Energy and Climate Change

Chapter 5
The Greenhouse Effect

Historical temperature trends

FIGURE 5-2 (a) Reconstruction of changes in yearly average global surface temperatures, relative to the 1961–1990 average. [Source: M. E. Mann and P. D. Jones, *Geophysical Research Letters* (2003):30, 1820.] (b) Global average land–ocean temperatures at the Earth' surface (5-year running average). [Source: adapted from Makiko Sato, *Updating the Climate Science*] (c) Linear temperature trends covering the 25, 50, 100, and 150 years to 2005. [Source: Adapted from S. Solomon et al., eds., *Climate Change 2007: The Physical Science Basis, Intergovernmental Panel on Climate Change*, Cambridge University Press.]

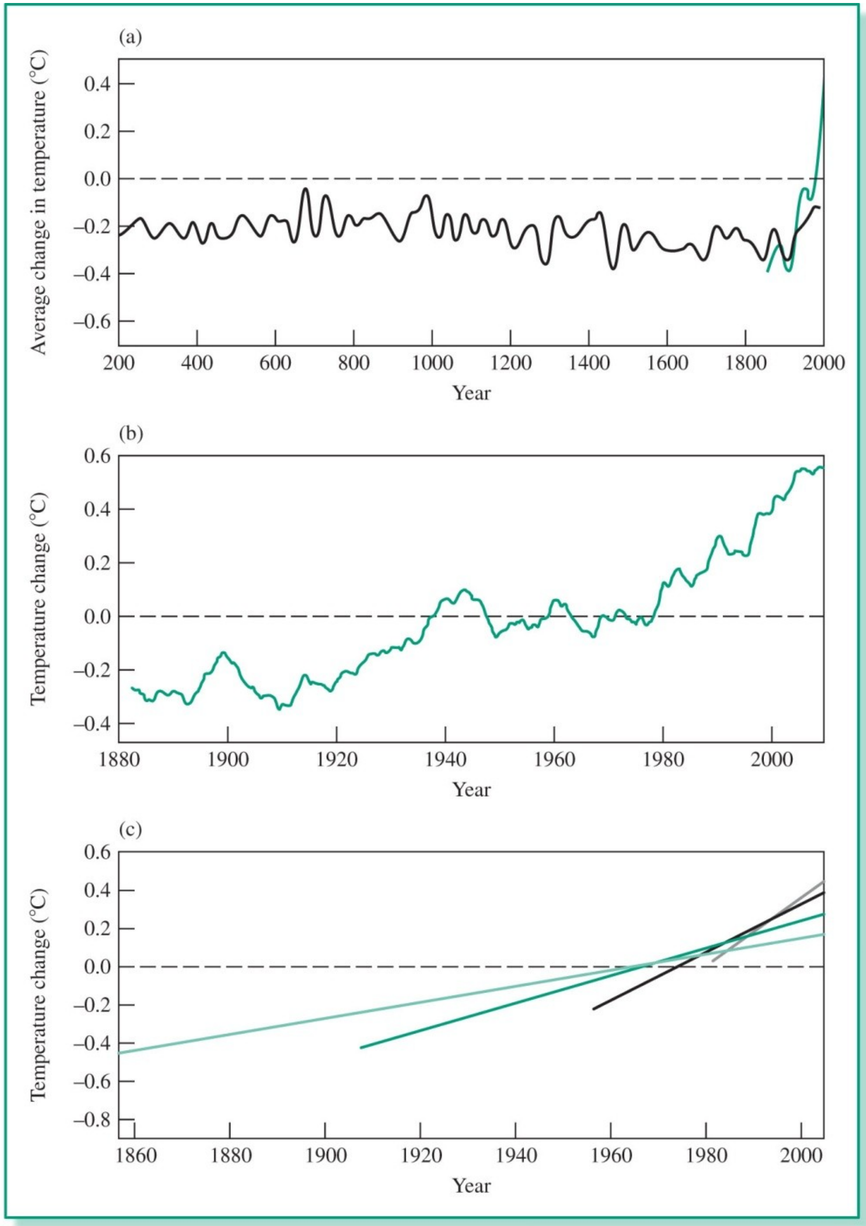
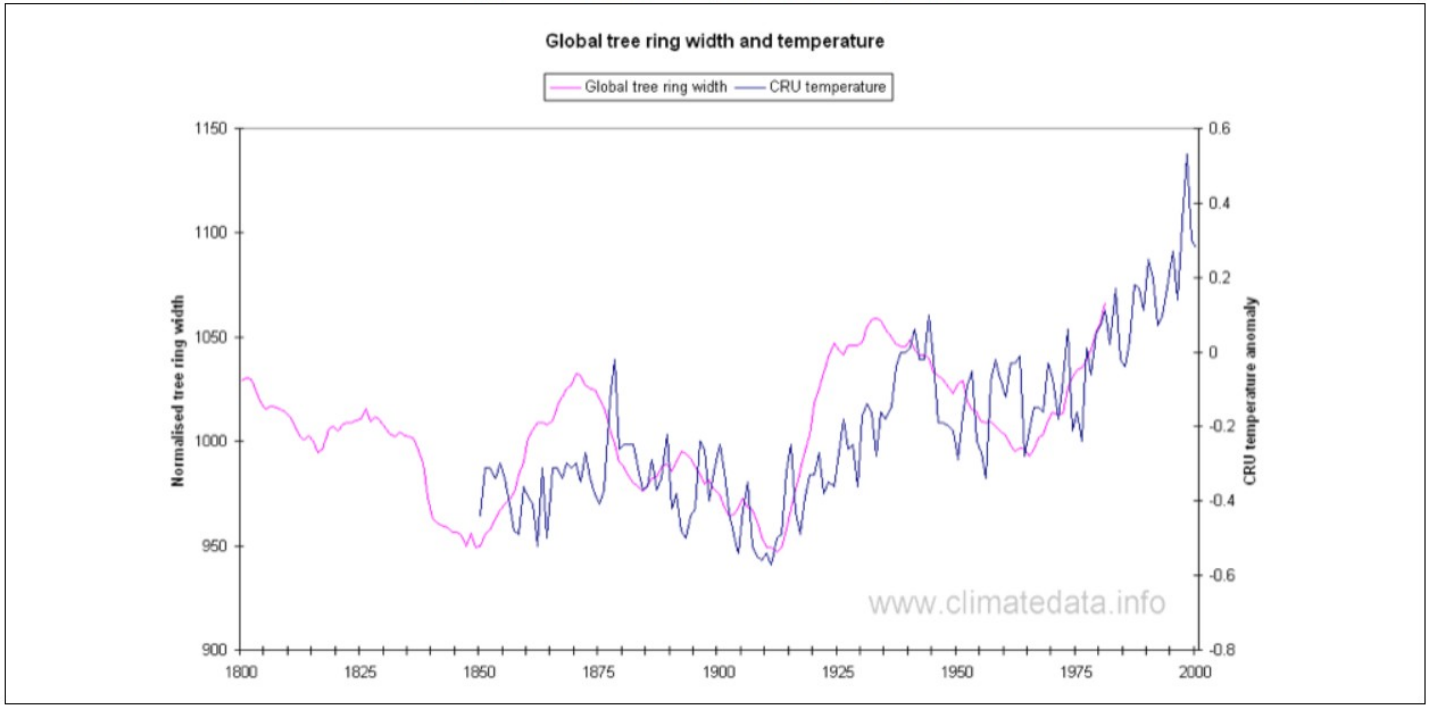


Figure 3: Global Tree Ring Width and Temperature



Greenhouse effect

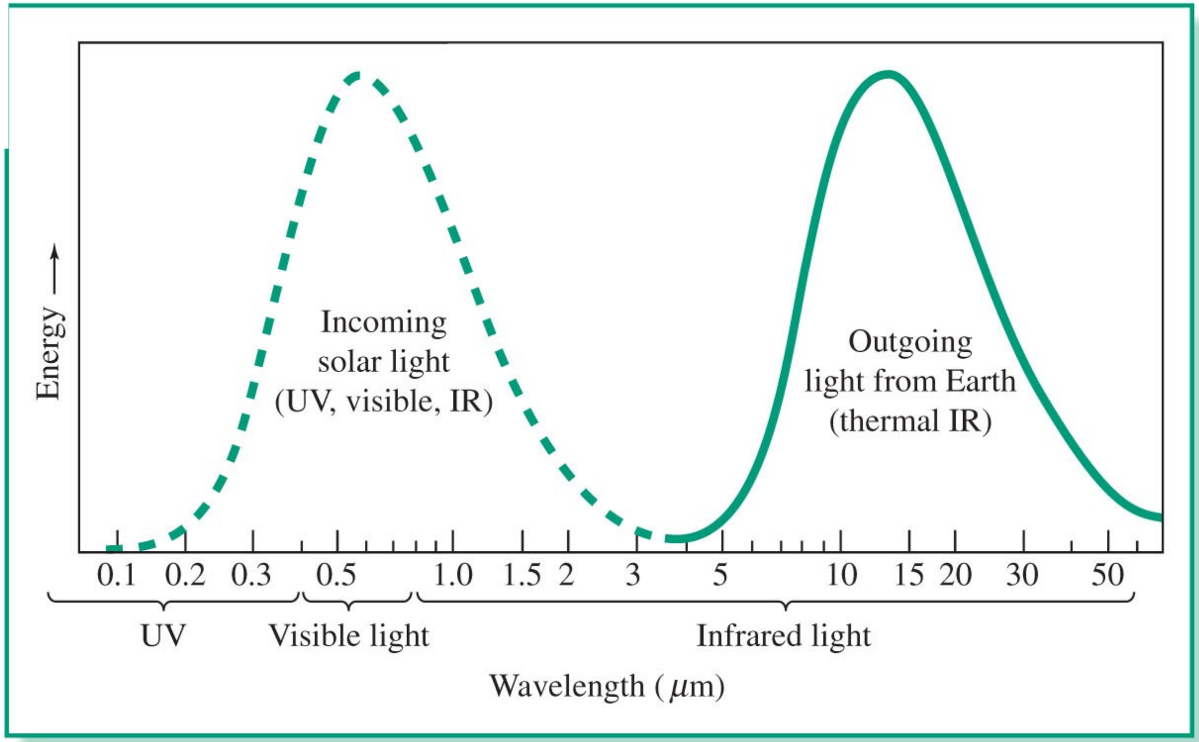
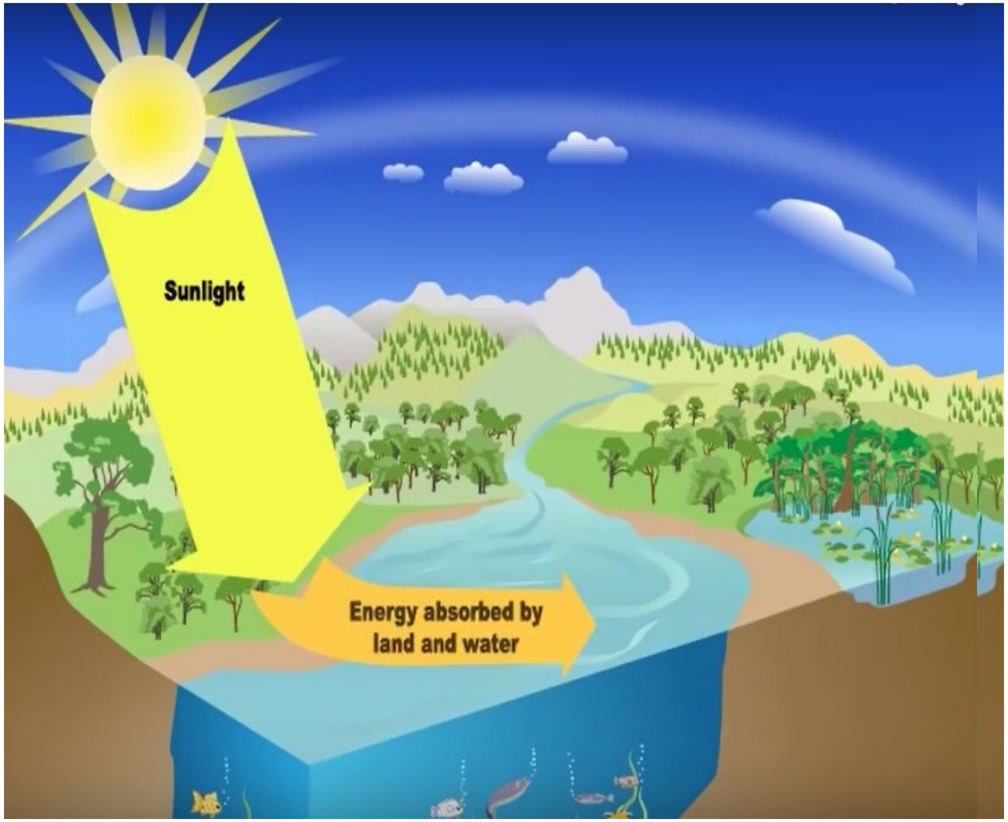
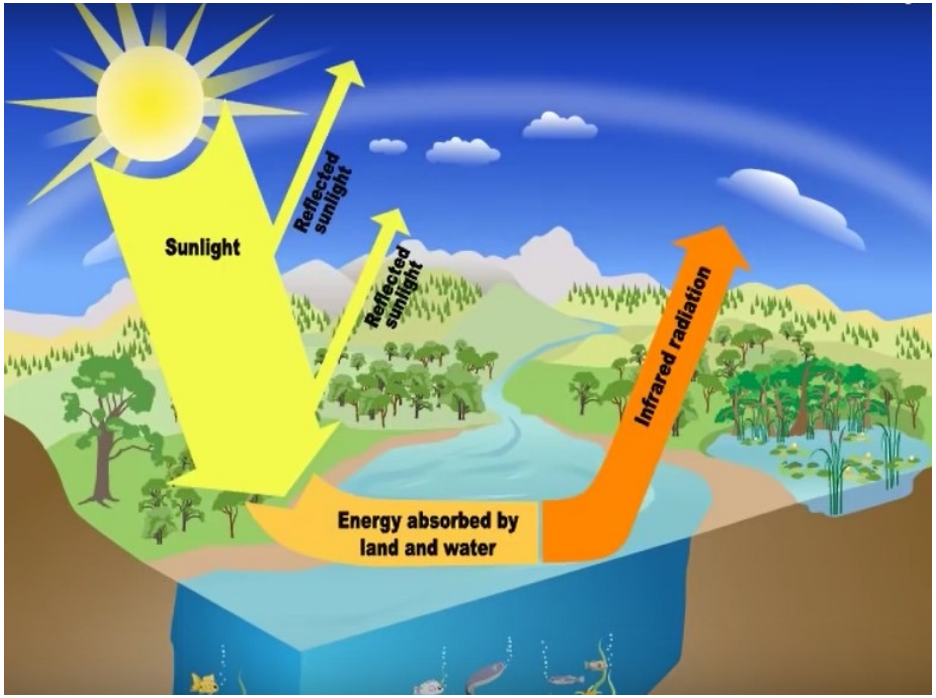


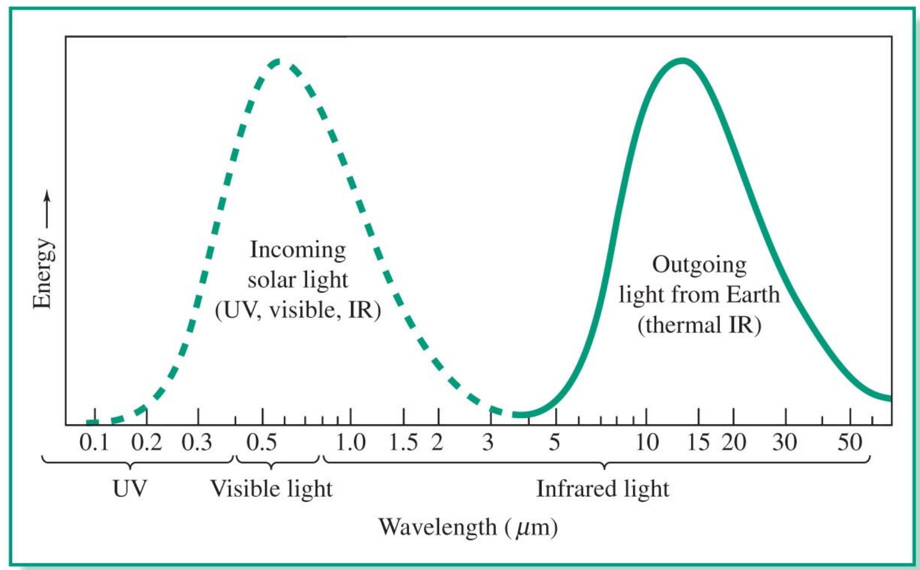
FIGURE 5-1 Wavelength distributions (using different scales) for light emitted by the Sun (dashed curve) and by the Earth's surface and troposphere (solid curve). [Source: Redrawn from J. Gribbin, "Inside Science: The Greenhouse Effect," *New Scientist*, supplement (22 October 1988).]

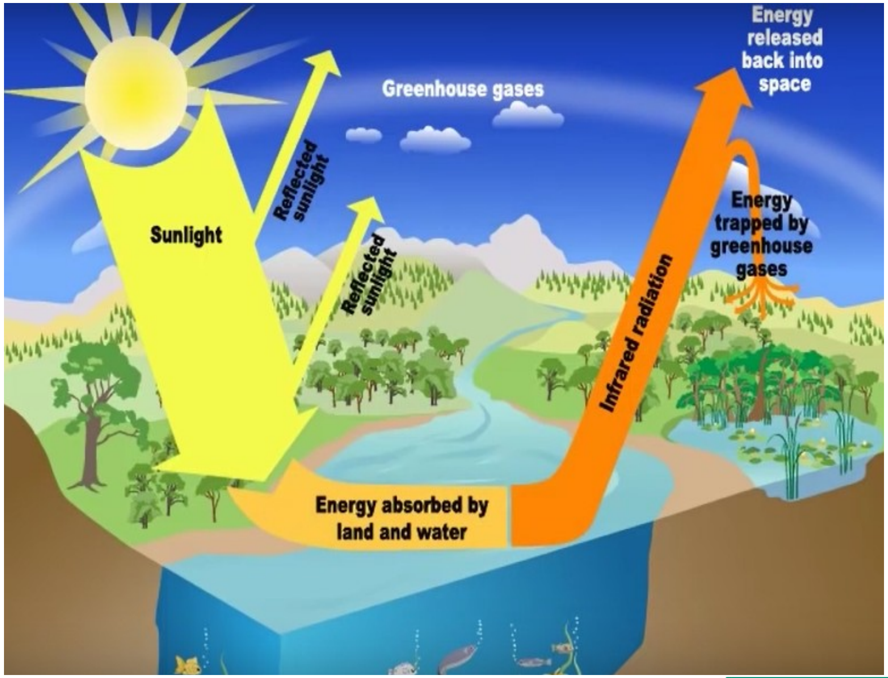
Greenhouse effect





Greenhouse effect





Greenhouse effect

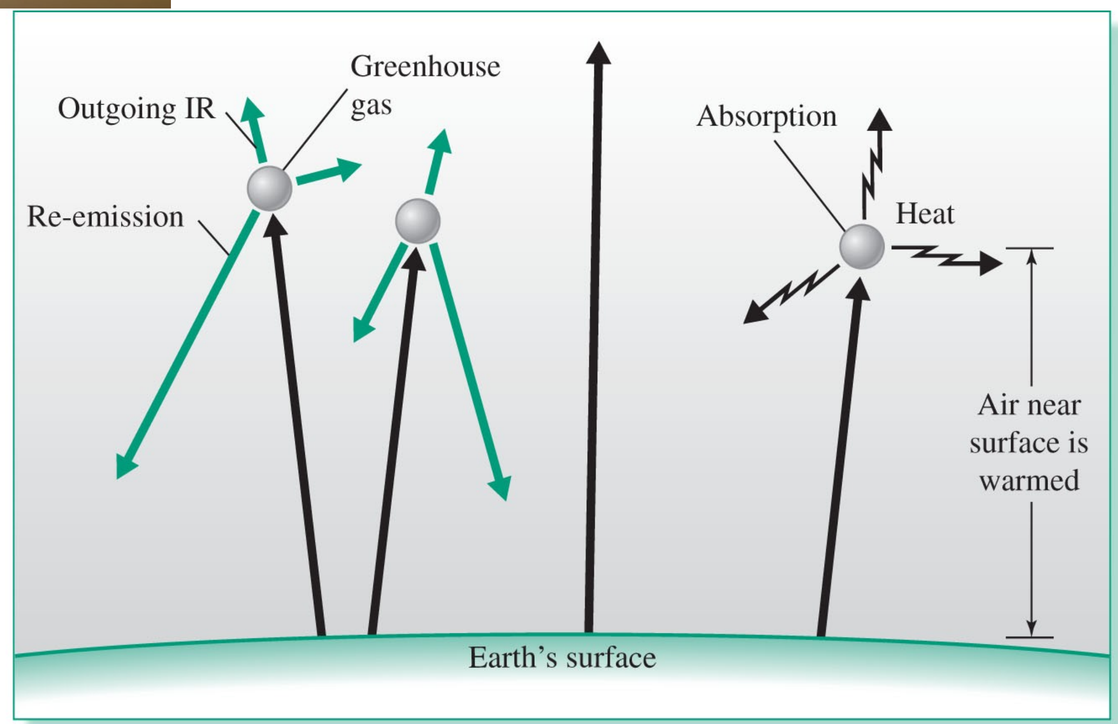
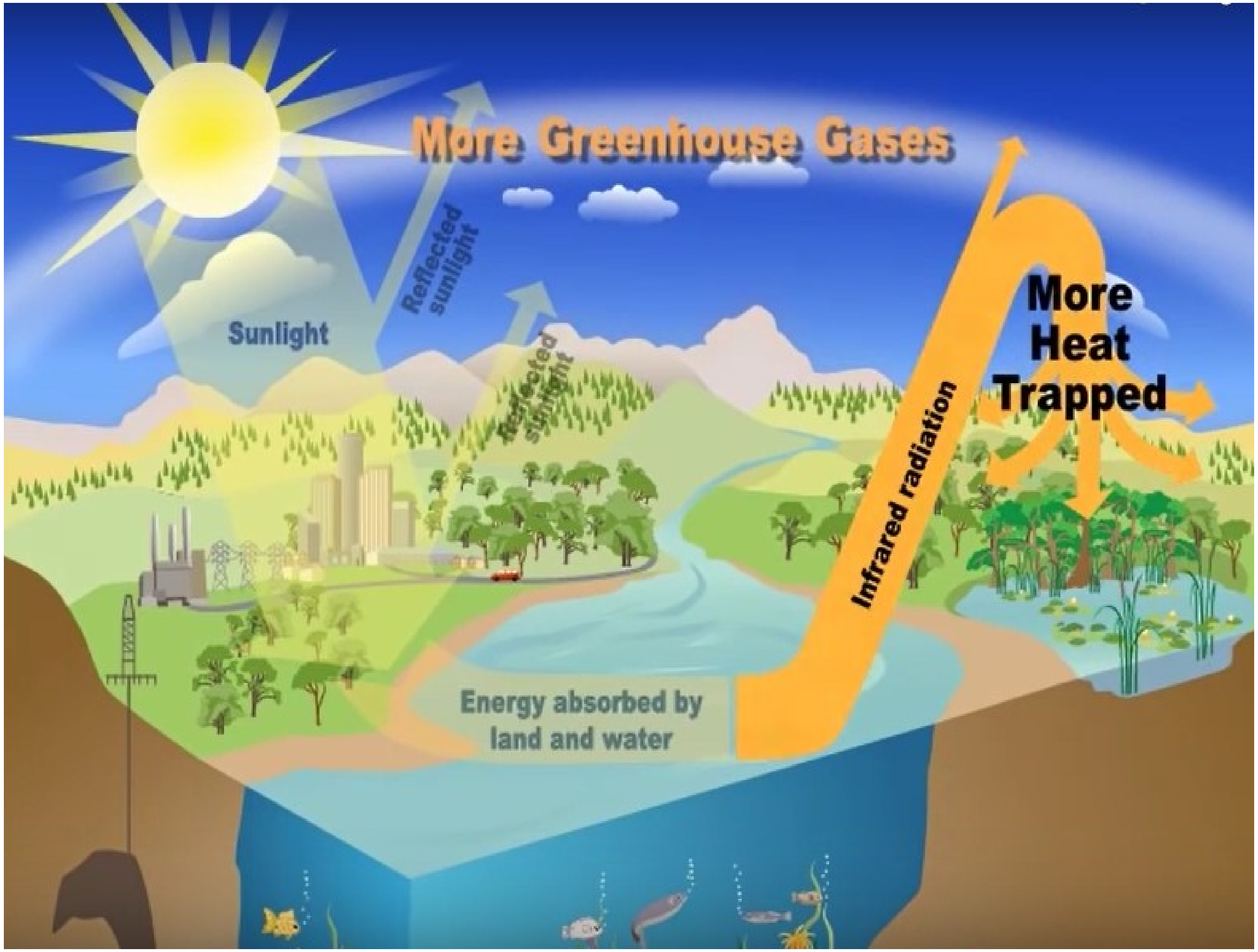


FIGURE 5-3 The greenhouse effect: outgoing IR absorbed by greenhouse gases is either re-emitted (left side of diagram) or converted to heat (right side).

Greenhouse effect



Greenhouse effect Models

Single-layer Model

Multilayer Model

Radiative Models

Radiative-convective Models

General Circulation Models

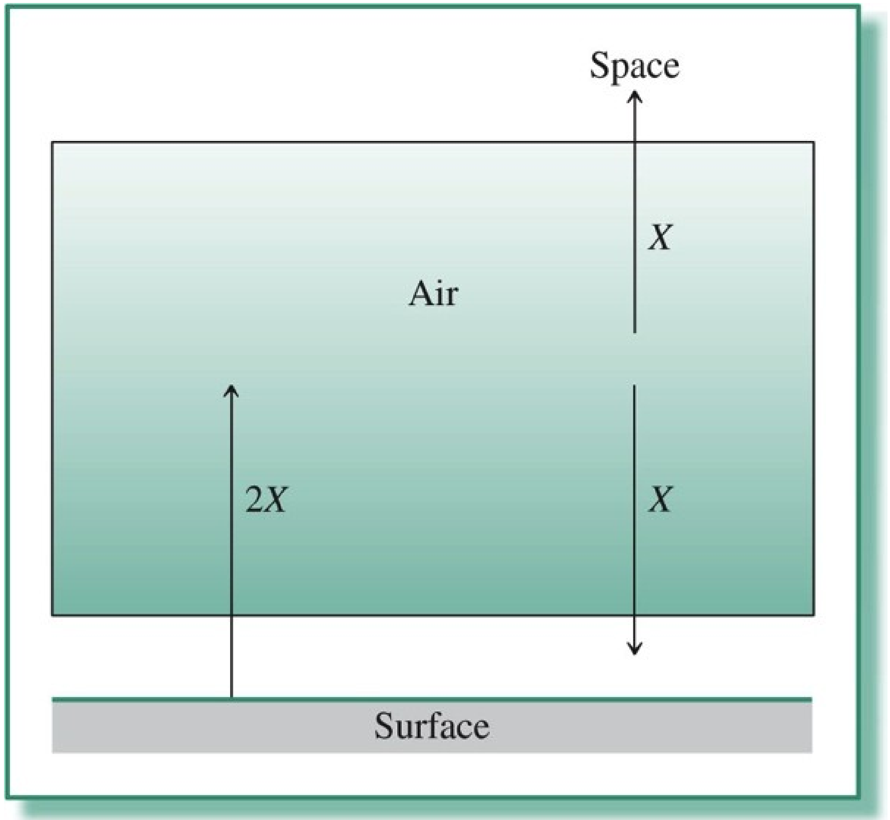


FIGURE 1 Energy released by the Earth's surface and absorbed and released by the atmosphere according to the model.

Earth's Energy Balance

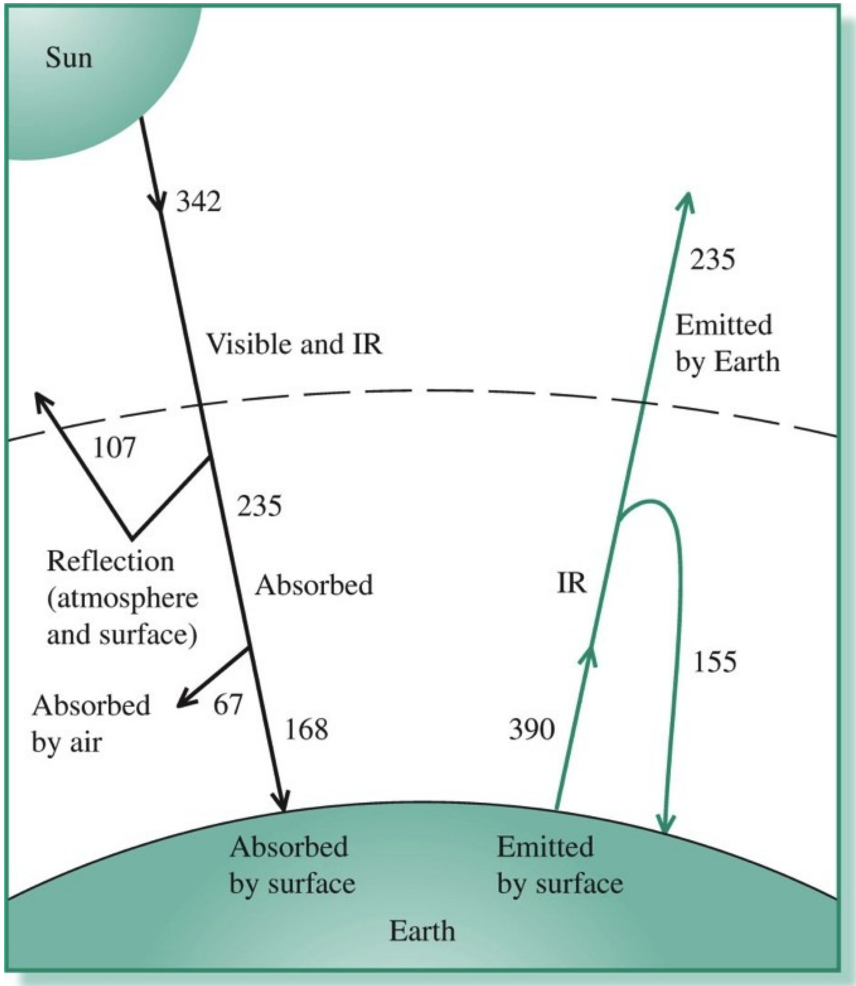
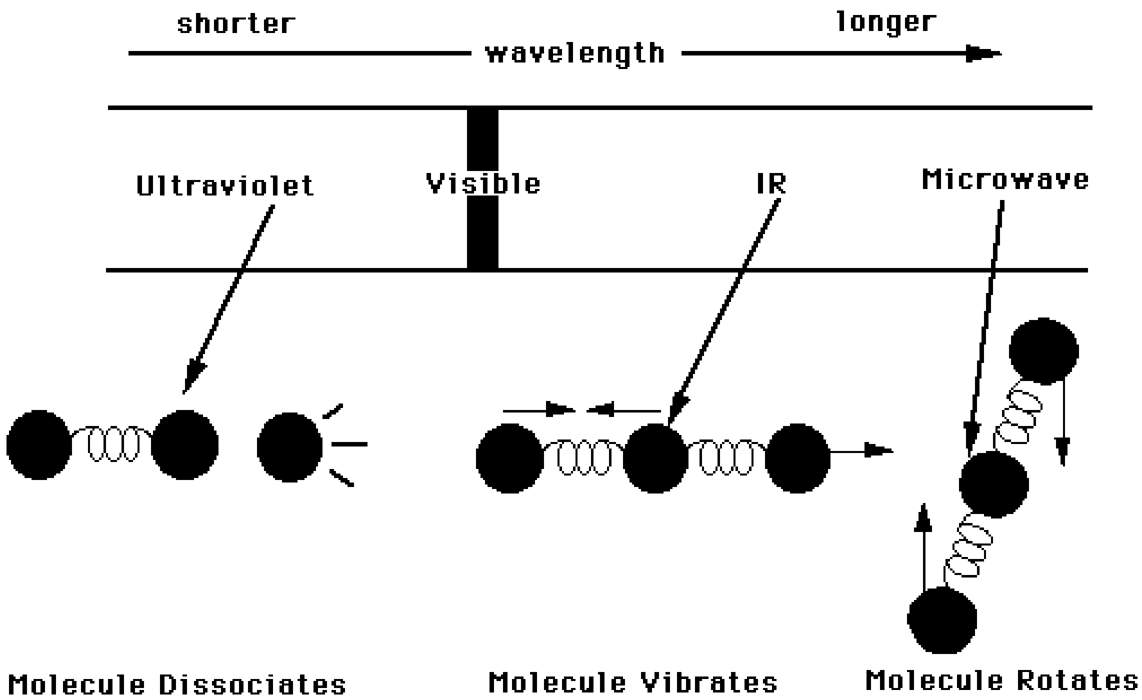


FIGURE 5-4 Globally and seasonally averaged energy fluxes to and from the Earth, in watts per square meter of surface. [Source: Data from Chapter 1 of J. T. Houghton et al., *Climate Change 1995—The Science of Climate Change (Intergovernmental Panel on Climate Change)* (Cambridge: Cambridge University Press, 1996).]

Energy absorption by greenhouse gases



Energy absorption by greenhouse gases

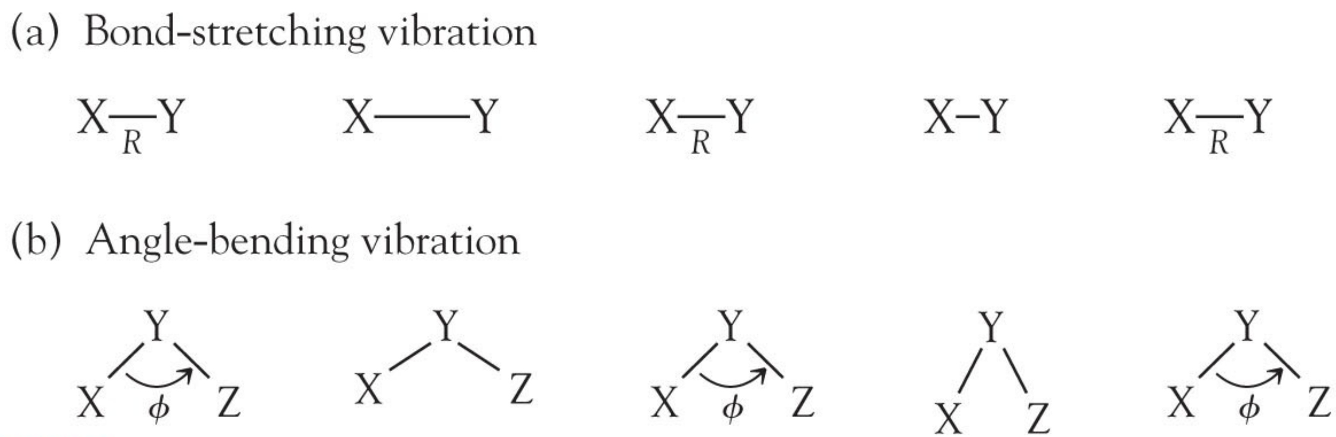


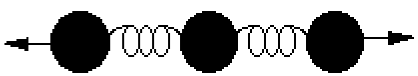
FIGURE 5-5 The two kinds of vibrations within molecules. Bond stretching (a) is illustrated for a diatomic molecule XY. The variable R represents the average value of the X–Y distance. In (b), the angle-bending vibration is shown for a triatomic molecule XYZ. The average XYZ angle is indicated by ϕ.

For a particular vibrational mode to be observed (active) in the infrared spectrum, the mode must involve a change in the dipole moment of the molecule

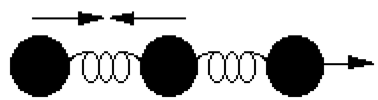
Carbon dioxide

Linear molecule

Number of vibrational modes = 3N-5



A



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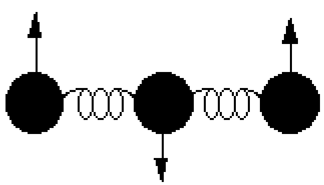
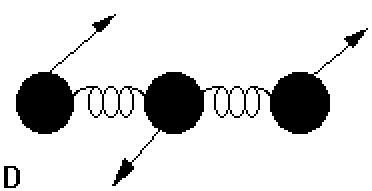


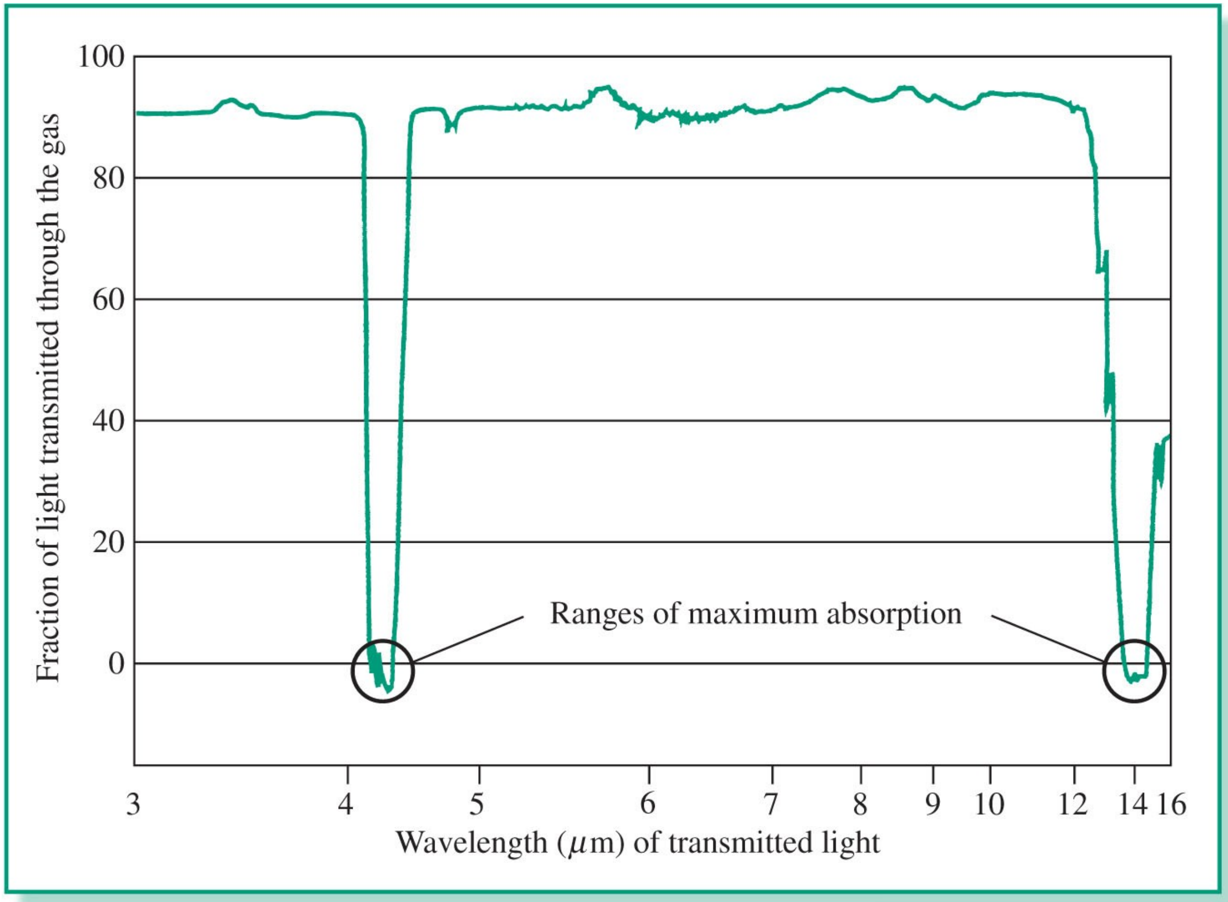
C



D

Carbon dioxide

FIGURE 5-6 The infrared absorption spectrum for carbon dioxide. The scale for wavelength is linear when expressed in wavenumbers, which have units of cm^{-1}; wavenumber = 10,000/wavelength in nm. [Source: Redrawn from A.T. Schwartz et al., *Chemistry in Context: Applying Chemistry to Society*, American Chemical Society (Dubuque, IA: Wm. C. Brown, 1994).]



Carbon dioxide

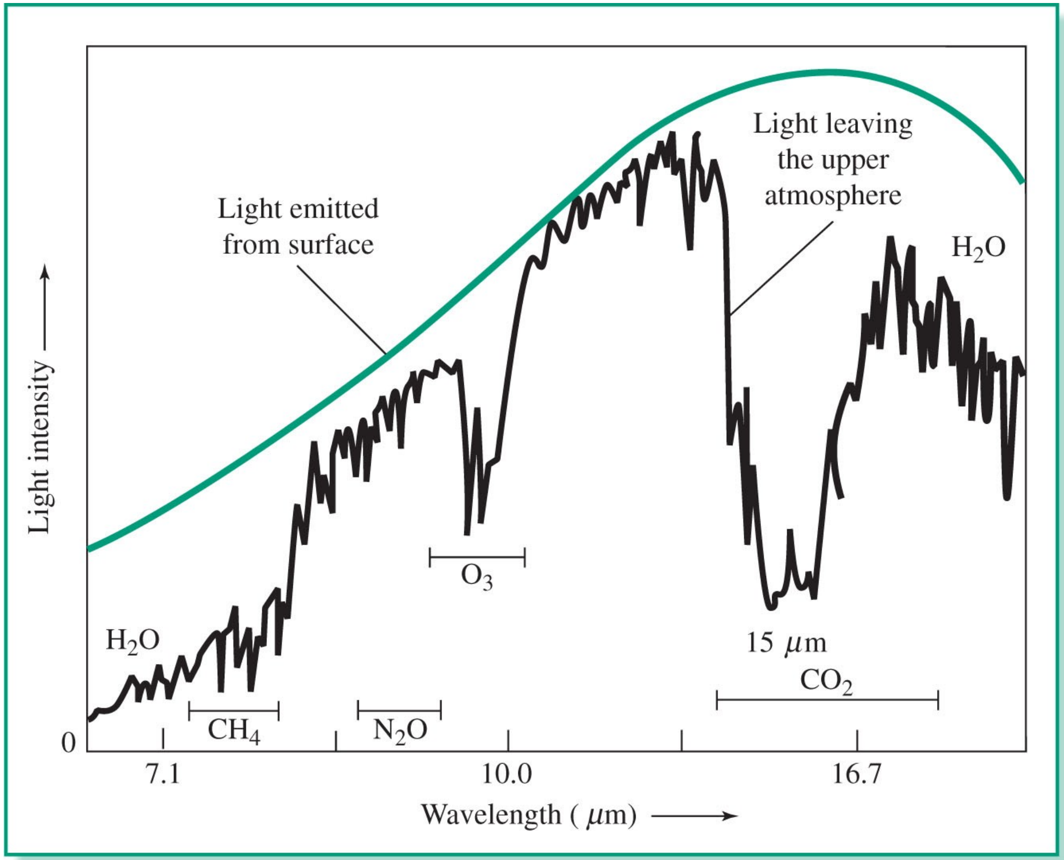
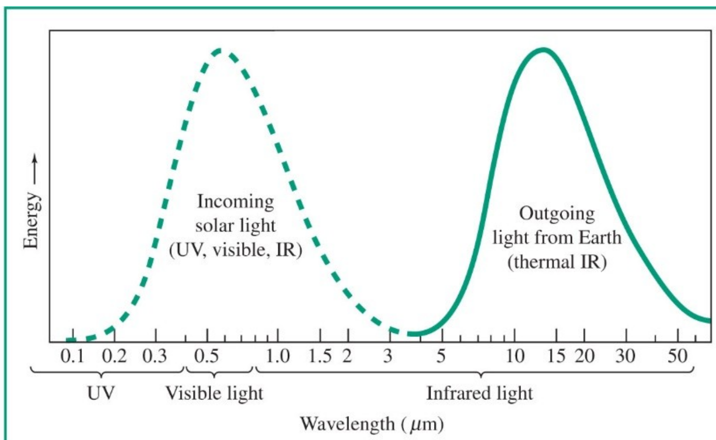
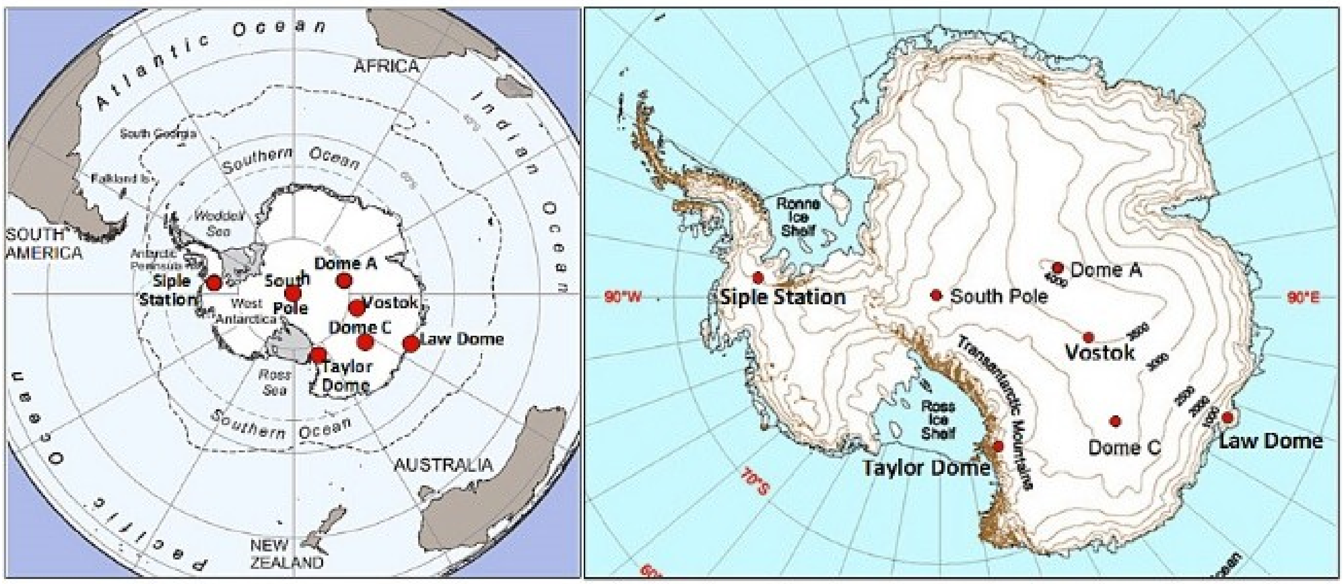


FIGURE 5-7 Experimentally measured intensity (black curve) of thermal IR light leaving the Earth's surface and lower atmosphere (above the Sahara desert) compared with the theoretical intensity (green curve) that would be expected without absorption by atmospheric greenhouse gases. The regions in which the various gases have their greatest absorption are indicated. [Source: E. S. Nesbit, *Leaving Eden* (Cambridge: Cambridge University Press, 1991).]



Carbon dioxide

800,000-year Ice-Core Records of Atmospheric Carbon Dioxide (CO_2)



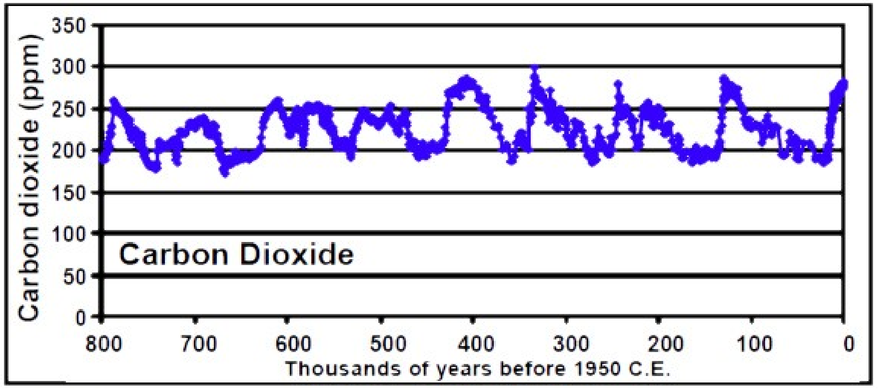
World Data Center for Paleoclimatology, National Oceanic and Atmospheric Administration (NOAA)

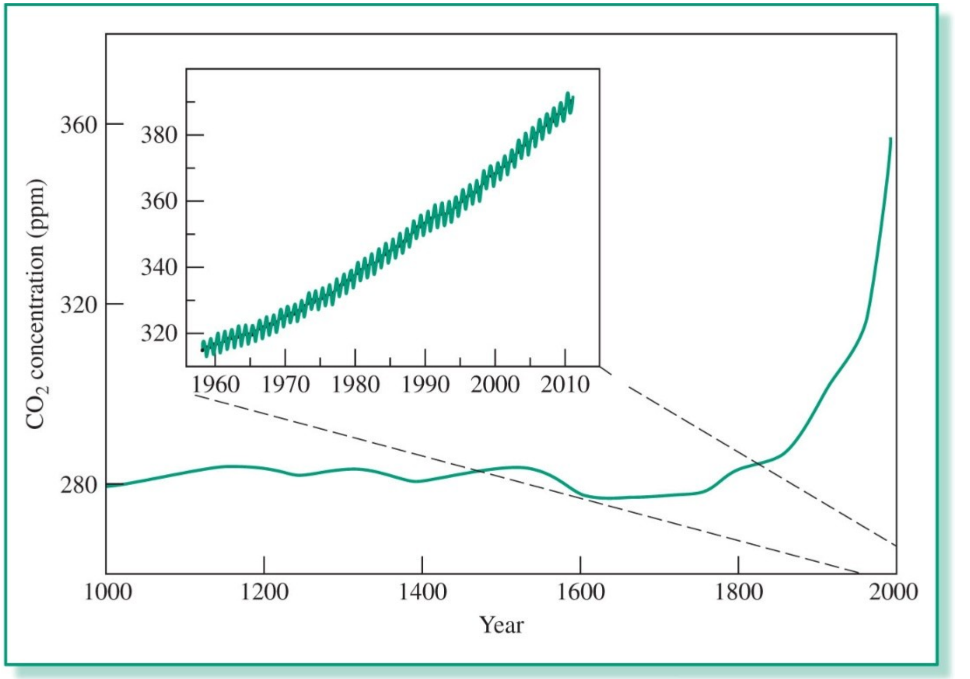
Carbon dioxide

- Over the last 800,000 years atmospheric CO_2 levels as indicated by the ice-core data have fluctuated between 170 and 300 parts per million by volume (ppmv), corresponding with conditions of glacial and interglacial periods.

- Prior to about 450,000 years before present time (BP) atmospheric CO_2 levels were always at or below 260 ppmv and reached lowest values, approaching 170 ppmv, between 660,000 and 670,000 years ago. The highest pre-industrial value recorded in 800,000 years of ice-core record was 298.6 ppmv, in the Vostok core, around 330,000 years ago.

- Atmospheric CO_2 levels have increased markedly in industrial times; measurements in year 2010 at Cape Grim Tasmania and the South Pole both indicated values of 386 ppmv, and are currently increasing at about 2 ppmv/year.





Carbon dioxide

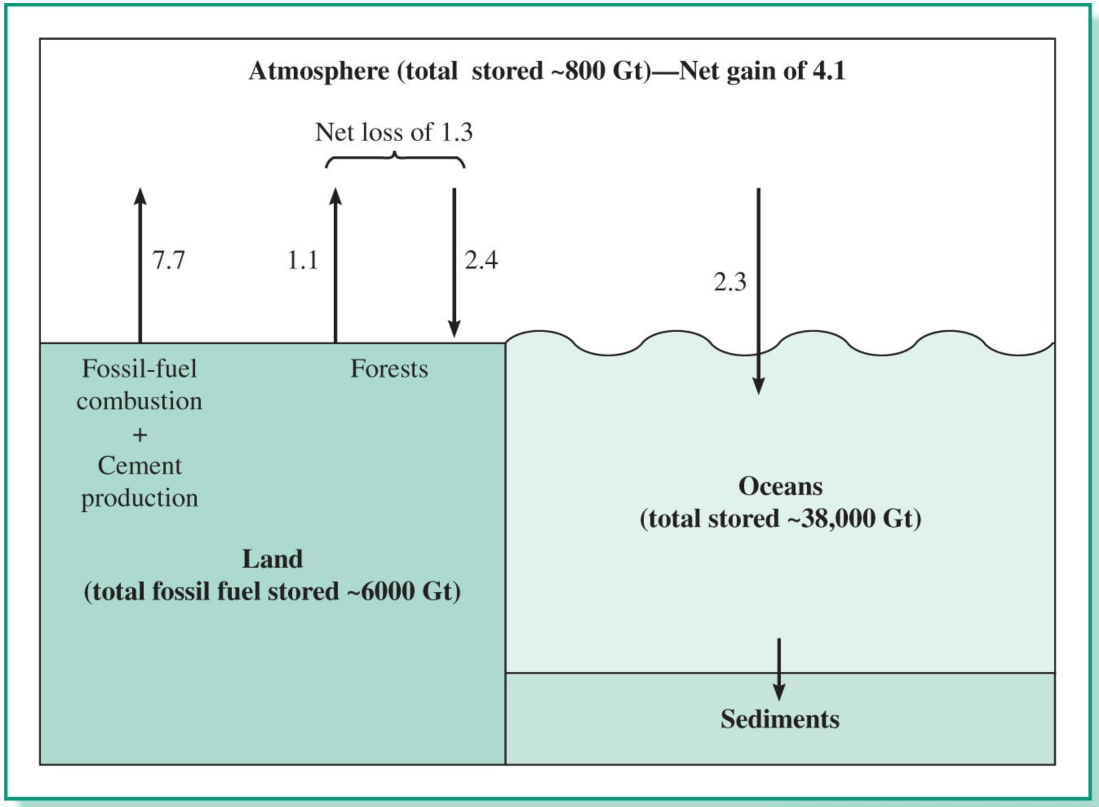


FIGURE 5-9 Annual fluxes of CO_2 to and from the atmosphere, in units of Gigatonnes (Gt) of carbon, averaged over the 2000–2009 period. [Data source: Adapted from *Carbon Budget,* Global Carbon Project, www.globalcarbonproject.org.]

Carbon dioxide

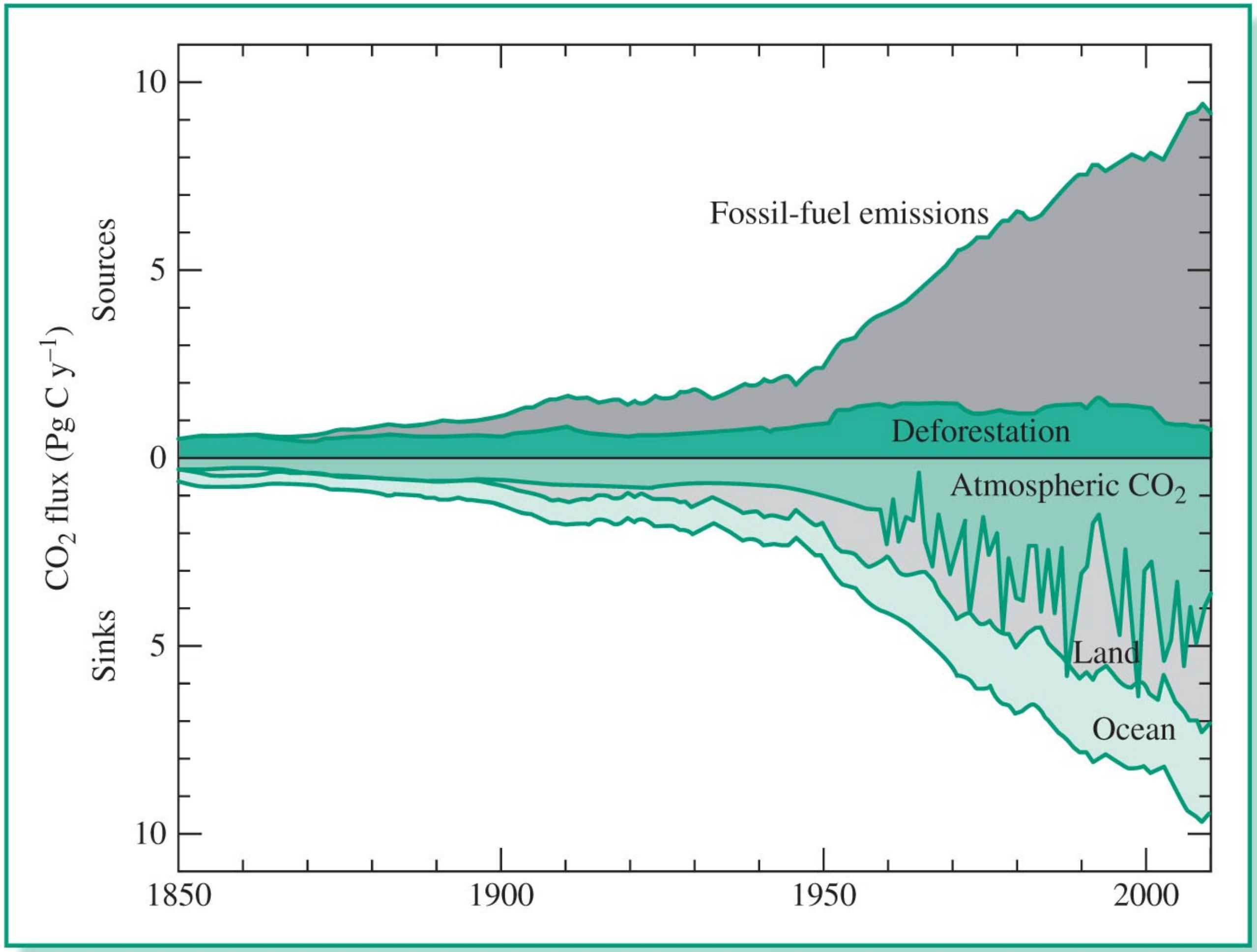


FIGURE 5-10 Annual fluxes of anthropogenic CO_2 from various sources and to various sinks from 1850 to 2010. The unit of Petagram (Pg), 10^{15} g, is equivalent to 1 Gigatonne (Gt). [Data source: Adapted from *Carbon Budget 2009*, Global Carbon Project, www.globalcarbonproject.org.]

Carbon dioxide

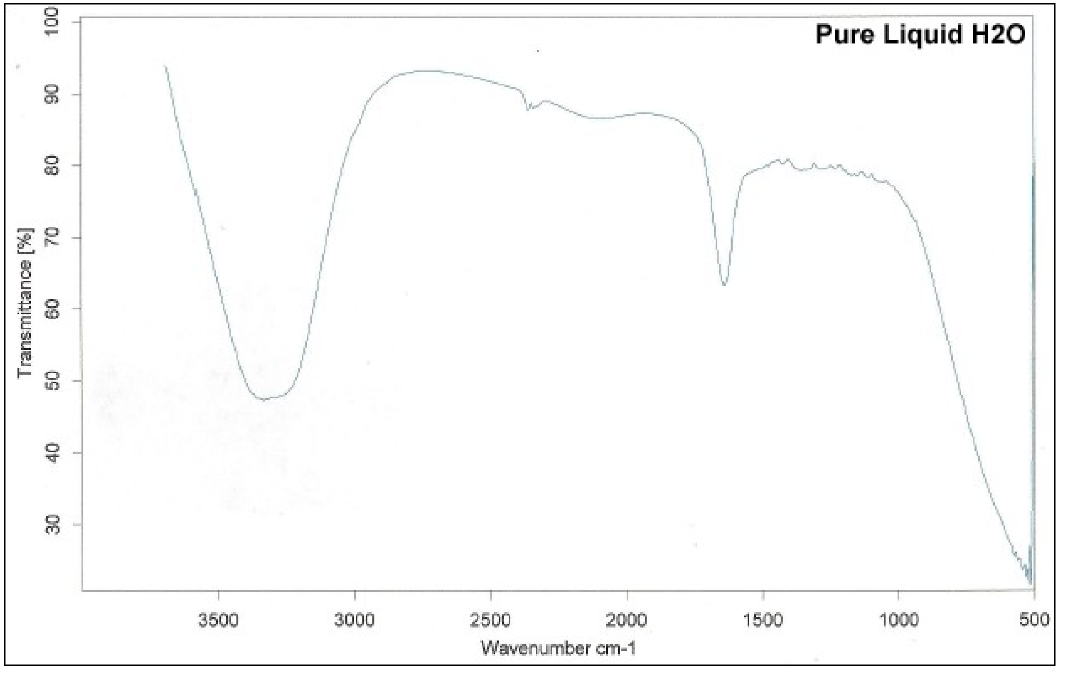
Atmospheric lifetime

- 1990 study: 50 to 200 years
- 1995 and 2001 studies: 5 to 200 years
- 2007 report:

"About 50% of a CO_2 increase will be removed from the atmosphere within 30 years, and a further 30% will be removed within a few centuries. The remaining 20% may stay in the atmosphere for many thousands of years."

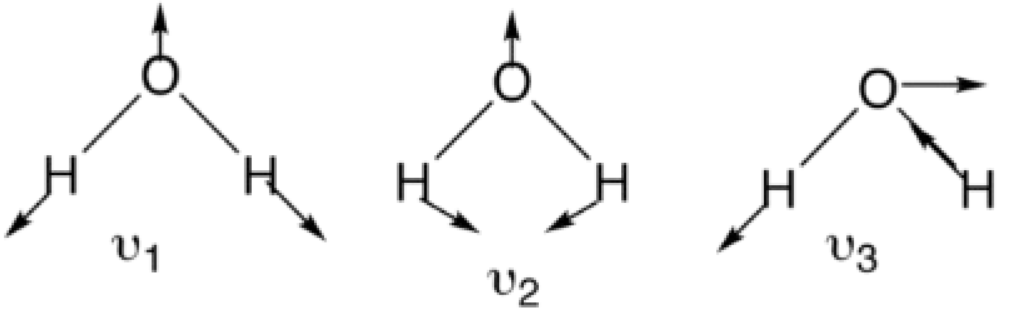
(nature reports climate change | VOL 2 | DECEMBER 2008 | www.nature.com/reports/climatechange)

Water vapor



Nonlinear molecule

Number of vibrational modes = 3N-6



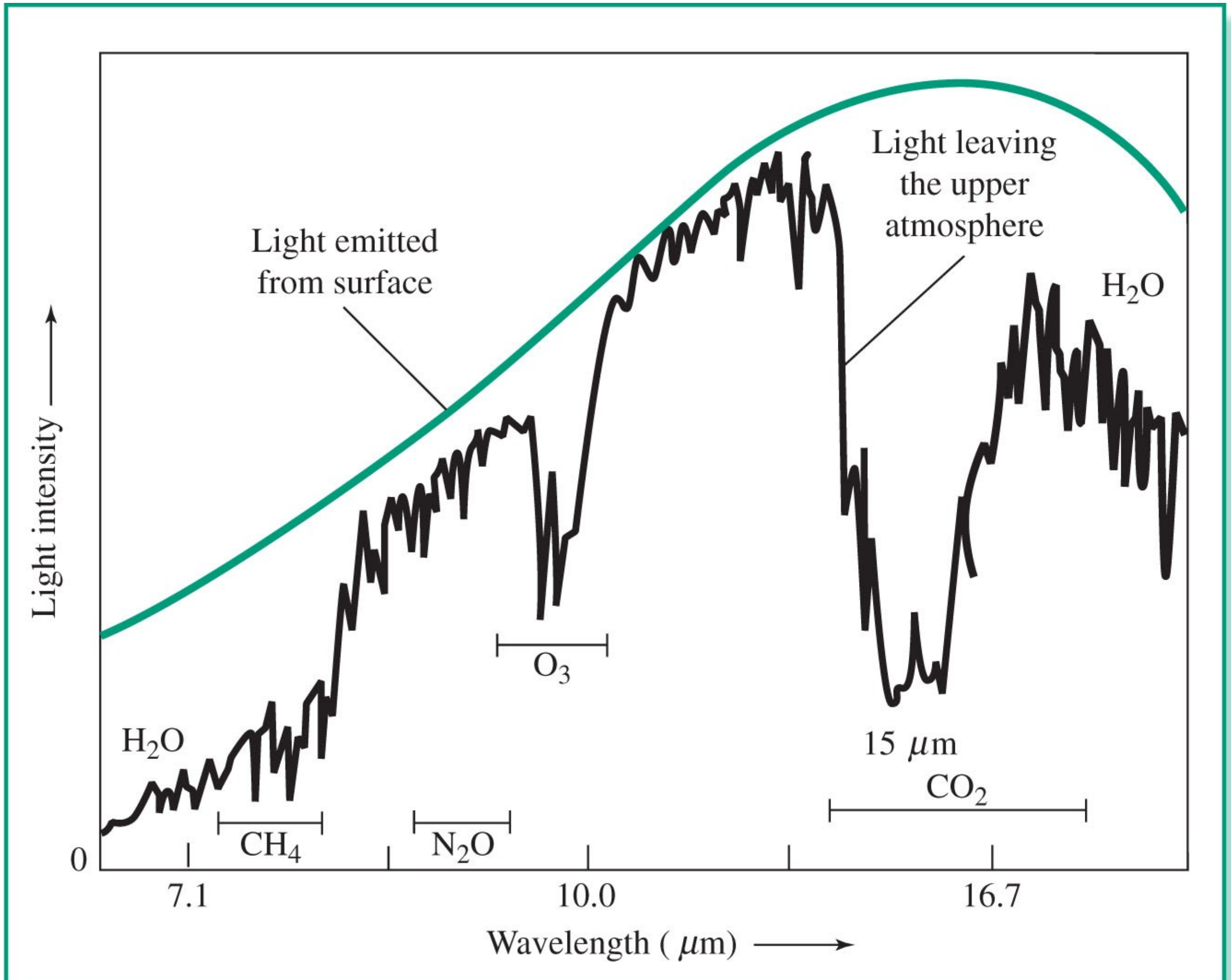
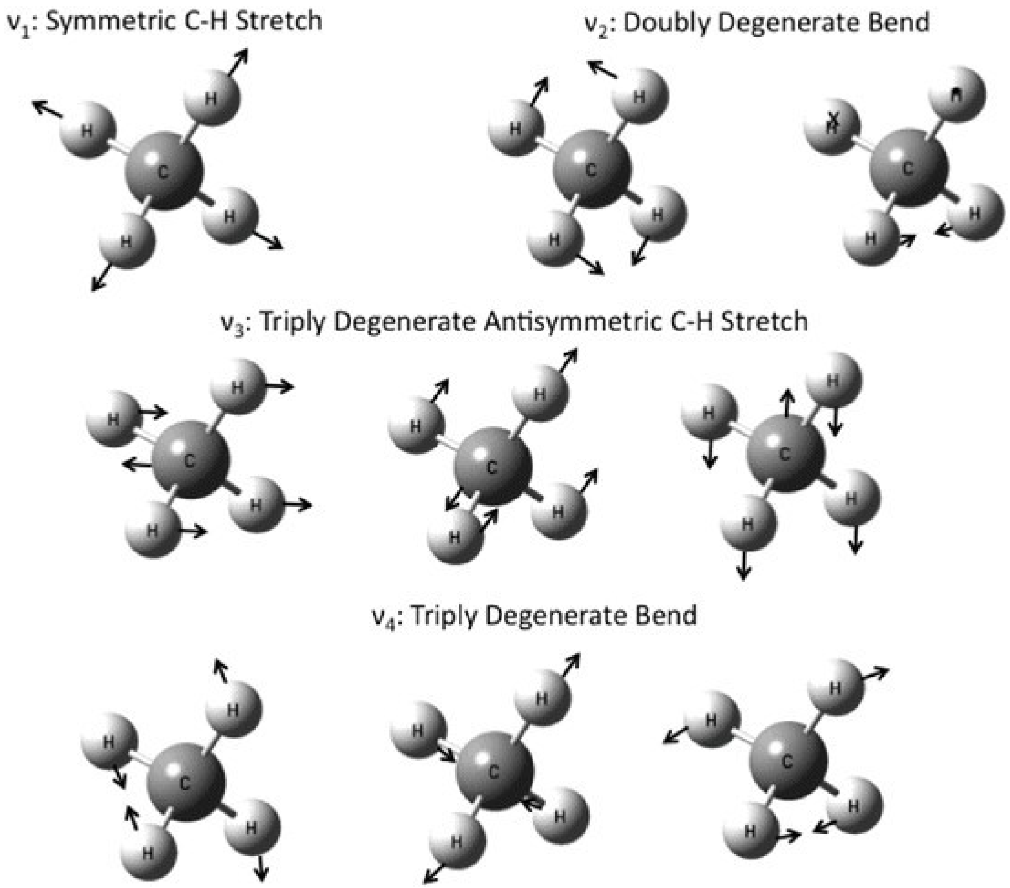


FIGURE 5-7 Experimentally measured intensity (black curve) of thermal IR light leaving the Earth's surface and lower atmosphere (above the Sahara desert) compared with the theoretical intensity (green curve) that would be expected without absorption by atmospheric greenhouse gases. The regions in which the various gases have their greatest absorption are indicated. [Source: E. S. Nesbit, *Leaving Eden* (Cambridge: Cambridge University Press, 1991).]

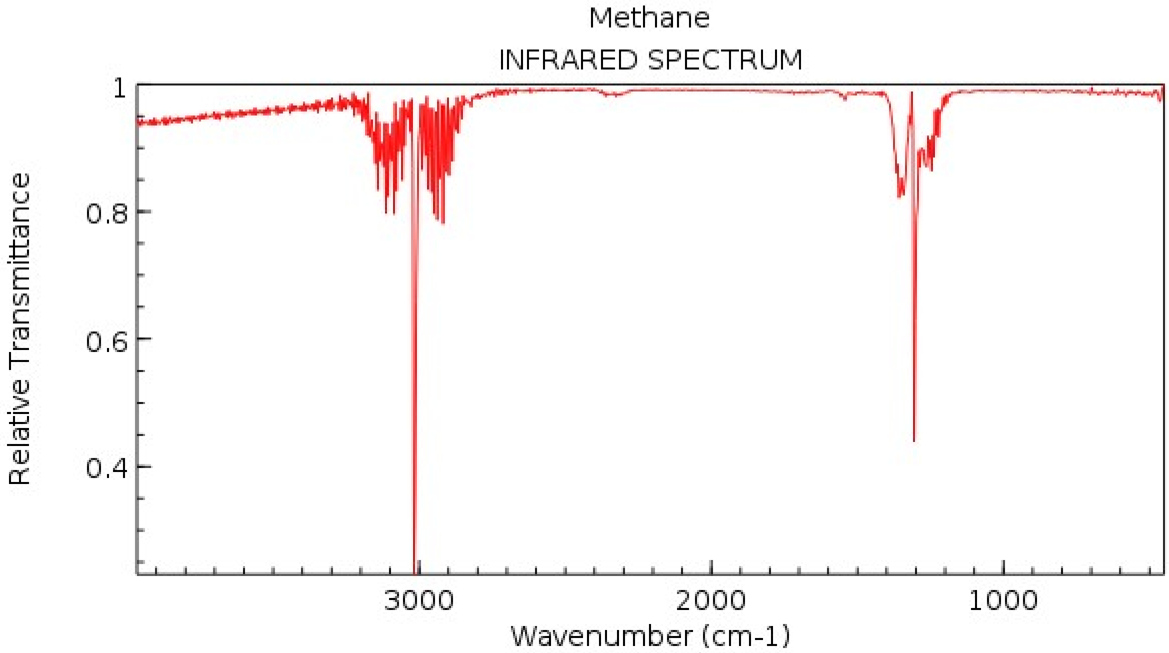
Methane

Nonlinear molecule
Number of vibrational modes = 3N-6

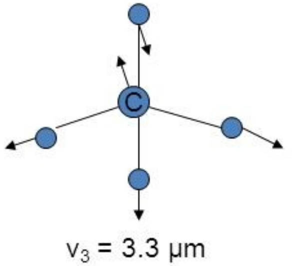


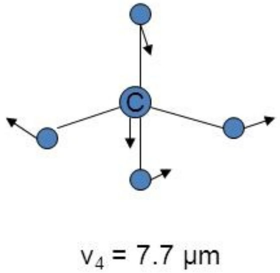
Methane vibrational normal modes
http://www.researchgate.net/figure/278652214_fig4_Figure-18-18-Methane-vibrational-normal-modes

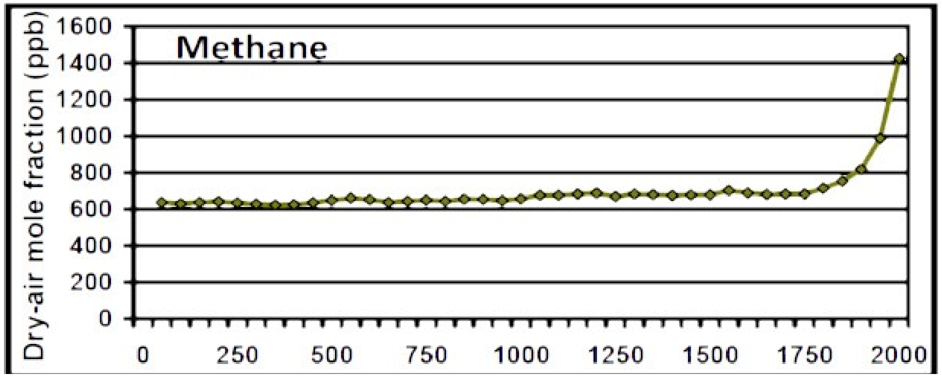
Methane



NIST Chemistry WebBook (http://webbook.nist.gov/chemistry)







Methane

Lifetime less than a decade

Sinks:

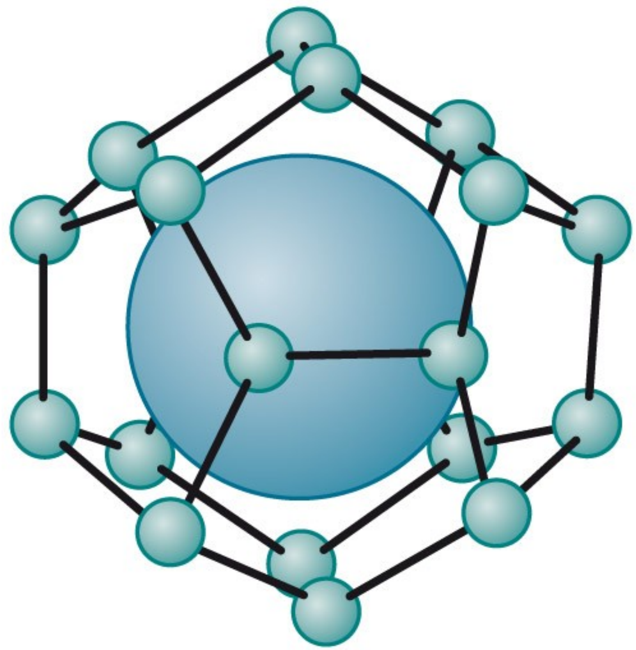
- Loss from air
- Soil
- Loss to the stratosphere

Sources

- Anaerobic decomposition of organic matter
  - natural wetlands
  - flooding of land
  - landfills

- Burning of biomass
- Ruminant animals

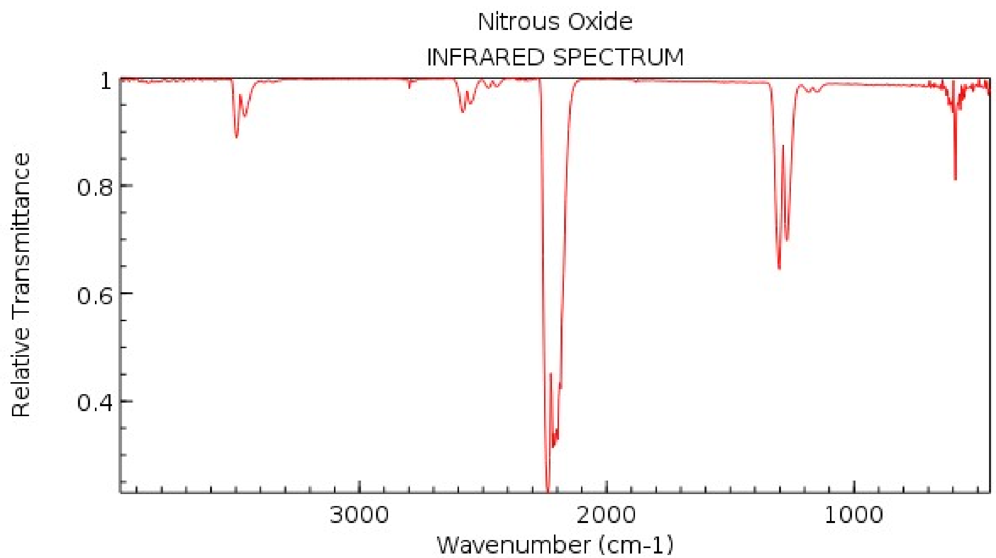
Methane Hydrate



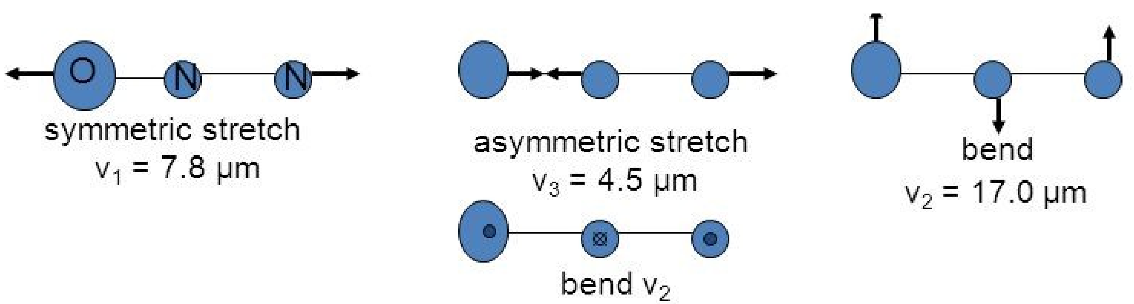
Nitrous oxide

Linear molecule

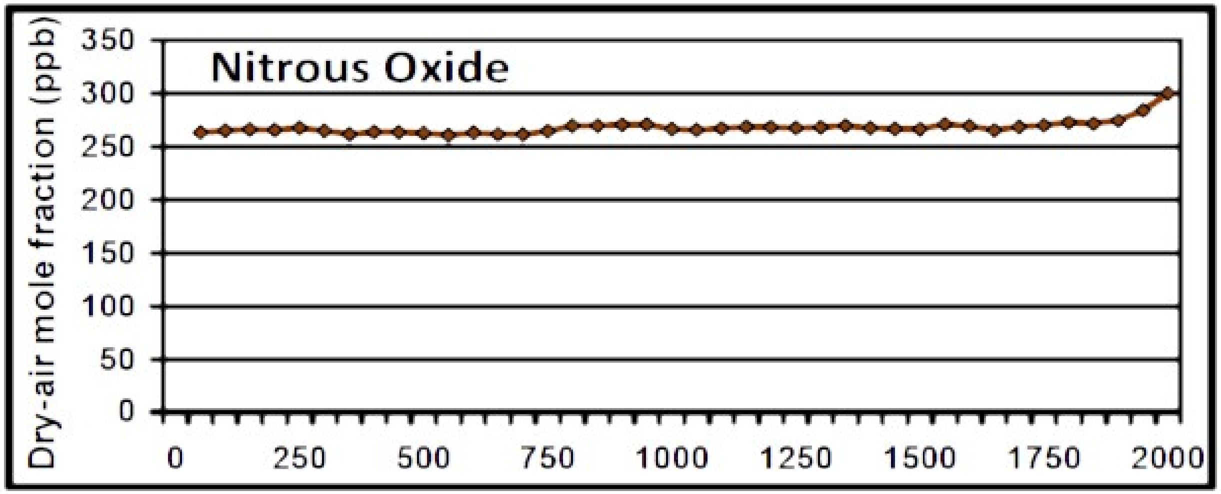
Number of vibrational modes = 3N-5



NIST Chemistry WebBook (http://webbook.nist.gov/chemistry)



Nitrous oxide



Nitrous oxide

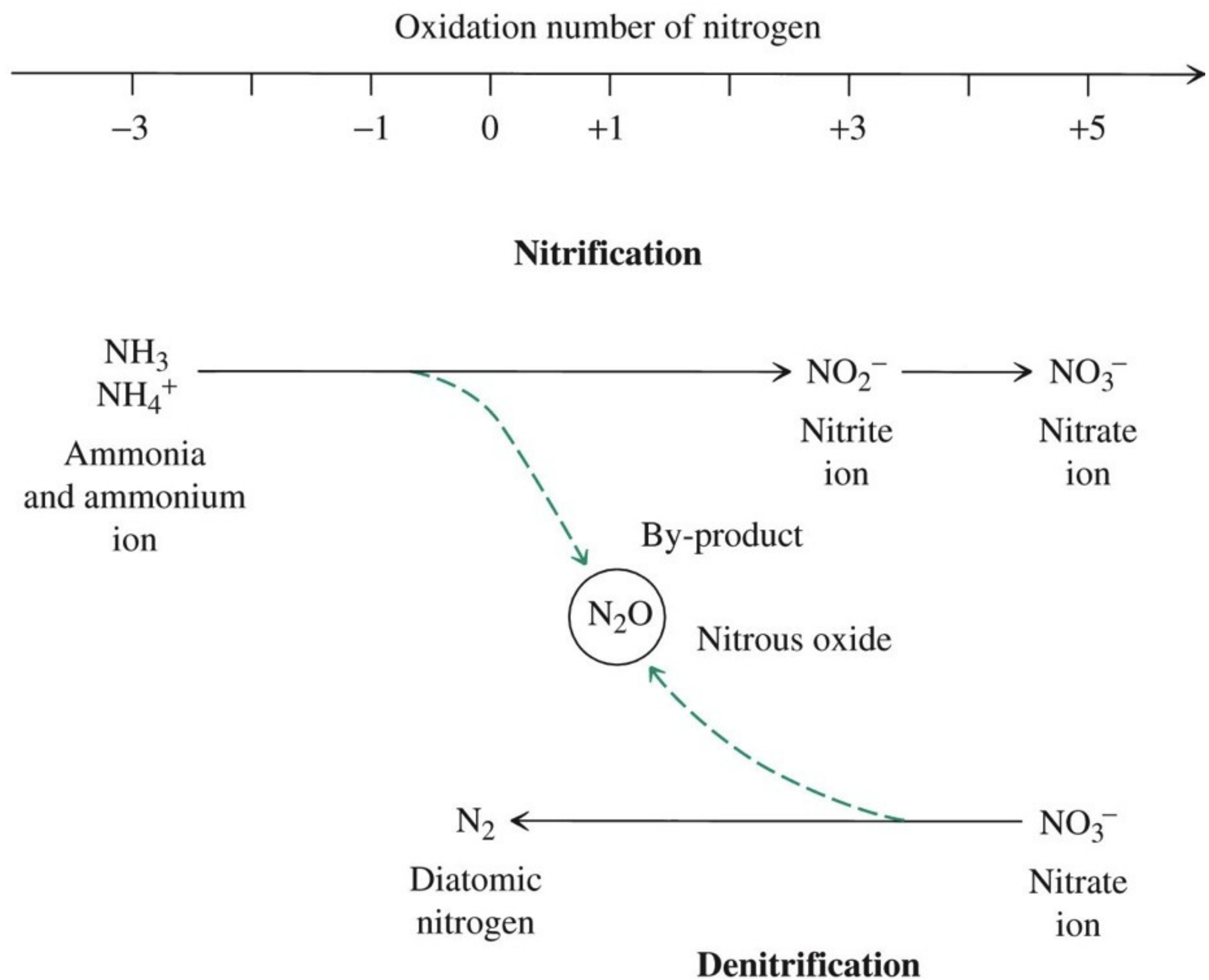
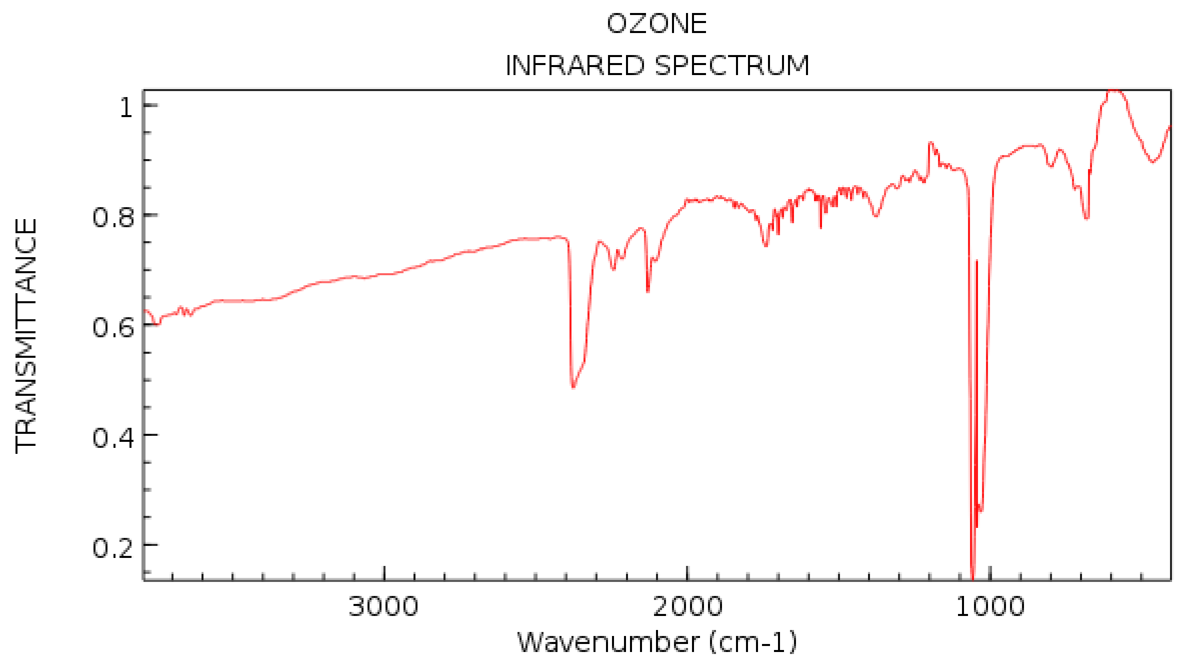


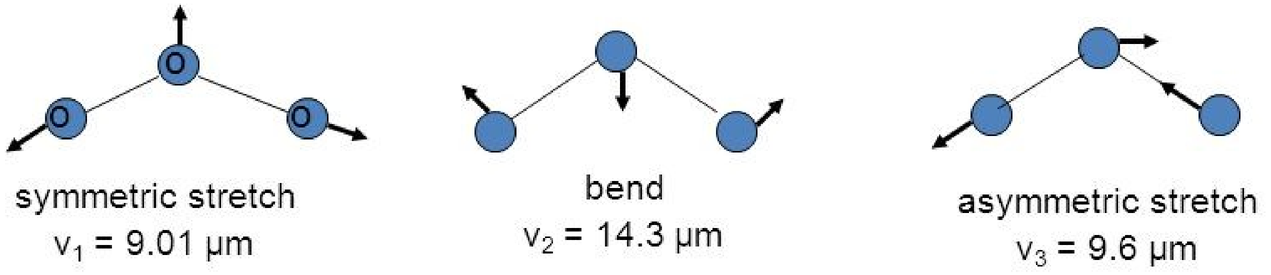
FIGURE 5-12 Nitrous oxide production as a by-product during the biological cycling of nitrogen.

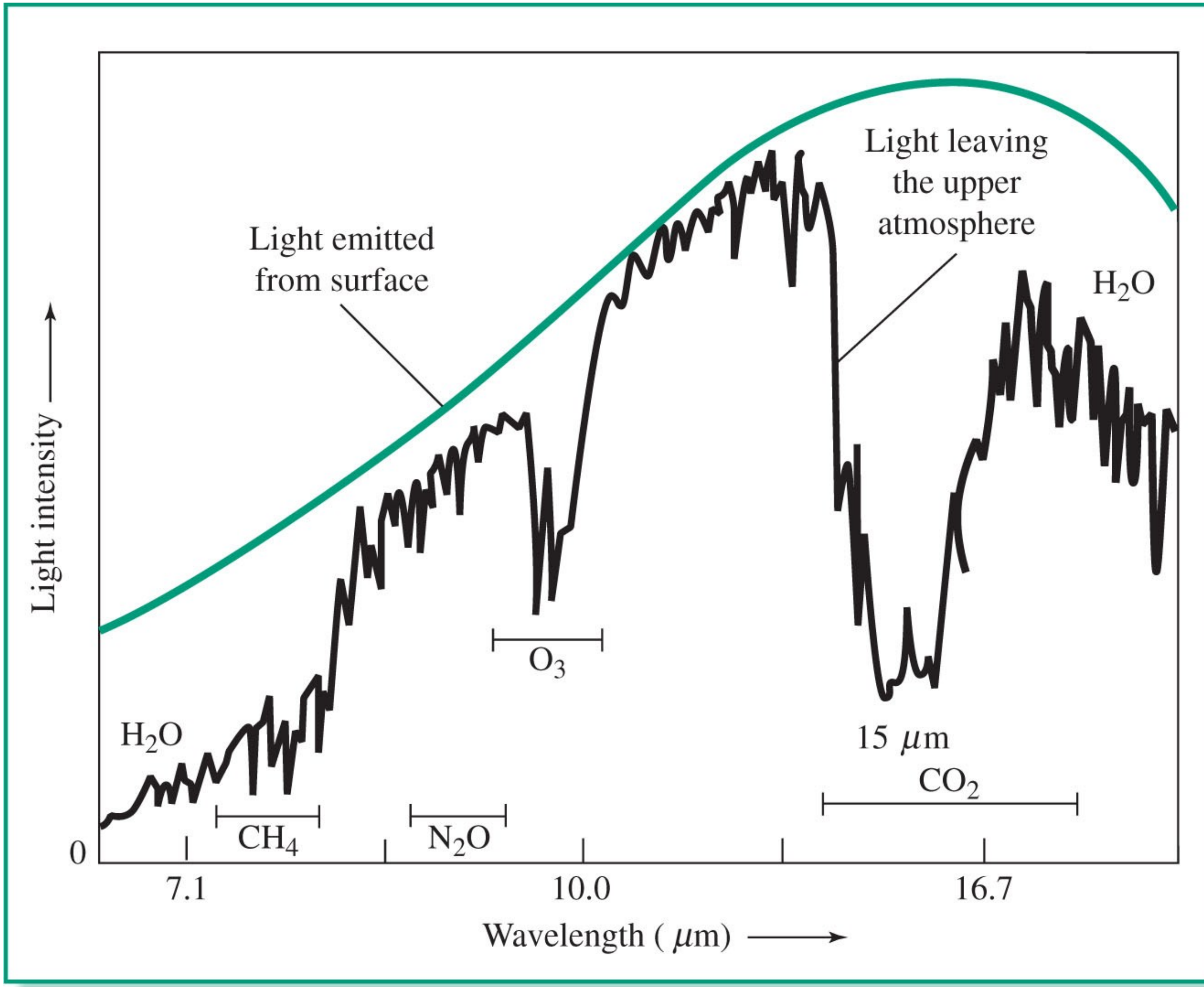
Ozone

Nonlinear molecule
Number of vibrational modes = 3N-6



NIST Chemistry WebBook (http://webbook.nist.gov/chemistry)





Light emitted from surface
Light leaving the upper atmosphere
H_2O
H_2O
CH_4
N_2O
O_3
15 μm
CO_2
0
7.1
10.0
16.7
Light intensity
Wavelength (μm)

Record Greenhouse Gas Concentrations in the Atmosphere

WMO Global Atmosphere Watch

Levels of the main long-lived greenhouse gases, carbon dioxide (CO_2), methane (CH_4)) and nitrous oxide (N_2O) have reached new highs.

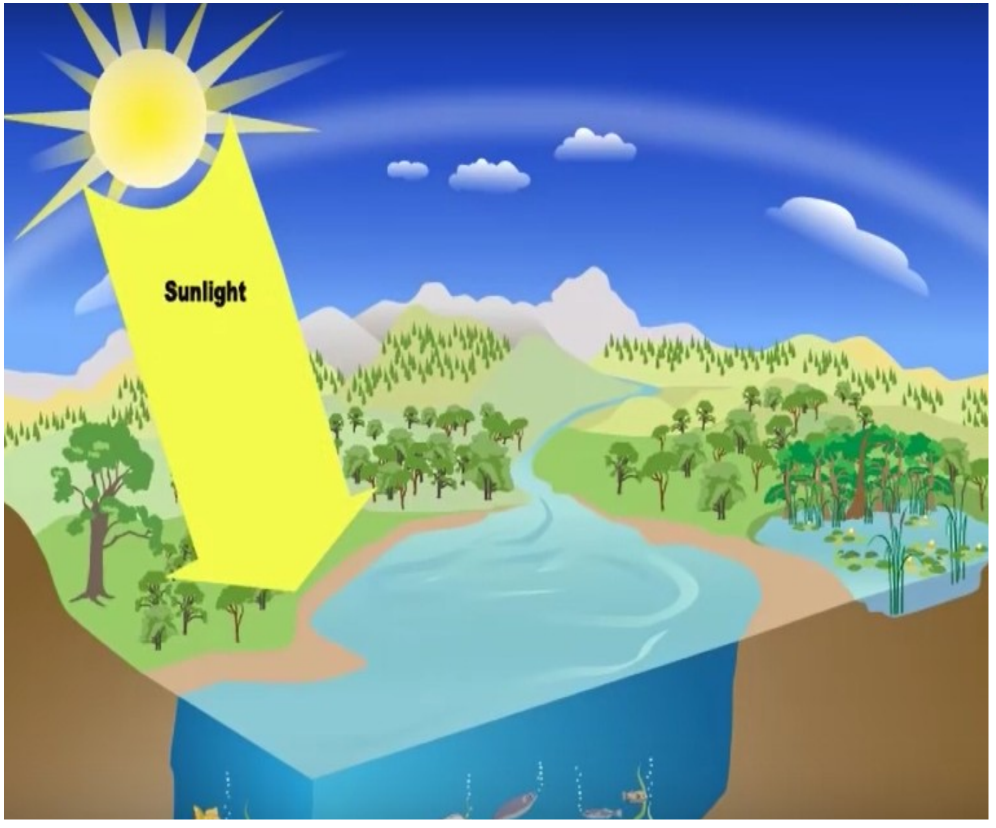
The last time Earth's atmosphere contained 400 parts per million CO_2 was about 3-5 million years ago, when global mean surface temperatures were 2-3°C warmer than today, ice sheets in Greenland and West Antarctica melted, parts of East Antarctica ice had retreated, all causing global see level rise of 10-20m compared with today.

In 2018, global CO_2 concentration was 407.8 parts per million (ppm), 2.2 ppm higher than 2017. Preliminary data from a subset of greenhouse gas monitoring sites for 2019 indicate that CO2 concentrations are on track to reach or even exceed 410 parts per million (ppm) by the end of 2019.

In 2017, globally averaged atmospheric concentrations of CO_2 were 405.6 ±0.1 ppm, CH_4) at 1859 ±2 parts per billion (ppb) and N_2O at 329.9 ±0.1 ppb. These values constitute, respectively, 146%, 257% and 122% of pre-industrial levels (pre-1750).

The growth rate of CO_2 averaged over three consecutive decades (1985–1995, 1995–2005 and 2005–2015) increased from 1.42 ppm/yr to 1.86 ppm/yr and to 2.06 ppm/yr

Aerosols



Collection of particulates, whether solid particles or liquid droplets, dispersed in air

Aerosol particles are emitted from Earth's surface both naturally (e.g., dust, sea-salt, biogenic emissions), and as a result of human activities.

Aerosols

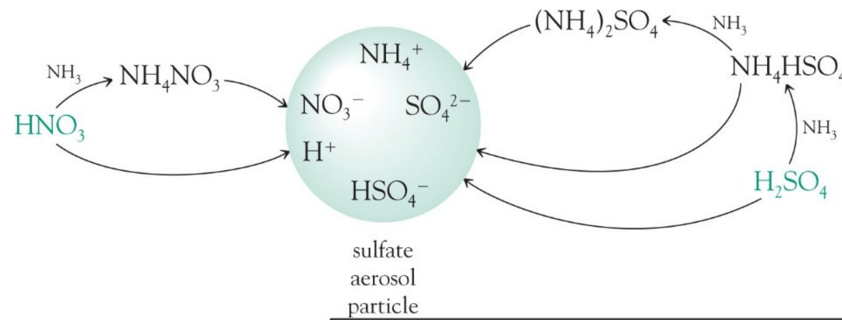
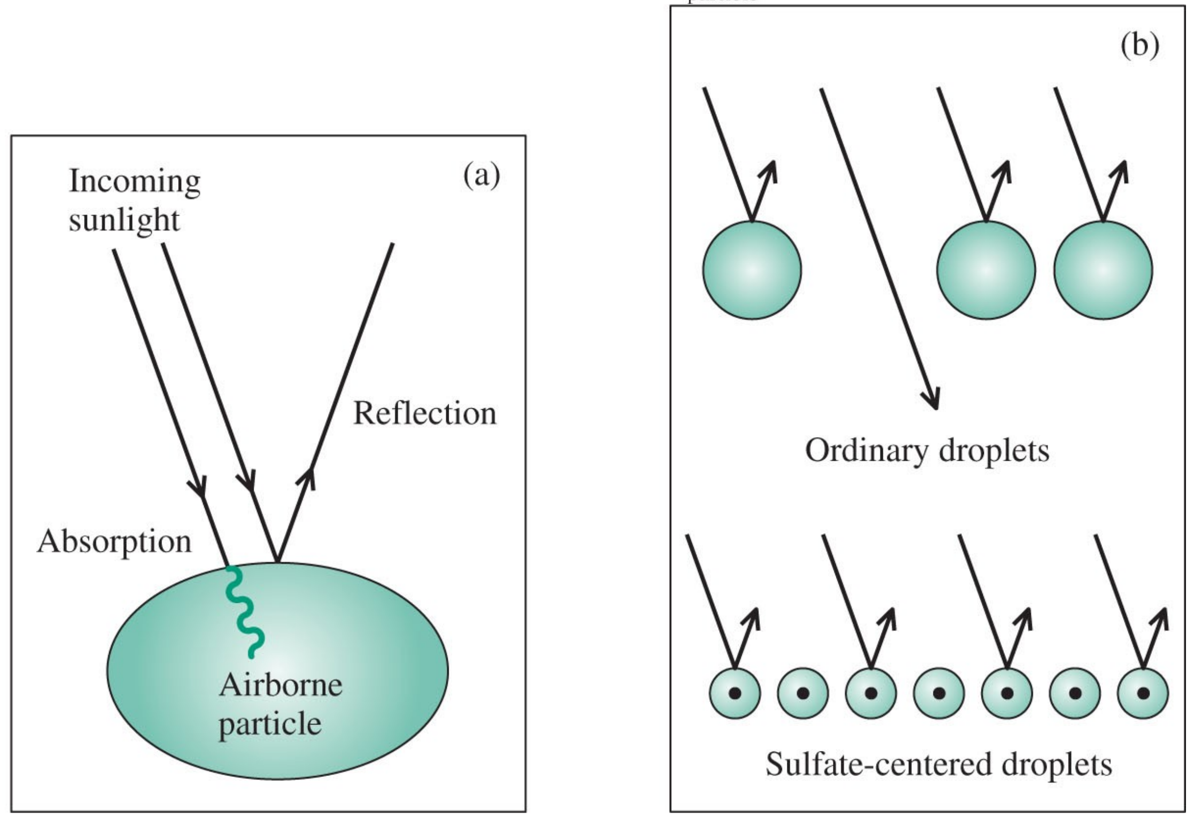


FIGURE 5-13 Interaction of sunlight with suspended atmospheric particles. (a) Modes of interaction. (b) Illustration of the indirect effect of producing increased reflection by small water droplets as compared to larger ones having the same total volume.



They have an effect on the energy balance of the atmosphere either by directly scattering and absorbing radiation, by serving as condensation nuclei during cloud formation, and by influencing precipitation.

Aerosols

The climactic eruption of Mount Pinatubo on June 15, 1991, was one of the largest eruptions of the twentieth century and injected a 20-million ton (metric scale) sulfur dioxide cloud into the stratosphere at an altitude of more than 20 miles.
The Pinatubo cloud was the largest sulfur dioxide cloud ever observed in the stratosphere since the beginning of such observations by satellites in 1978.
It caused cooled the Earth's surface for three years following the eruption, by as much as 1.3 degrees at the height of the impact.

Aerosols

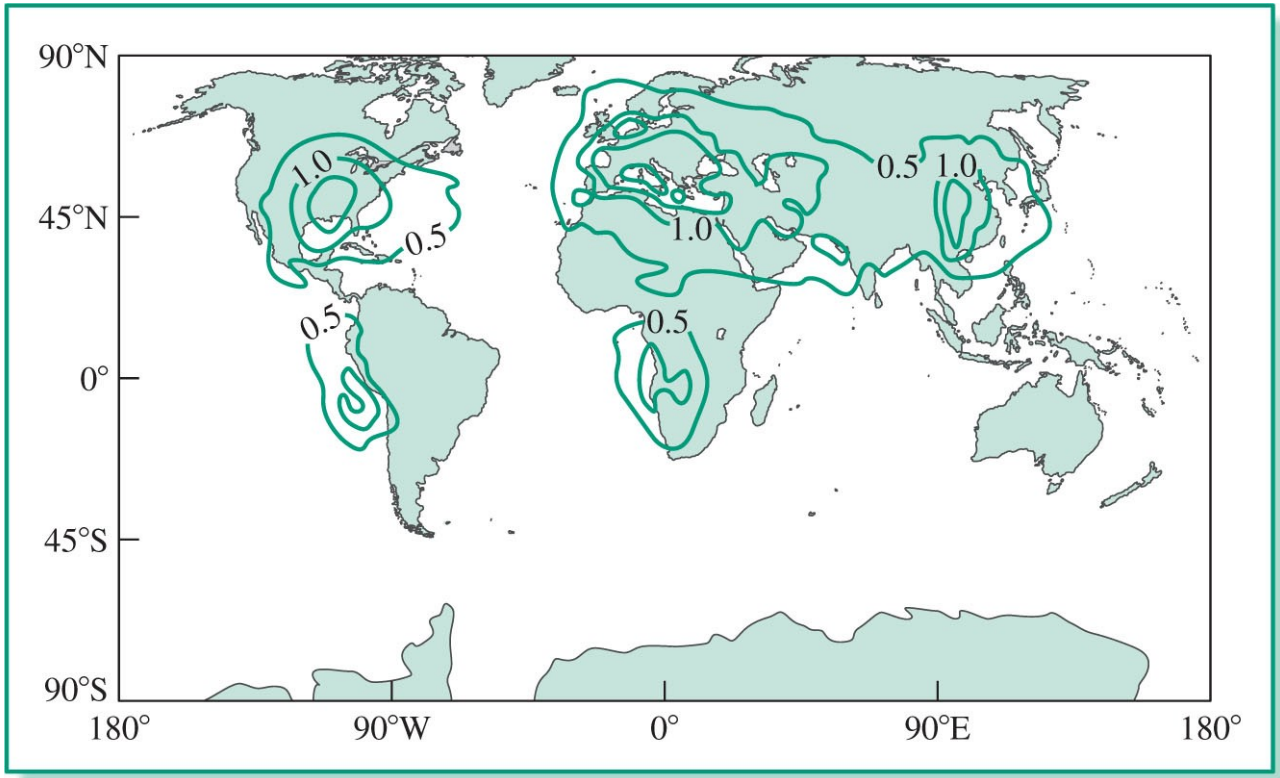


FIGURE 5-14 The amount of sunlight reflected into space by anthropogenic aerosols by the direct mechanism, in units of watts per square meter of the Earth's surface. [Source: J. T. Houghton et al., *Climate Change 1994— Radiative Forcing of Climate Change* (Intergovernmental Panel on Climate Change) (Cambridge: Cambridge University Press, 1995).]

Aerosols

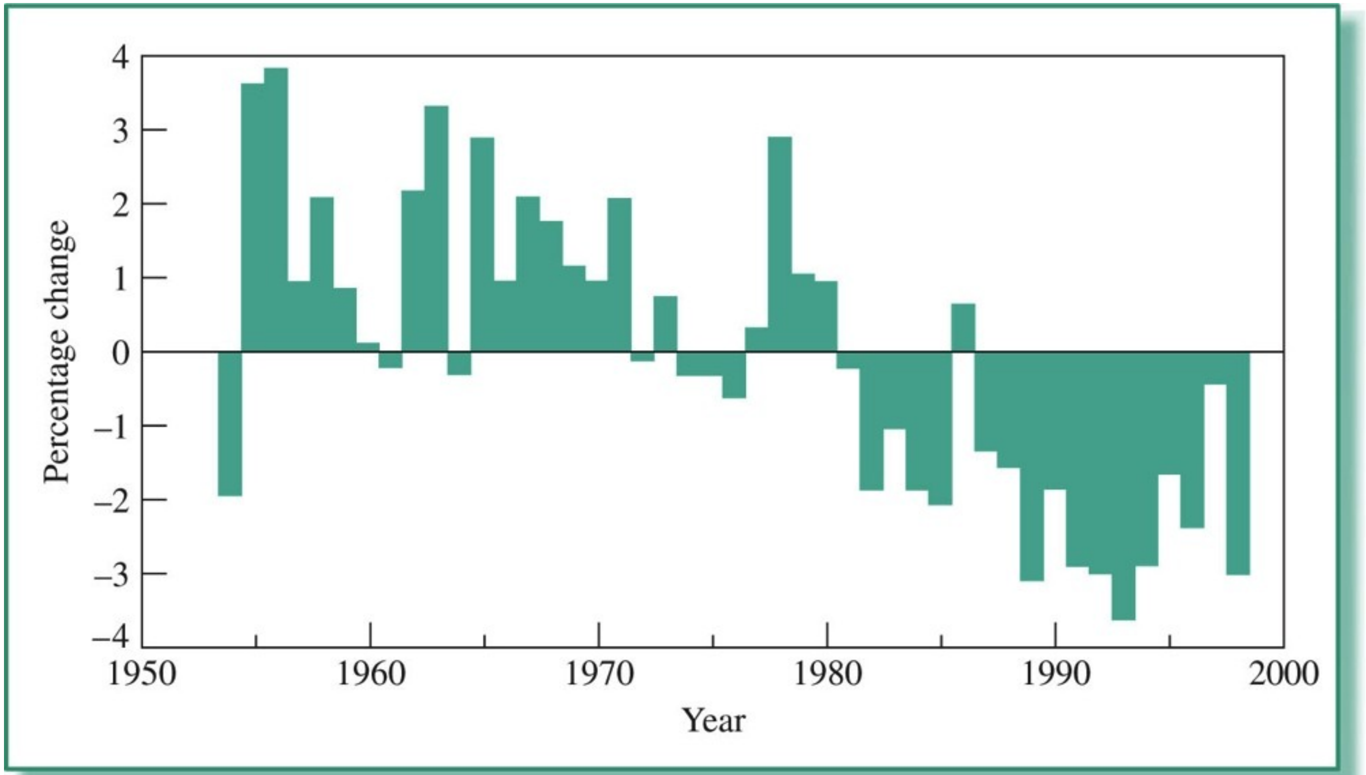


FIGURE 1 Change in the amount of sunlight reaching China relative to the average, over 50 years. [Source: F. Pearce, "Pollution Is Plunging Us into Darkness," *New Scientist* (14 December 2002):6.]

Global Warming

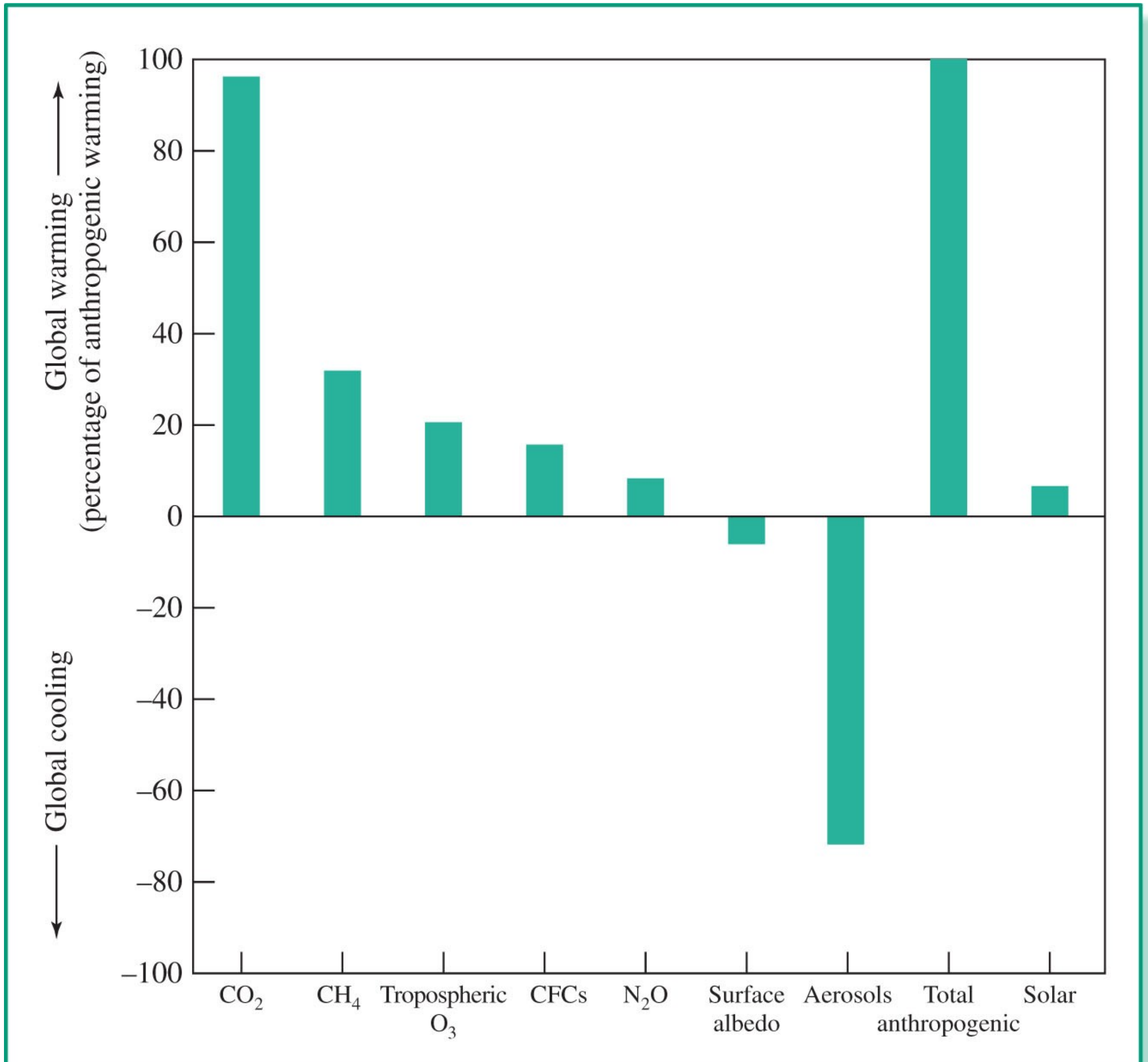
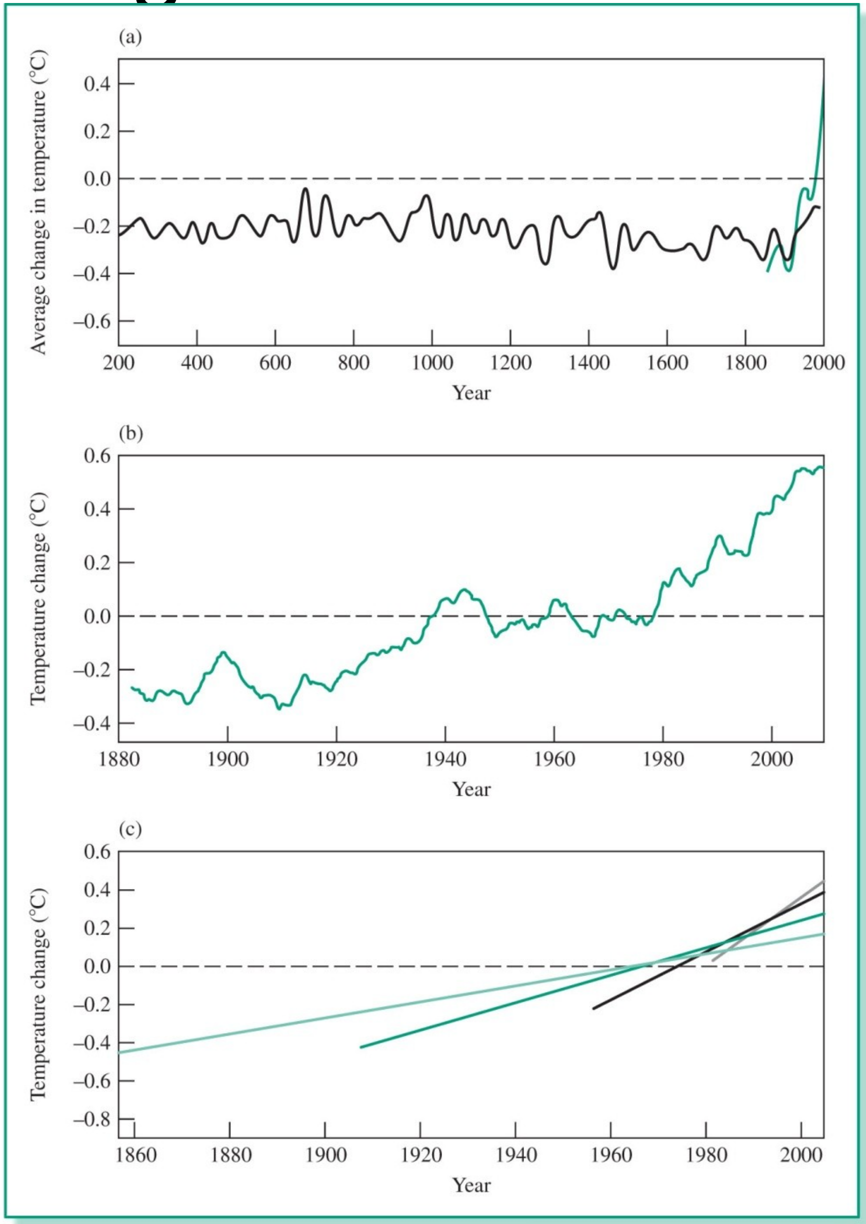


FIGURE 5-15 Contributions to global warming by 2005 and cooling produced by various factors, expressed as percentages of the total anthropogenic warming. [Data source: Intergovernmental Panel on Climate Change, *Climate Change 2007: The Physical Science Basis. Summary for Policymakers* (February, 2007).]

Global Warming

FIGURE 5-2 (a) Reconstruction of changes in yearly average global surface temperatures, relative to the 1961–1990 average. [Source: M. E. Mann and P. D. Jones, *Geophysical Research Letters* (2003):30, 1820.] (b) Global average land–ocean temperatures at the Earth' surface (5-year running average). [Source: adapted from Makiko Sato, *Updating the Climate Science*] (c) Linear temperature trends covering the 25, 50, 100, and 150 years to 2005. [Source: Adapted from S. Solomon et al., eds., *Climate Change 2007: The Physical Science Basis, Intergovernmental Panel on Climate Change*, Cambridge University Press.]



Global Warming

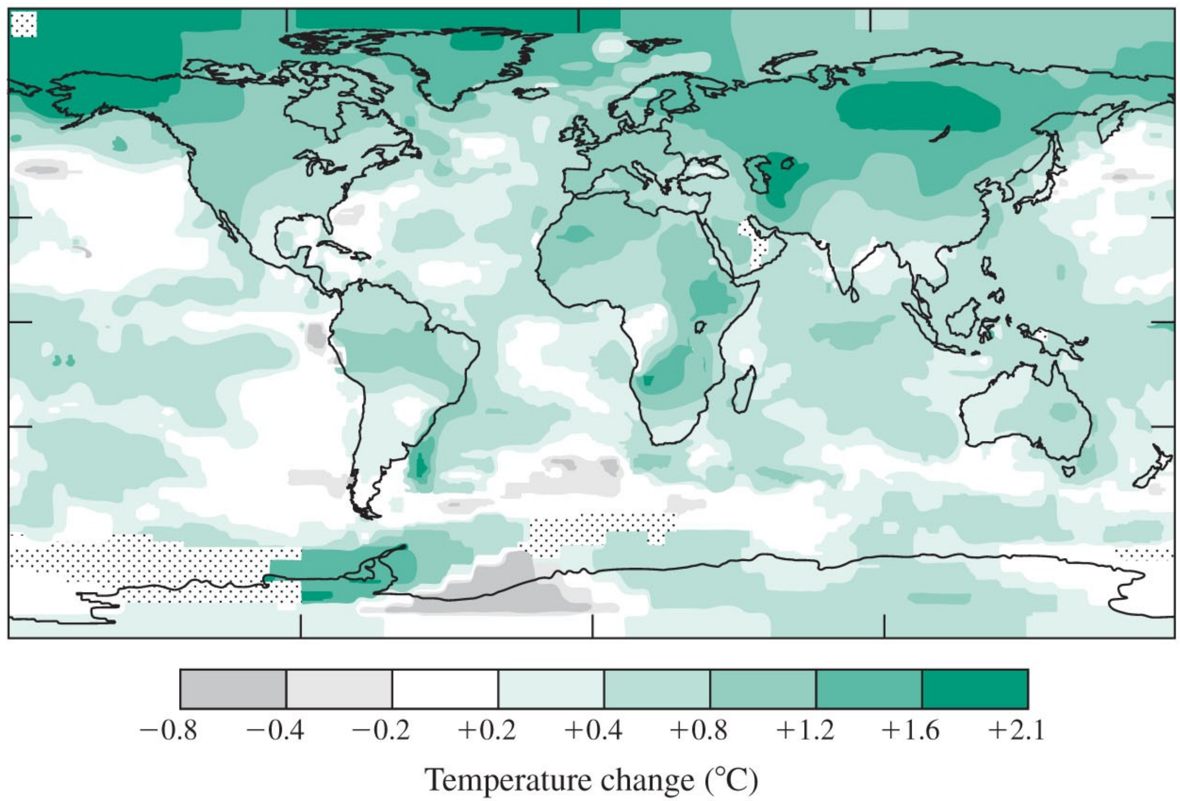
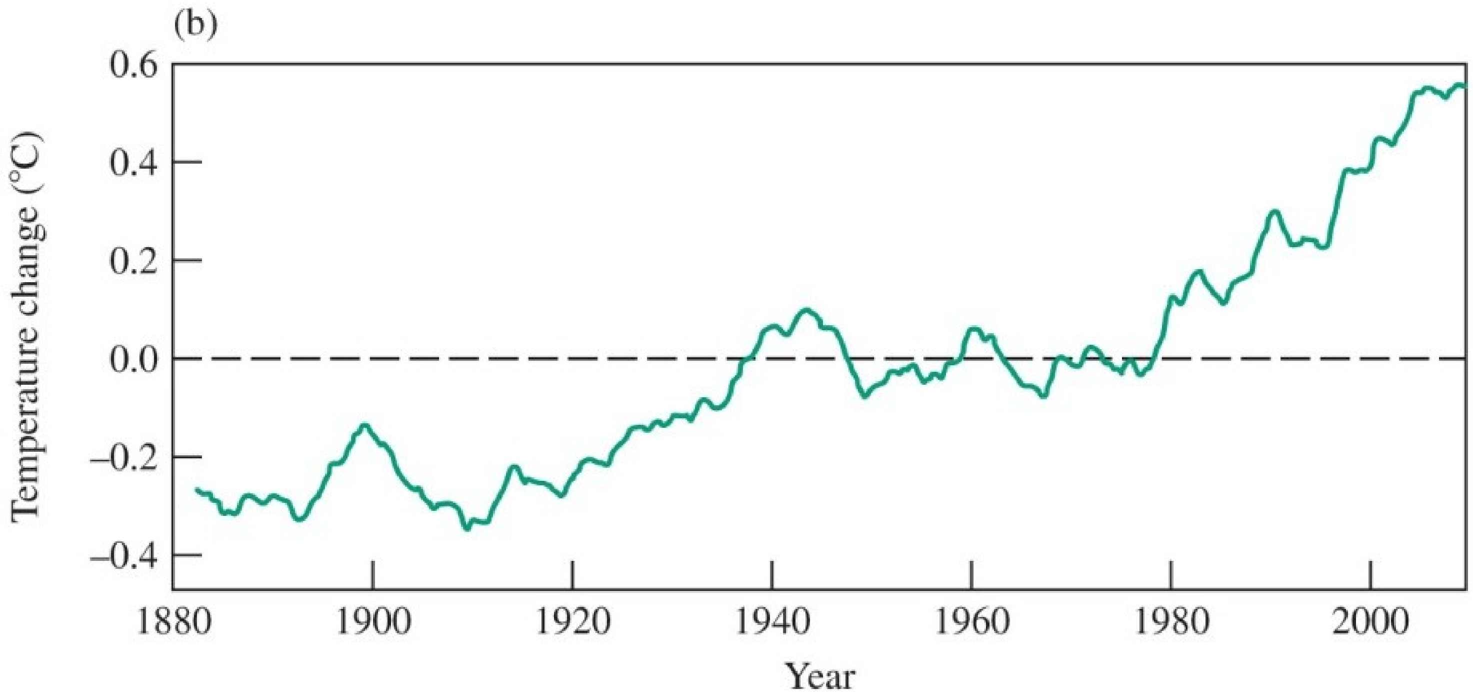


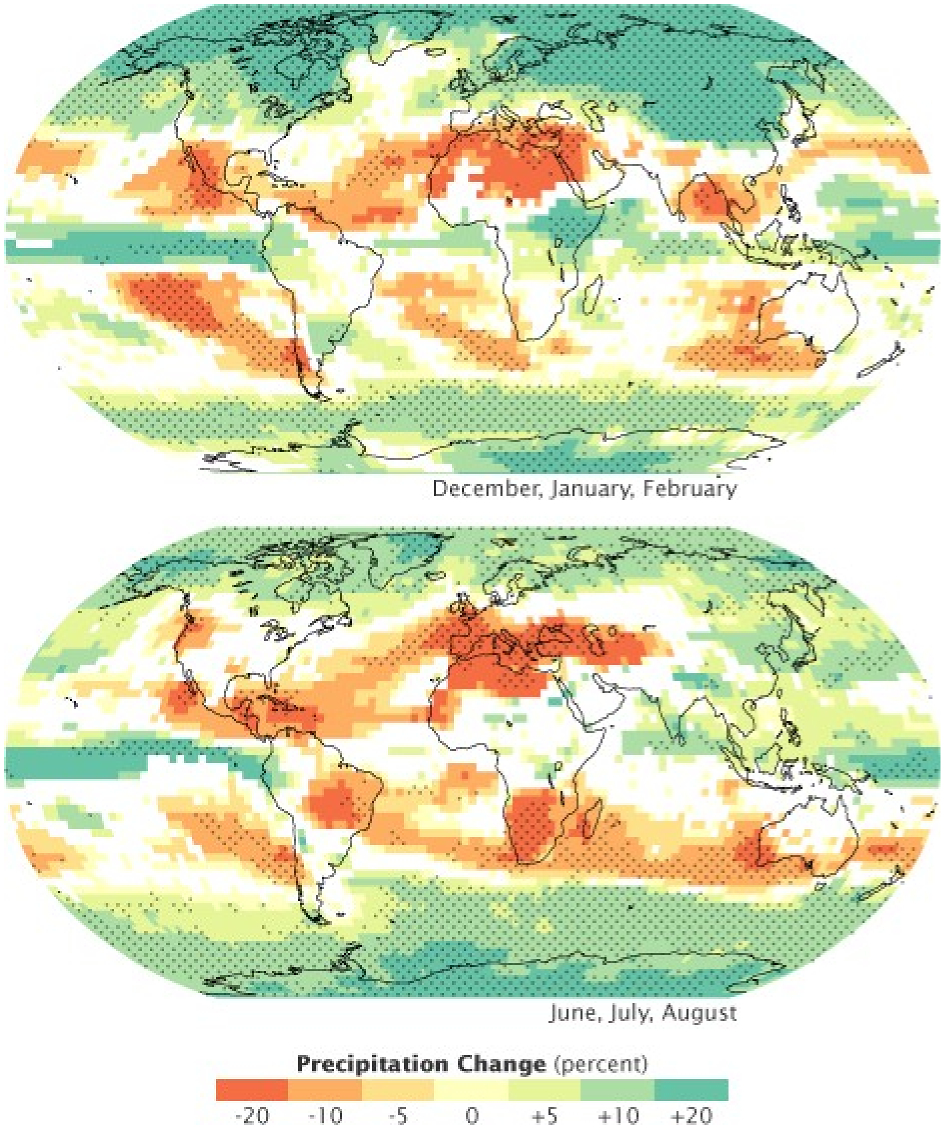
FIGURE 5-16 Changes, in degrees Celsius, in the mean surface temperature in 2001–2005 relative to the 1951–1980 mean. The dotted regions indicate areas for which data is insufficient. [Source: J. Hansen et al., "Global Temperature Change," *Proceedings of the National Academy of Science* 103 (2006): 14288.]

Global Warming



Climate Change

- Precipitation has increased in most area, but decreased in others

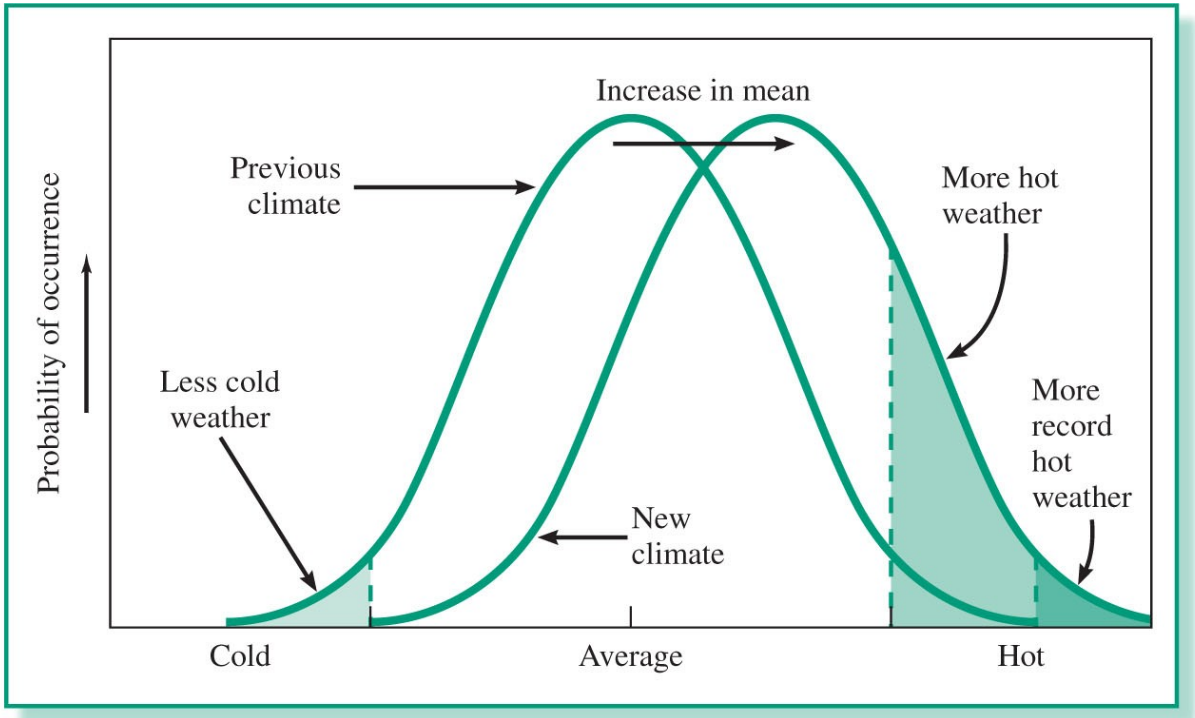


With some exceptions, the tropics will likely receive less rain (orange) as the planet warms, while the polar regions will receive more precipitation (green). White areas indicate that fewer than two-thirds of the climate models agreed on how precipitation will change. Stippled areas reveal where more than 90 percent of the models agreed.

Climate Change

- Extreme weather is becoming more common.

FIGURE 5-17 Schematic representation illustrating the effect on extreme hot and cold temperatures when the average temperature increases, based upon normal temperature distributions. [Source: Adapted from S. Solomon et al, editors, *Climate Change 2007: The Physical Science Basis,* Intergovernmental Panel on Climate Change, Cambridge University Press.]



Climate Change

- Winters have become shorter, by about 11 days
- Earth's ice cover is shrinking fast
- Warming water is killing much of the coral in ocean reefs and threatening sea life
- Mosquito-borne diseases have reached higher altitudes
- Rising seas are threatening to engulf Pacific Islands

The Global Climate in 2015-2019

- Warmest five-year period on record

The average global temperature for 2015–2019 is on track to be the warmest of any equivalent period on record. It is currently estimated to be 1.1°Celsius (± 0.1°C) above pre-industrial (1850–1900) times. Widespread and long-lasting heatwaves, record-breaking fires and other devastating events such as tropical cyclones, floods and drought have had major impacts on socio-economic development and the environment.

- Continued decrease of sea ice and ice mass

Arctic summer sea-ice extent has declined at a rate of approximately 12% per decade during 1979-2018. The four lowest values for winter sea-ice extent occurred between 2015 and 2019. Overall, the amount of ice lost annually from the Antarctic ice sheet increased at least six-fold between 1979 and 2017. Glacier mass loss for 2015-2019 is the highest for any five-year period on record.

- Sea-level rise is accelerating, sea water is becoming more acidic

The observed rate of global mean sea-level rise accelerated from 3.04 millimeters per year (mm/yr) during the period 1997–2006 to approximately 4mm/yr during the period 2007–2016. This is due to the increased rate of ocean warming and melting of the Greenland and West Antarctica ice sheets. There has been an overall increase of 26% in ocean acidity since the beginning of the industrial era.

Geoengineering Earth's Climate

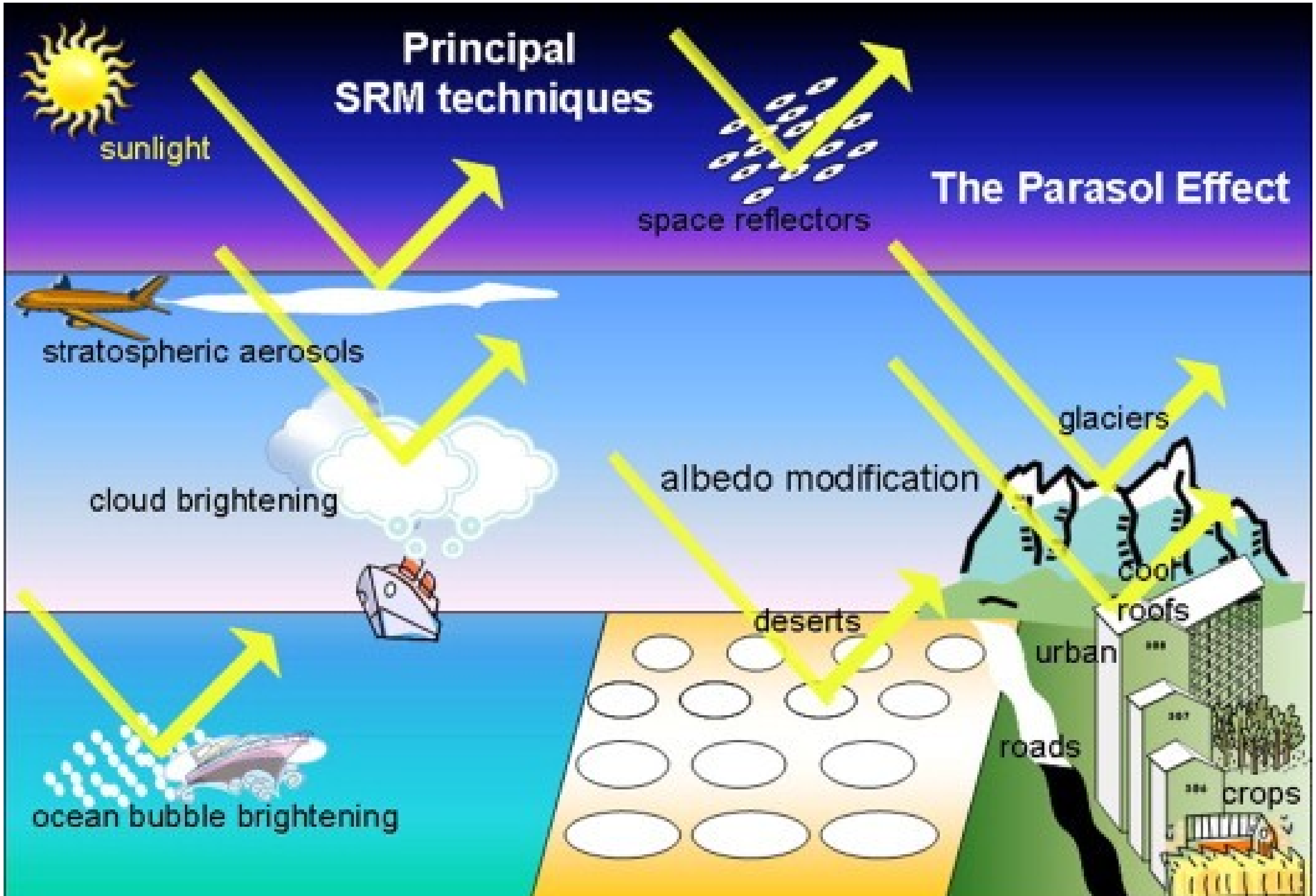
- **Solar Radiation Management**
  Reflecting a small fraction of the sunlight headed toward Earth back into space

- **Carbon Dioxide Removal**
  Removing carbon dioxide from ambient air, and storing it.

- **Earth Radiation Management**
  Increasing the heat transfer to outer

To date, no geoengineering method has been attempted on a significant scale.

Solar radiation management



Solar radiation management
Space projects

- giant mirrors (55,000 orbiting mirrors each of 100 km^2) made of wire mesh
- trillions of light and small mirrors (the size of a DVD), in order to deflect sunlight back to space
- deflector of 1400-km diameter at the first Lagrange Point, manufactured and launched from the Moon
- mine the moon to create a shielding cloud of dust

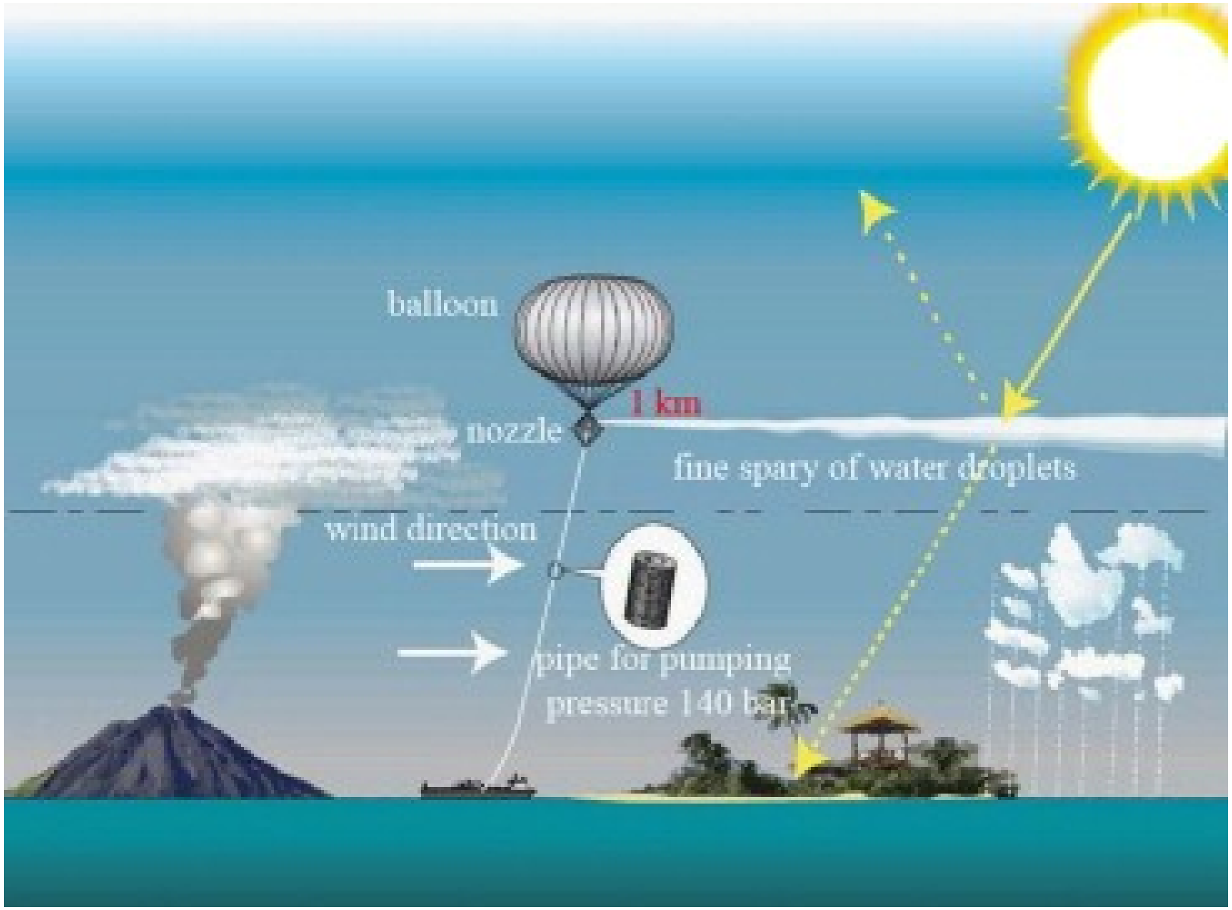
This option is widely considered unrealistic, as the expense is prohibitive, the potential of unintended consequences is huge and a rapid reversibility is not granted.

Solar radiation management
Stratospheric aerosols

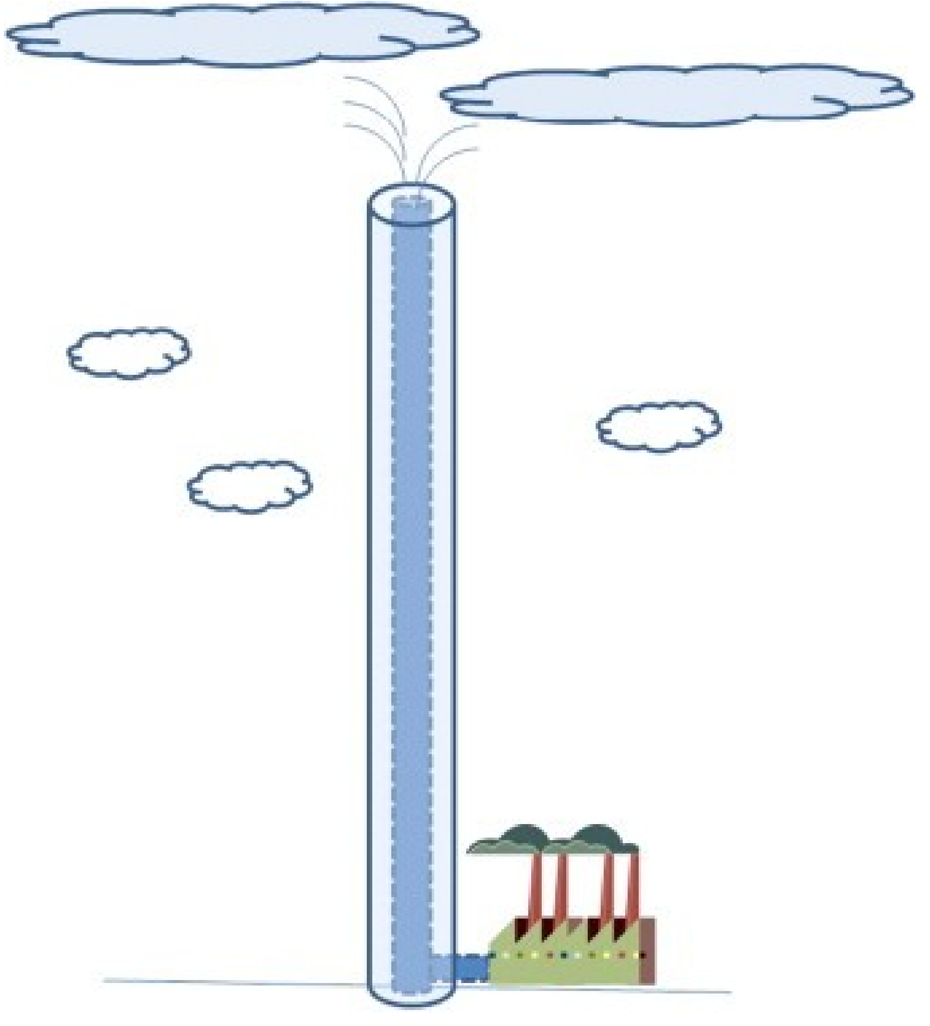
Artificially increase the concentration of the microscopic sulfate aerosols particles in the lower stratosphere to deflect an additional fraction of sunlight (2%) of incoming sunlight.

- inspired by studies of the Mount Pinatubo volcano eruption
- Few TG of sulfur per year would counter the global warming effect due to doubling the CO_2.
  - special aircrafts
  - artillery guns
  - balloons

- The SPICE (stratospheric particle injection for climate engineering) consisted in using a small hose-augmented balloon up just over one km high, pumping water into the air. The aim was to test the feasibility of later piping sulfates at 25 km high .



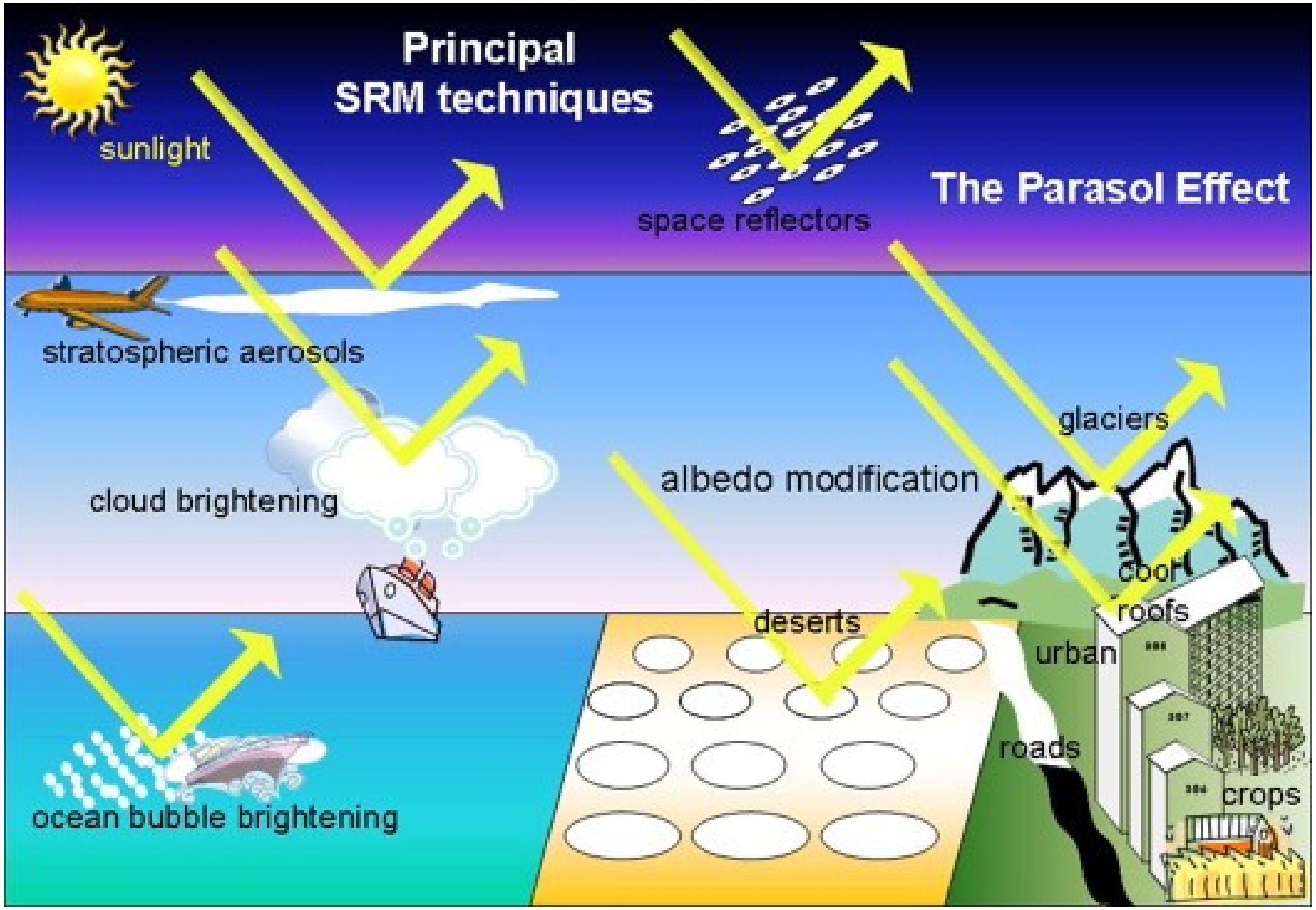
- Multi-kilometer height tall towers with a 15–50 km high altitude duct “conduit” for the aerosol injection in the stratosphere.



Solar radiation management
Stratospheric aerosols

- Continuous supply
- Full-scale implementation
- Less expensive than space projects
- Negative consequences:
  - reduction in regional rainfall
  - decrease in stratospheric ozone

Solar radiation management



Solar radiation management
Atmospheric projects

Cloud Brightening

Sea water can be pumped up and sprayed into the air to increase the number of droplets, and produce fine sea salt crystals increasing the reflectivity of low altitude clouds.

Many droplets and salt aerosols are expected to make whiter clouds and reflect more intensity of sunlight.

Solar radiation management
Ground-level projects

Increasing Earth's albedo

- painting roofs and paved roads white
- covering glaciers and deserts with reflective plastic sheeting
- putting white or pale-colored plastic floating panels over oceans or lakes
- planting genetically engineered paler crops

Solar radiation management
Ground-level projects

- In 2005 a small pilot project on the Gurschen glacier of the Swiss Alps was conducted to try to stop the ice melting of glaciers with a “ice protector” textile made of a lightweight dual-layer composite with polyester in the top side to reflect light, and polypropylene on the bottom to block heat and slow ice melting during the summer. It proved successful as the blanketed area had 80% less melt than surrounding ice.
- In the Peru Andean region, a local team that painted rocks in white won a $200,000 prize from the World Bank as part of its “*100 Ideas to Save the Planet*” competition.

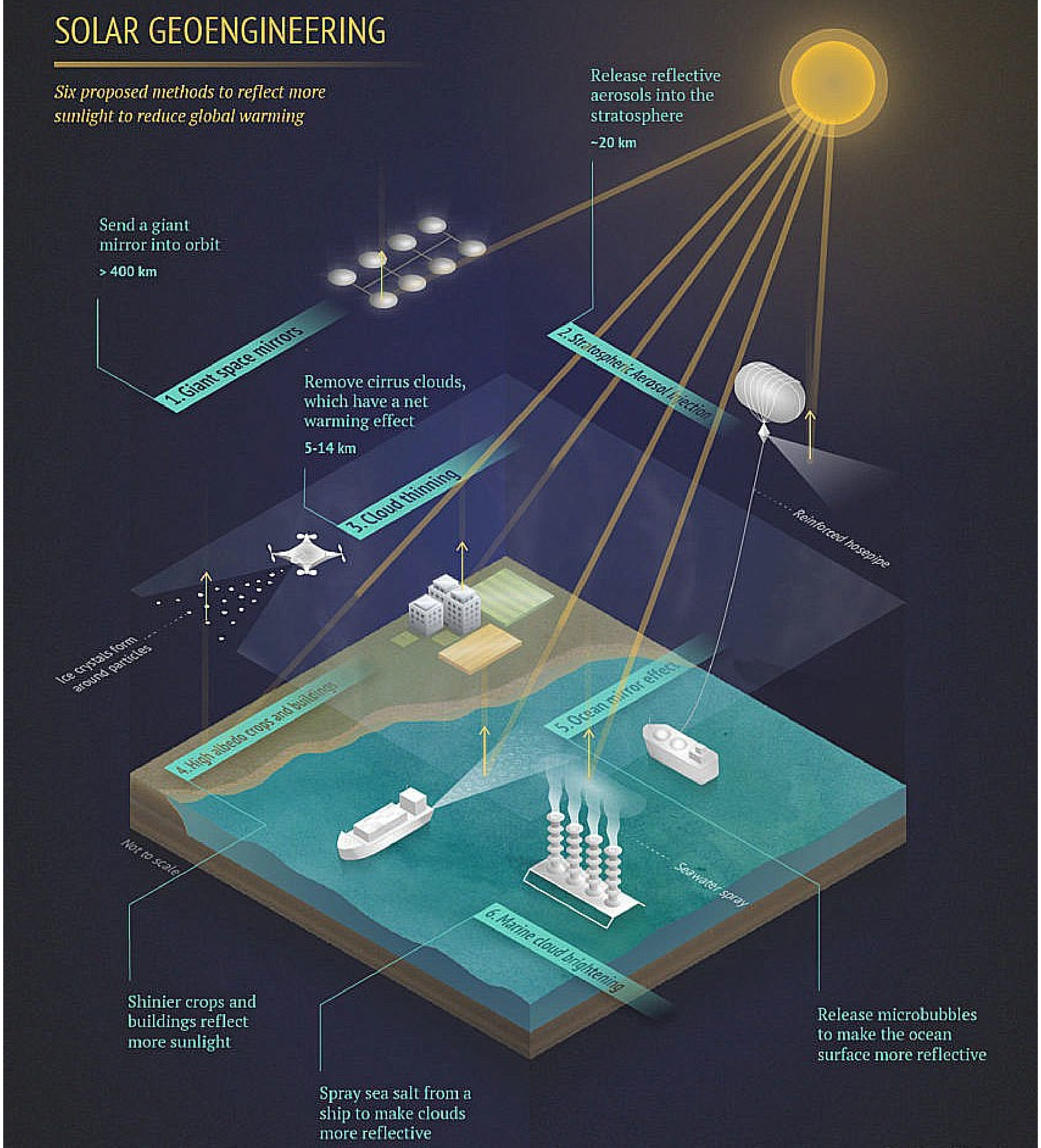
Solar radiation management

TABLE 5-1 Characteristics of SRM Schemes

Method	Effectiveness	Affordability	Timeliness	Safety
Space disks	High	Low to very low	Very low	Medium
Stratospheric aerosols	High	High	High	Low (rainfall problems)
Cloud whitening	Low to medium	Medium	Medium	Low (weather patterns)
Roof & road whitening	Very low	Very low	Medium to high	Very high
Desert reflectors	Low to medium	Very low	High	Very low

Note: Adapted from "Geoengineering the Climate," *The Royal Society*, Sept. 2009.

Solar


SOLAR GEOENGINEERING
Six proposed methods to reflect more sunlight to reduce global warming
Send a giant mirror into orbit
> 400 km
1. Giant space mirrors
Release reflective aerosols into the stratosphere
~20 km
2. Stratospheric Aerosol Injection
Reinforced hosepipe
Remove cirrus clouds, which have a net warming effect
5-14 km
3. Cloud thinning
Ice crystals form around particles
4. High-albedo crops and buildings
5. Ocean mirror effect
6. Marine cloud brightening
Not to scale
Seawater spray
Shinier crops and buildings reflect more sunlight
Spray sea salt from a ship to make clouds more reflective
Release microbubbles to make the ocean surface more reflective

Solar radiation management

https://www.youtube.com/watch?v=WR6uSXW-8p4

Geoengineering Earth’s Climate

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Geoengineering Earth's Climate

Carbon dioxide (CO_2) capture and sequestration is a three-step process that includes:

- Capture of CO_2
- Transport of the captured and compressed CO_2
- Sequestration

Geoengineering Earth's Climate

Capture of CO_2

- From coal, gas-power plants, large industrial plants
  - post-combustion
  - pre-combustion
- From air
  - direct air capture

https://www.youtube.com/watch?v=XHX9pmQ6m_s

Geoengineering Earth's Climate

Carbon dioxide (CO_2) capture and sequestration (CCS) is a three-step process that includes:

- Capture of CO_2
- **Transport of the captured and compressed CO_2**
- Sequestration

Carbon Dioxide

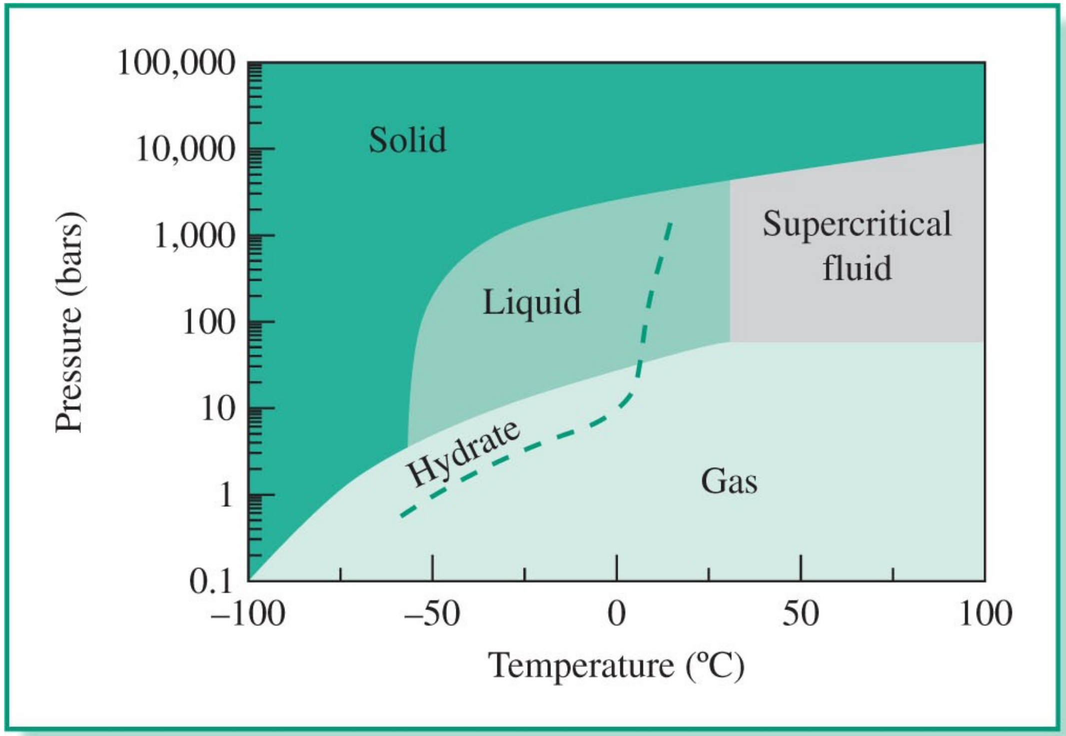


FIGURE 6-9 Phase diagram for carbon dioxide. Note that the pressure scale is logarithmic, and that 1 atm is approximately equal to 1 bar. [Source: Adapted from NOAA Pacific Marine Environmental Laboratory.]

Sequestration

- Ocean

  - acidic, neutral, fertilization

- Terrestrial environments

  - vegetation, soils, sediments

- Geologic formations

  - depleted oil and gas fields, deep coal seems,

saline formation, porous rock

Sequestration

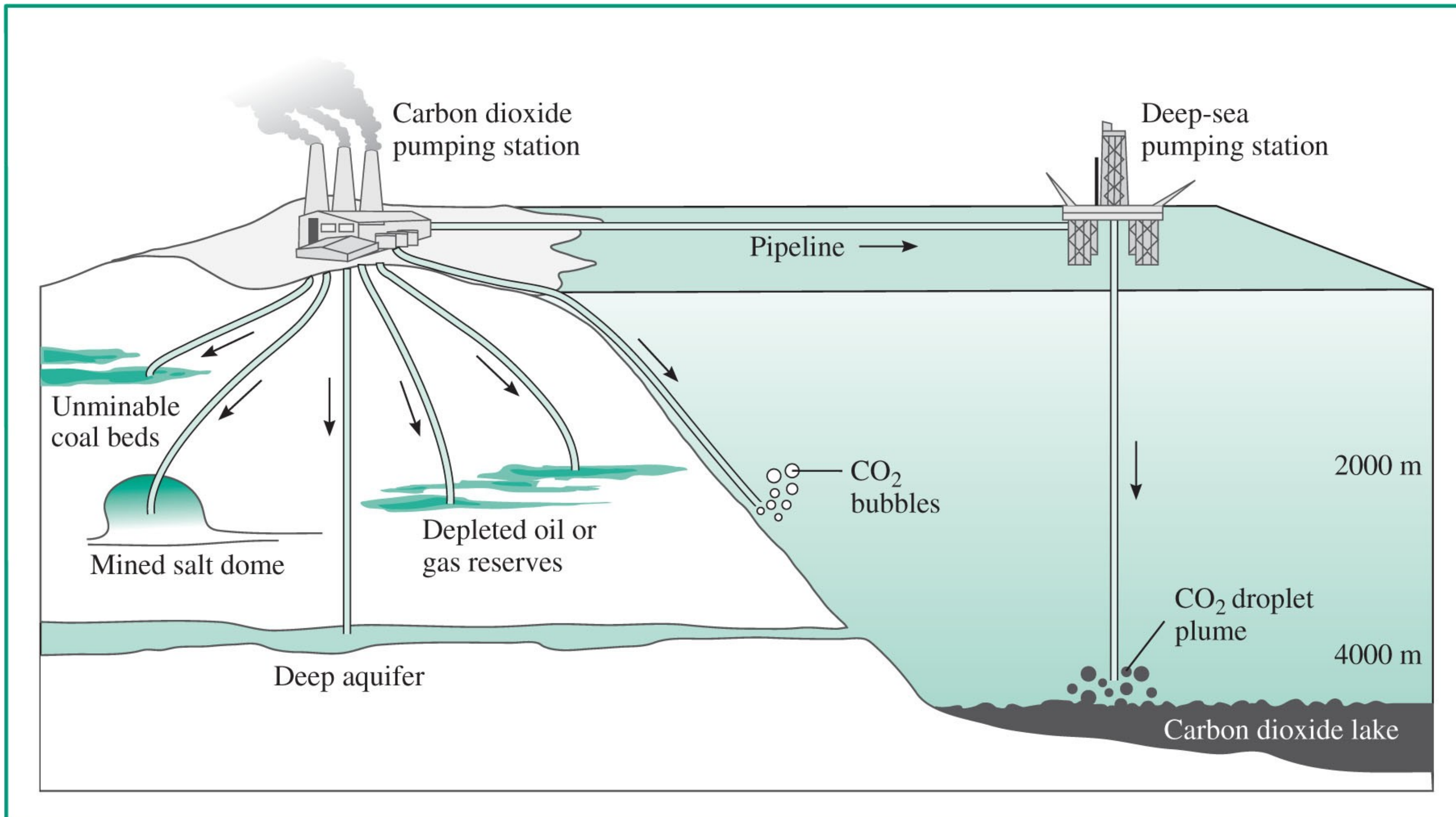
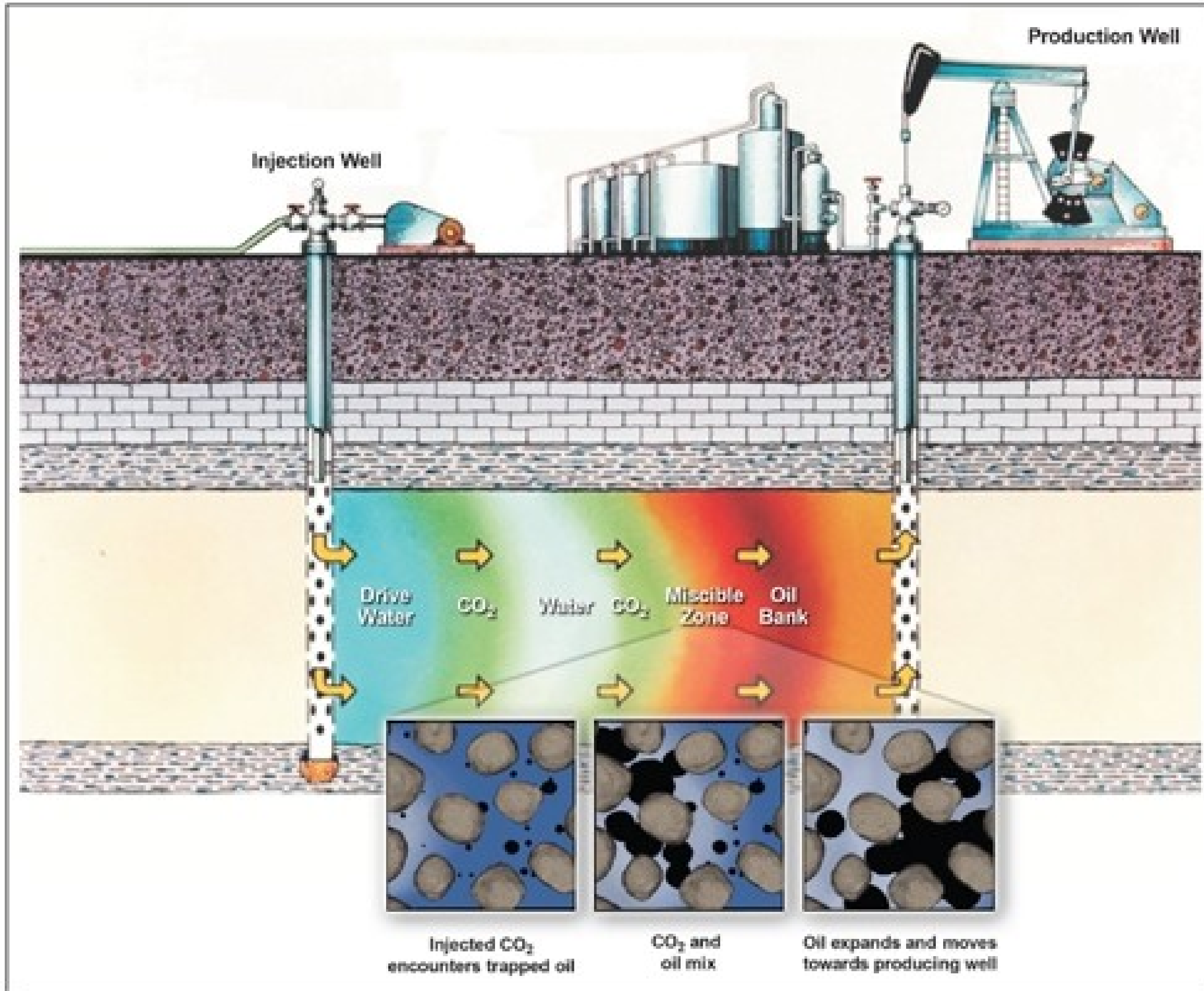


FIGURE 6-10 Potential sequestration sites for carbon dioxide. [Source: Redrawn from *Scientific American* (Feb. 2000): 72–79.]

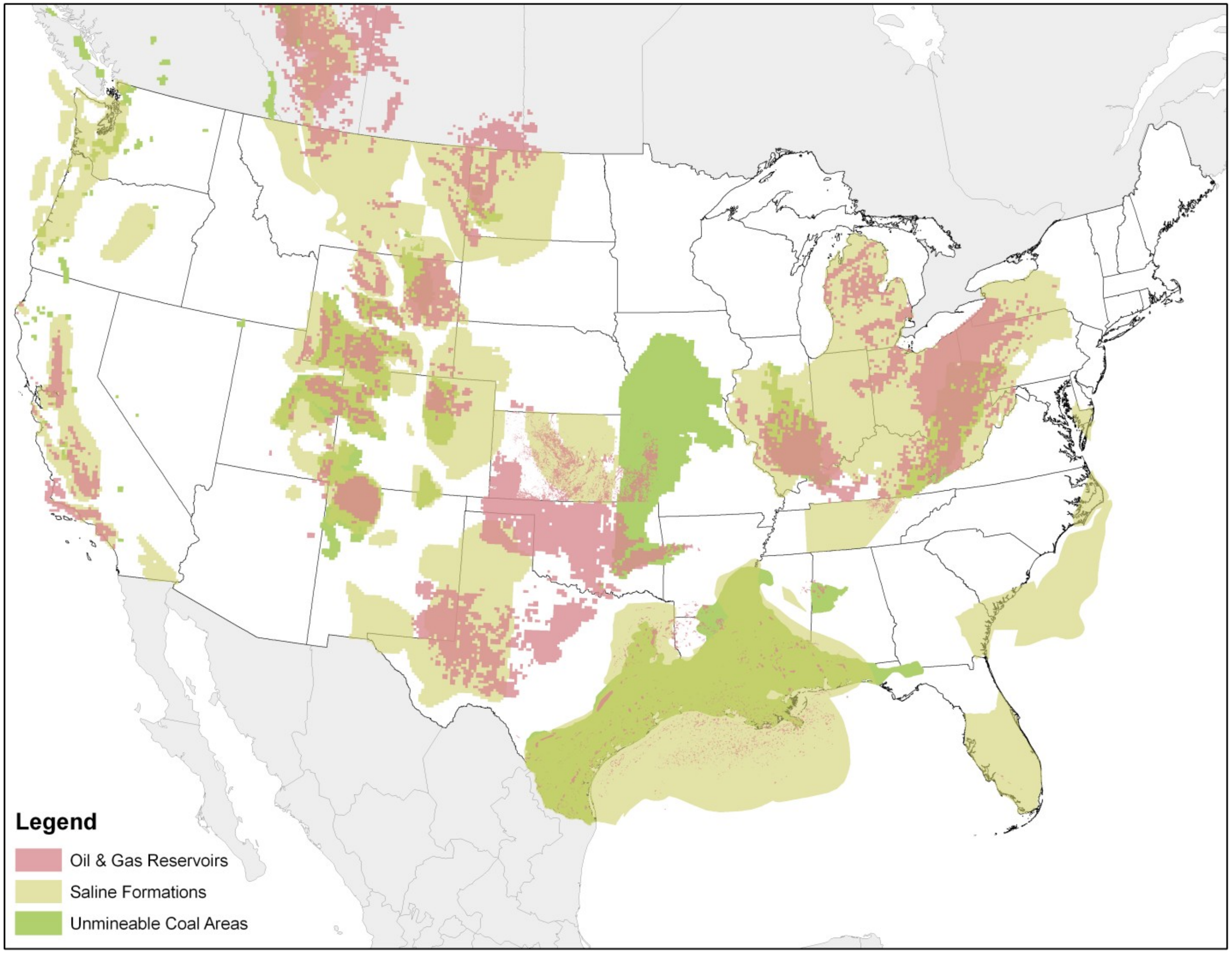
Sequestration

Geological



Sequestration

Geological



CO_2 emissions in the future

- Emission per unit of energy

  coal > oil > gas >> renewable and nuclear energy

Carbon intensity

- Economy
- Energy

Carbon footprint

CO_2 emissions in the future

- Emission per unit of energy

  coal > oil > gas >> renewable and nuclear energy

Carbon intensity
- Economy
- Energy

Carbon footprint

Per Capita

CO_2 emissions in the future

Intergovernmental Panel on Climate Change

https://www.ipcc.ch/2019/

- Predictions (2100)

  CO_2 500-900 ppm

  Temperature 1.4 to 4°C

  Snow and sea-iced areas, Permafrost

  Sealevel 30-60 cm or 60-110 cm

  Ocean Ecosystem: warming and acidification