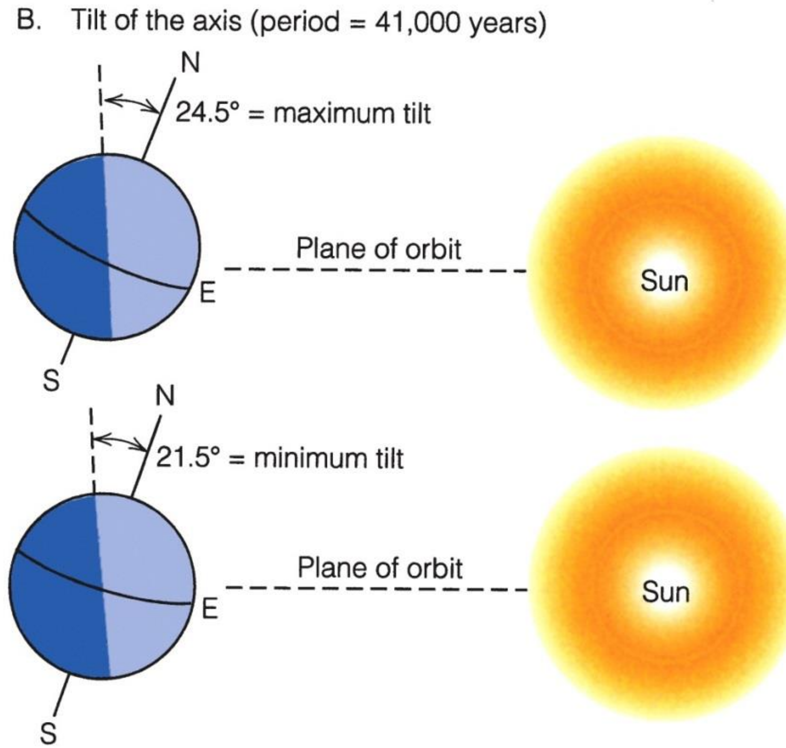

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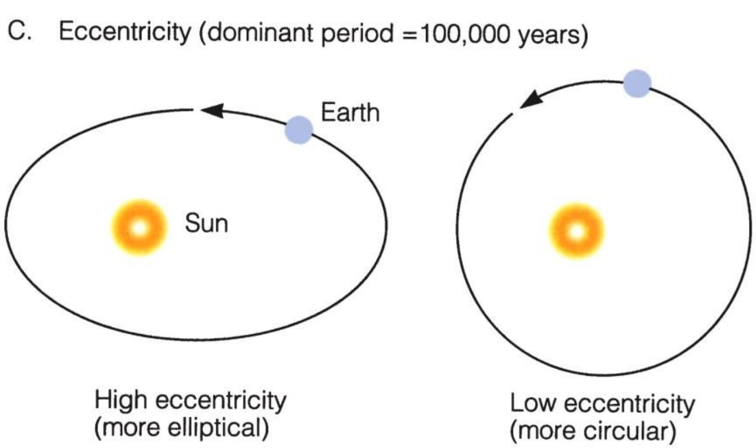

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FIGURE 20.15â•… The Melankovitch cycles, which are the result of the Earth wobbling, changing its tilt, and following an elliptical orbit that changes the orbit shape periodically.

An **equinox** is commonly regarded as the moment when the plane of Earth's equator passes through the center of the Sun's disk, which occurs twice each year, around 20-21 March and 23-24 September.

Causes of Climate Change

- The combination of these lead to periodic changes in the amount of sunlight reaching the Earth
  - Milankovitch showed that these variations correlated with major glacial and interglacial periods
- Don’t account for all climate variations

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Causes of Climate Change

- Once Earth receives energy from the sun, Earth's surface features affect the climate.
- These earthly factors that affect, and are in turn affected by, regional and global temperature changes include warmer ice sheet temperatures; changes in vegetation; changes in atmospheric gases, such as carbon dioxide, methane, and nitrous oxide; and particulates and aerosols.
- Volcanoes inject aerosols into the upper atmosphere, where they reflect sunlight and cool Earth's surface. A helpful way to think about the Milankovitch cycles is that they set up the basic situation where an ice age is possible or a warm, interglacial age is possible.
- Then the other factors that influence climate come into play. The question, as yet unresolved, is how much do Milankovitch cycles account for climate change compared to other influences.

Solar Cycles

- The sun goes through cycles
  - Sometimes hotter, sometimes cooler
  - Documented by differing amounts of radionuclides (e.g C14) isotopes trapped in glacial ice
- Variability of solar input of energy explains some of the climatic variability too

Evaluation of these radionuclides in ice cores from glaciers reveals that during the Medieval Warm Period, from approximately A.D. 950 to 1250, the amount of solar energy reaching Earth was relatively high, and that minimum solar activity occurred during the 14th century, coincident with the beginning of the Little Ice Age.

The variability of solar energy input explains a small part of Earth's climatic variability

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- Transparency of atmosphere to radiation affects the temp of the Earth
  - From the sun coming in
  - From the Earth’s surface going out
- Dust and aerosols absorb light
  - Volcanoes, forest fires and farming put dust into the atmosphere
  - Chemical and physical composition of atmosphere can make it warmer or cooler

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How Earth's Atmosphere, Oceans, and Land Affect Climate

- The surface of Earth and albedo effects
  - Albedo is the reflectivity of an object—darker surfaces absorb heat; lighter surfaces reflect heat
  - Approximate Earth albedos
    - Earth, as a whole, is 30%
    - Clouds, depending on type and thickness, 40–90%
    - Fresh snow, 85%
    - Glacial ice, 20–40%
    - A pine forest, 10%
    - Dark rock, 5–15%
    - Dry sand, 40%
    - A grass-covered meadow, 15%

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How Earth’s Atmosphere, Oceans, and Land Affect Climate

- Roughness of Earth’s surface affects the atmosphere
  - Above a completely smooth surface, air flows smoothly—a flow called laminar
  - A rough surface causes air to become turbulent—to spin, rotate, reverse, and so forth
  - Turbulent air gives up some of its kinetic energy, and that energy is turned into heat, affecting the weather above
  - Forests are a much rougher surface than smooth rock or glaciers, so in this way, too, vegetation affects weather and climate

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How Earth's Atmosphere, Oceans, and Land Affect Climate

- The chemistry of life affects the atmosphere
  - A planet with water vapor, liquid water, frozen water, and living things has a much more complex energy exchange system
  - A lifeless, waterless planet lacks the complex energy exchange system
- This is one reason (of many) why it is difficult to forecast climate change

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The Greenhouse Effect

- Each gas in the atmosphere has its own absorption spectrum
  - Certain gases are especially strong absorbers in the infrared
  - They absorb radiation emitted by the warmed surfaces of the Earth
  - They then re-emit this radiation
  - This increases the temperature of the Earth's surface

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The Greenhouse Effect

The process by which the heat is trapped is not the same as it is in a greenhouse (air in a closed greenhouse has restricted circulation and will heat up).
Still, in trapping heat this way, the gases act a little like a greenhouse’s glass panes, which is why it is called the **greenhouse effect**.

The major **greenhouse gases** are water vapor, carbon dioxide, methane, some oxides of nitrogen, and chlorofluorocarbons (CFCs).

The greenhouse effect is a natural phenomenon that occurs on Earth and on other planets in our solar system.

Most natural greenhouse warming is due to water in the atmosphere—water vapor and small particles of water in the atmosphere produce about 85% and 12%, respectively, of the total greenhouse warming.

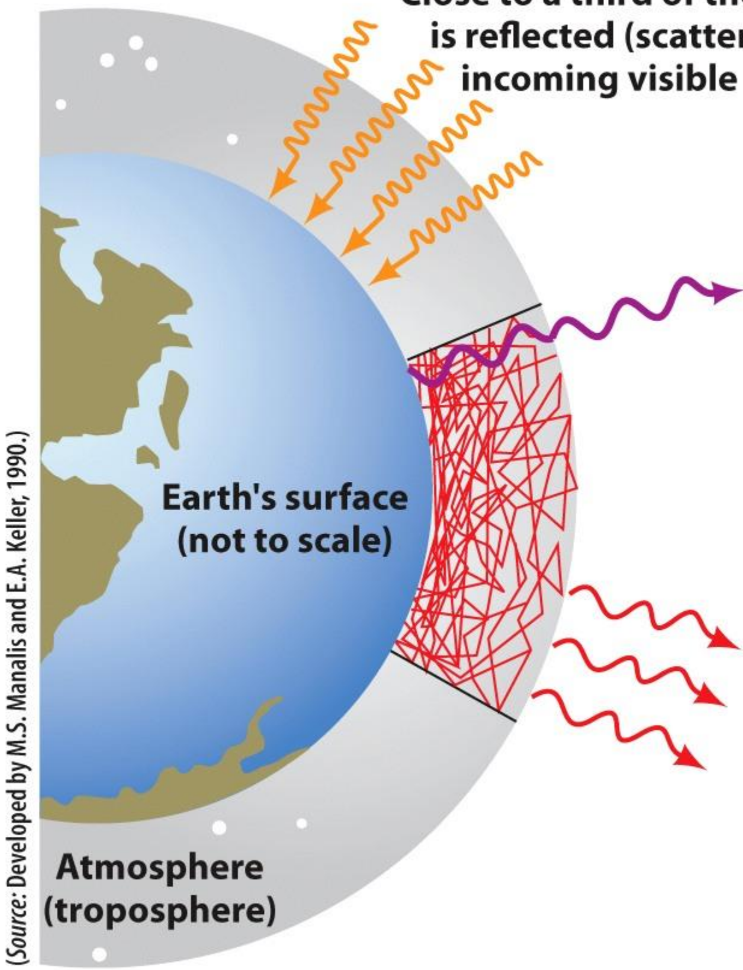

FIGURE 20.17 Idealized diagram showing the greenhouse effect. Incoming visible solar radiation is absorbed by Earth's surface, to be reemitted in the infrared region of the electromagnetic spectrum. Most of this reemitted infrared radiation is absorbed by the atmosphere, maintaining the greenhouse effect.

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The Greenhouse Effect

FIGURE 20.18 What the major greenhouse gases absorb in the Earth's atmosphere. Earth's surface radiates mostly in the infrared, which is the range of electromagnetic energy.

Water and carbon dioxide absorb heavily in some wavelengths within this range, making them major greenhouse gases.

The other greenhouse gases, including methane, some oxides of nitrogen, CFCs, and ozone, absorb smaller amounts but in wavelengths not absorbed by water and carbon dioxide.

(*Source:* Modified from T.G. Spiro and W.M. Stigliani, *Environmental Science in Perspective* [Albany: State University of New York Press, 1980].)

- Natural phenomenon
- Major greenhouse gases
  - Water vapor
  - Carbon dioxide
  - Methane
  - Some oxides of nitrogen
  - CFCs

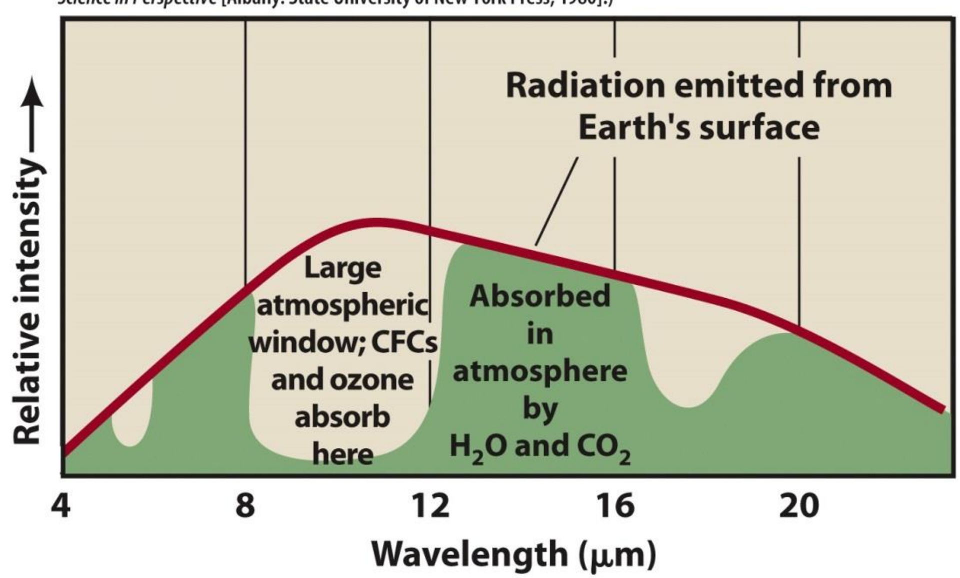

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Table 20.1 MAJOR GREENHOUSE GASES

TRACE GASES	RELATIVE CONTRIBUTION (%)	GROWTH RATE (%/YR)
CFC	15[a]-25[b]	5
CH_4	12[a]-20[b]	0.4[c]
O_3(troposphere)	8[d]	0.5
N_2O	5[d]	0.2
Total	40–50	
Contribution of CO_2	50–60	0.3[e]–0.5[d,f]

[a] W. A. Nierenberg, "Atmospheric CO_2: Causes, Effects, and Options," *Chemical Engineering Progress* 85, no.8 (August 1989): 27

[b] J. Hansen, A. Lacis, and M. Prather, "Greenhouse Effect of Chlorofluorocarbons and Other Trace Gases," *Journal of Geophysical Research* 94 (November 20, 1989): 16, 417.

[c] Over the past 200 yrs.

[d] H. Rodha, "A Comparison of the Contribution of Various Gases to the Greenhouse Effect," *Science* 248 (1990): 1218, Table 2.

[e] W. W. Kellogg, "Economic and Political Implications of Climate Change," paper presented at Conference on Technology-based Confidence Building: Energy and Environment, University of California, Los Alamos National Laboratory, July 9–14, 1989.

[f] H. Abelson, "Uncertainties about Global Warming," *Science* 247 (March 30,1990): 1529.

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Greenhouse Gases and Climate

Carbon Dioxide

Current estimates suggest that approximately 200 billion metric tons of carbon in the form of carbon dioxide (CO_2) enter and leave Earth's atmosphere each year as a result of a number of biological and physical processes: of greenhouse gases emitted by human activities, an estimated 50% to 60% is attributed to this gas. Measurements of carbon dioxide trapped in air bubbles in the Antarctic ice sheet suggest that 160,000 years before the Industrial Revolution, the atmospheric concentration of carbon dioxide varied from approximately 200 to 300 ppm

About 140 years ago, just before the major use of fossil fuels began as part of the Industrial Revolution, some of the first chemical measurements of the atmosphere showed that the carbon dioxide concentration was approximately 280 ppm.[15] Since then, and especially in the past few decades, the concentration of CO_2 in the atmosphere has grown rapidly. Today, the CO_2 concentration is about 396 ppm, and its current rate of increase is about 0.5% per year. At current rates, the level could rise to as much as 450 ppm by the year 2050—more than 1.5 times the preindustrial level.[15]

Methane

The concentration of methane (CH_4) in the atmosphere has more than doubled over the past 200 years and is estimated to contribute approximately 12% to 20% of the anthropogenic greenhouse effect.[16,17]

Certain bacteria that can live only in oxygenless atmospheres produce methane and release it. These bacteria live in the guts of termites and the intestines of ruminant mammals, such as cows, which produce methane as they digest woody plants.

These bacteriaalso live in oxygenless parts of freshwater wetlands where they decompose vegetation, releasing methane as a decay product.

Methane is also released with seepage from oil fields and seepage from methane hydrates

landfills (the major methane source in the United States), the burning of biofuels, production of coal and natural gas, and agriculture, such as raising cattle and cultivating rice.

Chlorofluorocarbons

Chlorofluorocarbons (CFCs) are inert, stable compounds that have been used in spray cans as aerosol propellants and in refrigerators. The rate of increase of CFCs in the atmosphere in the recent past was about 5% per year, and it has been estimated that approximately 15% to 25% of the anthropogenic greenhouse effect may be related to CFCs.

Because they affect the stratospheric ozone layer and also play a role in the greenhouse effect, the United States banned their use as propellants in 1978. In 1987, 24 countries signed the Montreal Protocol to reduce and eventually eliminate production of CFCs and accelerate the development of alternative chemicals.

Potential global warming from CFCs is considerable because each CFC molecule may absorb hundreds or even thousands of times more infrared radiation emitted from the surface than is absorbed by a molecule of carbon dioxide. Furthermore, because CFCs are highly stable, their residence time in the atmosphere is long. Even though their production was drastically reduced, their concentrations in the atmosphere will remain significant

Nitrous Oxide

Nitrous oxide (N_2O) is increasing in the atmosphere and probably contributes as much as 5% of the anthropogenic greenhouse effect.[18]

Anthropogenic sources of nitrous oxide include agricultural application of fertilizers and the burning of fossil fuels.

This gas, too, has a long residence time; even if emissions were stabilized or reduced, elevated concentrations of nitrous oxide would persist for at least several decades.

Greenhouse Gases and Climate

- The sum of the reflected solar radiation and the outgoing infrared radiation balances with the energy arriving from the sun
- Infrared radiation is transmitted back and forth between the atmosphere, oceans, ice, and solid surfaces
- The amount of IR absorbed at Earth's surface from the greenhouse effect estimated to be greater than 2x the amount of shortwave solar radiation absorbed by Earth's surface

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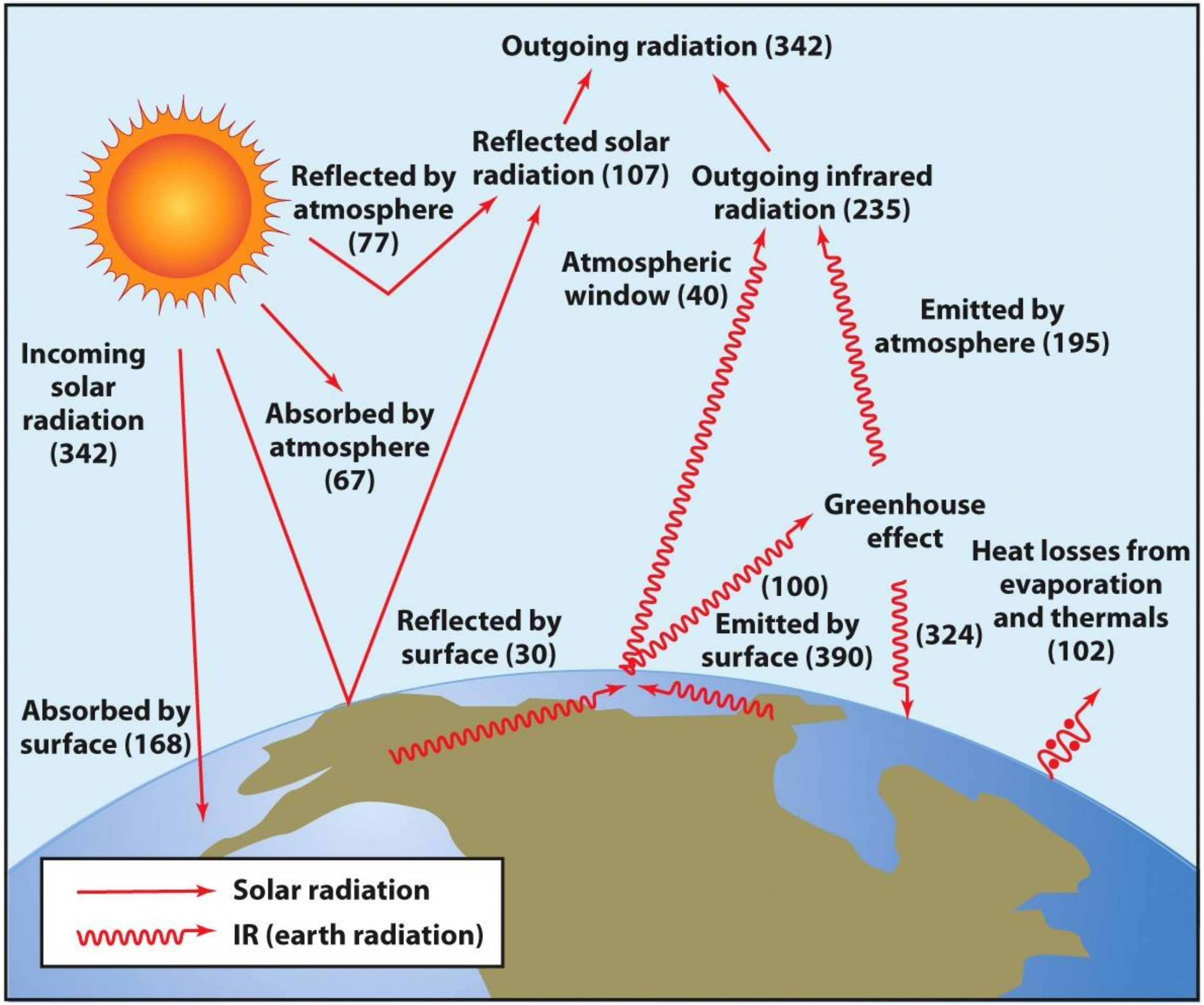

(Source: IPCC, Climate Change 2007: The Physical Science Basis: Working Group I. Contribution to the Forth Assessment Report. New York: Cambridge University Press, 2007. Reprinted with permission.)

FIGURE 20.19 Idealized diagram showing some details of Earth's greenhouse effect. Incoming solar radiation in units of w/m_2 is balanced by outgoing radiation. Notice that some of the fluxes (rates of transfer) of infrared radiation (IR) are greater than incoming solar radiation, reflecting the role of the greenhouse effect.

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(*Source:* Modified from T.G. Spiro and W.M. Stigliani, *Environmental Science in Perspective* [Albany: State University of New York Press, 1980].)

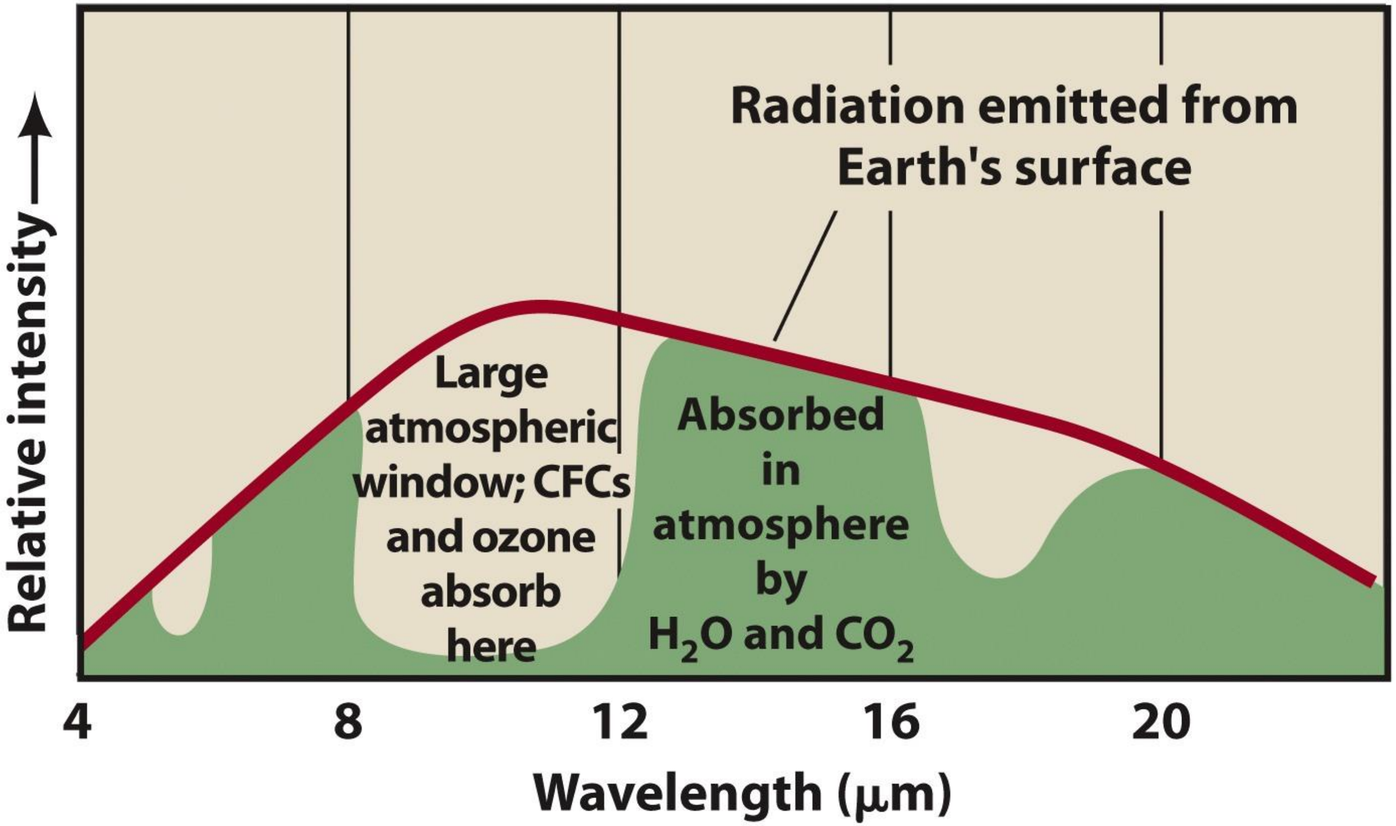

FIGURE 20.18 What the major greenhouse gases absorb in the Earth's atmosphere. Earth's surface radiates mostly in the infrared, which is the range of electromagnetic energy shown here. Water and carbon dioxide absorb heavily in some wavelengths within this range, making them major greenhouse gases. The other greenhouse gases, including methane, some oxides of nitrogen, CFCs, and ozone, absorb smaller amounts but in wavelengths not absorbed by water and carbon dioxide.

Greenhouse Gases and Climate

- The greenhouse effect keeps Earth's lower atmosphere approximately 33°C warmer than it would otherwise be
- Performs other important service functions as well such as:
  - Without the strong downward emission of IR from the greenhouse effect, the land surface would cool much faster at night and warm much more quickly during the day
  - The greenhouse effect helps to limit temperature swings from day to night and maintain relatively comfortable surface temperatures
- Not the greenhouse effect itself but the changes in greenhouse gases that have become a concern

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Greenhouse Gases and Climate

- Within Earth's biosphere—the planetary system that includes living things—infrared radiation can be transmitted back and forth between the atmosphere, oceans, ice, and solid surfaces.
- Infrared radiation emitted by the land can be absorbed by gases in the atmosphere.
- The temperature of these gases rises and also radiate in the infrared, some of which goes back down to the surface.
- The amount of IR absorbed at Earth's surface from the greenhouse effect is estimated to be greater than twice the amount of shortwave solar radiation absorbed by Earth's surface

The Oceans and Climate Change

- Complex, dynamic, and ongoing relationship between the oceans and the atmosphere
- Water has the highest heat capacity of any compound
  - Large amount of heat energy is stored in oceans
- Ocean absorbs dissolved CO_2
  - As CO_2 increases in atmosphere it also increases in the oceans
  - This can cause seawater to become more acidic as carbonic acid increases

$$(H_2O + CO_2 \longrightarrow H_2CO_3)$$

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Forecasting Climate Change Using Computer Simulation

- General circulation models (GCM)
  - Based around the atmosphere being divided into rectangular solids
    - Each a few km high and several km N or S
    - For each the flux of energy and matter is calculated to each adjacent cell
  - Steady state model—cannot account for randomness
- The models have not been validated adequately
- The models are nevertheless widely used, and many of the current conclusions about climate change are based on their forecasts

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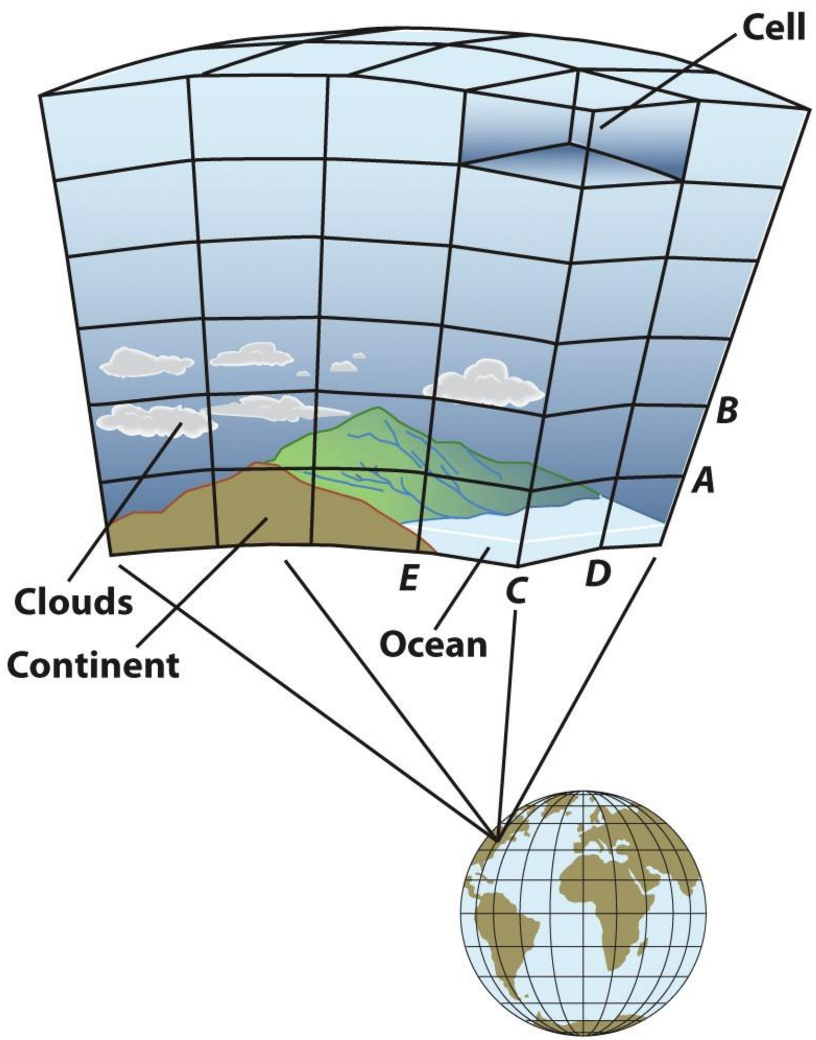

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FIGURE 20.20 Idealized diagram of how the huge, general circulation models (models of the entire Earth's climate) are viewed by the computers that run the programs.

The atmosphere is divided into hundreds of rectangular cells, and the flow
of energy and material is calculated for the transfer between each boundary of every cell to its adjacent cells.

Climate Change and Feedback Loops

- The atmosphere and its interactions with the ocean and land surfaces experience positive and negative feedbacks
- Negative feedback
  - Warm temperatures warm air and lead to increased evaporation
  - Evaporation leads to more cloud formation which reflects more sunlight which could cool the surface

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- As global warming occurs, the warmth and additional carbon dioxide could stimulate the growth of algae. The algae, in turn, could absorb carbon dioxide, reducing the concentration of CO_2 in the atmosphere and cooling Earth's climate.

- Increased CO_2 concentration with warming might similarly stimulate growth of land plants, leading to increased CO_2 absorption and reducing the greenhouse effect.

- If polar regions receive more precipitation from warmer air carrying more moisture, the increasing snowpack and ice buildup could reflect solar energy away from Earth's surface, causing cooling.

- Warming could increase water evaporation from the ocean and the land, leading to cloudier conditions (the water vapor condenses), and the clouds would reflect more sunlight and cool the surface.

Climate Change and Feedback Loops

- Positive feedback
  - Warm temperatures warm air and lead to increased evaporation but instead of clouds forming, remains as water vapor
  - Water vapor is a greenhouse gas
  - The warmer it gets the more water vapor, and the process continues

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The warming Earth increases water evaporation from the oceans, adding water vapor to the atmosphere. Water vapor is a major greenhouse gas that, as it increases, causes additional warming. If more clouds form from the increased water vapor, and more solar radiation is reflected, this would cause cooling, as our discussion of negative feedback shows. Thus, water vapor is associated with both positive and negative feedback. This makes study of clouds and global climate change complex.

- The warming Earth could melt a large amount of permafrost at high latitudes, which would in turn release the greenhouse gas methane, a by-product of decomposition of organic material in the melted permafrost layer. This would cause additional warming.

- Replacing some of the summer snowpack or glacial ice with darker vegetation and soil surfaces decreases the albedo (reflectivity), increasing the absorption of solar energy and further warming the surface. This is a powerful positive feedback, explaining, in part, why the Arctic is warming faster than lower latitudes.

- In warming climates, people use more air conditioning and thus more fossil fuels. The resulting increase in carbon dioxide could lead to additional global warming.

- Since negative and positive feedback can occur simultaneously in the atmosphere, the dynamics of climate change are all the more complex. Research is ongoing to better understand the negative feedback processes associated with clouds and their water vapor.

The Greenhouse Effect

- No one doubts that the greenhouse effect exists and affects planets
- The puzzle arises on the Earth about relative importance of greenhouse gases in affecting climate
- Evidence indicates that carbon dioxide, methane, and temperature rise and fall together
- Most scientists conclude that greenhouse gases are causing climate change

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New Understanding of the Interplay Between the Oceans and the Atmosphere

- Natural oscillations of the ocean are linked to the atmosphere
- The effect of the oscillations can be 10x as strong as long-term warming that has been observed over the past century—larger, even, over a period of a few decades, than human-induced climate change

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Climate Forcing

It can be helpful to view climate change in terms of **climate forcing**—defined as an imposed perturbation of Earth's energy balance.[15]

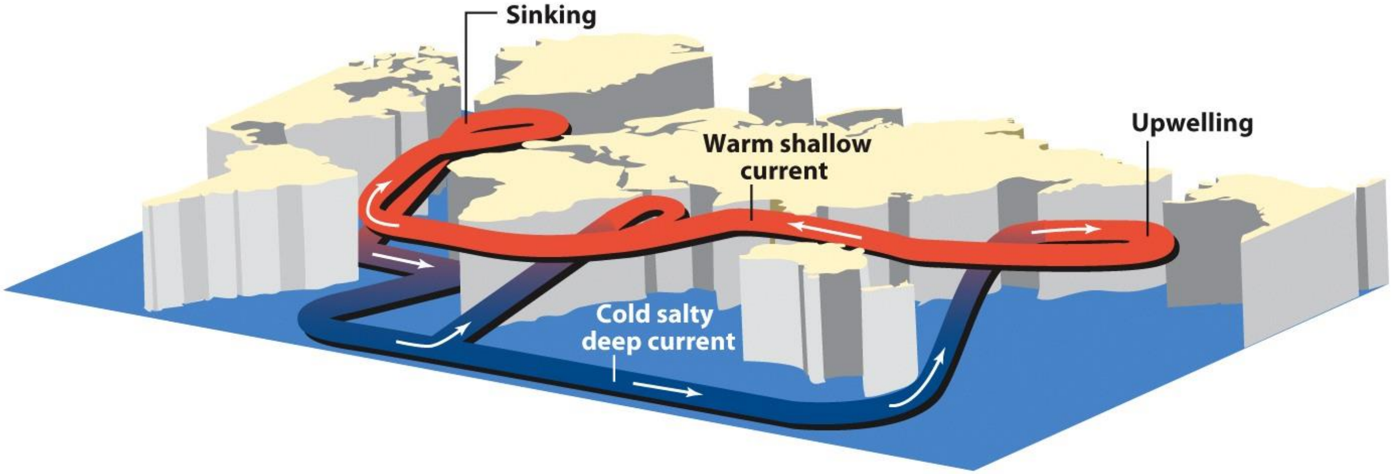
human-caused forcings are estimated to have dominated over natural forcings. The total climate forcing from greenhouse gases is about 1.6 W/m^$_2$.

Forcings change the states of the atmosphere and the surface, which feeds back to affect climate. Positive forcings cause warming, and negative forcings cause cooling. For example, as ice sheets grow, they reflect more incoming solar radiation, which enhances cooling

The aerosol black carbon (soot) is about 0.8 W/m$_2$. Recent revised estimates are higher, at about 1.1 W/m^$_2$.
Thus, total climate forcing in very recent times may have increased from 1.6 to about 1.9 W/m^$_2$.

The Ocean's Effect on Climate Change

- Climate system driven (in part) by "ocean conveyor belt"
  - A global circulation of ocean waters
  - If the conveyor was shut down, major changes in climate would occur



(*Source:* Modified from W. Broker, "Will Our Ride into the Greenhouse Future Be a Smooth One?" *Geology Today* 7, No. 5 [1997]: 2–6.)

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El Niño and Climate

- El Niño refers to a specific periodic variation of Pacific Ocean currents
- Under non-El Niño conditions
  - Trade winds blow west across the tropical Pacific
  - Warm surface water pile up in Western Pacific

Spanish settlement of the west coast of South America, people observed a strange event that occurred about every seven years.

Under normal conditions, there are strong vertical, rising currents, called upwellings, off the shore of Peru. These are caused by prevailing winds coming westward off the South American continent, which move the surface water away from the shore and allow cold water to rise from the depths, along with important nutrients that promote the growth of algae (the base of the food chain) and thus produce lots of fish. Seabirds feed on those fish and nest in great numbers on small islands just offshore.

El Niño and Climate

- During El Niño years
  - Trade winds weaken
  - Western moving current weakens or reverses
    - As a result eastern equatorial ocean unusually warm
    - High rates of precipitation and flooding in Peru on the eastern Pacific
- Changes global atmospheric circulation
  - Causes changes in weather in regions that are far removed from tropical Pacific

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El Niño and Climate

- Surface water temperature rise off the South American coast inhibits the upwelling of nutrient-rich cold water from deeper levels
  - Upwelling releases carbon dioxide
  - El Niño events reduce the amount of oceanic carbon outgassing

El Niño occurs when those cold upwellings weaken or cease altogether. As a result, nutrients decline, algae grow poorly, and so do the fish, which either die, fail to reproduce, or move away. The seabirds, too, either leave or die. Rainfall follows warm water eastward during El Niño years, so there are high rates of precipitation and flooding in Peru, while droughts and fires are common in Australia and Indonesia.

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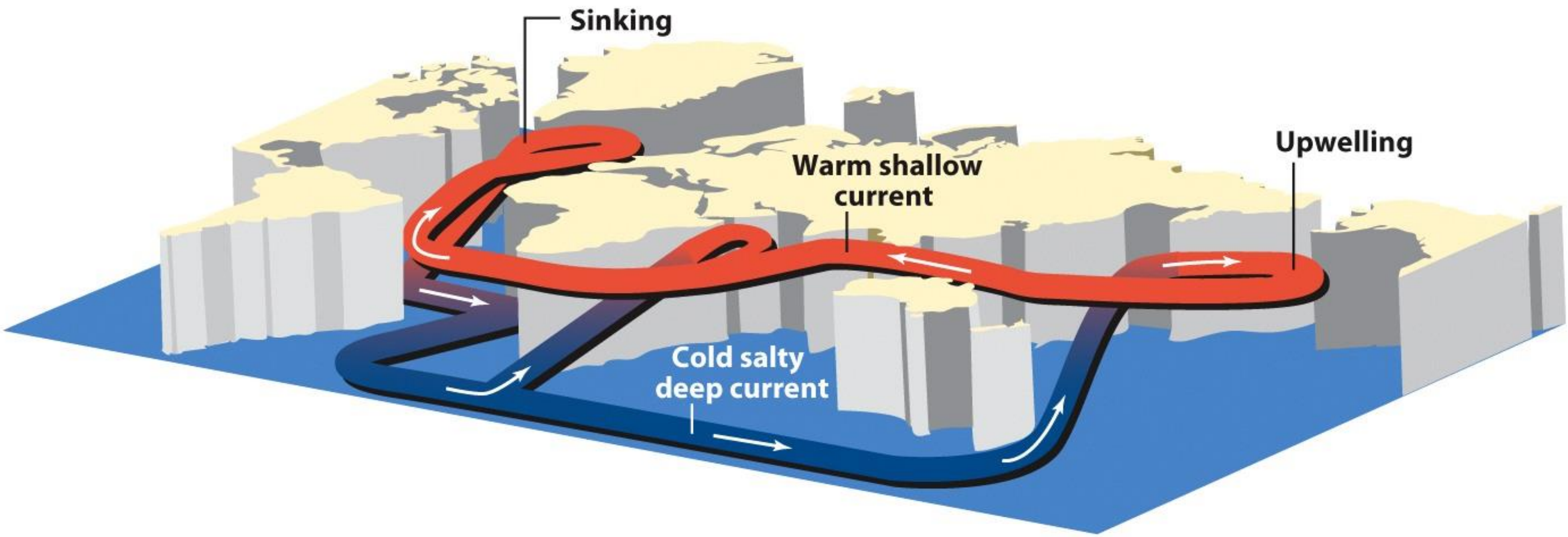
The “Ocean Conveyor Belt”

The ocean conveyor belt—a global circulation of ocean waters characterized by strong northward movement of upper warm waters of the Gulf Stream in the Atlantic Ocean—was understood in the 20th century to play a role in climate. The temperature of these waters is approximately 12°–13°C when they arrive near Greenland, and they are cooled in the North Atlantic to a temperature of 2°–4°C

As the water cools, it becomes saltier and denser, causing it to sink to the bottom. The cold, deep current flows southward, then eastward, and, finally, northward in the Pacific Ocean. Upwelling in the North Pacific starts the warm, shallow current again. The flow in this conveyor belt current is huge—20 million m^3/sec, about equal to 100 Amazon Rivers. If the ocean conveyor belt were to stop, some major changes might occur in the climates of some regions. Western Europe would cool but probably not experience extreme cold or icebound conditions.[27]



(*Source:* Modified from W. Broker, "Will Our Ride into the Greenhouse Future Be a Smooth One?" *Geology Today* 7, No. 5 [1997]: 2–6.)

FIGURE 20.23 Idealized diagram of the oceanic conveyor belt. The actual system is more complex, but in general the warm surface water (red) is transported westward and northward (increasing in salinity because of evaporation) to near Greenland, where it cools from contact with cold Canadian air.

As the surface water becomes denser, it sinks to the bottom and flows south, then east to the Pacific, then north, where upwelling occurs in the North Pacific.

The masses of sinking and upwelling waters balance, and the total flow rate is about 20 million m^3/sec. The heat released to the atmosphere from the warm water keeps northern Europe 5°C–10°C warmer than if the oceanic conveyor belt were not present.

Chapter Summary

- Major climate changes have occurred throughout Earth's history
  - Of special interest to us is that periodic glacial and interglacial episodes have characterized Earth since the evolution of our species
- During the past 1,000 years, several warming and cooling trends have affected civilizations
- During the past 100 years, the mean global surface air temperature has risen by about 0.8°C
  - About 0.5°C of this increase has occurred since around 1960

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Chapter Summary

- Major greenhouse gases
  - Water vapor
  - Carbon dioxide
  - Methane
  - Oxides of nitrogen
  - CFCs
- The vast majority of the greenhouse effect is produced by water vapor, a natural constituent of the atmosphere
- Carbon dioxide and other greenhouse gases also occur naturally in the atmosphere
- However, especially since the Industrial Revolution, human activity has added substantial amounts of carbon dioxide, methane, and CFCs to the atmosphere

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Chapter Summary

- Climate models suggest that a doubling of carbon dioxide concentration in the atmosphere
  - Could raise the mean global temperature 1°–2°C in the next few decades
  - Could raise it by 1.5°–4.5°C by the end of this century
- Many complex positive feedback and negative feedback cycles affect the atmosphere as well as
  - Natural cycles
  - Solar forcing
  - Aerosol forcing
  - Particulate forcing from volcanic eruptions
  - El Niño events also affect the temperature of Earth

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Chapter Summary

- Concerns based on scientific evidence
  - Global warming is leading to changes in climate patterns
  - A rise in sea level
  - Melting of glaciers
  - Changes in the biosphere
- A potential threat from future warming, as in the Medieval Warm Period, is the occurrence of prolonged drought that would compromise the world's food supply
- Adjusting to global warming includes
  - Learning to live with the changes
  - Attempting to mitigate warming by reducing emissions of greenhouse gases

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