Earth System Processes (ES1201)

Instructors: Manoj K. Jaiswal & Gaurav Shukla

(Spring 2025)

Syllabus

Earth as a system- an introduction

I. Lithospheric processes (Manoj K. Jaiswal)

a) Isotopic reservoir: Introduction to evolution of isotopic reservoirs particularly relevant to core, mantle and crust formation.

b) Exogenous processes and products: Agents and processes responsible for shaping landscapes Tectonics and landform evolution Tectonics and climate

Syllabus

II. Atmospheric and oceanic processes in relation to climate (Gaurav Shukla)

a) Climate system concepts: State, coupling, feedback, equilibrium; formation of the atmosphere; composition of the early atmosphere; formation of oceans.

b) Role of the atmosphere and oceans in energy redistribution: Global energy distribution; general circulation of the atmosphere; surface and deep-ocean circulation; energy redistribution over short and long timescales; global profiles of temperature and precipitation.

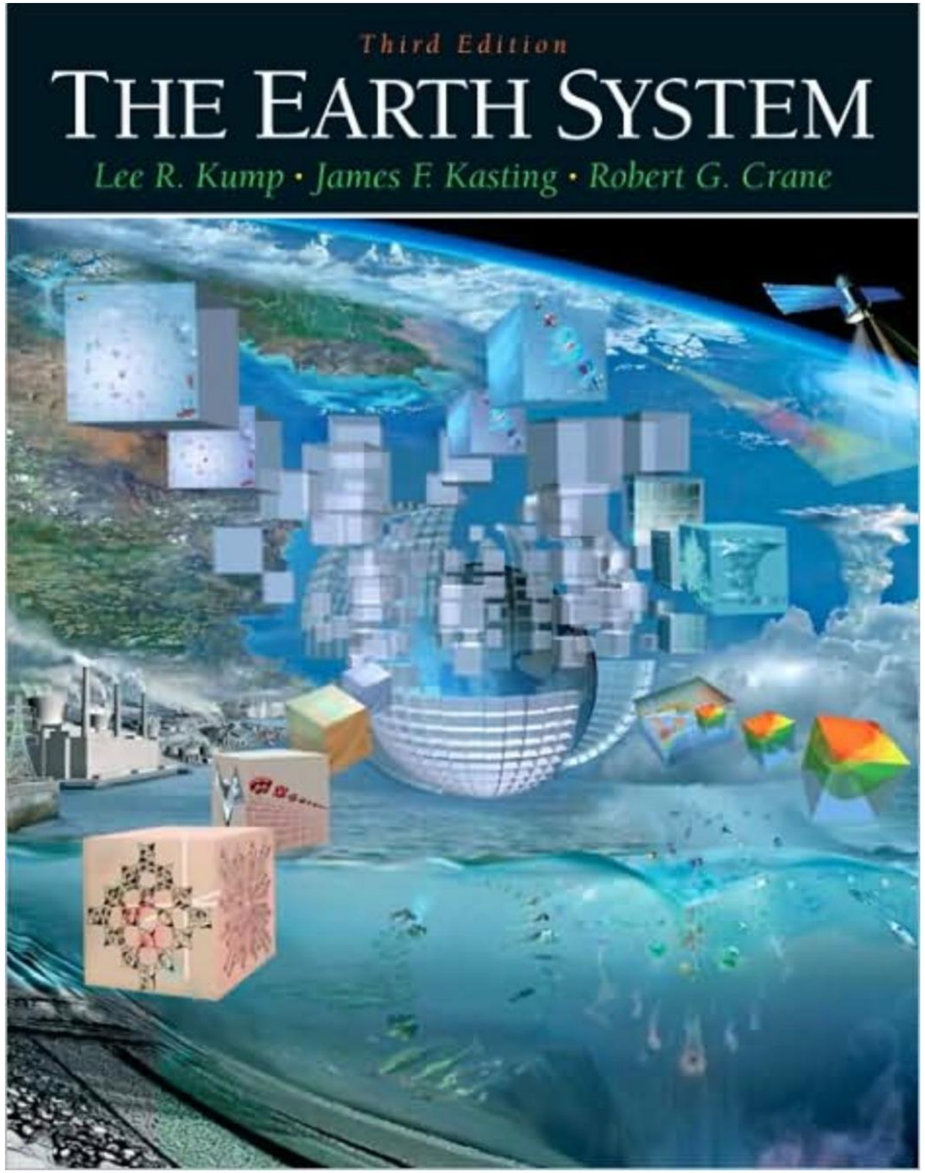
c) Global energy balance and climate change: Fundamentals of planetary energy balance and the greenhouse effect; long-term climate regulation glacial-interglacial periods and Milankovitch cycles; long-term CO2 records; examples of climate regulation by natural factors the faint young sun paradox and the snowball earth; a critical review of the Gaia hypothesis and the Daisyworld climate system.

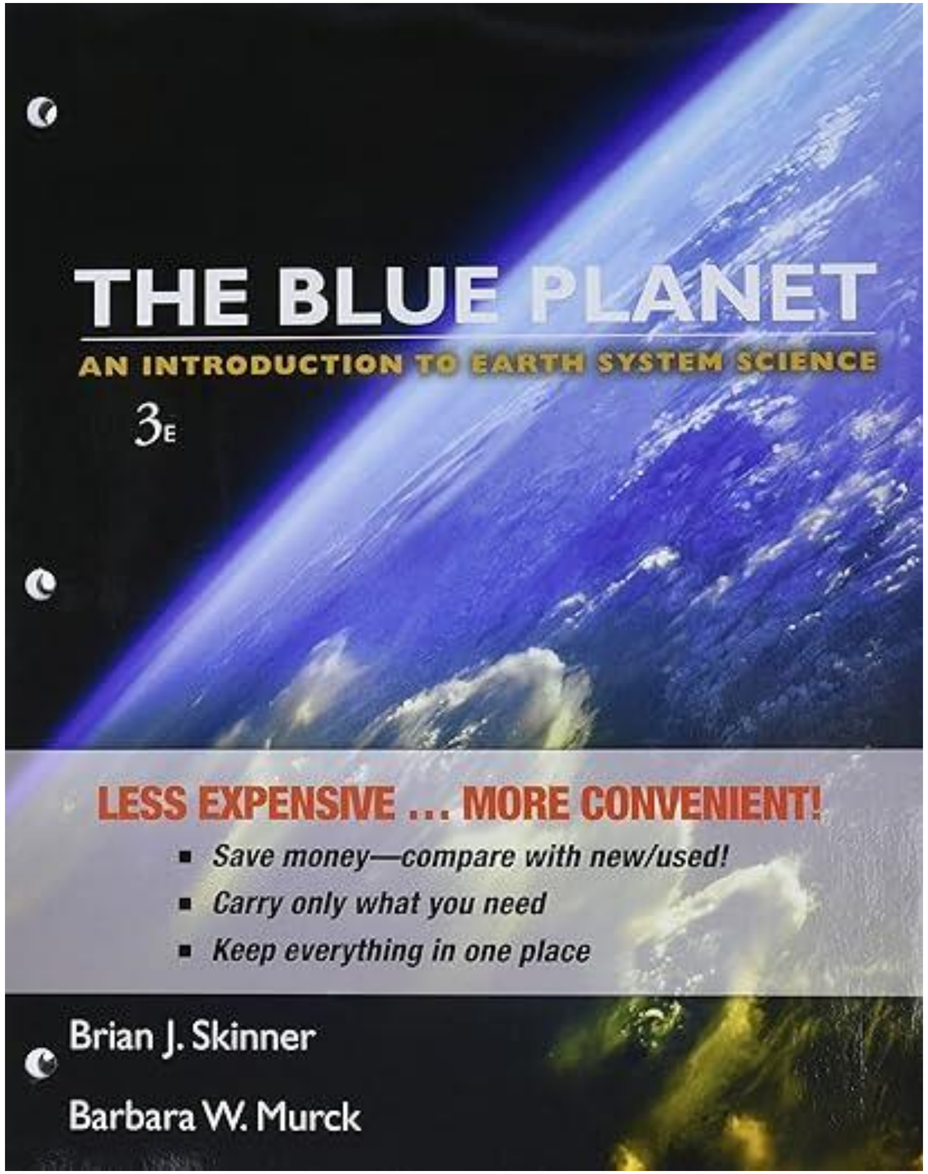
Earth System Processes (ES1201)

Atmospheric and Oceanic Processes in Relation to Climate

(Spring 2024 by Gaurav Shukla)

Books: **1) *The Earth System* by L.R. Kump, J.F. Kasting and R.G. Crane**
2) The Blue Planet: An Introduction to Earth System Science by Skinner and Murck

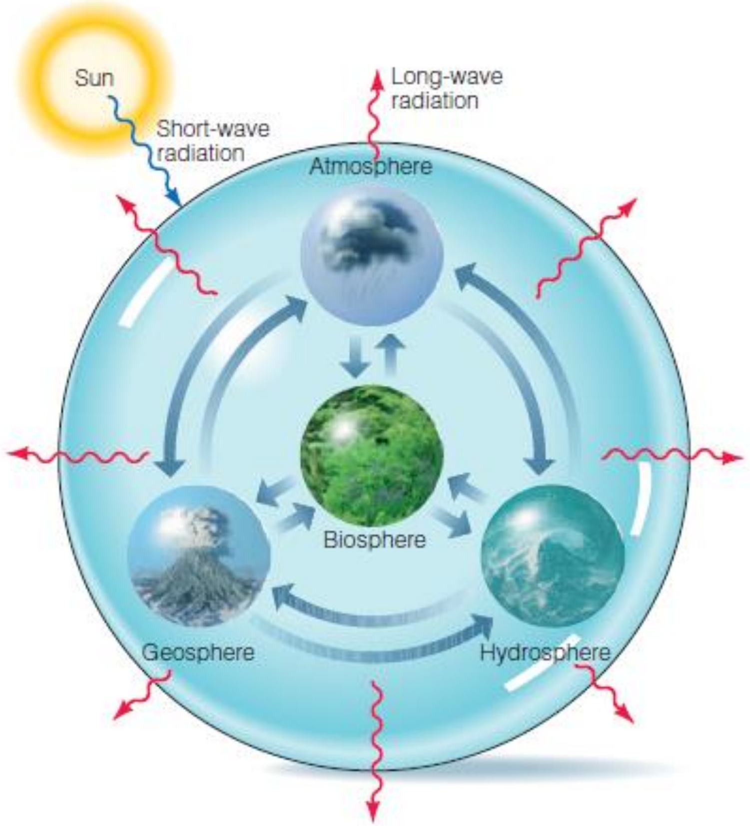

Third Edition
THE EARTH SYSTEM
Lee R. Kump • James F. Kasting • Robert G. Crane


THE BLUE PLANET
AN INTRODUCTION TO EARTH SYSTEM SCIENCE
3E
LESS EXPENSIVE … MORE CONVENIENT!
Save money—compare with new/used!
Carry only what you need
Keep everything in one place
Brian J. Skinner
Barbara W. Murck

Earth System Concepts

A System is a group of components that interact. The *Earth system* is composed of primary four parts:

FIGURE 1.7 **Earth as a closed system**
Earth essentially operates as a closed system. Energy reaches Earth from an external source and eventually returns to space as long-wavelength radiation, but the matter within the system is basically fixed. The subsystems within Earth are open systems, freely exchanging matter and energy.



1) **Atmosphere: A thin envelope of gases that surrounds the earth.**
2) **Hydrosphere: Reservoirs of water, ice (Cryosphere).**
3) **Biosphere: All living organisms.**
4) **Geosphere/Lithosphere/Solid Earth: All rocks.**

- **Our goal is to understand how the different components of the Earth system interact in response to various internal and external *influences* or *forcings*.**

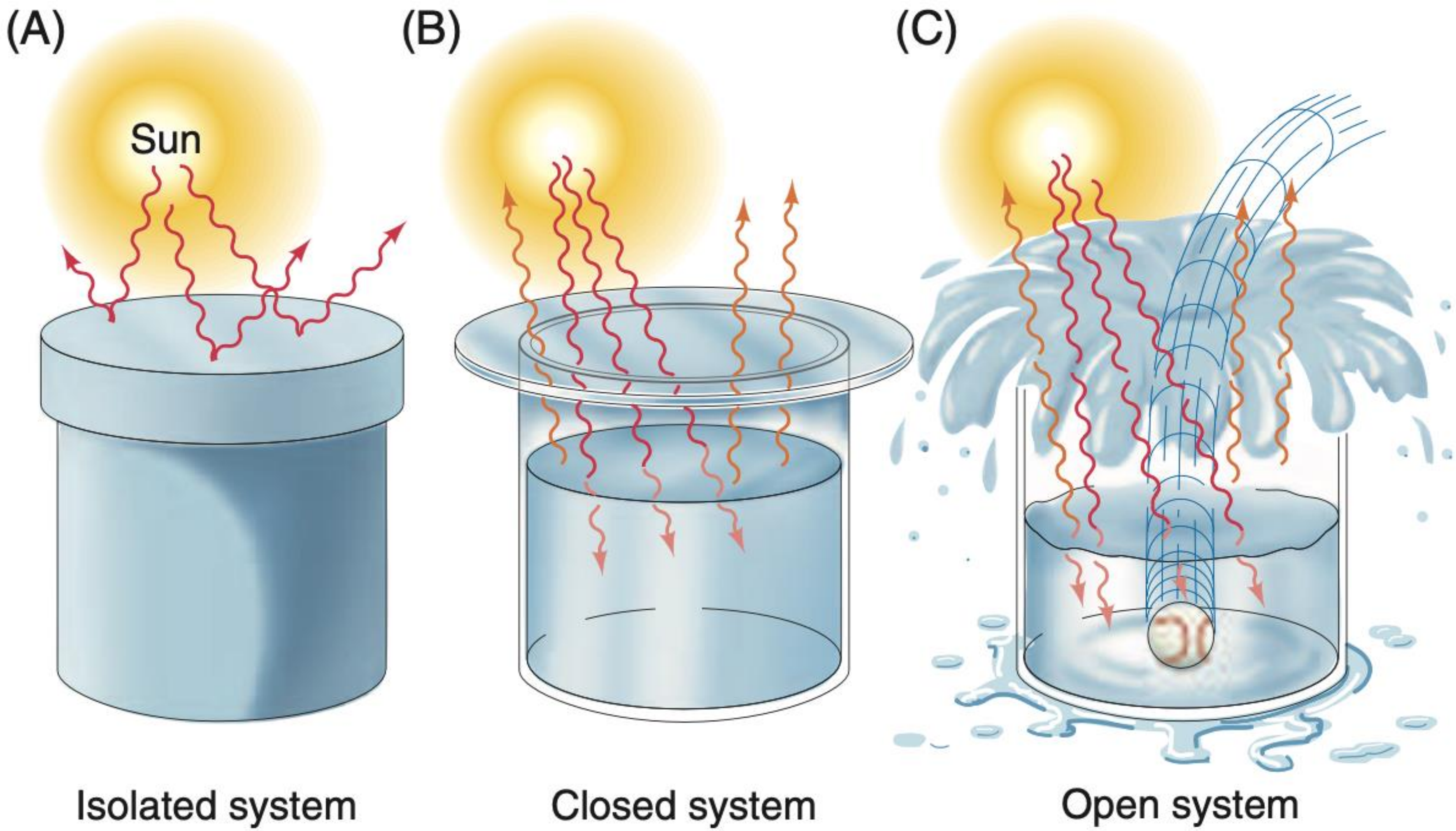


FIGURE B1.1 Systems
The three basic types of systems are: (A) An isolated system. (B) A closed system. (C) An open system.

FIGURE 1.1 **Earth's interacting parts**
Earth system science is the study of the whole planet as a system of many interacting parts, with a particular focus on the changes within and among those parts, including the impacts of human activities.

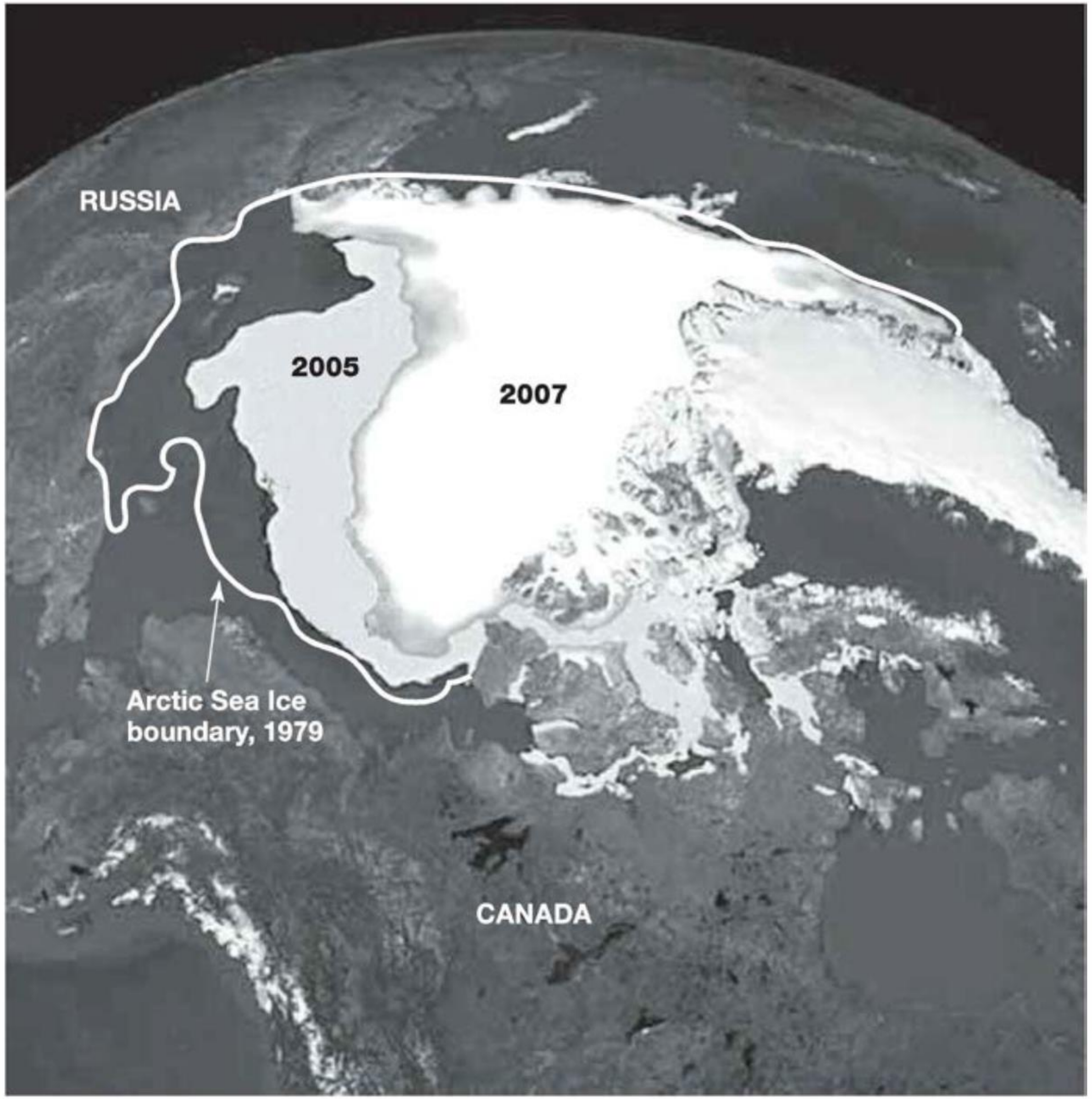


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FIGURE 1-5 Arctic sea ice minimum extent in 1979, 2005, and 2007 as measured from orbit by the Special Sensor Microwave Imager (SSMI). The pictures are electronically processed composites of images obtained in late September when the Arctic ice pack is at its smallest extent. (*Source:* NASA/Goddard Space Center.)

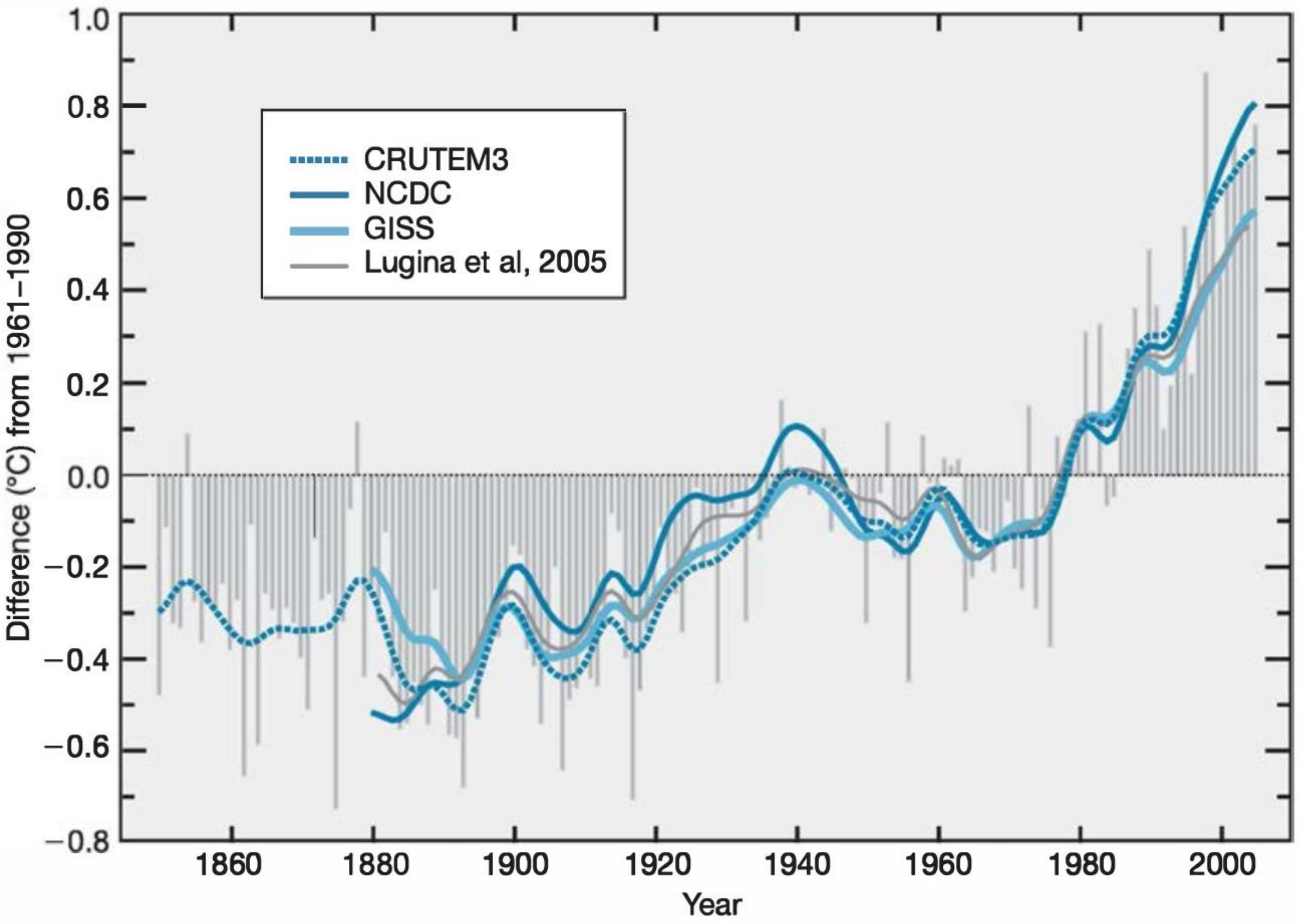

FIGURE 1-4 Change in global average surface temperature since 1861. The data are expressed as deviations from the 1961 to 1990 mean value. (*Source:* IPCC, *Climate Change 2007,* Fourth Assessment Report, Cambridge: Cambridge University Press, 2007, Chapter 3, p. 241, http://www.ipcc.ch/ipccreports/ar4-wg1.htm.)

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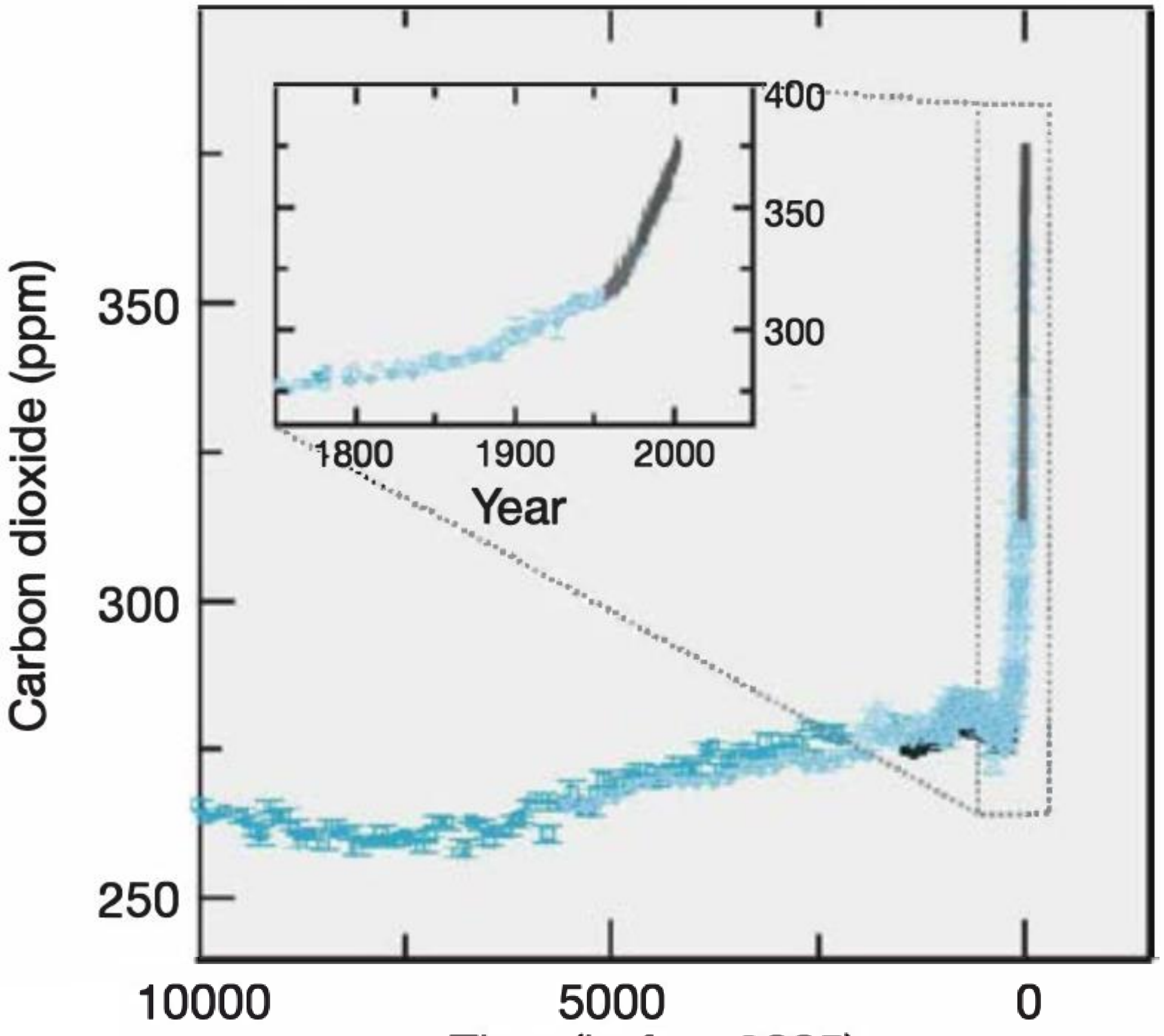


Carbon dioxide (ppm)
350
300
250
400
350
300
1800
1900
2000
Year
10000
5000
0
Time (before 2005)

(c)

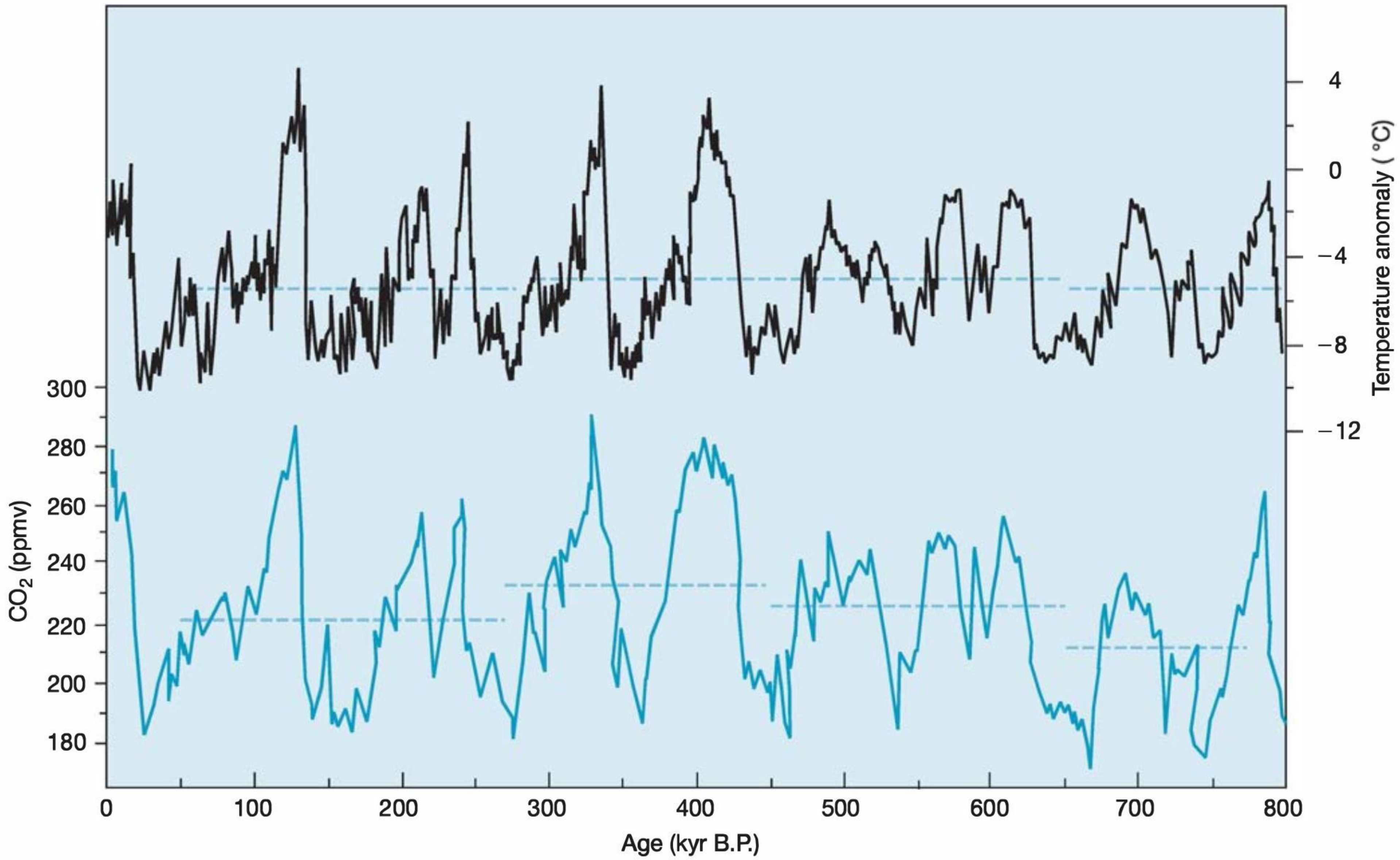


FIGURE 1-10 Measurements of atmospheric CO_2 and temperature for the Dome C ice core. The temperature is determined from the deuterium content of the ice. (*Source:* IPCC, *Climate Change 2007,* Technical Summary, Fourth Assessment Report, Cambridge: Cambridge University Press, 2007, p. 24, http://www.ipcc.ch/ipccreports/ar4-wg1.htm.)

Earth System Concepts

- **The systems approach has been used almost in every area of natural and social sciences.**

- **For example, human physiology where system approach is illuminating. Human body is made up of a number of systems that perform the vital functions of life: a respiratory system, a cardiovascular system, a digestive system etc.**

- **These systems are interrelated, functioning together to maintain the human body in a healthy state.**

The Essentials of Systems

- The *state* of a system is the set of important attributes that characterize at a particular point of time.

- Each system is an entity composed of diverse but interrelated parts that function as a complex whole. The individual parts of the system are called **components**. These components are usually linked through **positive** and **negative couplings**.

- **Positive coupling**: Changes in the components are in the same direction, i.e., increase/increase or decrease/decrease (→).

- **Negative coupling**: Changes are in opposite direction, i.e., increase/decrease (o).

The Essentials of Systems

- **Feedback loop: A self-perpetuating mechanism of change (initial disturbance) and response to that change.**

- **Positive feedback: Amplifies/reinforces the effects of disturbances.**

- **Negative feedback: Diminishes/restricts the effects of disturbances.**

Schematic view of components of the climate system and its interactions

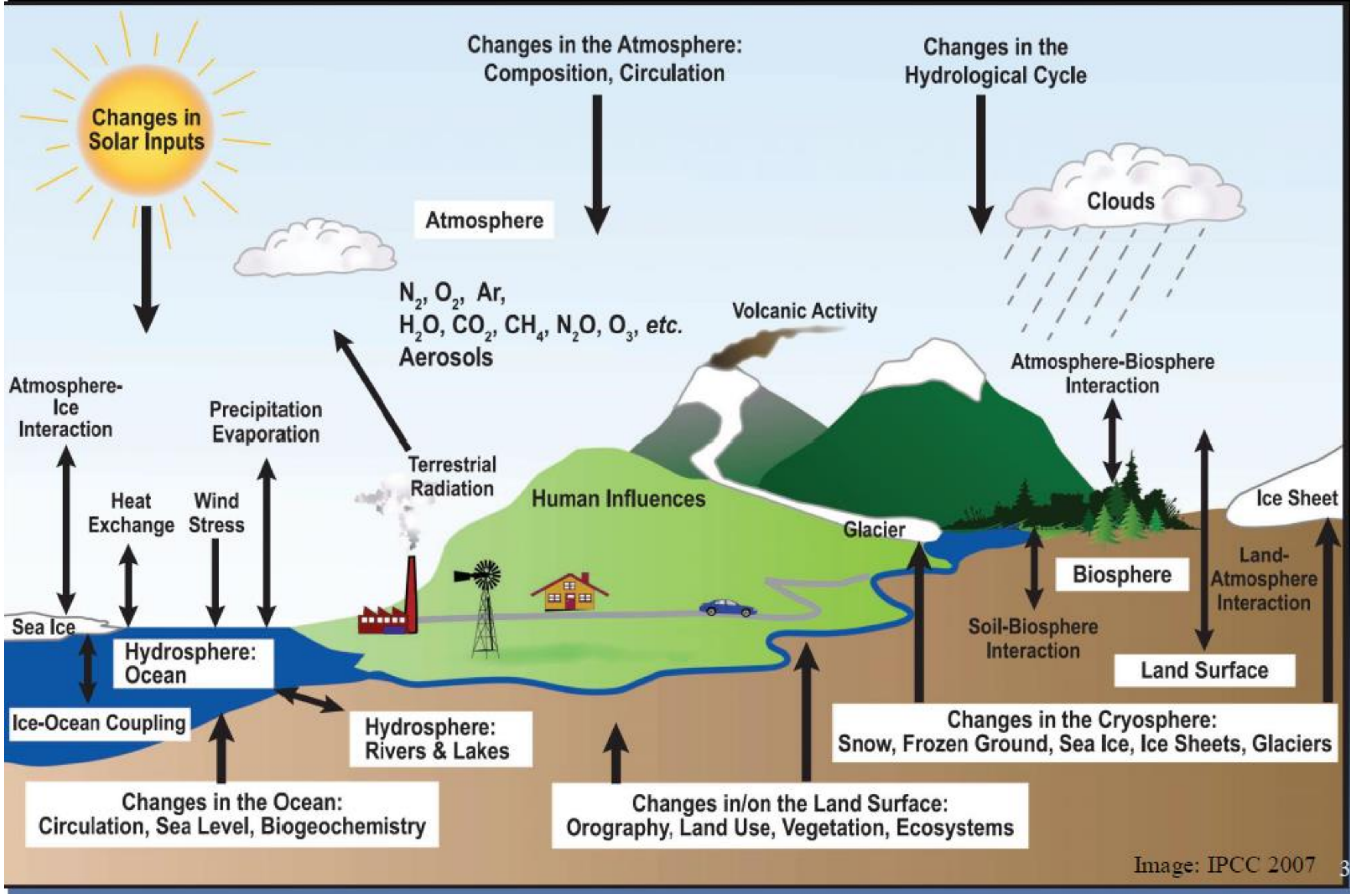
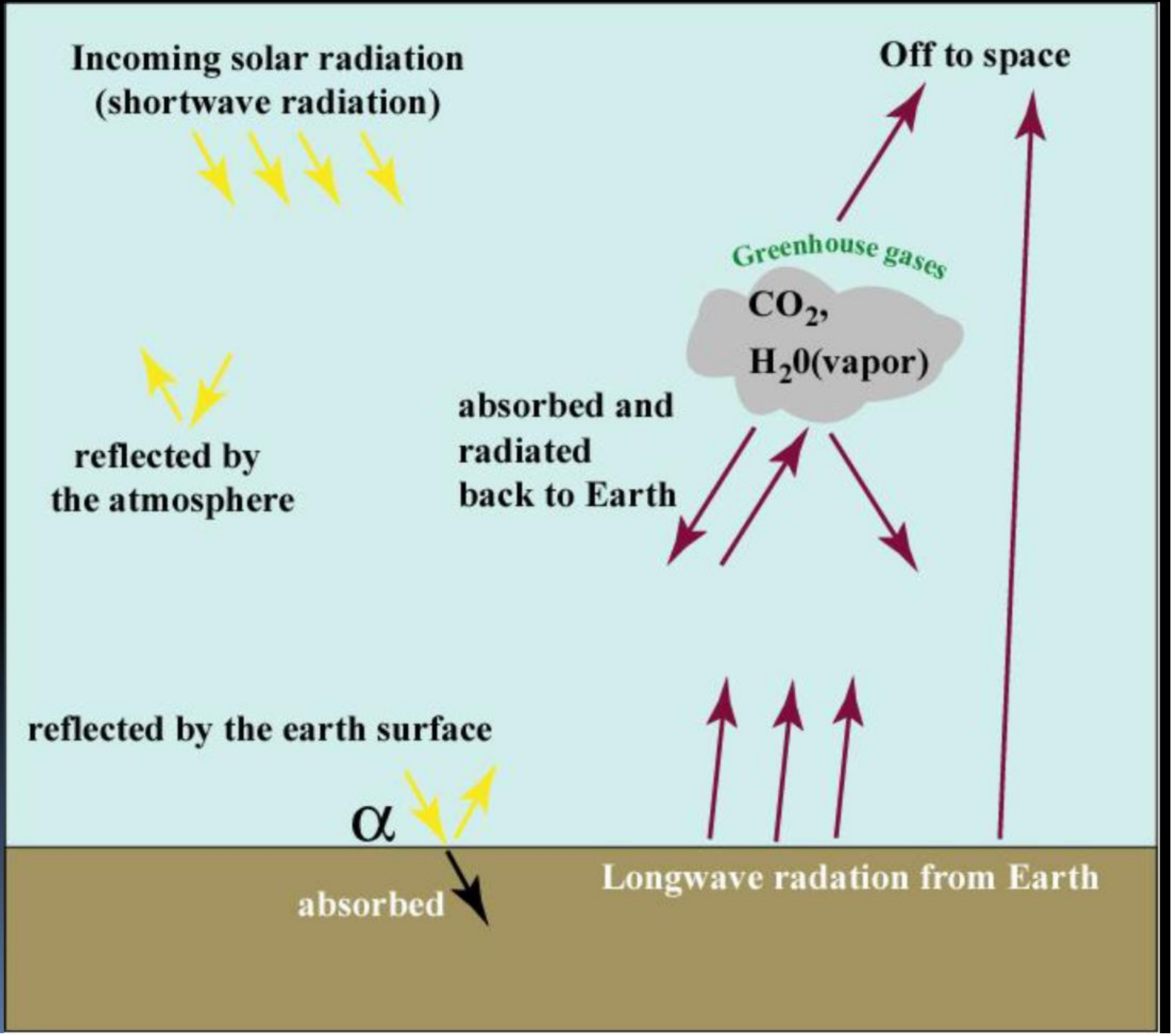


Image: IPCC 2007

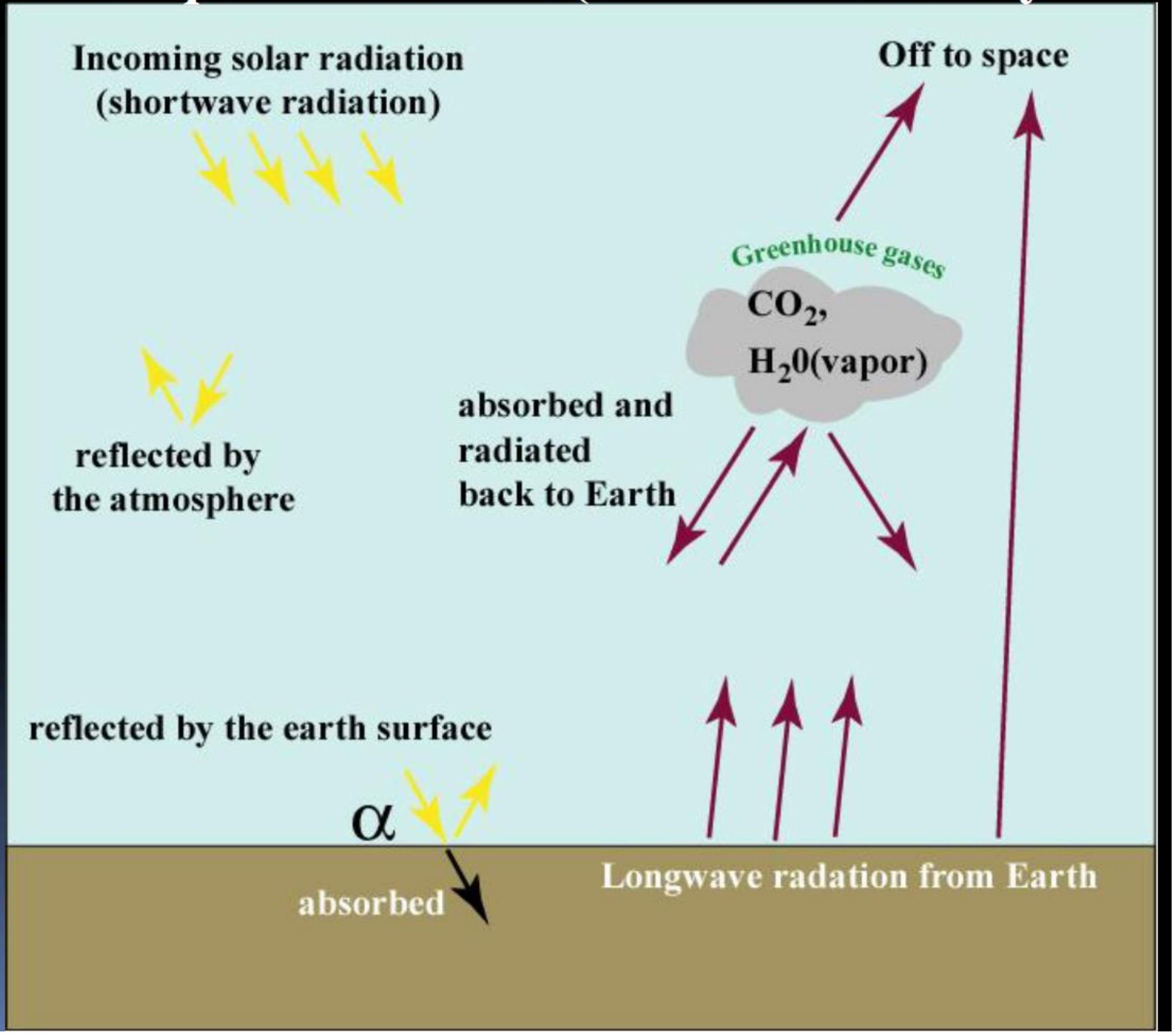
Climate varies with the long term *radiative balance*:

The balance between incoming solar radiation and radiation emitted back to space from Earth.



The albedo of the atmosphere varies with the amount of cloud cover and the concentration of *atmospheric aerosols* (solid dust and tiny liquid particles).

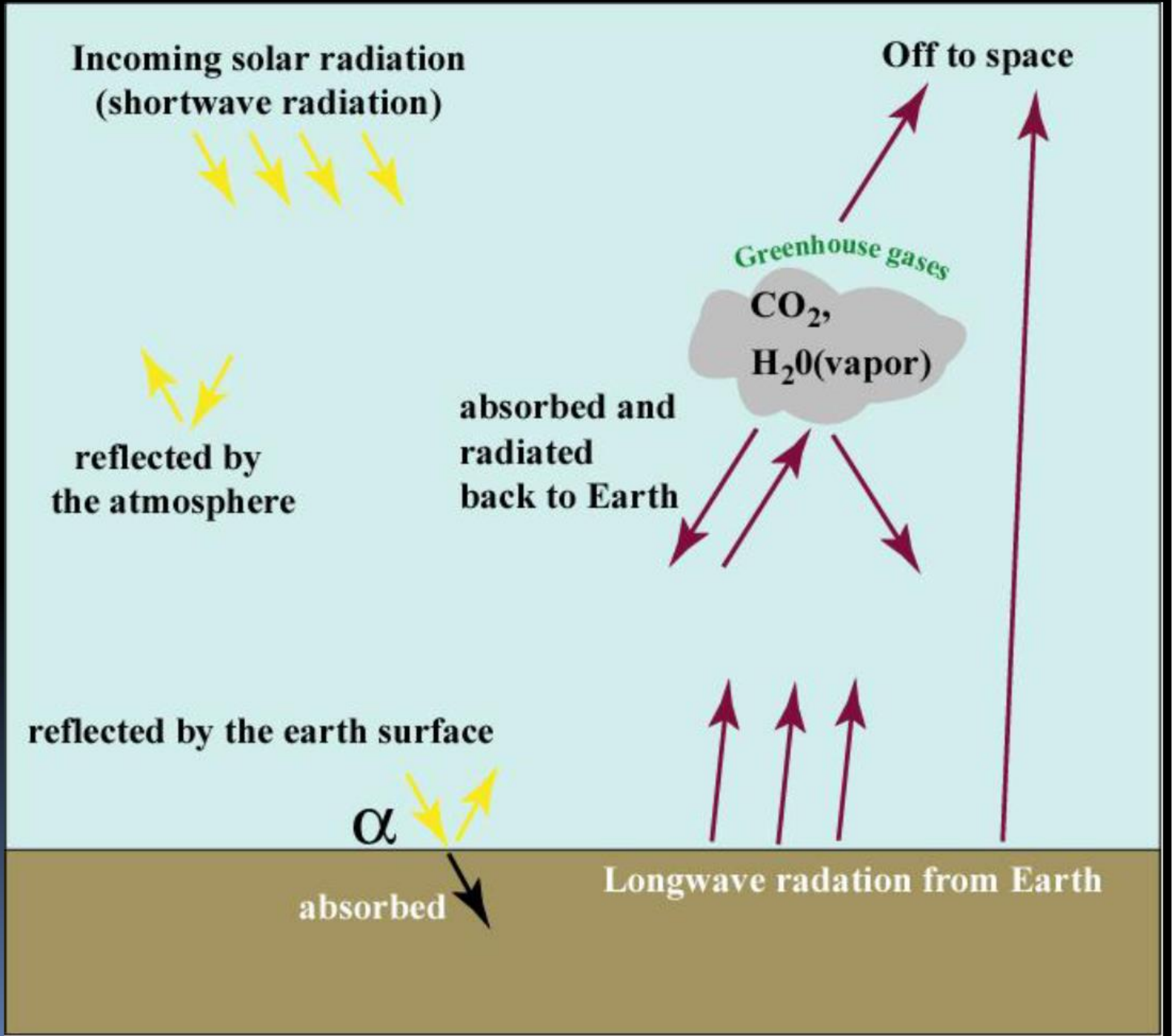
Surface	α
Fresh snow	0.8-0.95
Old snow	0.42-0.70
Sandy soils	0.25-0.45
Clay soils	0.20-0.35
Peat soils	0.05-0.15



Greenhouse gases: absorb longwave radiation and emit some of it back to the Earth as heat.

Water vapor and CO_2 are important greenhouse gas, others include:

Methane
Nitrous oxide
Chlorofluorocarbons



Overall, there is a balance between incoming energy and energy emitted to space; over the long term they are equal.

Climate changes as any component of the system changes.

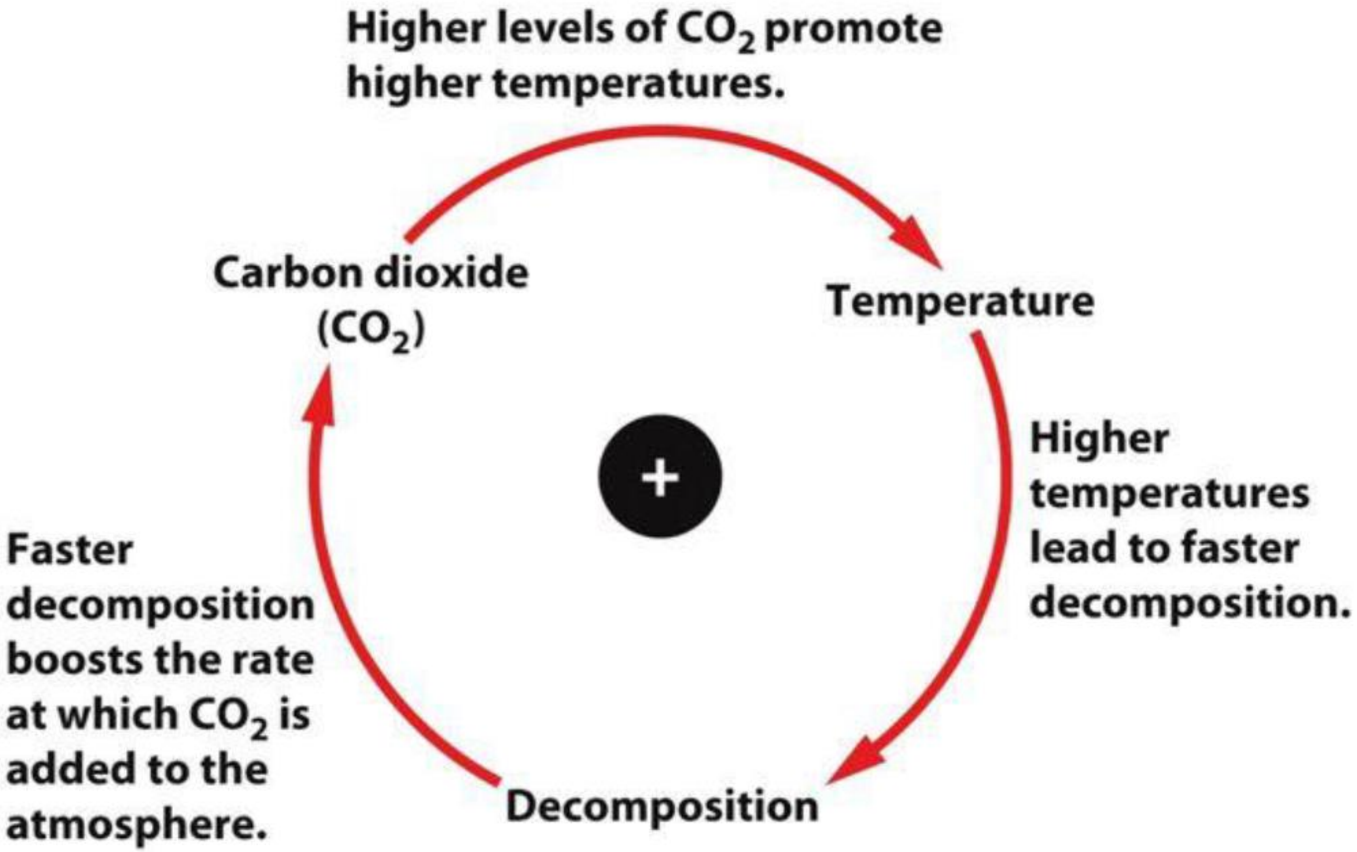
Especially:

The amount and distribution of incoming energy from the Sun.

The reflectivity of the Earth (changes in snow cover and atmospheric aerosols).

The concentration of “greenhouse” gases in the atmosphere.

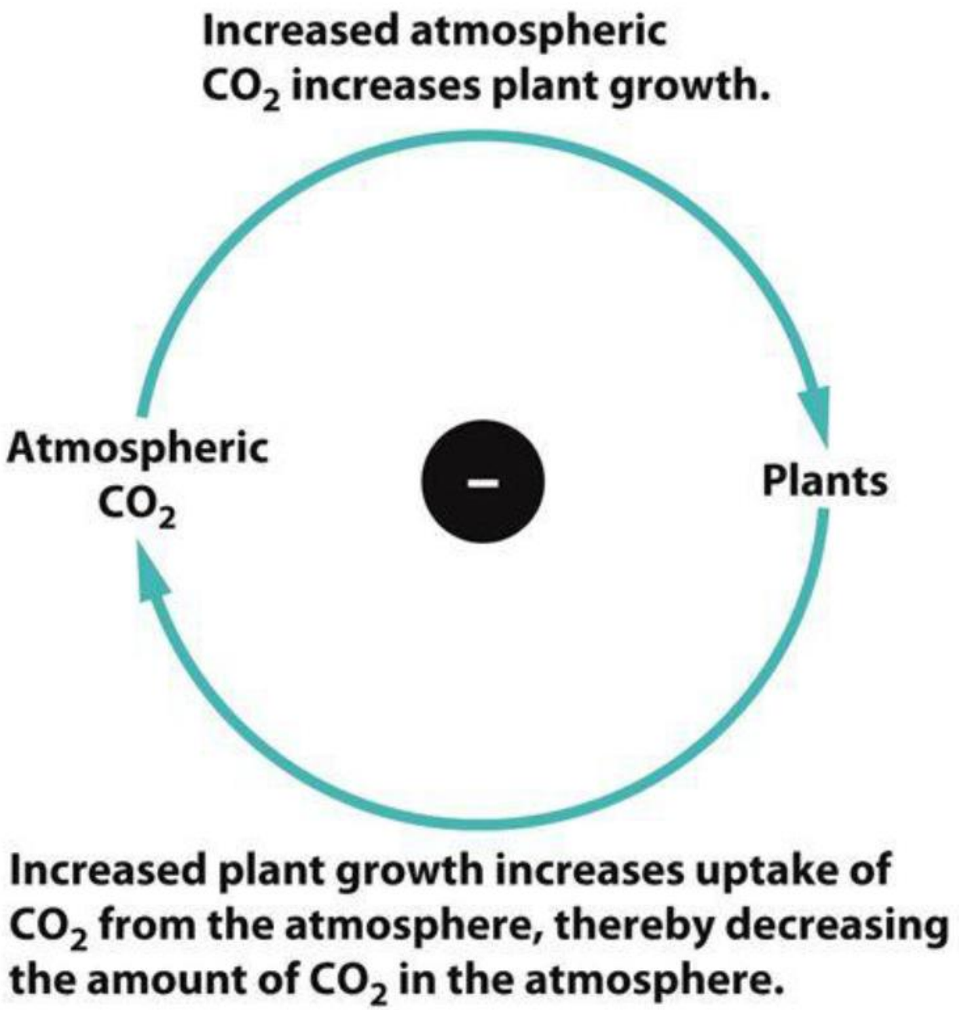
Positive Feedback Loop



Positive feedback system

Figure 19.18a
Environmental Science

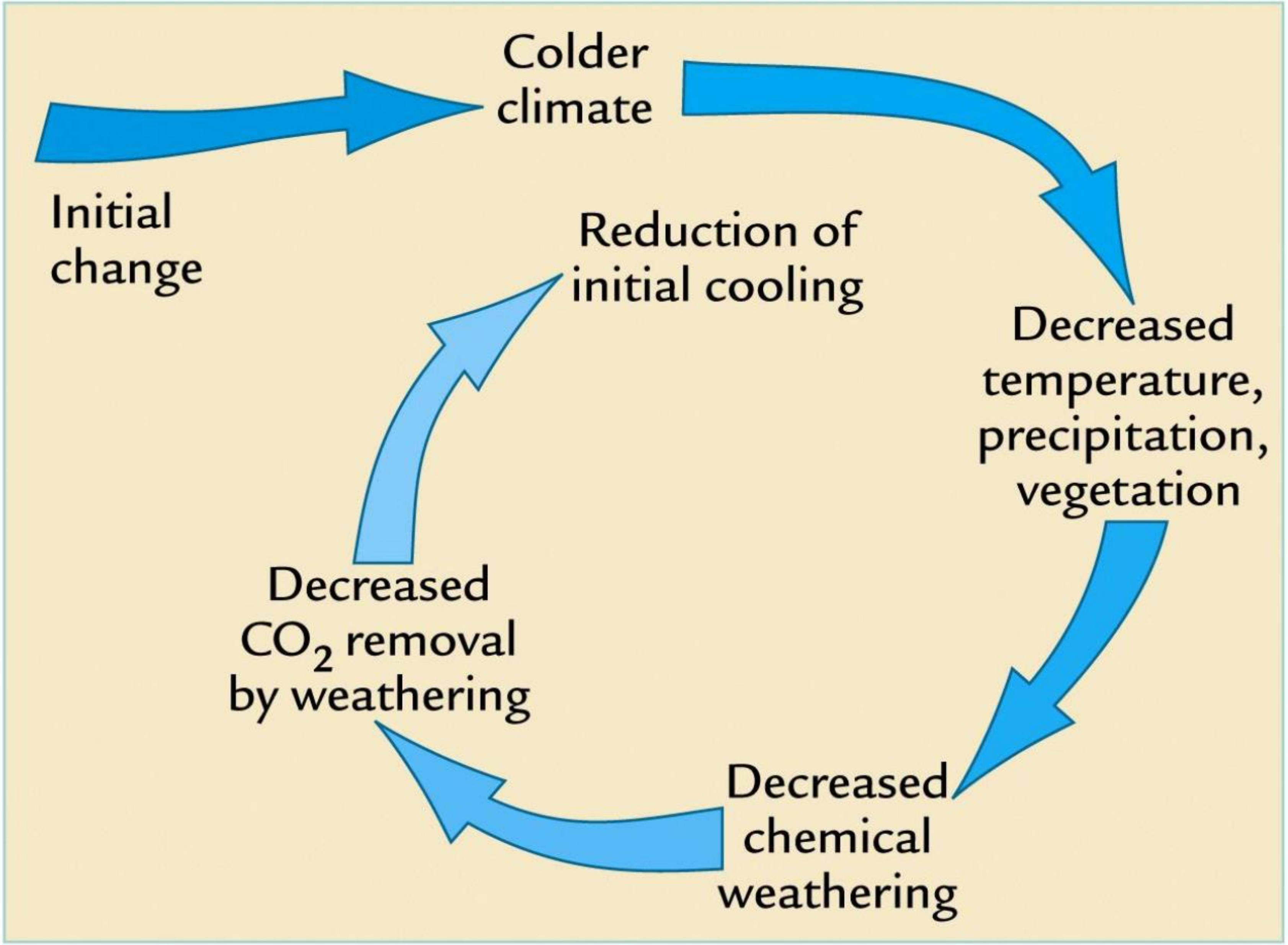
Negative Feedback Loop



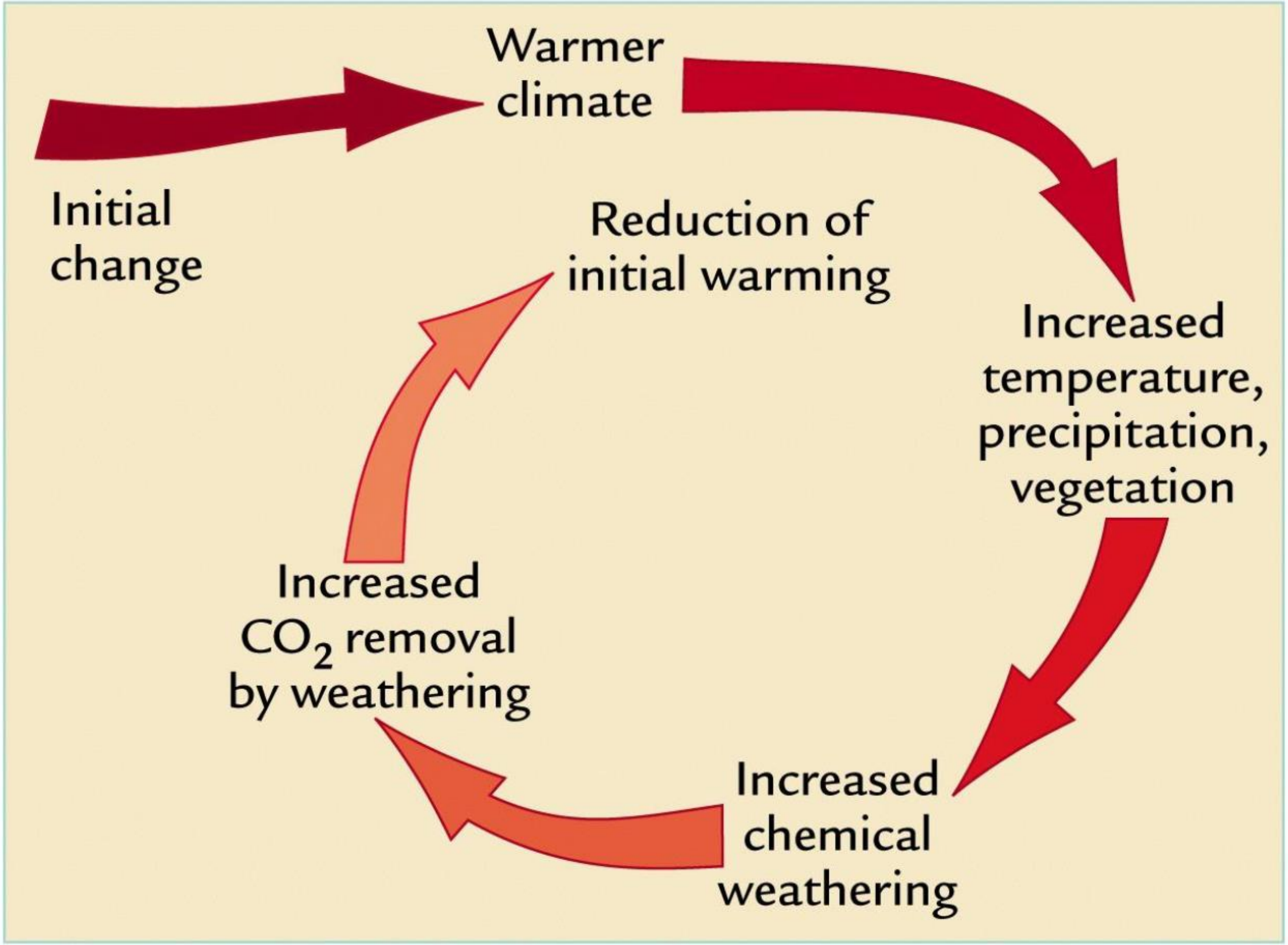
Negative feedback system

Figure 19.18b
Environmental Science

Temperature - weathering feedback:



Temperature - weathering feedback:



Earth System Concepts

Equilibrium States: **The system will not change unless it is disturbed.**

- **A system with *a negative* feedback loop has *stable equilibrium.***
- **A system with *a positive* feedback loop has *unstable equilibrium.***
- **Natural systems tend to have many positive and negative feedback loops.**

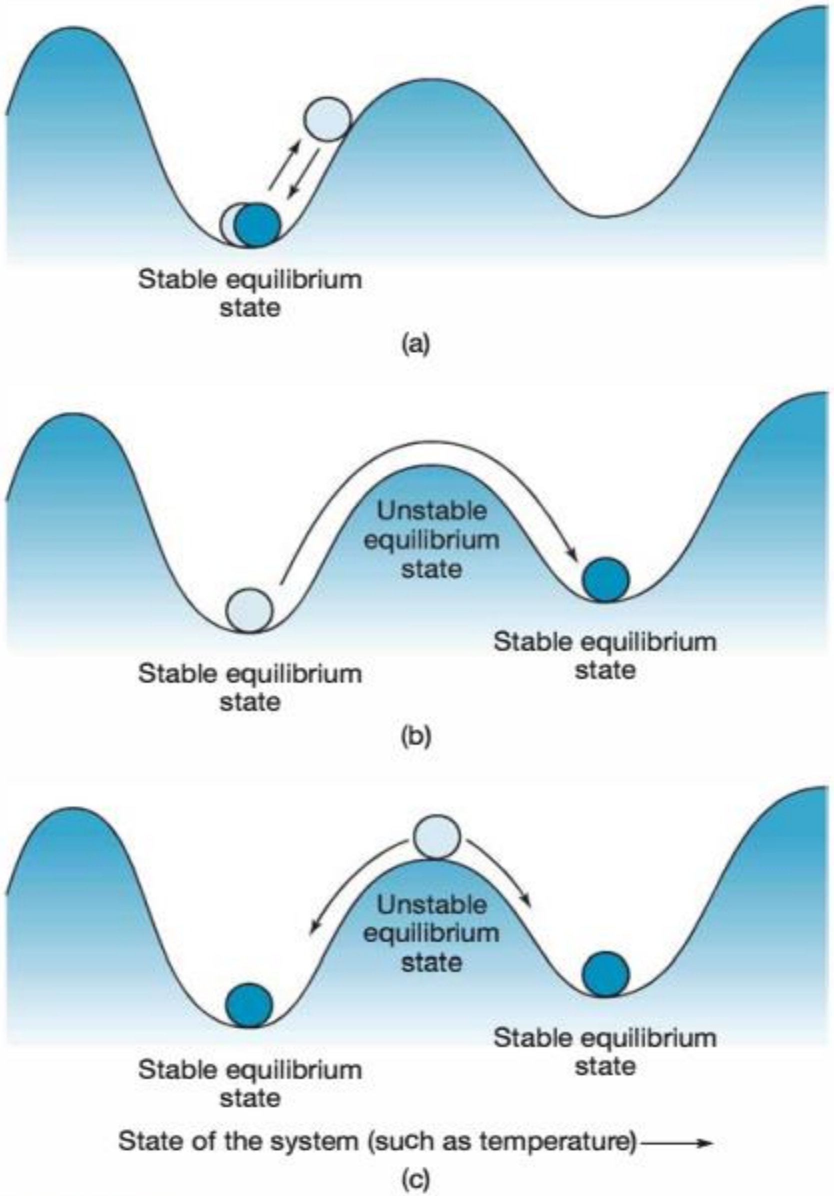


FIGURE 2-3 The equilibrium states of a system, represented as peaks (unstables) and valleys (stables). On disturbance, the system returns to stable equilibrium states but moves away from unstable equilibrium states.

Earth System Concepts

Perturbations and Forcings

- **We can learn about the Earth system by observing how it responds to disturbances.**

- **Earth's climate is being modified by variety of *natural* and *anthropogenic* factors.**

- **A temporary disturbance of the system is called *perturbation* whereas a more persistent disturbance is known as *forcing*.**

- **For example, the injection of sulfur dioxide (SO_2) into the atmosphere during volcanic eruptions is a *perturbation* which results in drop by Earth's surface by ~0.5°C globally.**

- **Gradual increase in the amount of sunlight Earth has been receiving over billions of years is an example of *forcing*. Understanding the response of the Earth system to this forcing will be our major focus.**

Schematic view of components of the climate system and its interactions

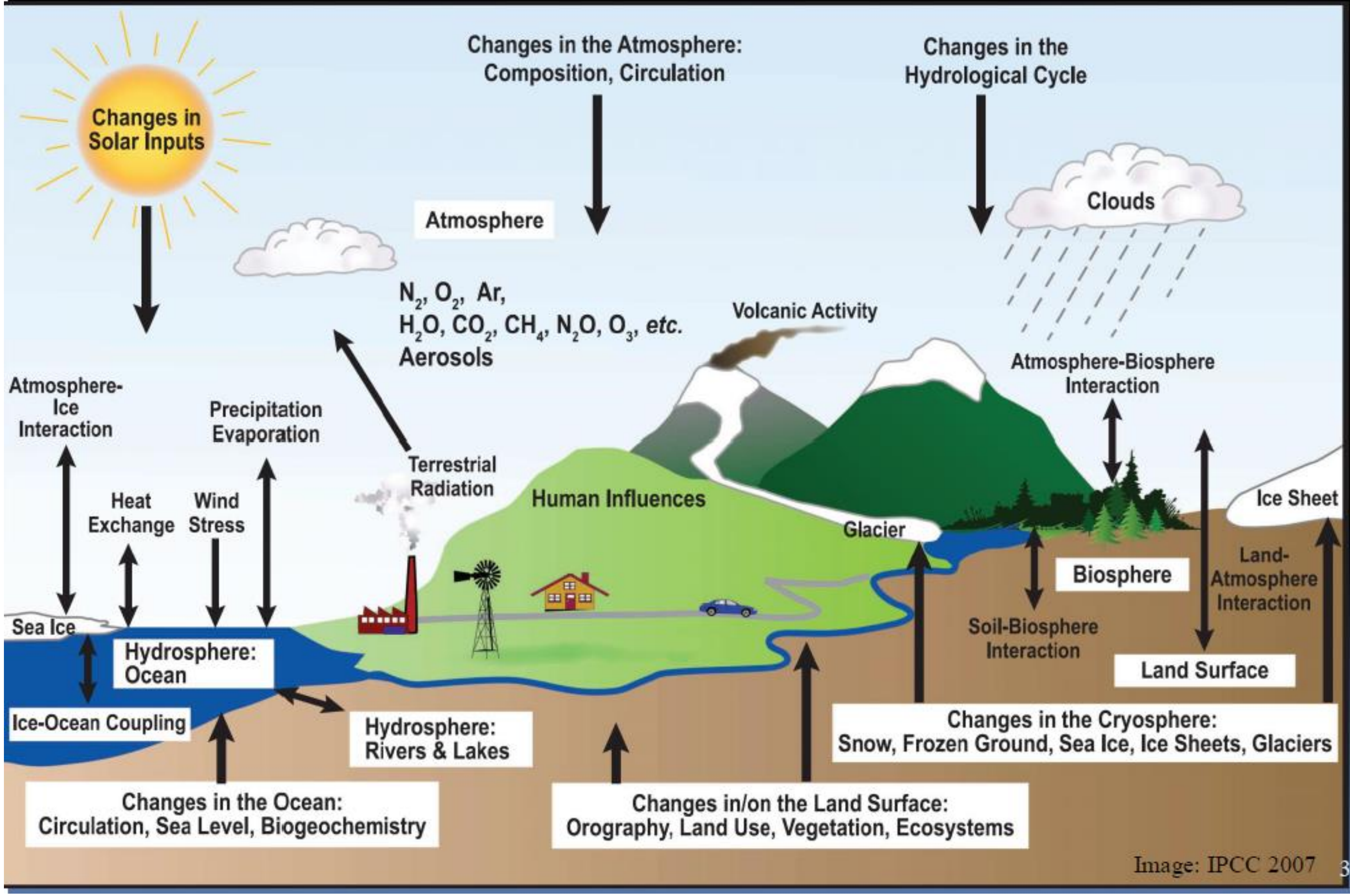


FIGURE 1.12 The energy cycle
Energy from both internal and external sources cycles through the reservoirs of the Earth system, driving processes from wind and waves to photosynthesis.

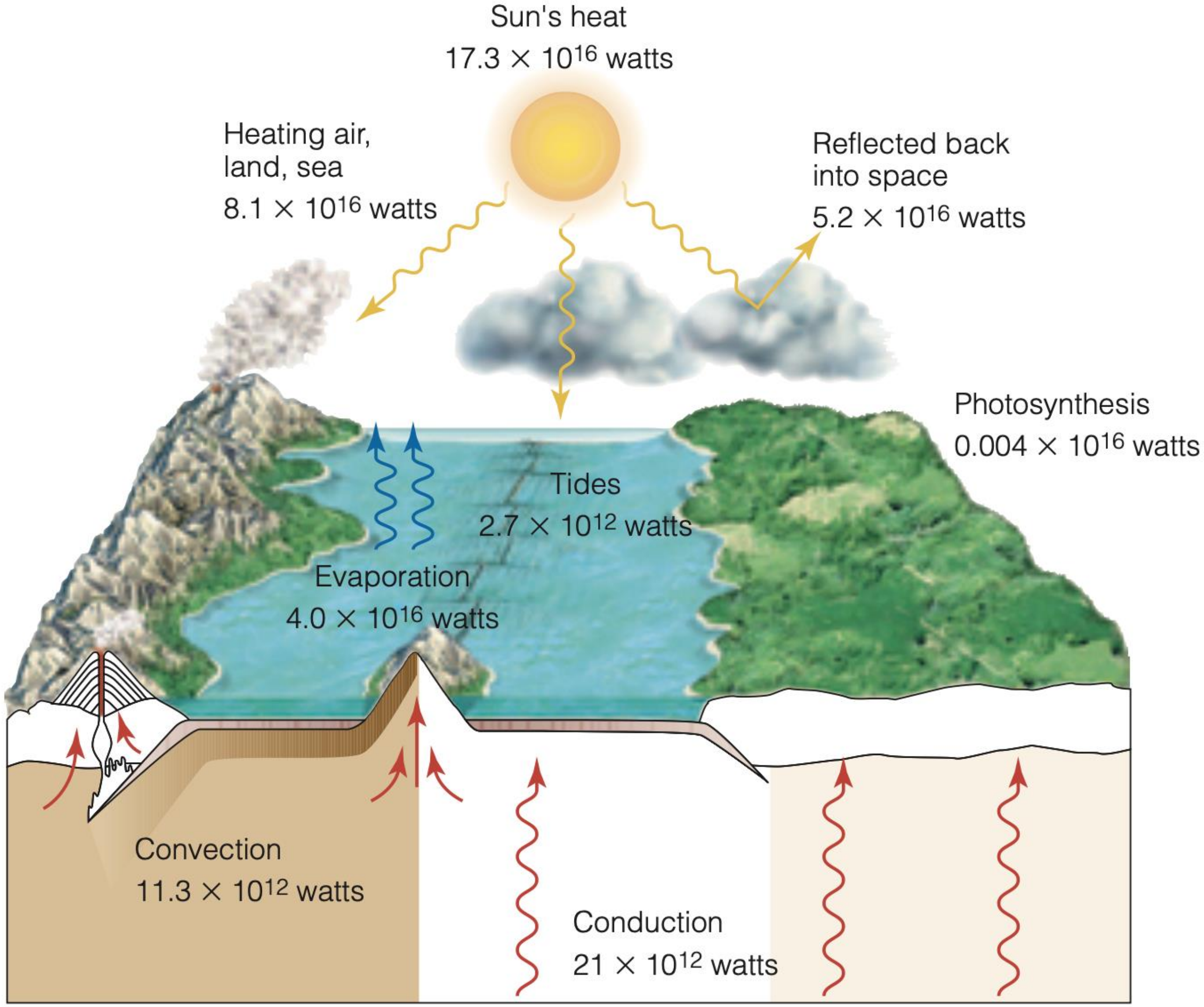
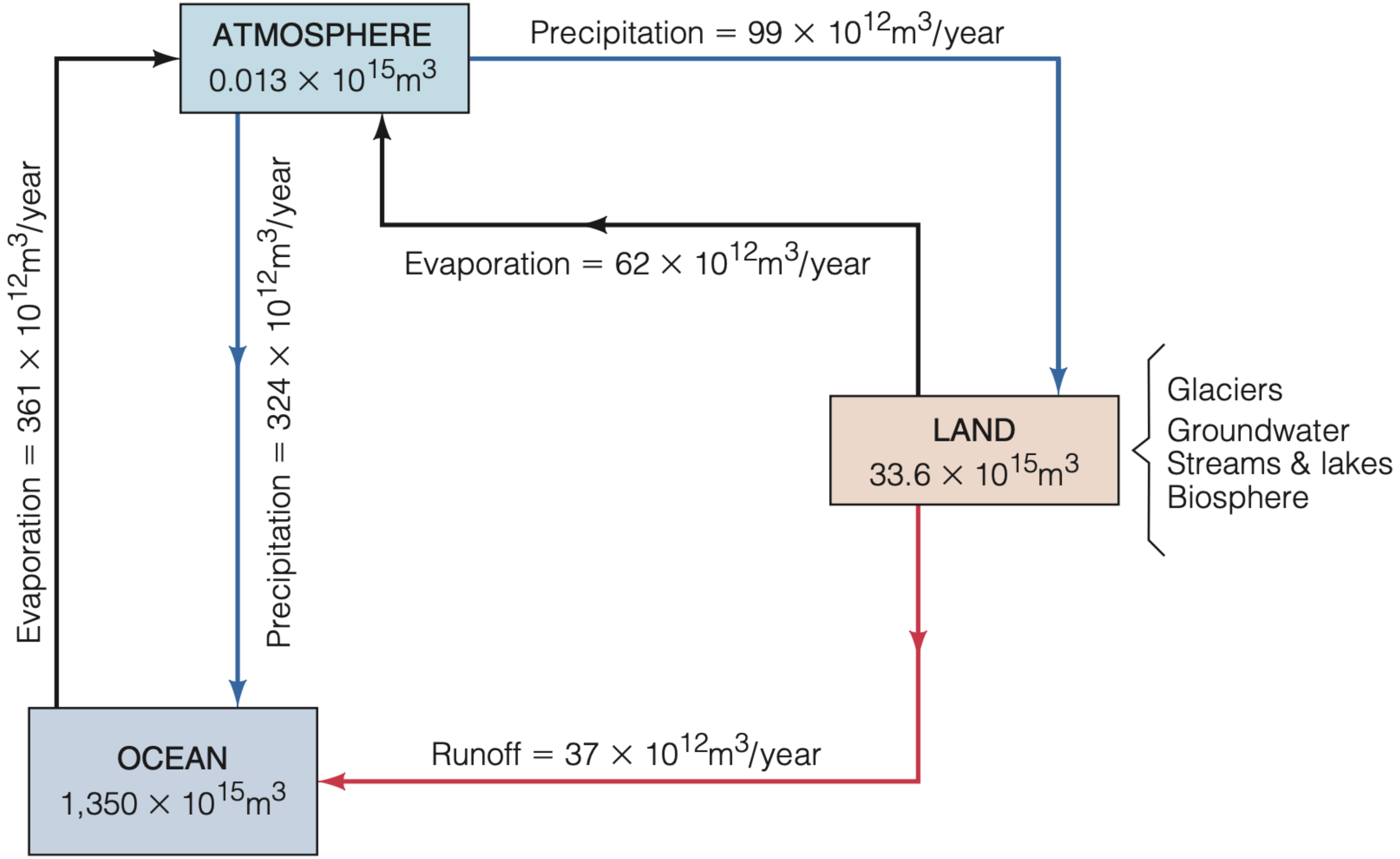


FIGURE 1.11 **The global hydrologic cycle**
The hydrologic cycle is probably the most familiar of Earth's important cycles. It traces the movement of water from one reservoir to another throughout the Earth system. Here the global hydrologic cycle is portrayed as a simple box model. Compare this to Fig. 1.5B, C.



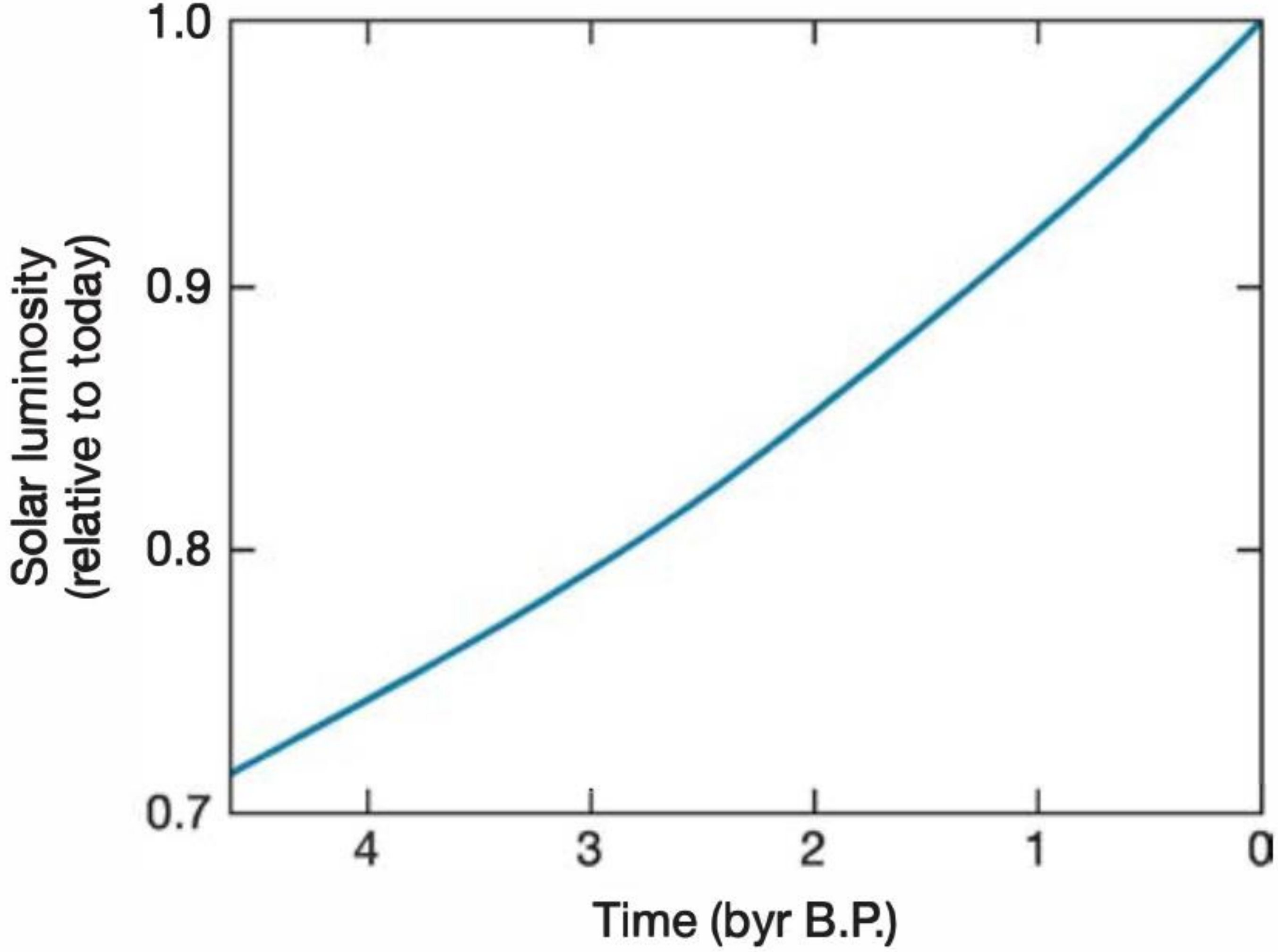
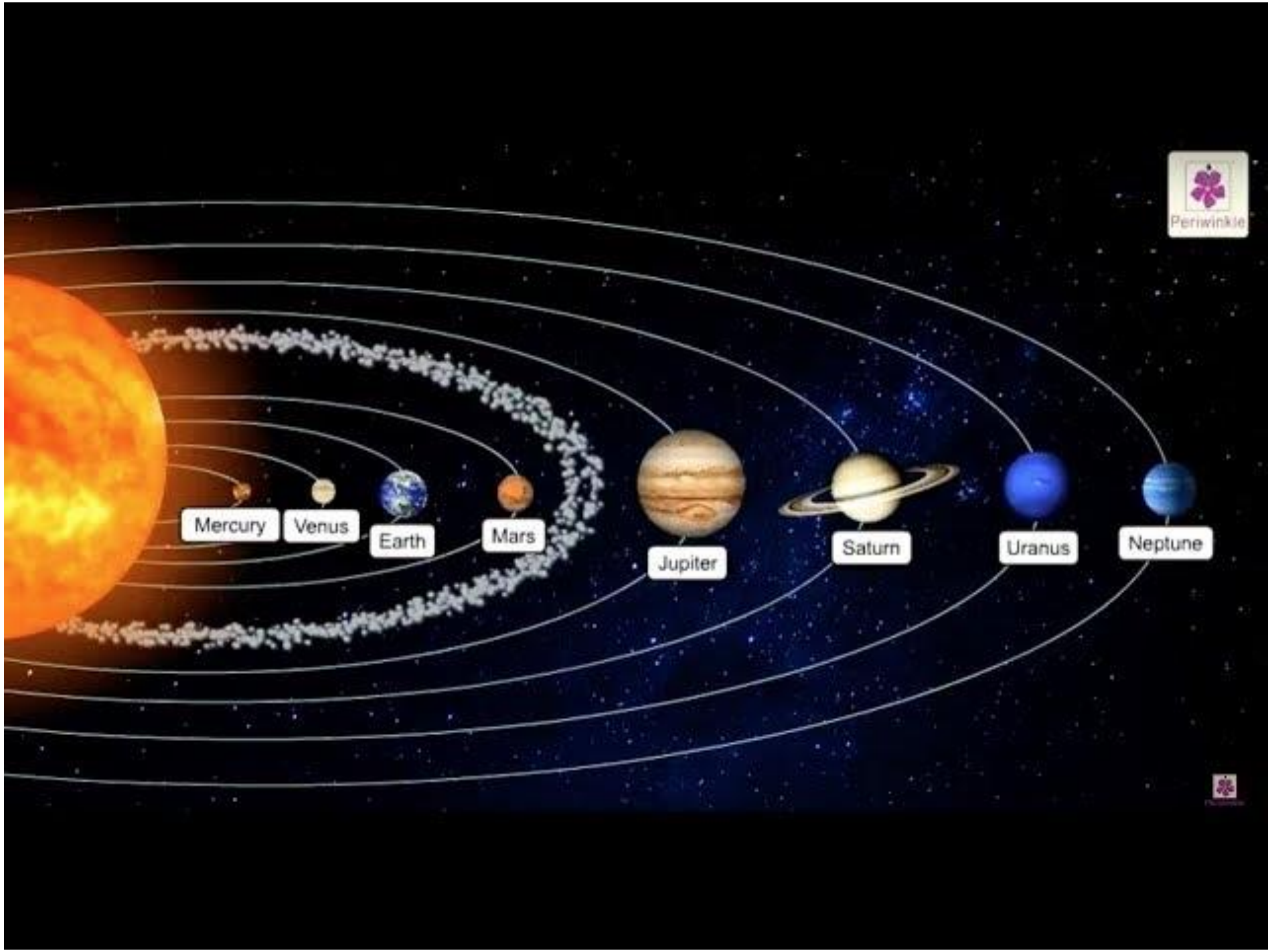


FIGURE 1-13 Estimated change in solar luminosity with time. The unit of age on the horizontal axis, byr B.P., stands for "billions of years before the present." (*Source:* D. O. Gough, *Solar Physics* 74, 1981, p. 21.)


Periwinkle
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune

Global Energy Balance

$T \sim 460℃$ $T \sim 15℃$ $T \sim -55℃$

FIGURE 3-1 Venus, Earth, and Mars, shown roughly to scale. (*Source:* NASA (left and center) and Photodisc/Getty Images (right).)

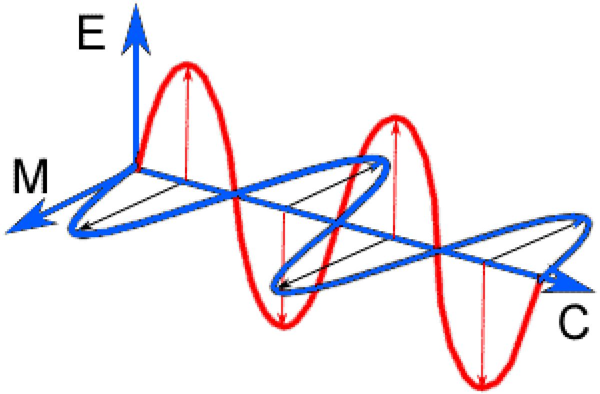
- ***The Earth is suitable for life is largely a consequence of its temperature climate.***
- **Venus is too hot, Mars is too cold, and Earth has just right temperature to have liquid water. Is it that Earth happens to lie at right distance from the sun???**
- **Greenhouse effect is the cause of this just right temperature.**

Global Energy Balance

Electromagnetic Radiation

- **To estimate the magnitude of atmospheric greenhouse effect, we need to study the balance between incoming solar energy and outgoing (reflected) infrared energy.**

- **Electromagnetic wave is a propagating disturbance consisting of mutually perpendicular oscillating electric and magnetic field.**



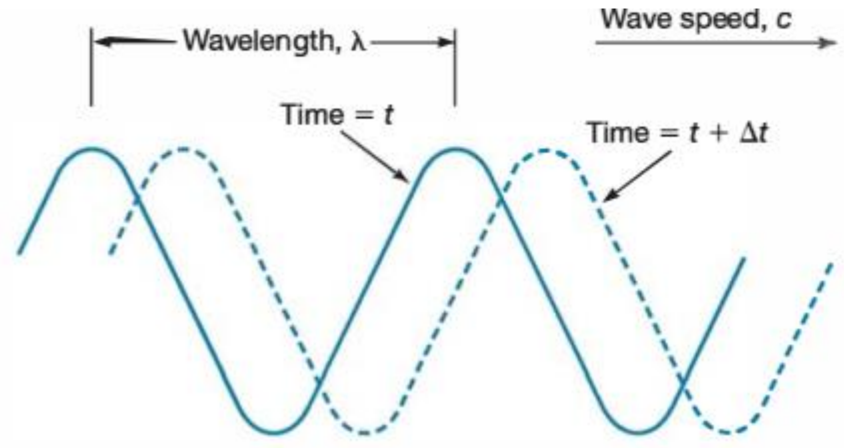


FIGURE 3-2 Simplified representation of an electromagnetic wave, illustrating the concept of wavelength. The solid curve shows the position of the wave at some time t. The dashed curve shows the wave at time $t + \Delta t$.

The speed of light c, frequency ν, and wavelength λ are related as

$$c = \nu\lambda$$

Global Energy Balance

Electromagnetic Radiation

- **Electromagnetic radiation behave wave as well as stream of particles. A particle of light known as *photon* has energy $E = h\nu = \frac{hc}{\lambda}$, where h is *Planck's constant* $(h = 6.62607004 \times 10^{-34}\ \text{joule} - \text{seconds})$.**
- **This *wave-particle duality* is a general characteristic of mater and energy.**

Electromagnetic Spectrum

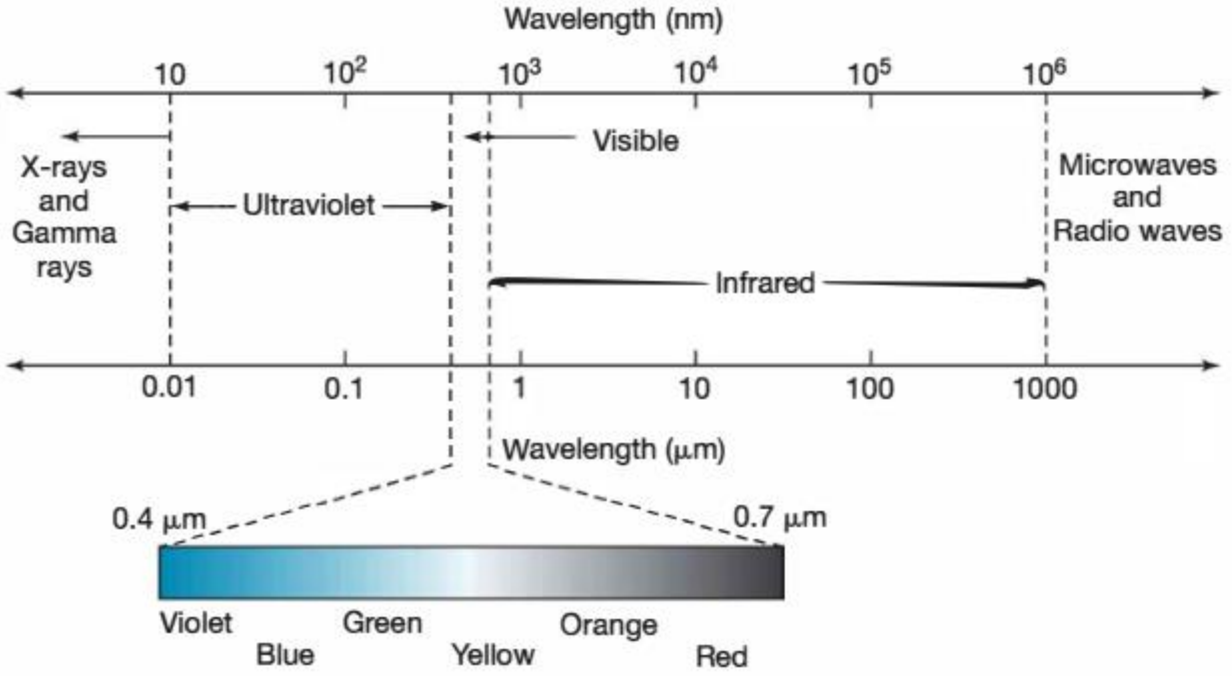


FIGURE 3-3 [See color section]
The electromagnetic spectrum.

Global Energy Balance

Flux

In general, *flux* is the amount of energy (or material) that passes through a given area per unit time.

- For electromagnetic radiation,

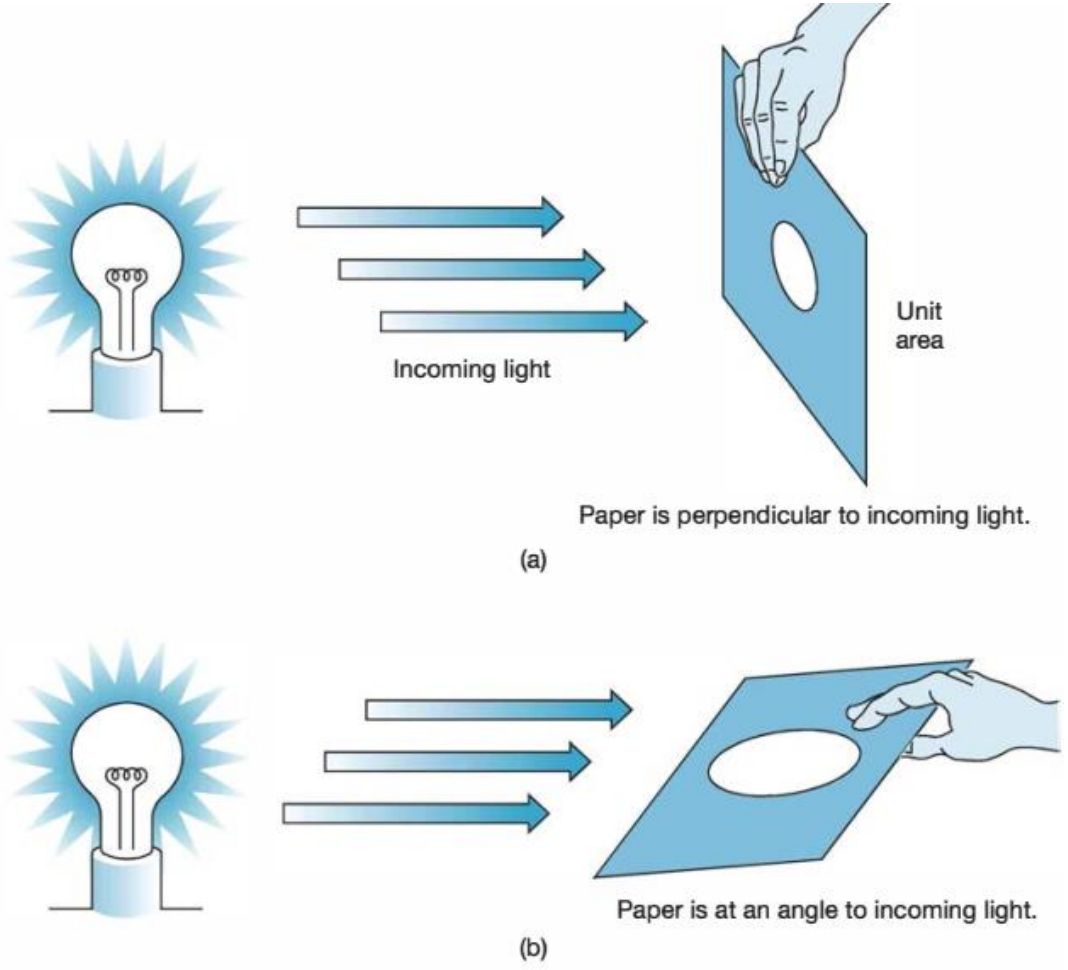
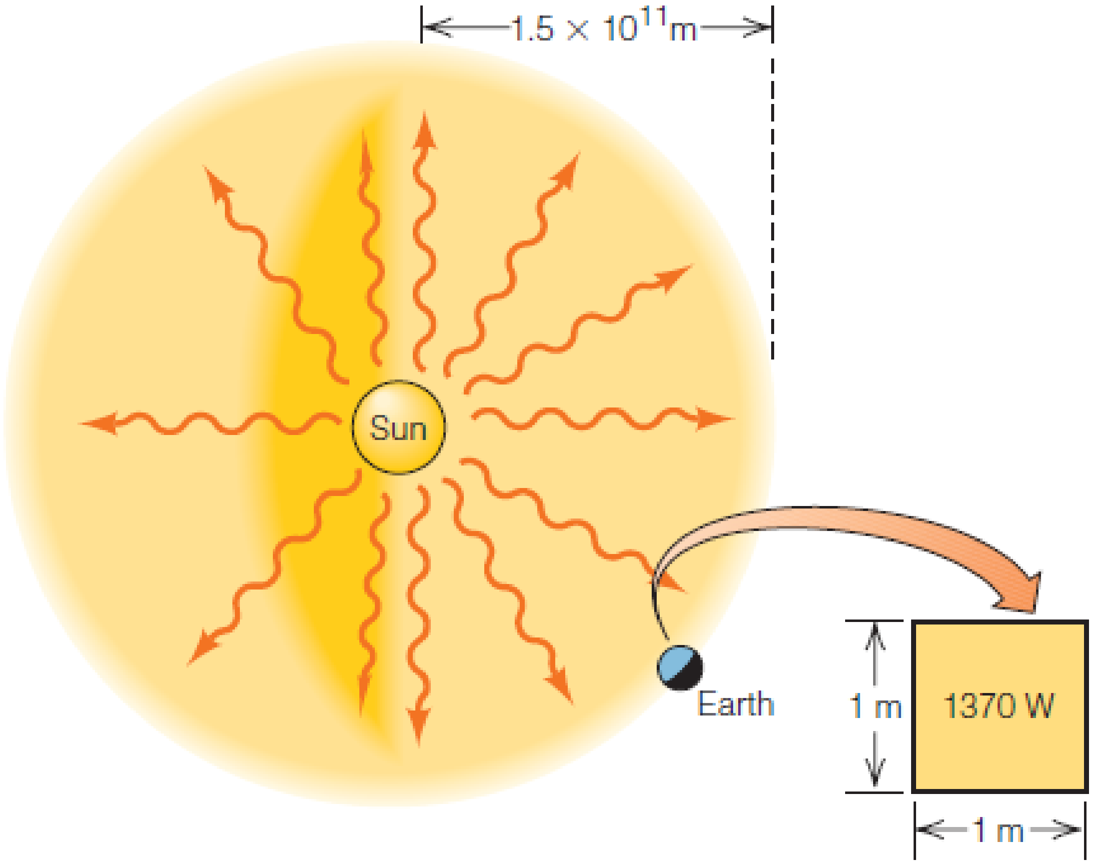


FIGURE 3-4 Schematic diagram of the concept of flux. The flux of radiation into the paper is reduced when the paper is tilted at an angle to the incoming light.

Sun’s Luminosity

FIGURE 2.4 The Sun’s luminosity
As discussed in the text, we can calculate the Sun’s luminosity by imagining a sphere centered on the Sun. The energy that falls on Earth’s surface, which we know to be 1370 W/m^2, is a portion of the whole sphere and can be used to calculate the total energy reaching the sphere.



Global Energy Balance

Inverse-square Law

The flux of solar energy is inversely proportional to the square of the distance from the sun:

$$S = S_0 \left(\frac{r_0}{r}\right)^2 ,$$

where S represents the solar flux at some distance r from the source and S_0 is represents the flux at some reference distance r_0.

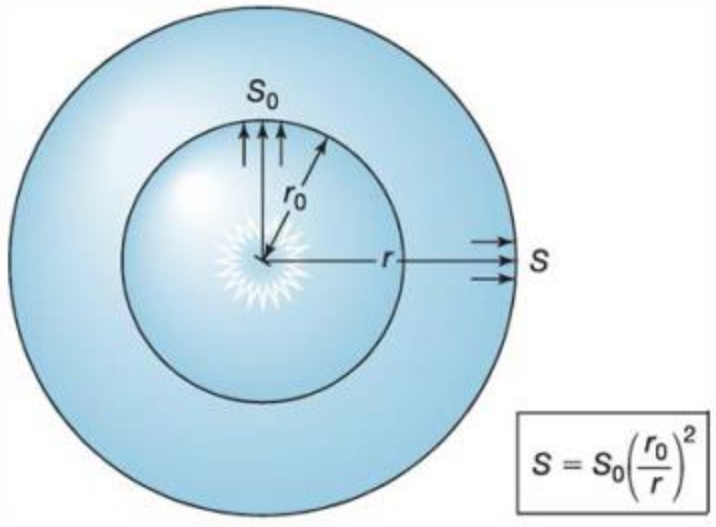


FIGURE 3-5 Diagram illustrating the inverse-square law.

For an example, consider a hypothetical planet X located twice as far from the sun as is Earth.

- **Distance between Earth and Sun ~149600000 km.**
- **Solar Flux at the earth is 1366 W/m^2.**
- **So the solar flux at planet X is 341.5 W/m^2.**

Global Energy Balance

Flux

- **For electromagnetic radiation, flux refers to the amount of electromagnetic energy (or total number of photons) passing through per unit area per unit time. It's measured as W/m^2.**

- **A typical object emits radiation over a continuous spectrum of frequency (or wavelength).**
- **One can measure the *radiation flux* $\Delta\phi$ in the wavelength range $(\lambda, \lambda + \Delta\lambda)$.**

- **Since $\Delta\phi$ depends on $\Delta\lambda$ which is defined by resolution of the spectrometer, we normalize the radiation flux $\Delta\phi$ with $\Delta\lambda$ and define *spectral density* ϕ_λ as**

$$\phi_\lambda = \lim_{\Delta\lambda=0}\left(\frac{\Delta\Phi}{\Delta\lambda}\right).$$

- **Total radiation flux emitted by a unit surface area of the object is**

$$\Phi_T = \int_0^\infty \phi_\lambda d\lambda.$$

Global Energy Balance

Blackbody Radiation

A *blackbody* is an idealized object that emits (or absorbs) electromagnetic radiation with 100% efficiency.

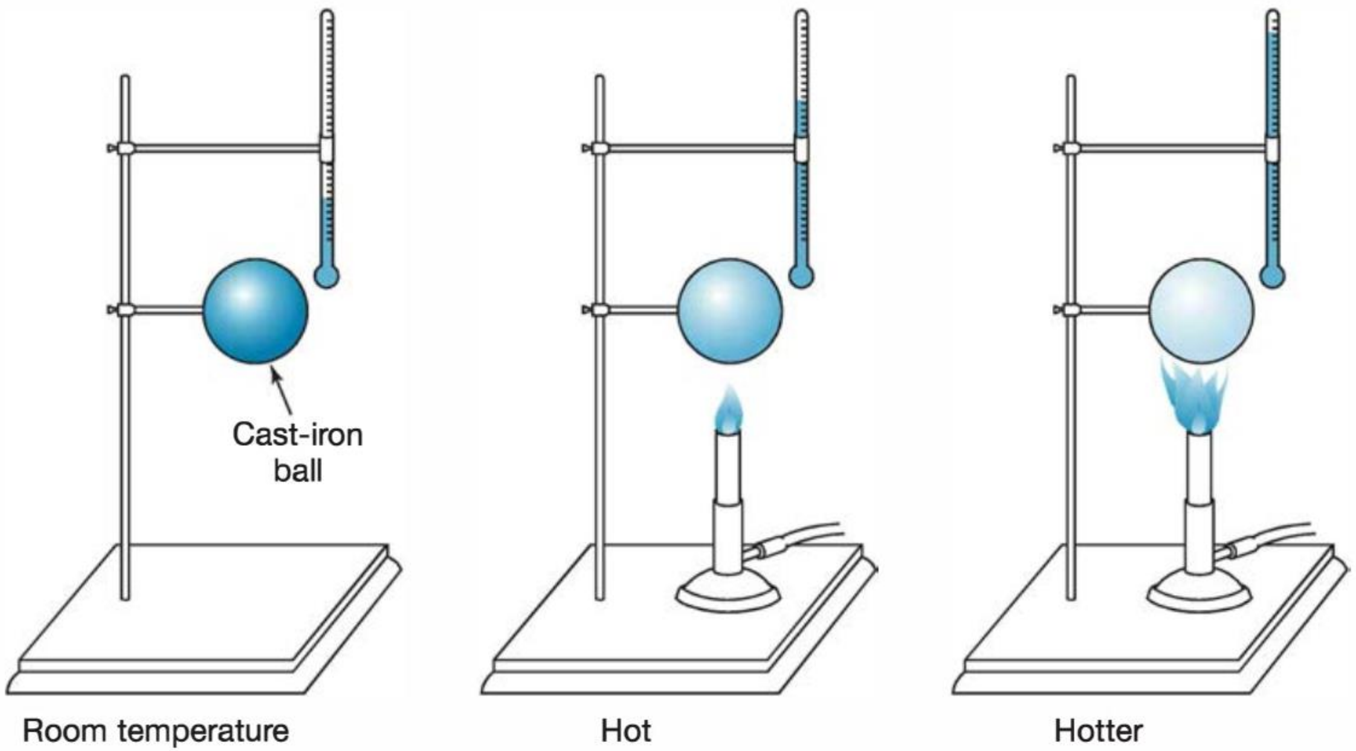


FIGURE 3-6 Change in emitted radiation by a blackbody as it is warmed.

From black (absorbs all incident light) to dull red to white (radiates all visible wavelengths)

Global Energy Balance

Blackbody Radiation

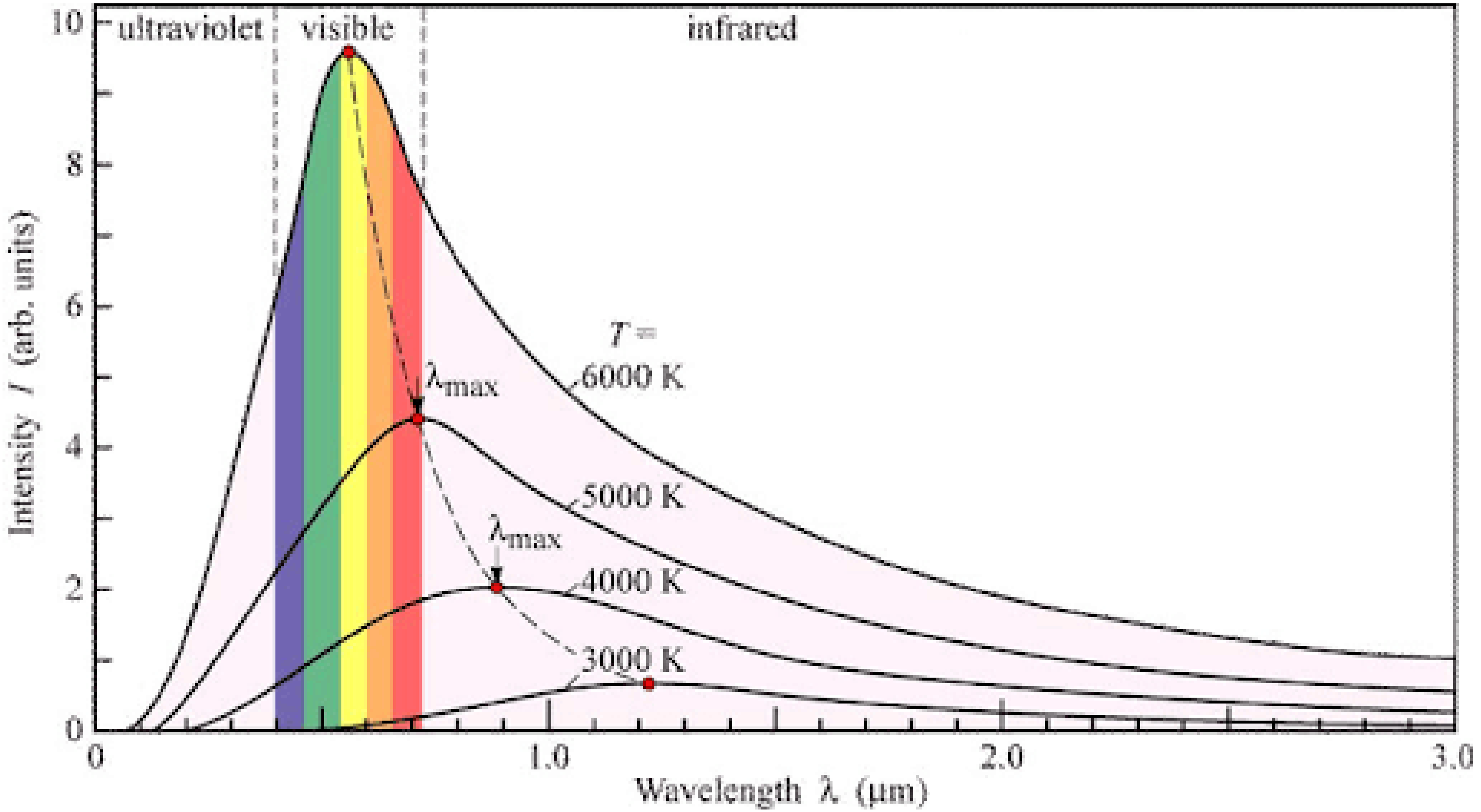
A *blackbody* is an idealized object that emits (or absorbs) electromagnetic radiation with 100% efficiency. The *Planck function* relates the intensity of radiation from blackbody to its wavelength and temperature. The flux distribution (spectral density) for blackbody is given by

$$\phi_\lambda^b = \frac{2\pi h c^2}{\lambda^5} \frac{1}{\exp\left(\frac{hc}{\lambda k_B T}\right) - 1},$$

where *Planck constant* $h = 6.63 \times 10^{-34} Joule/second$ and *Boltzmann constant* $k_B = 1.38 \times 10^{-23} Joule/Kelvin$

Global Energy Balance

Blackbody Radiation



Two important rules (*Wien's law and Stefan-Boltzmann law*) for climate study can be obtained from Planck distribution function.

Global Energy Balance

Blackbody Radiation

Wein's Law **states that the flux of radiation emitted by a blackbody reaches its maximum (peak value) at λ_{max}, which is inversely proportional to body's absolute temperature.**

$$\lambda_{max} \approx \frac{2898}{T}.$$

This relationship can be obtained by solving $\frac{\partial \phi_\lambda^b}{\partial \lambda} = 0$.

- **Wien's law allows us to understand why the Sun's radiation peaks in the visible part of the electromagnetic spectrum.**
- **The sun emits most of its radiation from the surface layer (photosphere) which has a temperature ~5780K and radiation flux peaks at ~500*nm*.**
- **The surface temperature of the Earth is ~288K and radiation from the Earth peaks at ~ 10μm (infrared range).**

Global Energy Balance

Blackbody Radiation

Wein's Law

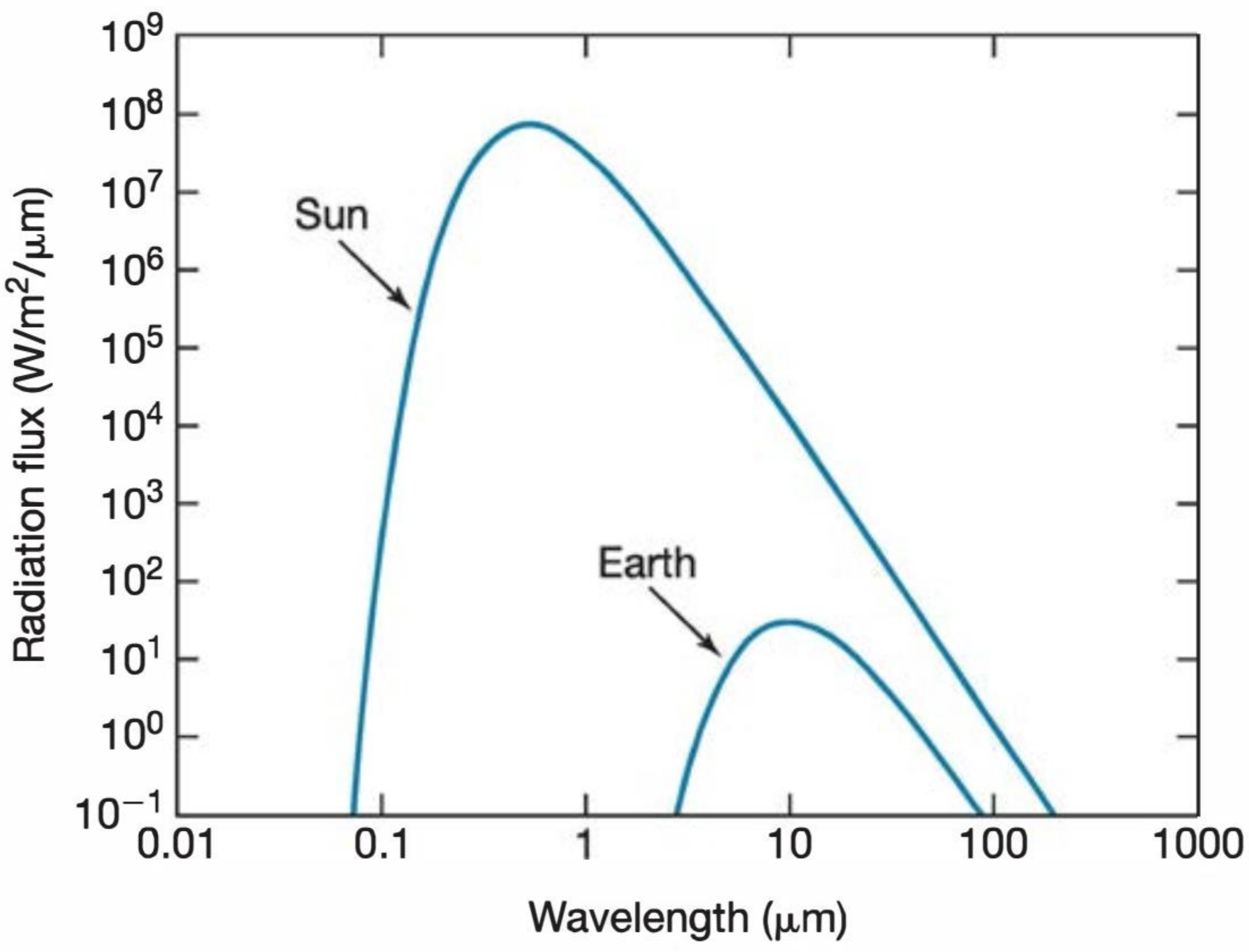


FIGURE 3-8 Blackbody emission curves for the Sun and Earth. The Sun emits more energy per unit area at all wavelengths.

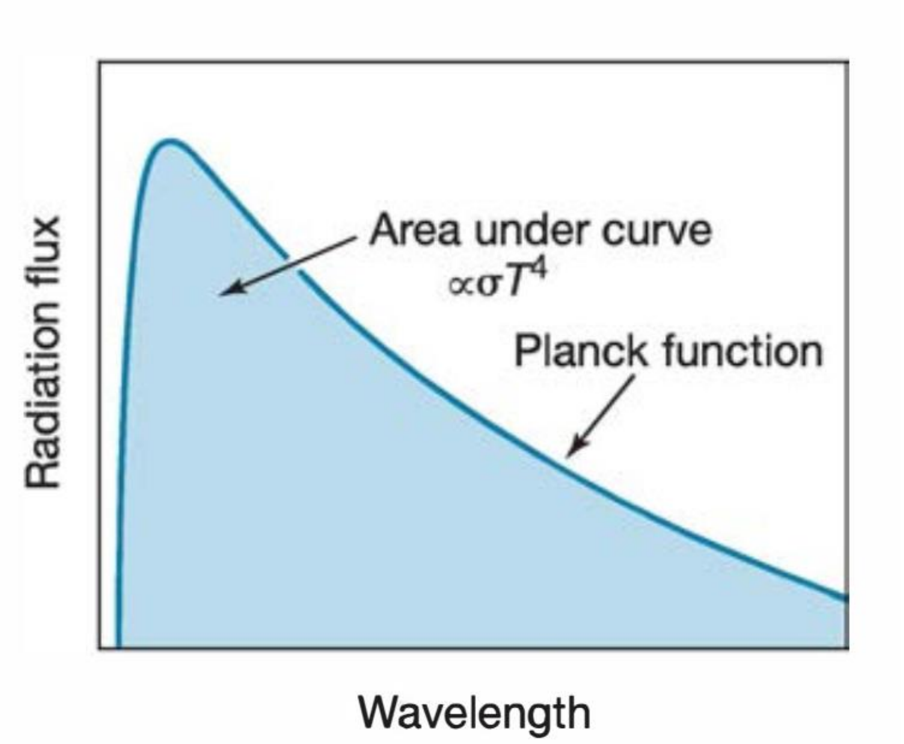
Global Energy Balance

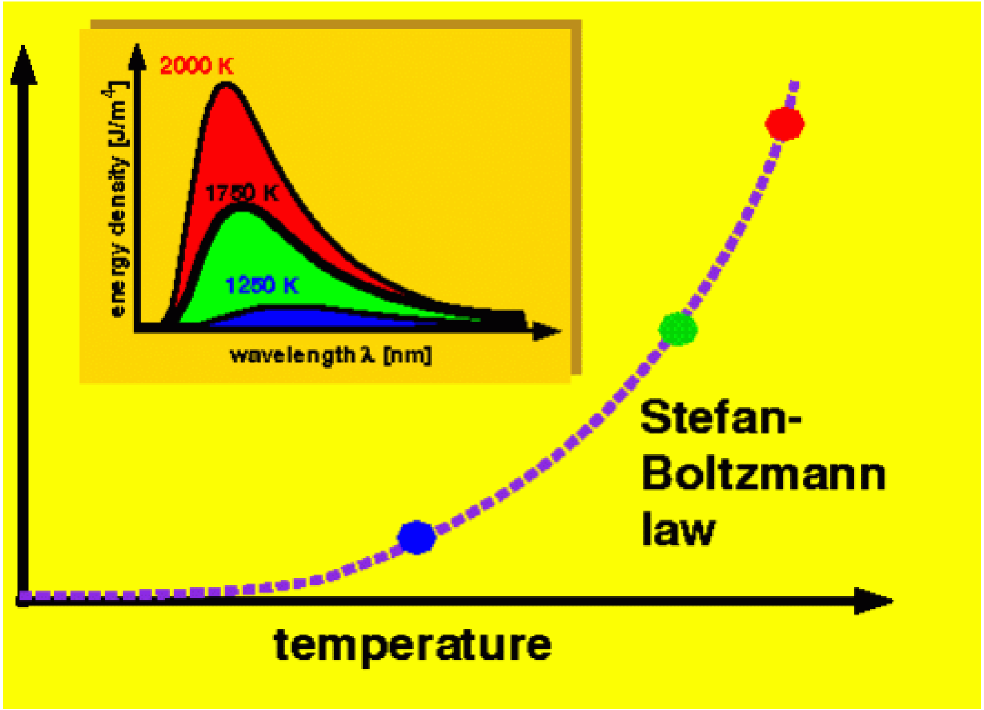
Blackbody Radiation

Stefan-Boltzmann law **states that the energy flux emitted by a blackbody is related to the fourth power of the body's absolute temperature.**

$$\boldsymbol{\Phi_{\mathrm{T}} = \int_0^\infty \phi_\lambda^b d\lambda = \sigma T^4},$$

where $\boldsymbol{\sigma = 5.67 \times 10^{-8} wm^{-2} K^{-4}}$.





Global Energy Balance

Planetary energy balance

- **As per the principle of *energy balance*, if the energy absorbed by the Earth is equal to the energy emitted then the Earth's average surface temperature would never change.**
- **However, evidence suggests that surface temperature of Earth is increasing (global warming) because *Earth's energy budget is slightly out of balance.***
- **The flux of incoming solar energy exceeds the outgoing IR flux.**
- **This imbalance may be caused by natural fluctuations within the climate system or increase in CO_2 and other greenhouse gases in the atmosphere.**

Scientific evidences overwhelmingly indicate the dominance of increase in greenhouse gases for this imbalance.

Global Energy Balance

Planetary energy balance

Primarily, Earth's surface temperature depends on three factors

- **Solar Flux available at the Earth's orbit (S)**
- **Earth's reflectivity (aka *albedo* A = reflected/incident sunlight)**
- **Warming by atmosphere (Greenhouse effect)**

To calculate the magnitude of greenhouse effect, it is convenient to treat Earth as *blackbody* and define and *effective radiating temperature* T_E as the temperature that a true blackbody would need to radiate the same amount of energy that Earth radiates.

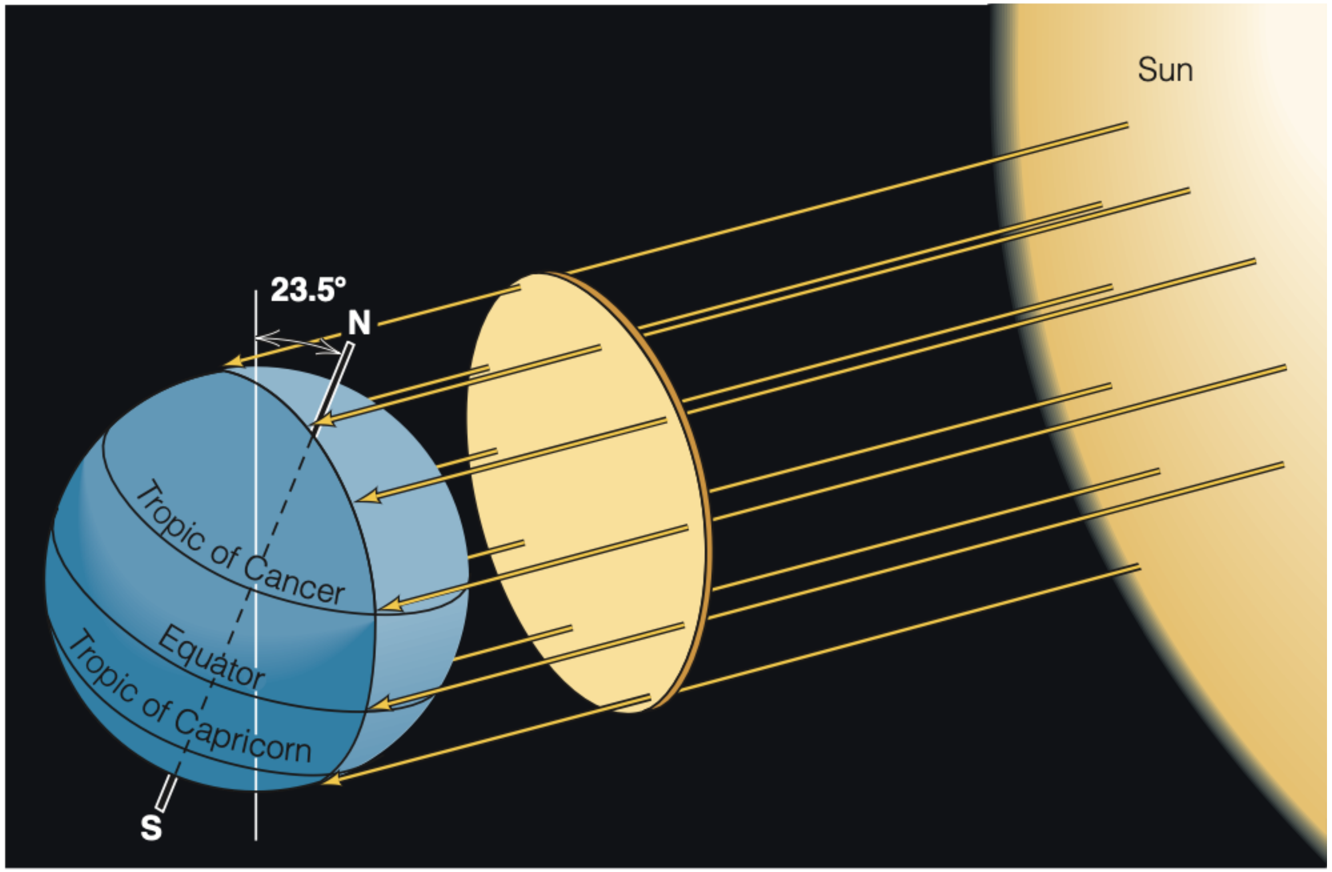
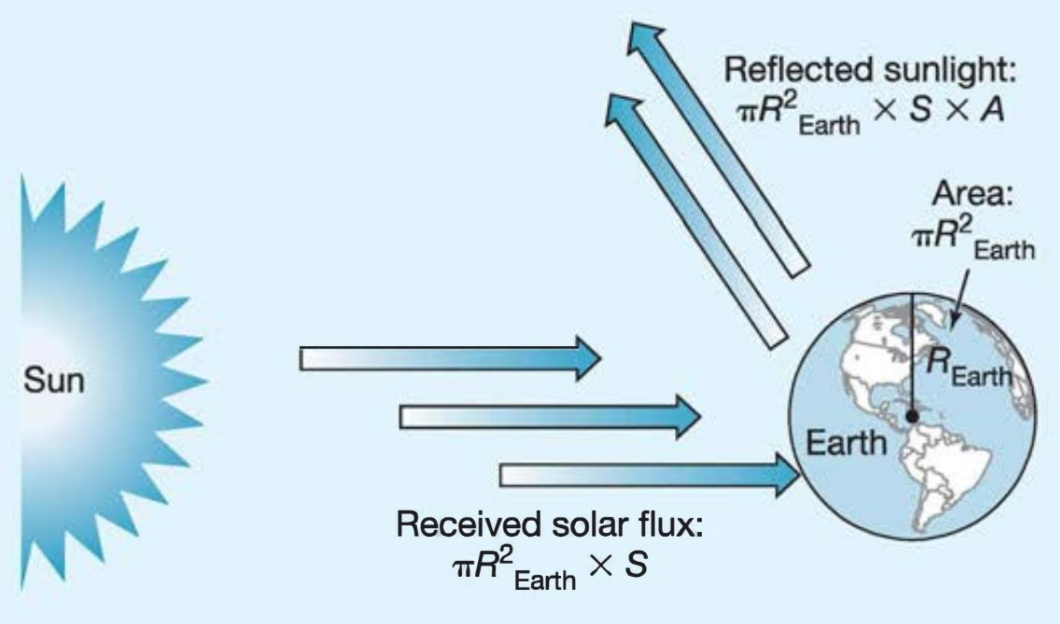


FIGURE 2.5 Solar energy flux
Energy from the Sun passes through an imaginary disc that has a diameter equal to Earth's diameter. The flux of energy through the disc is 1370 watts per square meter. The amount of energy that hits a square meter on Earth's surface is a maximum at the point where the incoming radiation is perpendicular to Earth's surface (that is, where the Sun is directly overhead at midday). This point changes daily because Earth's axis is tilted at 23.5° to the ecliptic, the plane of the solar system.

Global Energy Balance

Planetary energy balance (calculation of the greenhouse effect)



BOX FIGURE 3-1 The amount of sunlight received by and reflected by Earth.

- **Assuming Earth as a blackbody with an effective radiating temperature T_E.**
- **As per the Stefan-Boltzmann law, the total energy emitted by the Earth is $\sigma T_E^4 \times 4\pi R_{Earth}^2$.**

- **From the sun, Earth appears as a circle with radius R_{Earth}. The area projected against the sun rays is πR_{Earth}^2.**
- **Therefore, the total incident energy is $=$ Solar flux$(S) \times \pi R_{Earth}^2$**
- **Reflected energy $= incident\ energy \times albedo = S\pi R_{Earth}^2 \times A$.**
- **Therefore, energy absorbed = incident energy – reflected energy $\pi R_{Earth}^2 S(1-A)$.**

If we assume, Energy emitted by the Earth = Energy absorbed by the Earth, then

$$\sigma T_E^4 = \frac{S}{4}(1-A).$$

Global Energy Balance

Planetary energy balance (calculation of the greenhouse effect)

Let's use the known value for the Earth, $S = 1366\frac{W}{m^2}$, $A = 30\%\ (or\ 0.3)$, and $\sigma = 5.67 \times 10^{-8} W m^{-2} K^{-4}$.

$$T_E = \left(\frac{S}{4\sigma}(1 - A)\right)^{\frac{1}{4}} = 255\mathrm{K} = -18℃.$$

Therefore, the magnitude of the greenhouse effect is

$$\Delta T_g = T_{surface} - T_{Earth} = 15℃ - (-18℃) = 33℃.$$

Global Energy Balance

Planetary energy balance (For Venus and Mars)

- For Venus, $S \approx 2642.8 \frac{W}{m^2}, A = 0.8,$ So $T_{Venus} = 219.7$ K
- For Mars, $S \approx 593.0 \frac{W}{m^2}, A = 0.22,$ So $T_{Mars} = 212.5$ K

FIGURE 3-1 Venus, Earth, and Mars, shown roughly to scale. (*Source:* NASA (left and center) and Photodisc/Getty Images (right).)

Why $T_{Venus} \approx 220\text{K} < T_E = 255\text{K}$?

The high value of albedo for Venus causes much of the radiation to be reflected. As a result, the effective temperature is lower than the expected.

Global Energy Balance

Atmospheric Composition and Structure

Table 3-2 Major Constituents of Earth's Atmosphere Today

Name and Chemical Symbol	Concentration (% by volume)
Nitrogen, N_2	78
Oxygen, O_2	21
Argon, Ar	0.9
Water vapor, H_2O	0.00001 (South Pole)–4 (tropics)
Carbon dioxide, CO_2	0.039*

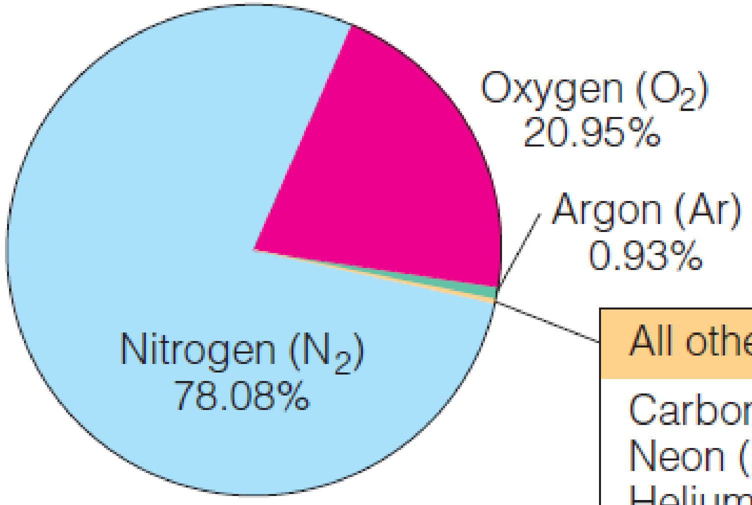
*In 2008.

Table 3-3 Important Atmospheric Greenhouse Gases

Name and Chemical Symbol	Concentration (ppm by volume)
Water vapor, H_2O	0.1 (South Pole)–40,000 (tropics)
Carbon dioxide, CO_2	390
Methane, CH_4	1.7
Nitrous oxide, N_2O	0.3
Ozone, O_3	0.01 (at the surface)
Freon-11, CCl_3F	0.00026
Freon-12, CCl_2F_2	0.00048

Global Energy Balance

Atmospheric Composition and Structure



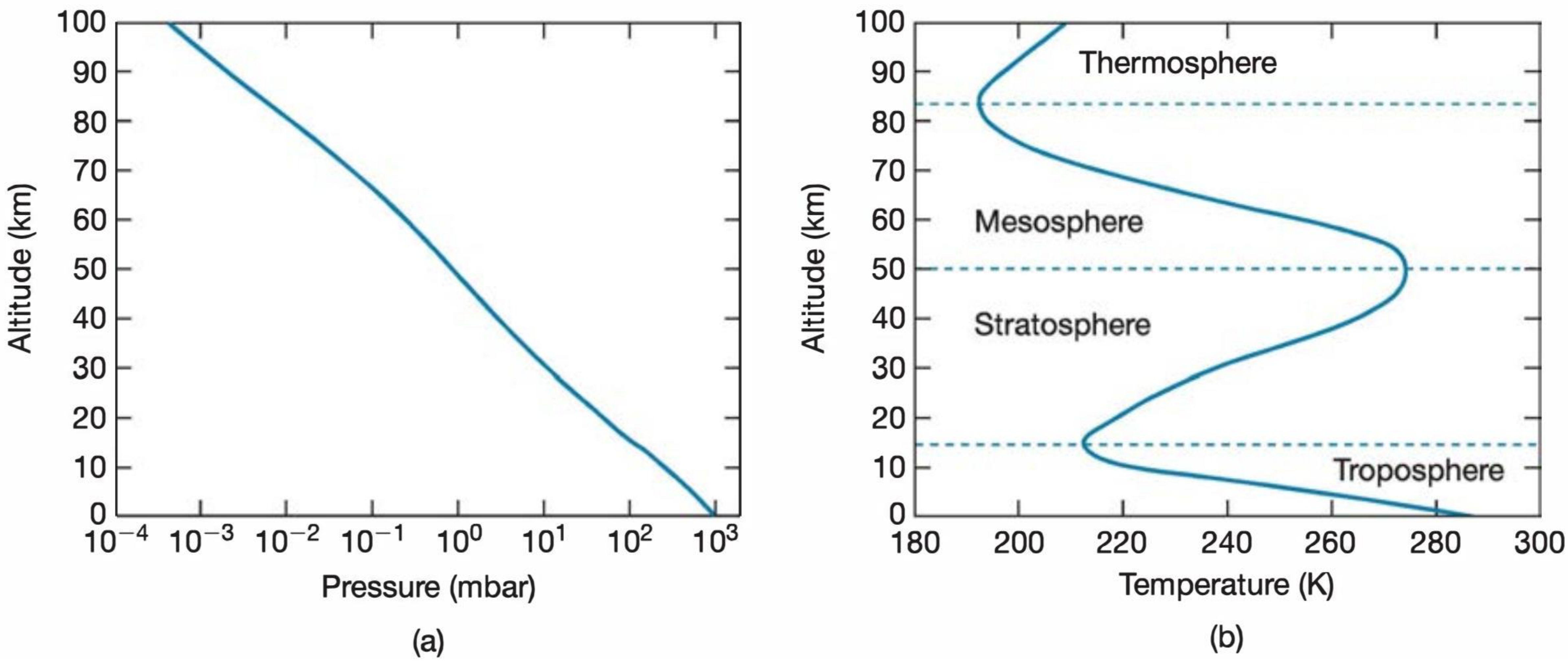
All other gases, 0.04%	
Carbon dioxide (CO_2)	0.035%
Neon (Ne)	0.0018%
Helium (He)	0.00052%
Methane (CH_4)	0.00014%
Krypton (Kr)	0.00010%
Nitrous oxide (N_2O)	0.00005%
Hydrogen (H_2)	0.00005%
Ozone (O_3)	0.000007%

Variable substances	
Water vapor (H_2O) Aerosols	1-4% variable

FIGURE 11.5 What air is made of
Air contains two substances whose concentration varies from place to place and day to day: water vapor and aerosols. The rest of the atmosphere consists primarily of nitrogen and oxygen, with small amounts of other gases.

Global Energy Balance

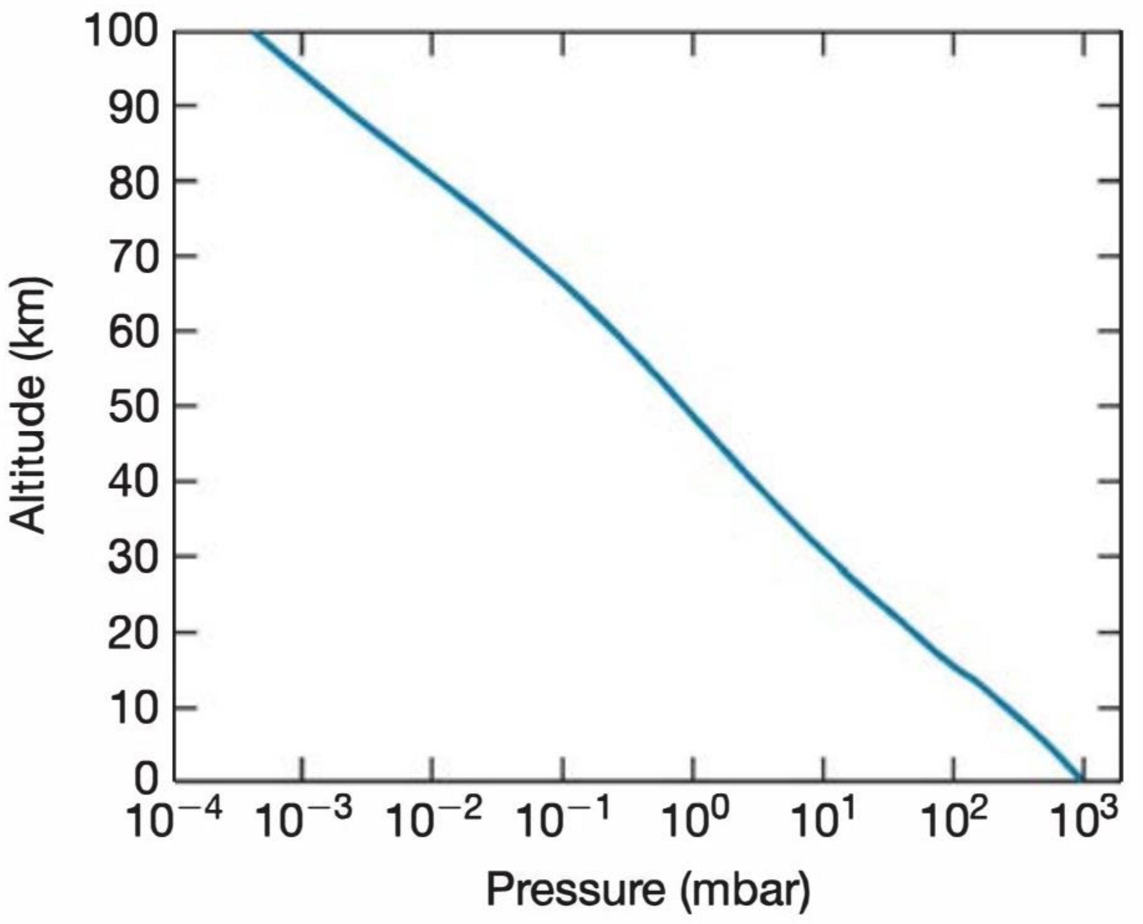
Atmospheric pressure and temperature variation.

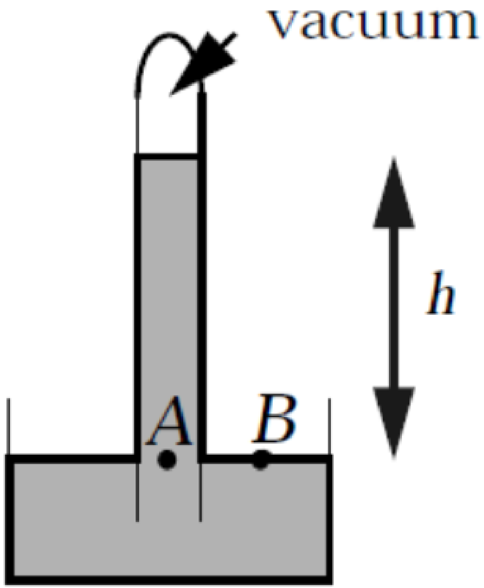


- **Note that the pressure profile is NOT A LINEAR function of altitude.**

Global Energy Balance

Atmospheric pressure variation





$P_A = \rho_{Hg} g h.$
$\rho_{Hg} = 13.6\ g/cm^3.$
At sea level, $h = 76\ cm.$
$g = 9.8\ m/s^2.$
Therefore, sea level pressure
$P_A = 1.013 \times 10^5 kgm^{-1}s^{-2}.$

$$\mathbf{1\ atm = 1.013\ bar = 1013\ mbar}$$

In SI Unit, pressure unit is *pascal, Pa*.

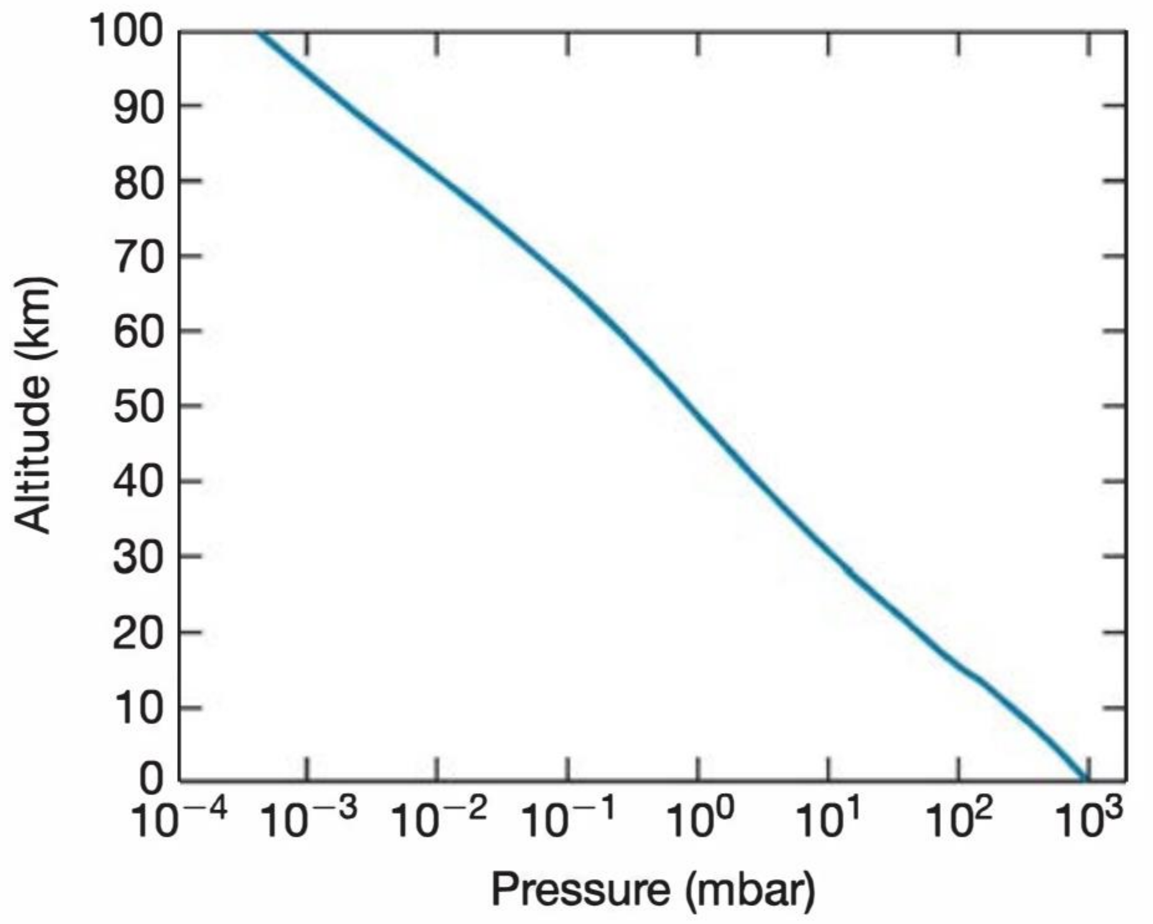
$$\mathbf{1\ Pa = 1\ kgm^{-1}s^{-2} = 1 \times 10^{-5} bar}$$

Barometric formula:

$$\boldsymbol{P(h) = P(0)exp\left(-\frac{Mgh}{RT}\right).}$$

Global Energy Balance

Atmospheric pressure variation



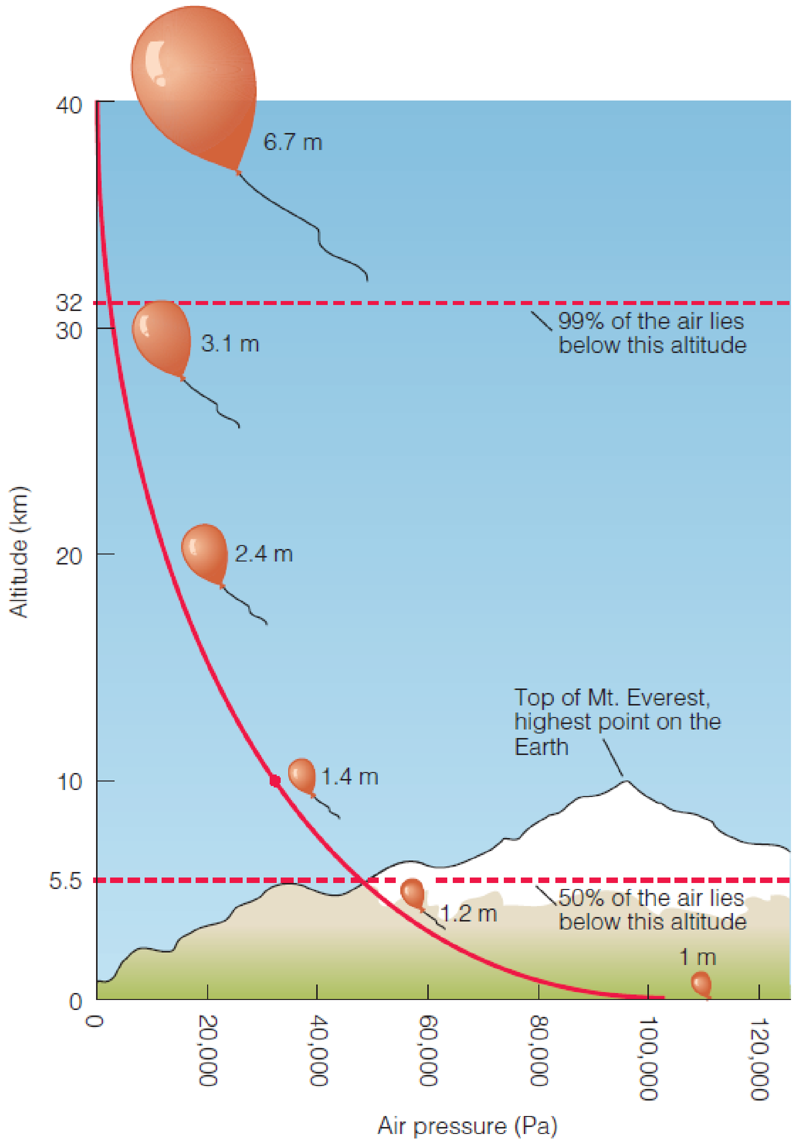
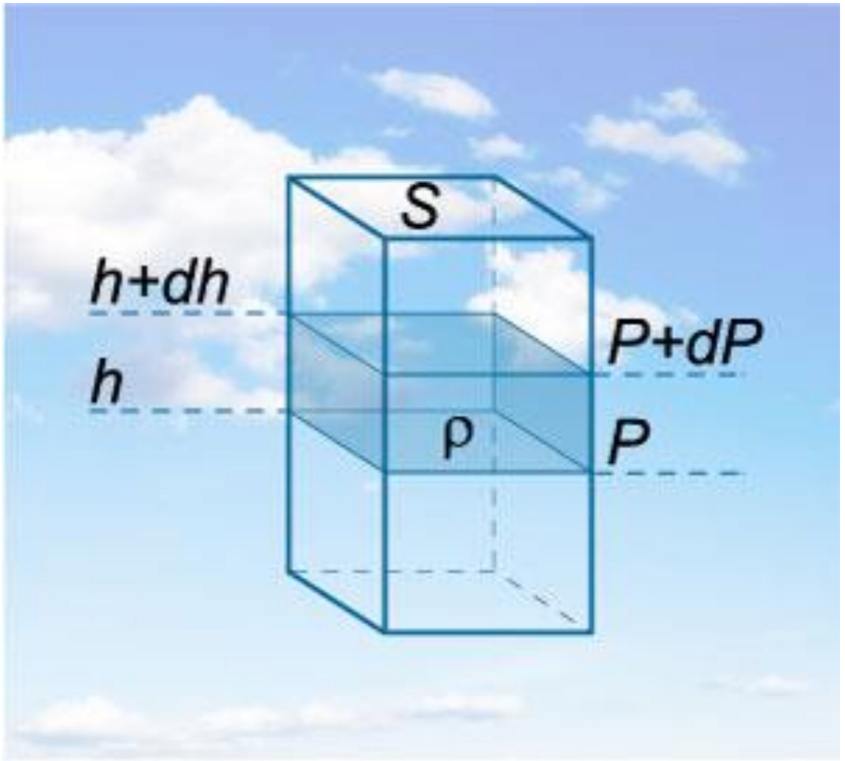


FIGURE 11.13 Change in air pressure with altitude
Air pressure decreases smoothly with altitude. If a helium balloon 1 m in diameter is released at sea level, it expands as it floats upward because of the pressure decrease. If the balloon did not burst, it would be 6.7 m in diameter at a height of 40 km.

Global Energy Balance

Atmospheric pressure



$$dP = -\rho g \, dh$$

Considering atmospheric air as an ideal gas,

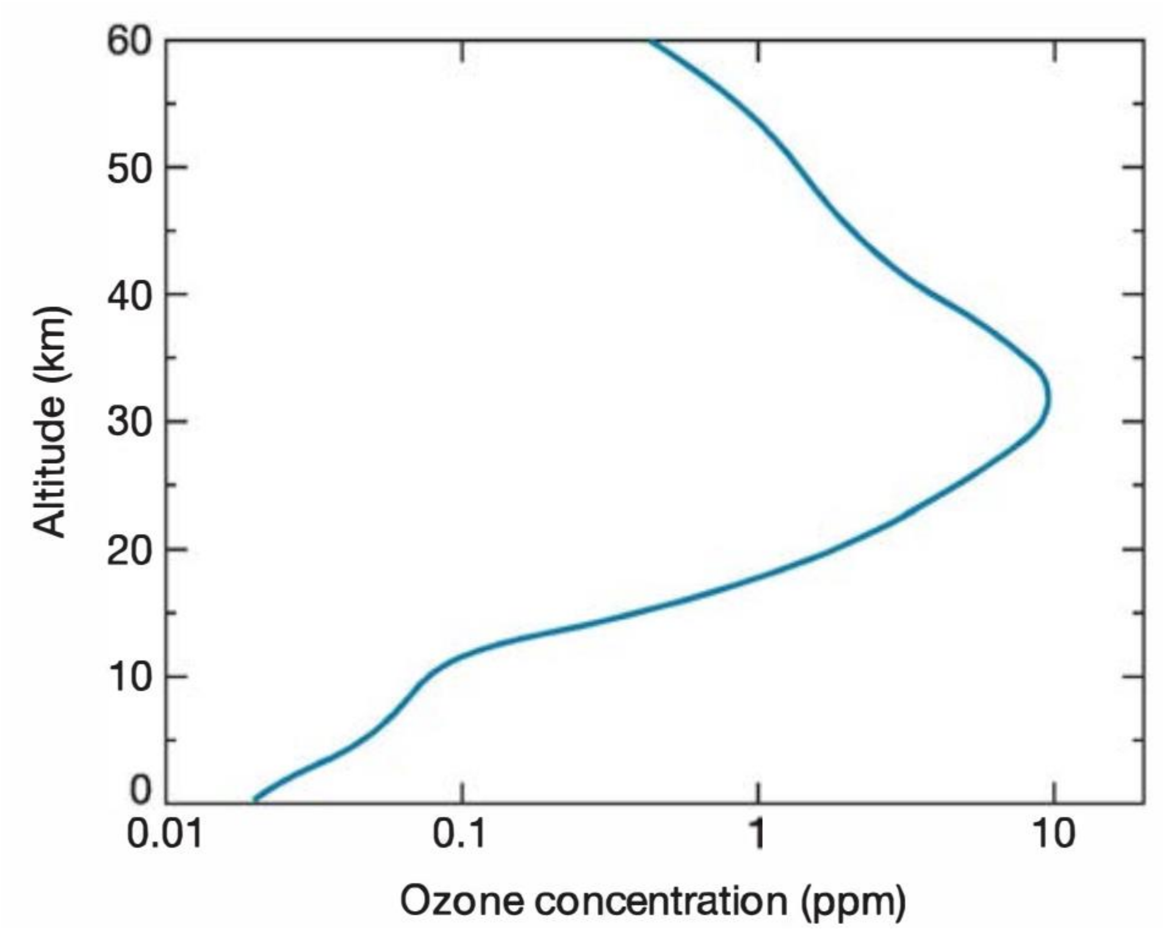
$$PV = nRT = \frac{m}{M}RT \Rightarrow P = \frac{m}{MV}RT = \frac{\rho}{M}RT$$

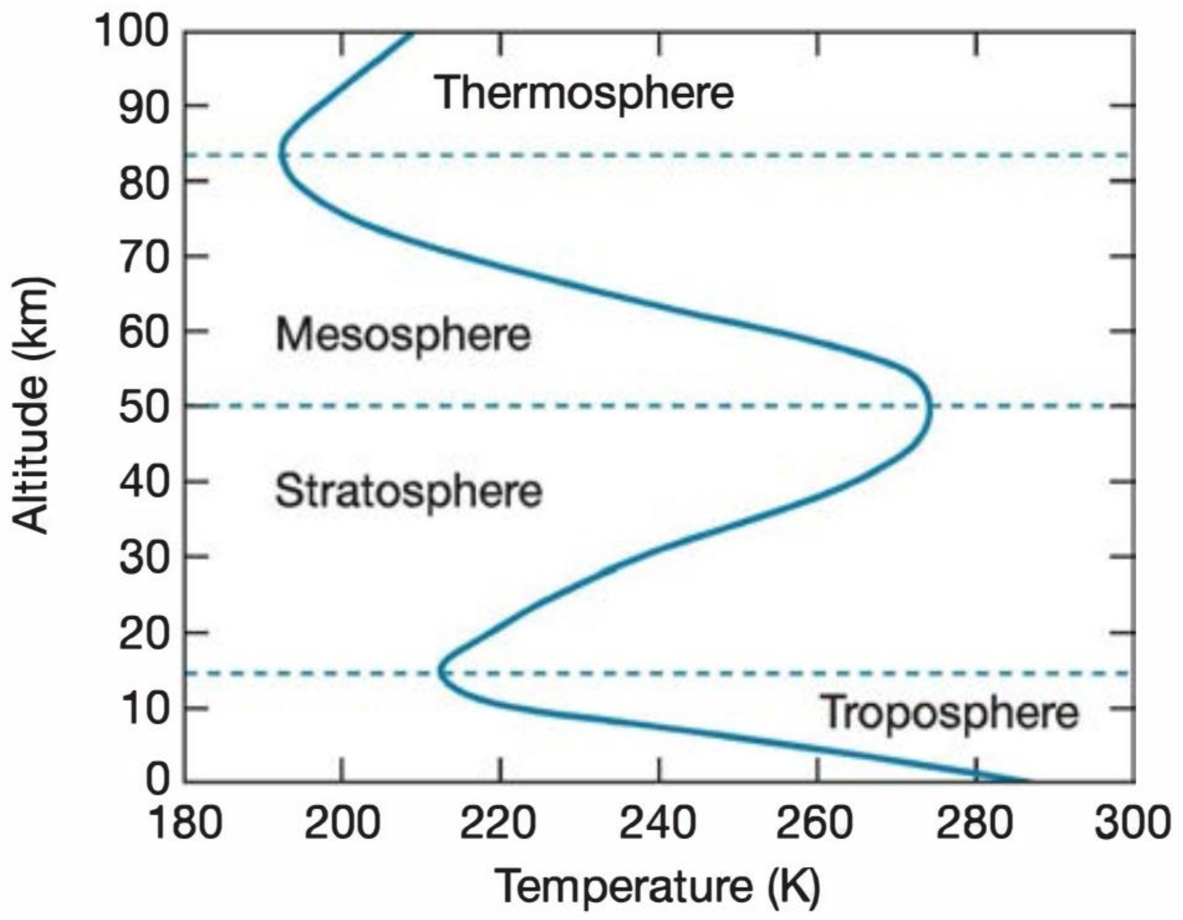
Therefore, $dP = -\frac{PM}{RT} g \, dh \Rightarrow \frac{dP}{P} = -\frac{Mg}{RT} dh$

$$P(h) = P(0)exp\left(-\frac{Mgh}{RT}\right).$$

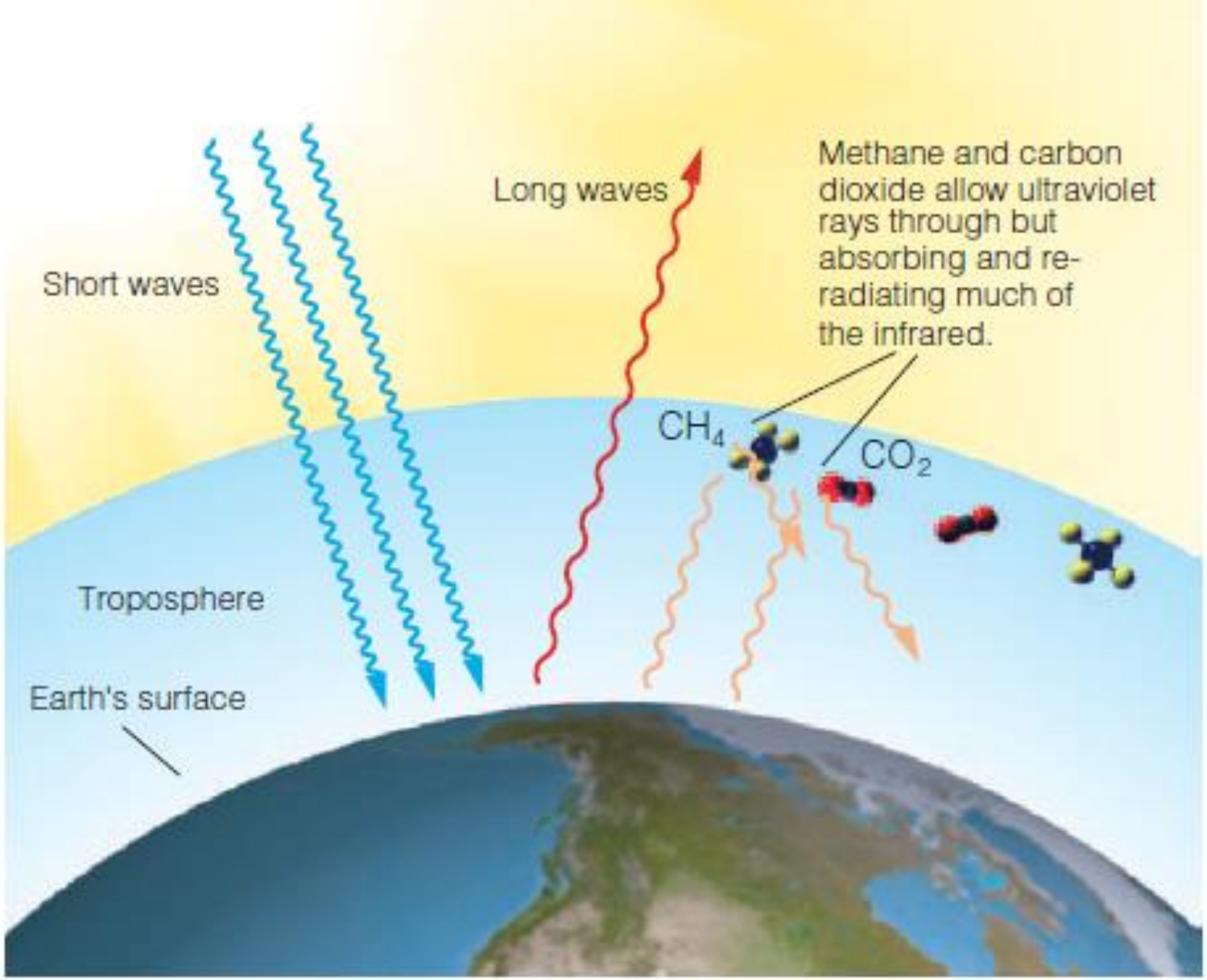
Global Energy Balance

Atmospheric temperature variation





➢ **Ozone concentration peaks around 30 km.**


Short waves
Long waves
Methane and carbon dioxide allow ultraviolet rays through but absorbing and re-radiating much of the infrared.
CH_4
CO_2
Troposphere
Earth's surface

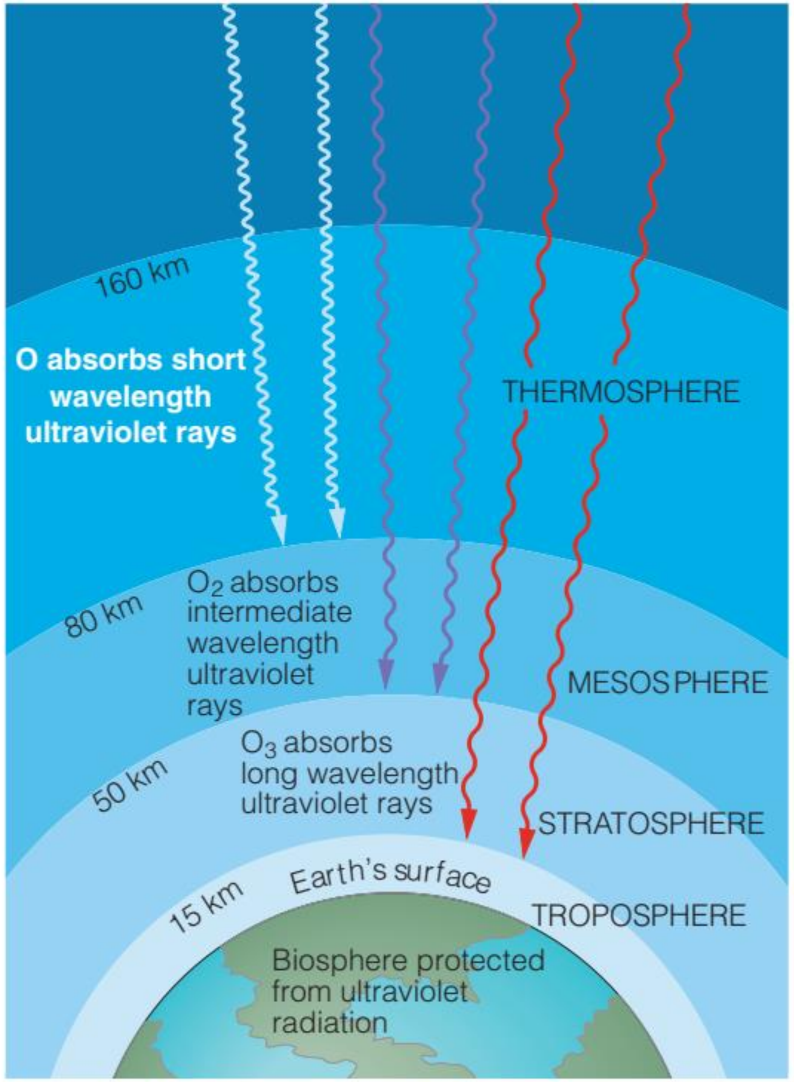
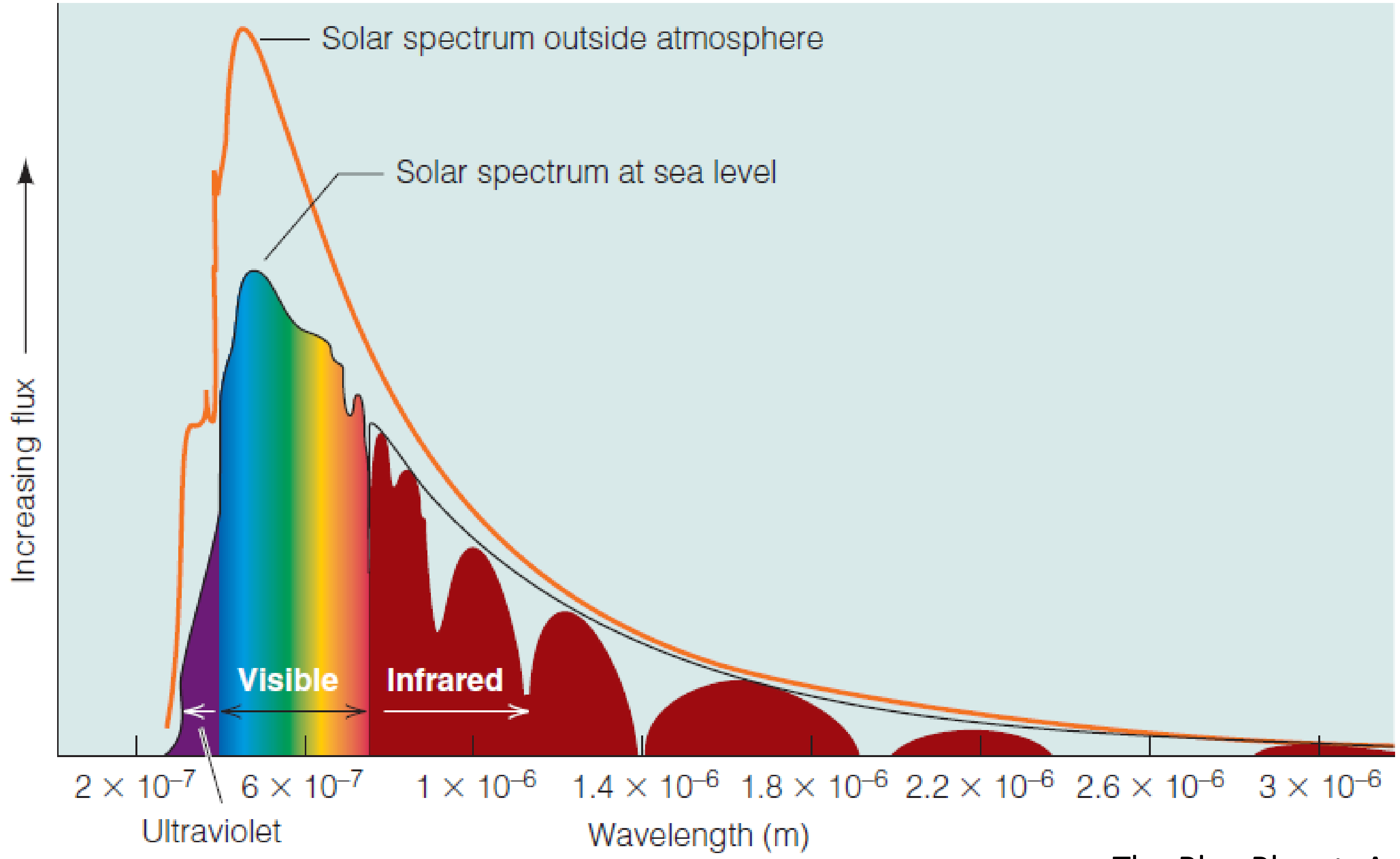


FIGURE 11.7 A shield against harmful radiation
Ultraviolet radiation coming from the Sun can be harmful or lethal; generally speaking, the shorter the wavelength, the more harmful the radiation. Fortunately, the atmosphere protects us from almost all these rays because they are absorbed by three kinds of oxygen—O, O_2, and O_3 (ozone).

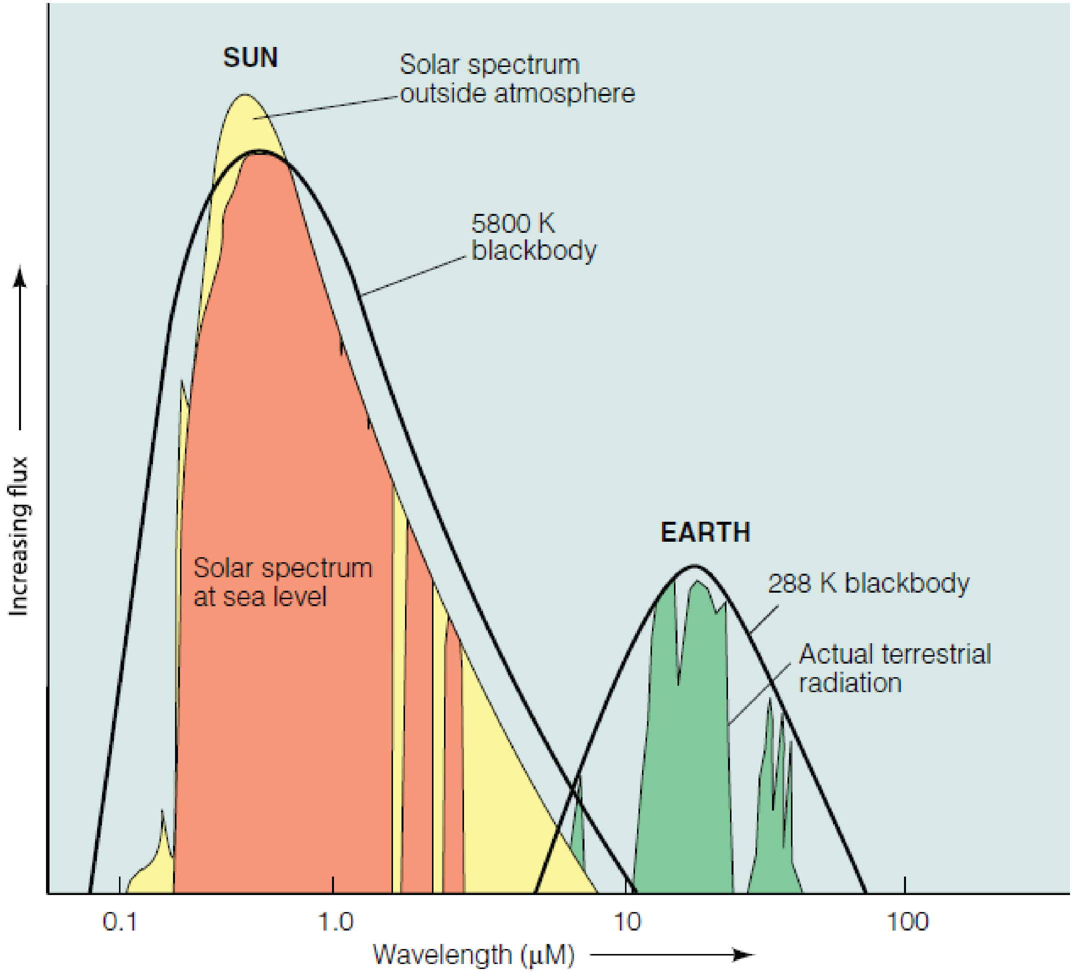
FIGURE 2.8 **Outer-space and sea-level spectra**

The outer-space spectral curve for the Sun is different from the sea-level spectral curve, because gases in Earth's atmosphere selectively absorb some of the wavelengths of solar radiation. Notably, ozone (O_3) in the stratospheric ozone layer absorbs radiation in the very short-wavelength (ultraviolet) portion of the Sun's spectrum, thus preventing some of the highest energy and most biologically harmful solar energy from reaching the surface.



The Blue Planet: An Introduction to Earth System Science, 3rd Ed by Skinner and Murck

FIGURE 2.12 Solar and terrestrial spectra
The spectra of the Sun and Earth are different because they are radiating at different temperatures. Shown are the smooth curves for perfect blackbody radiators at the relevant temperatures. The "actual" curves differ from the "ideal" curves (in black) principally because of absorption of radiation in certain wavelengths by Earth's atmosphere.



The Blue Planet: An Introduction to Earth System Science, 3rd Ed by Skinner and Murck

Global Energy Balance

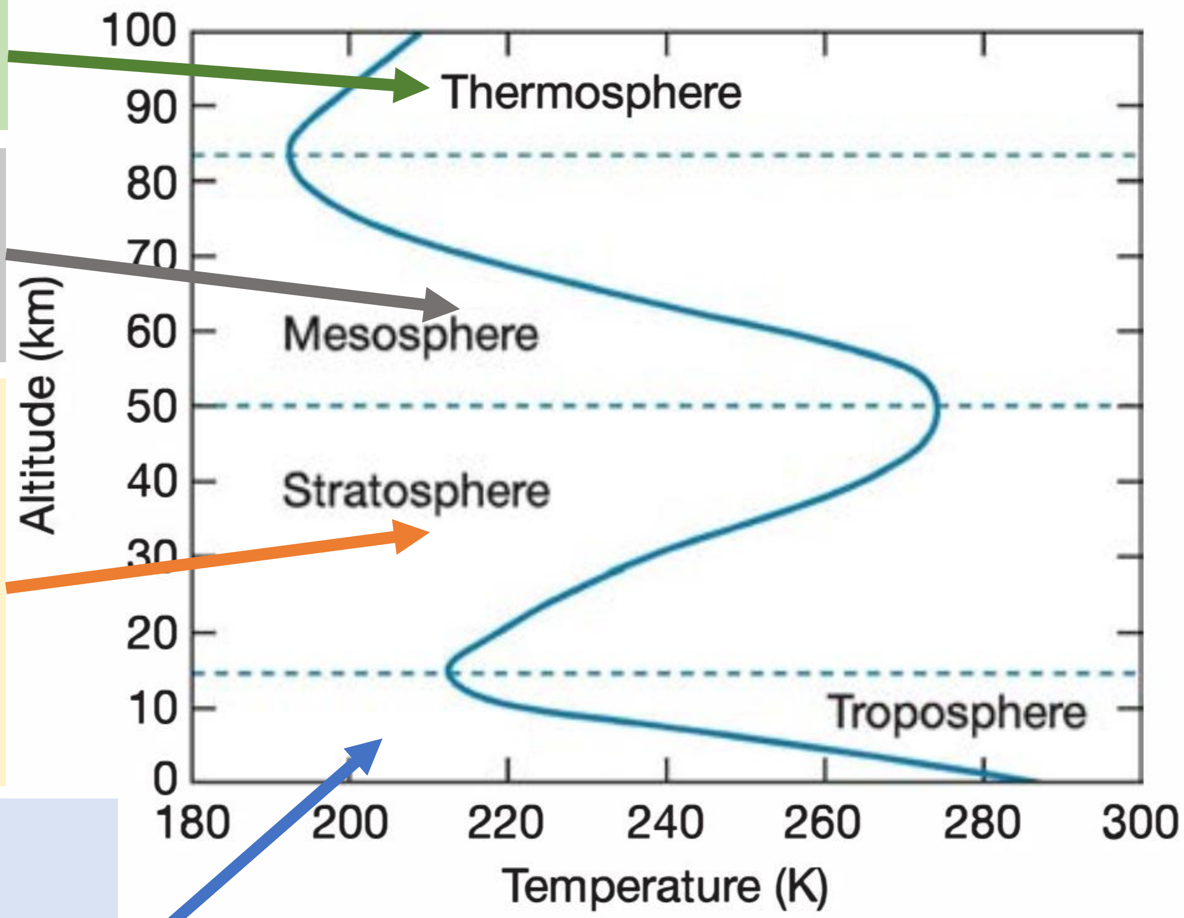
Atmospheric temperature variation

- The rise of temperature in thermosphere is caused by absorption of short-wavelength UV radiation.

- Ozone concentration decreases significantly, so is the heating rate. So temperature decreases rapidly in mesosphere.

- Pressure is substantially lower.
- Most of the Earth's ozone is here.
- No convection, so air is almost stratified.
- Solar UV radiation is absorbed.
- Heating rate is highest in upper part as more UV radiation is available.

- Weather: clouds, rain, snow, and storm.
- Heat energy is transported through ***convection.***
- Almost half of the incoming sun light is absorbed and reradiated to space as IR radiation, which is absorbed by greenhouse gases and clouds.



Global Energy Balance

Atmospheric temperature variation

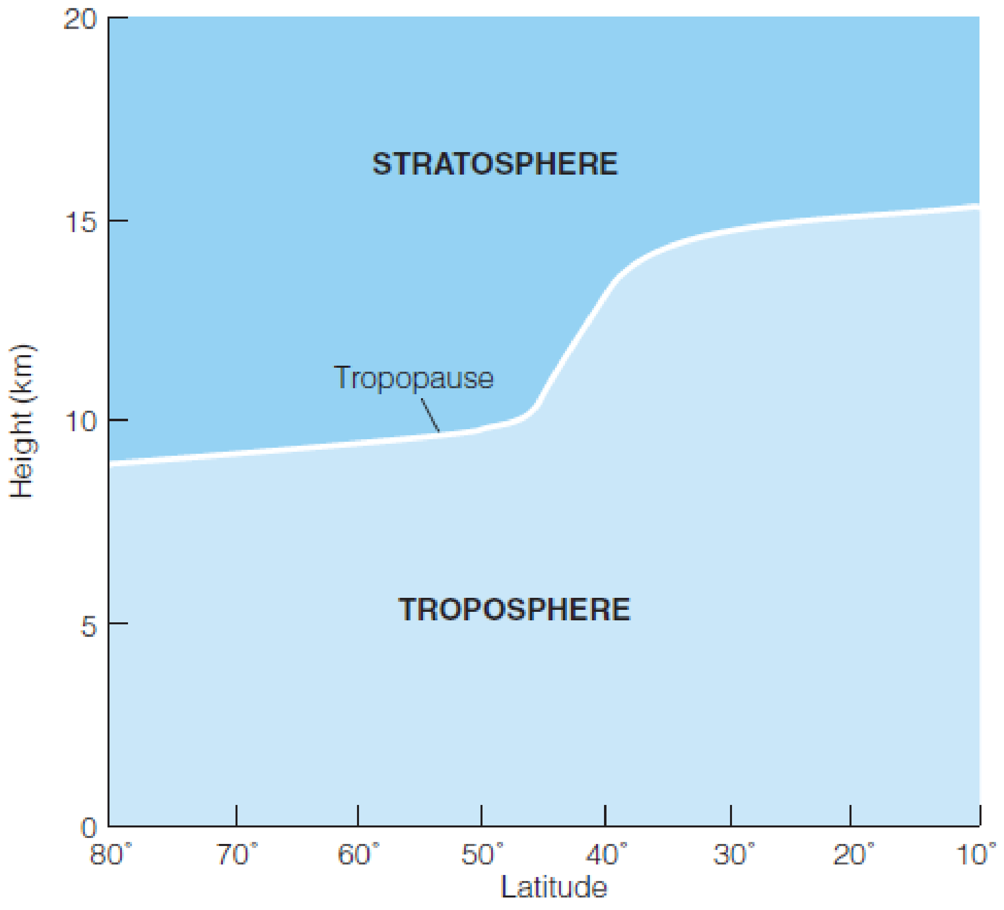
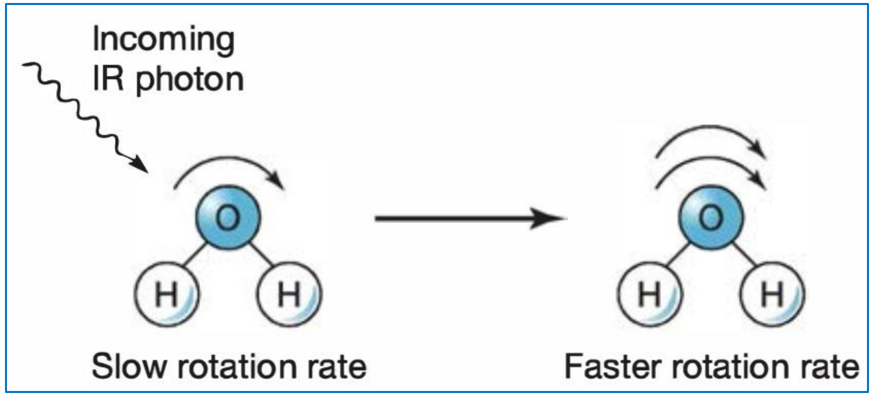


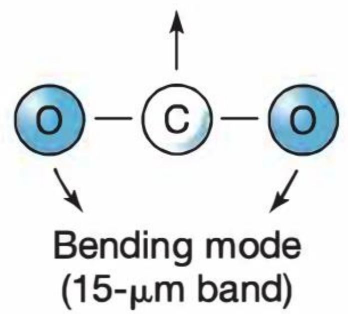
FIGURE 11.9 Altitude of the tropopause
The altitude of the tropopause varies with latitude. It is high from the equator to about 40° latitude, where it drops precipitously, continuing at this lower level and declining gently toward the poles. The precipitous drop at 40° latitude facilitates the development of jet streams.

Global Energy Balance

Physical causes of the greenhouse effect

- As we estimated before, the magnitude of greenhouse effect is ~33°C and this warming has been attributed to the presence of mainly H_2O and CO_2.
- Why do some gases contribute to the greenhouse effect whereas others, such as O_2 and N_2 do not?
- Gas molecules can absorb or emit radiation in the IR range by changing the rate of **(1) rotation, and (2) vibration.**





H_2O rotation band ($12\ \mu m$ and longer)

Bending vibration mode ($15\ \mu m\ CO_2$ Band)

Global Energy Balance

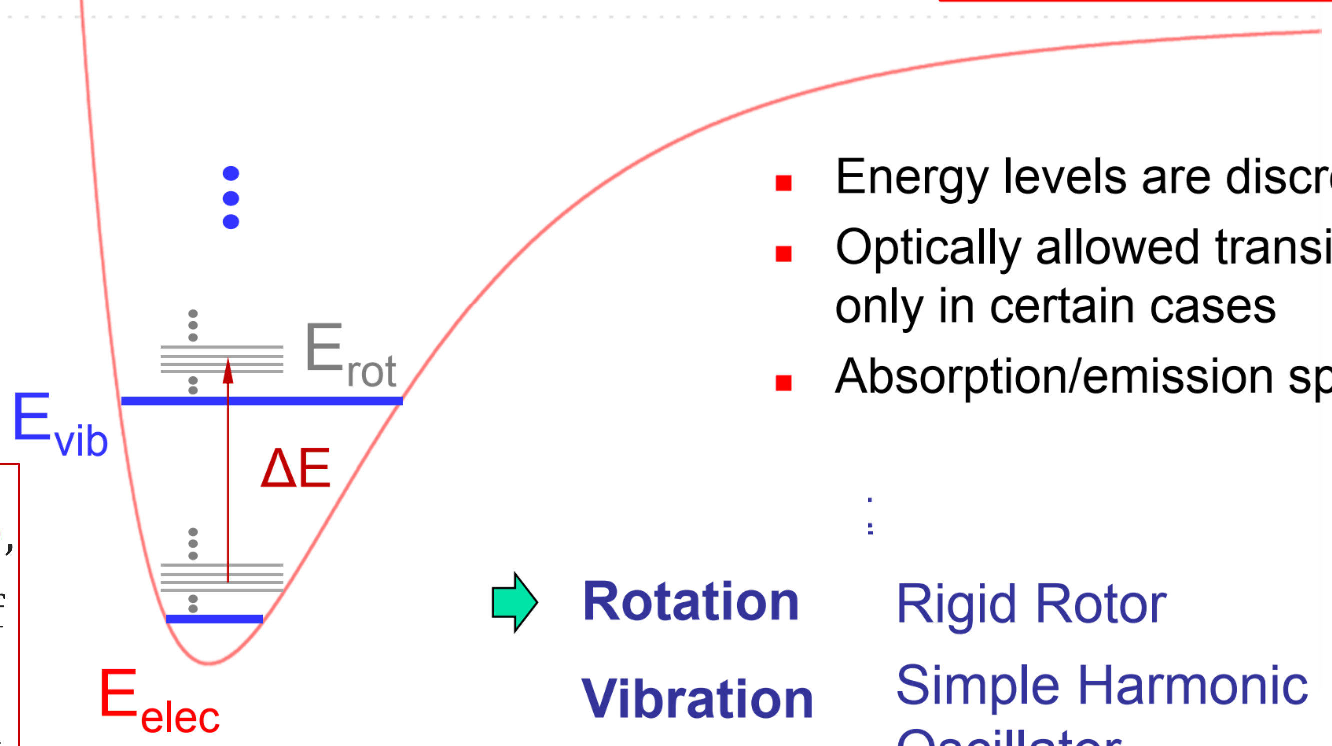
Physical causes of the greenhouse effect

➢ Gas molecules can absorb or emit radiation in the IR range by changing the rate of **(1) rotation, and (2) vibration.**

$E_{int} = E_{elec}(n) + E_{vib}(\nu) + E_{rot}(J)$

$\boxed{\Delta E_{rot} < \Delta E_{vib} < \Delta E_{elec}}$

$$\boxed{E_{vib} = \left(n + \frac{1}{2}\right) h\nu}$$



- Energy levels are discrete
- Optically allowed transitions may occur only in certain cases
- Absorption/emission spectra are discrete

$$E_{rot} = \frac{h^2}{8\pi^2 I} J(J+1),$$
where I is moment of inertia of rotor and J is rotational quantum number.

➡	**Rotation**	Rigid Rotor
	Vibration	Simple Harmonic Oscillator

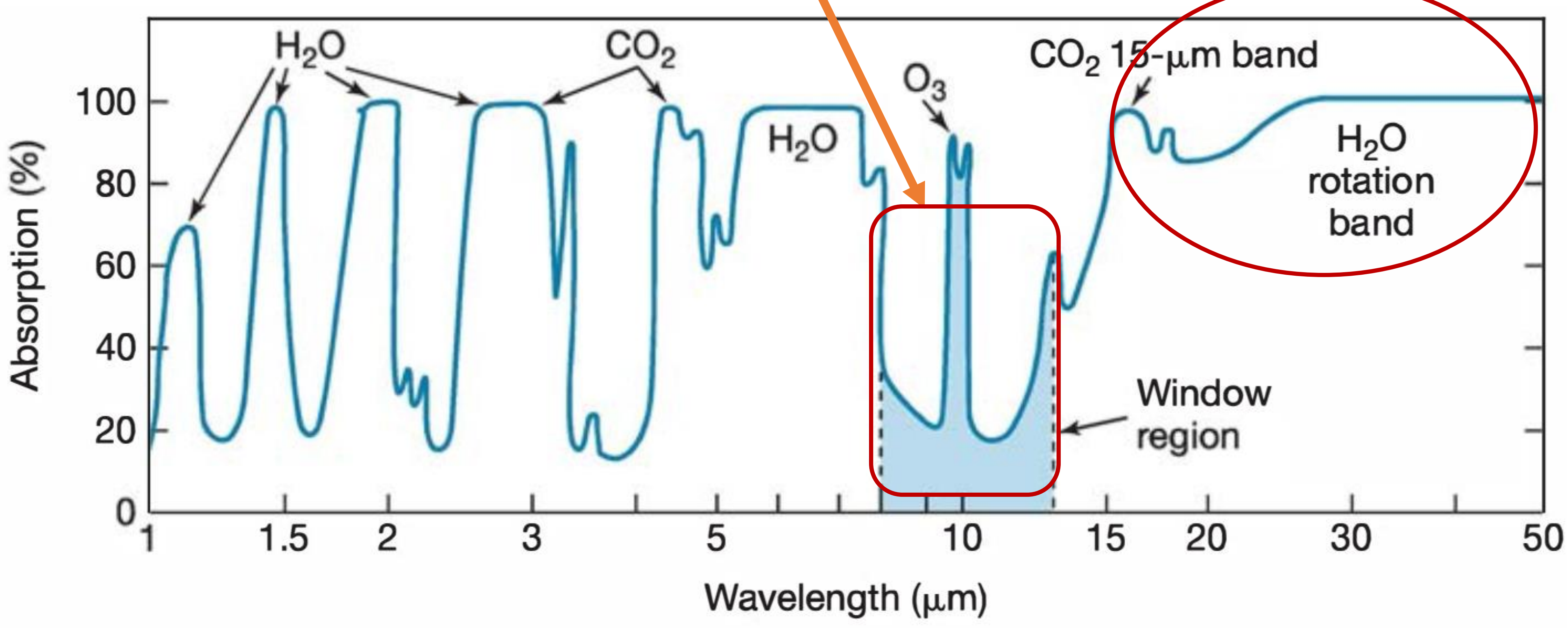
From Hanson notes, Princeton

Global Energy Balance

Physical causes of the greenhouse effect

Freons absorption band is within 8-12 μm range

Near –total absorption by water vapor and CO_2.



Percentage of radiation absorbed during vertical passage through atmosphere.

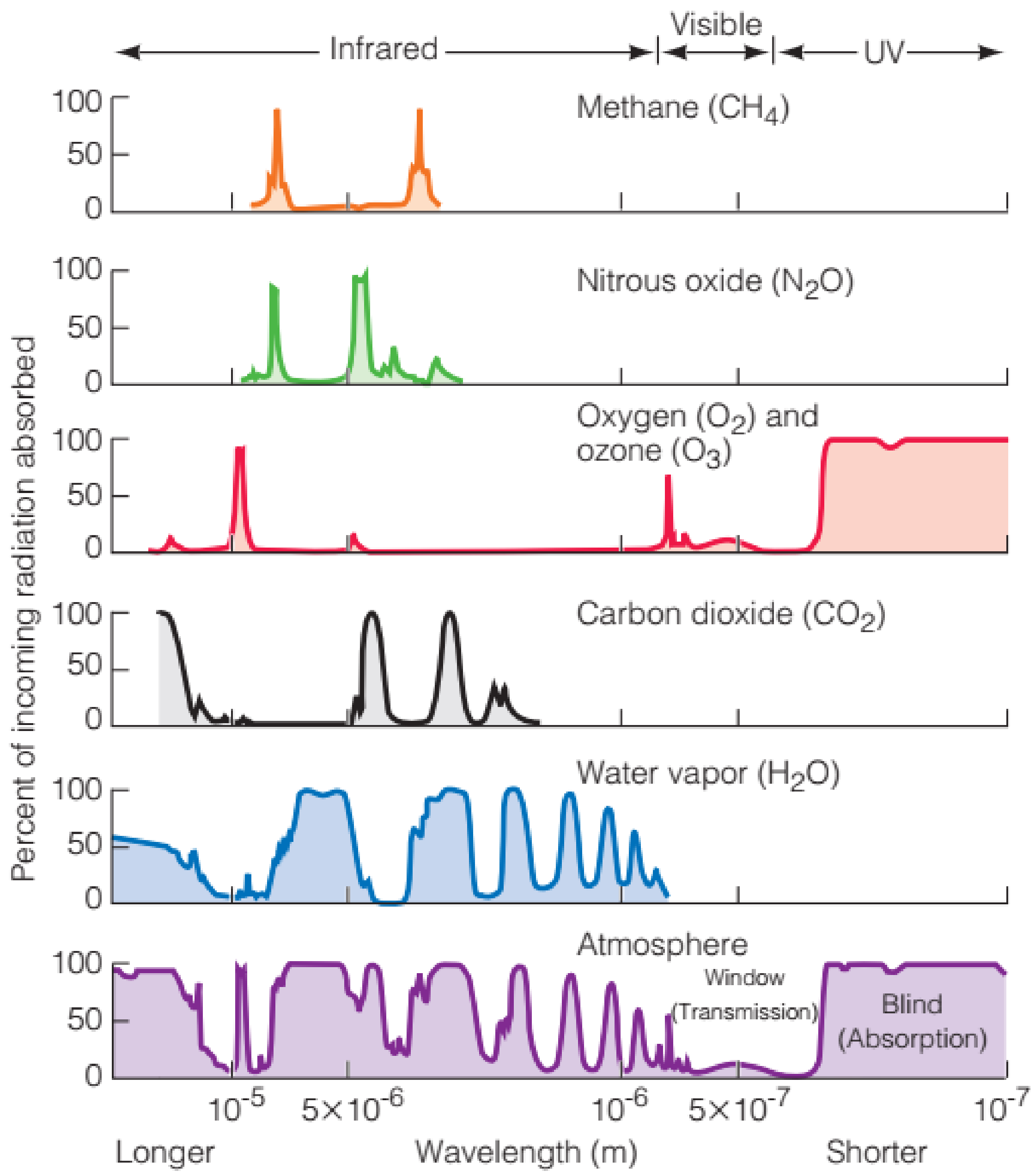


FIGURE B11.1 Atmospheric windows and blinds Some wavelengths of electromagnetic radiation are transmitted easily through the atmosphere; there is an atmospheric window for those wavelengths of light. For example, there is an atmospheric window for light in the visible portion of the spectrum. Other wavelengths of electromagnetic radiation do not pass through the atmosphere because they are absorbed by atmospheric gases; there is an atmospheric window for those wavelengths of light. For example, ozone (along with some other gases) absorbs electromagnetic radiation in the ultraviolet part of the spectrum, creating an atmospheric blind.

Global Energy Balance

Physical causes of the greenhouse effect (Solar and terrestrial emission and absorption spectrum)

- H_2O ($12\mu m$ – *and beyond*) and CO_2 ($15\mu m$) bands are fairy near the peak of Earth's outgoing radiation. Earth's surface emits strongly in this wavelength region but very little of it is able to escape directly to space.

- H_2O and CO_2 are the most important greenhouse gases, but several other trace gases: CH_4, N_2O , O_3, and freons have quite a significant contribution in greenhouse effect than their small concentration would otherwise suggest because they absorb at different wavelength than those absorbed by H_2O and CO_2.

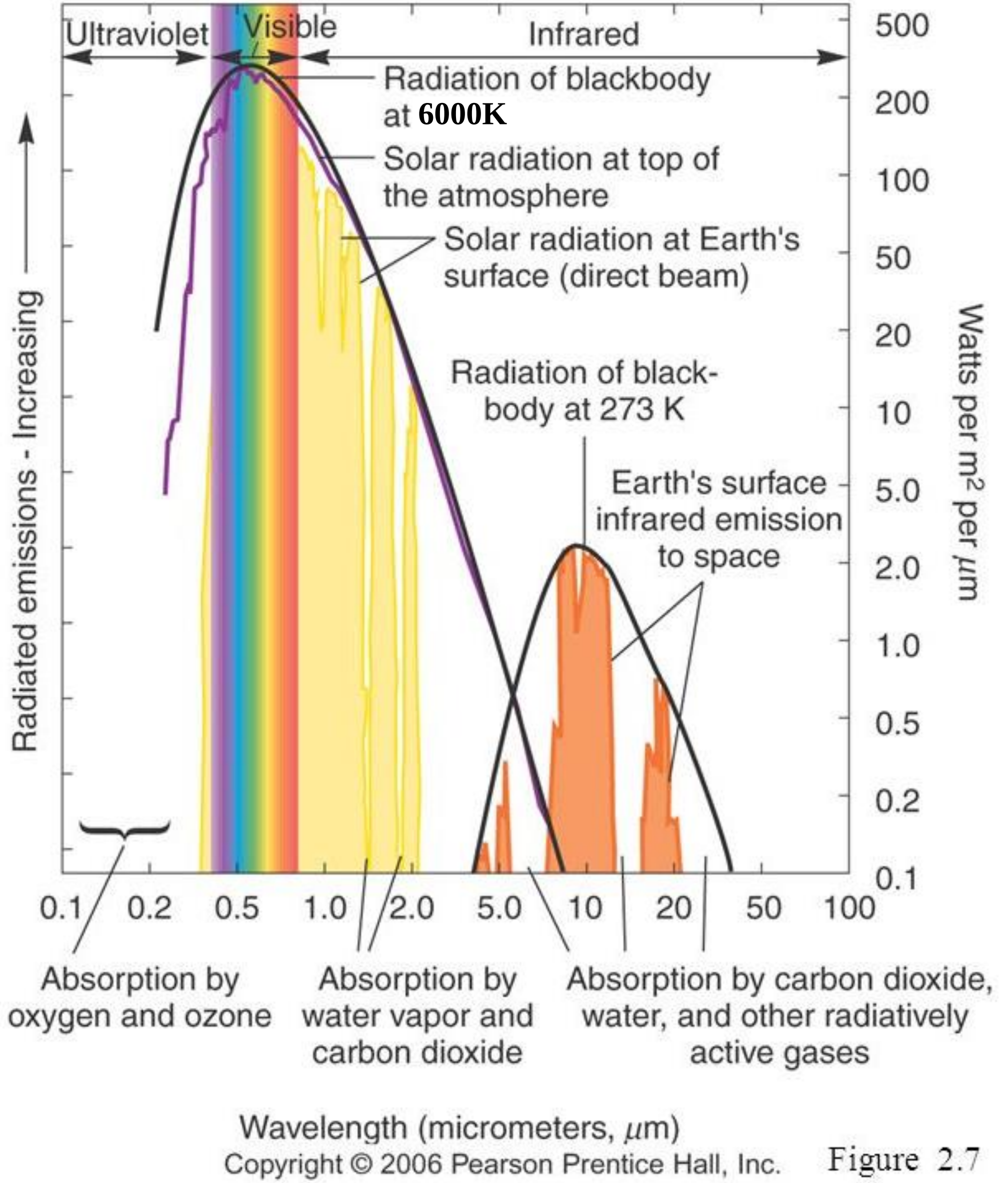


Figure 2.7

Global Energy Balance

Physical causes of the greenhouse effect

Why do some gases contribute to the greenhouse effect whereas others, such as O_2 and N_2 do not?

O_2 and N_2 molecules are perfectly symmetric as both constituents atoms are identical. As a consequence, there is no separation between $+ve$ and $-ve$ charge (no effective dipole moment). Therefore, electromagnetic radiation (oscillating electric and magnetic fields) does not interact with O_2 and N_2 molecules effectively (to a first approximation).

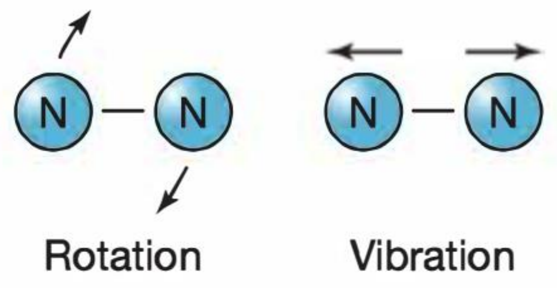


FIGURE 3-15 Rotation and vibration for a diatomic molecule, such as N_2 or O_2.