Topic 2

Energy: Warming the Earth and Atmosphere

Energy and Power

- Energy 能量
  - Traditional definition: The ability to do work (push, pull, lift) on some form of matter
  - SI （International System）Unit: joule（J） 焦耳
- Power 功率
  - The rate at which energy is released, transfer, or received
  - SI （International System）Unit: watt（W） 瓦特
- Solar Radiation
  - Initiates atmospheric motions and weather processes
- Energy balance
  - Earth emits exactly as much energy as it absorbs from the sun - energy balance

Energy and Power

- Energy Classified as
  - *Kinetic* or *potential*
  - Potential energy is the potential for work (mass x gravity x height)
  - Kinetic energy is energy of a moving object (half of mass x velocity squared)

- Heat is the energy in the process of being transferred from one object to another because of a difference in temperature.
- Energy cannot be destroyed or created; First Law of Thermodynamics

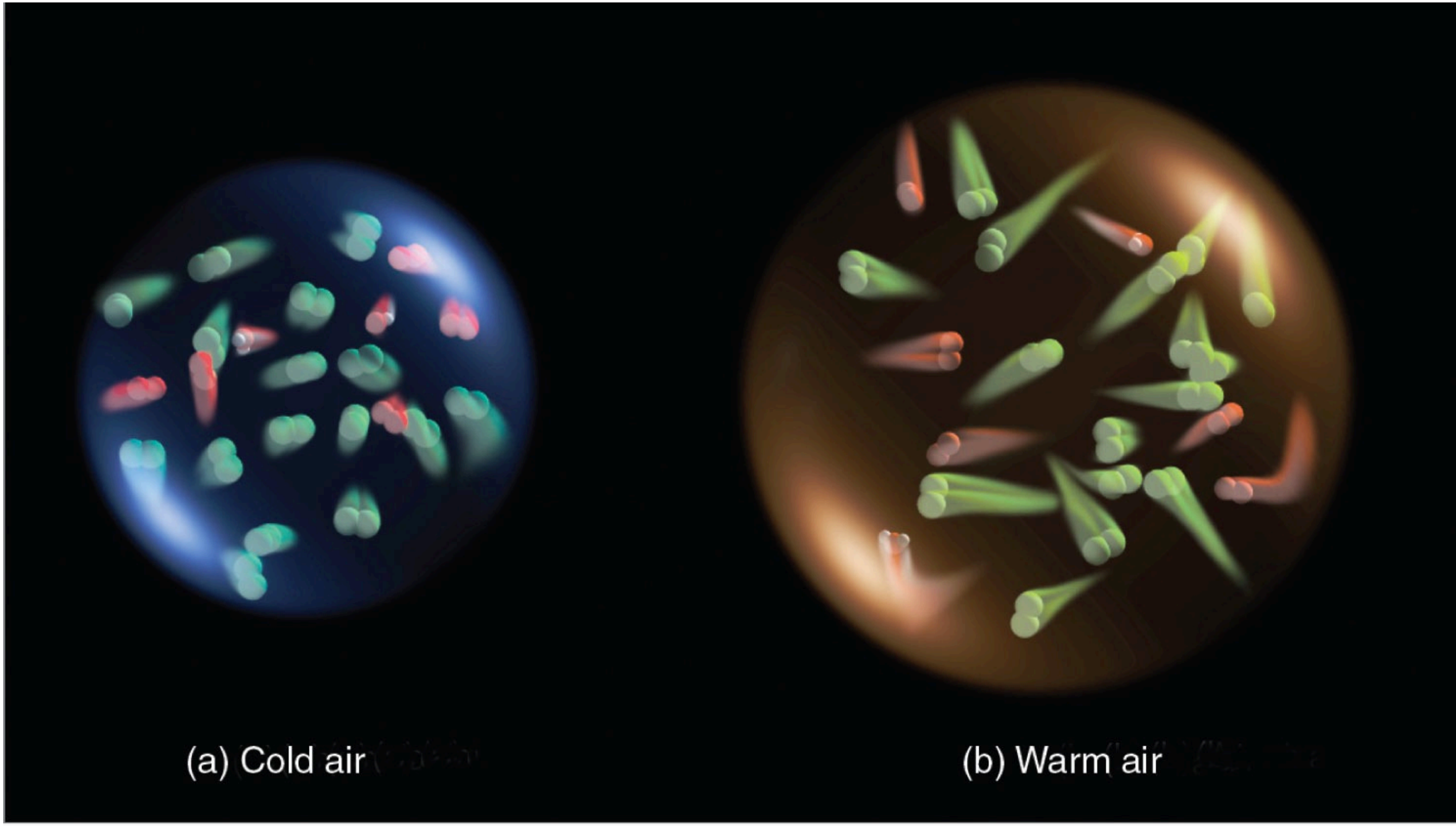
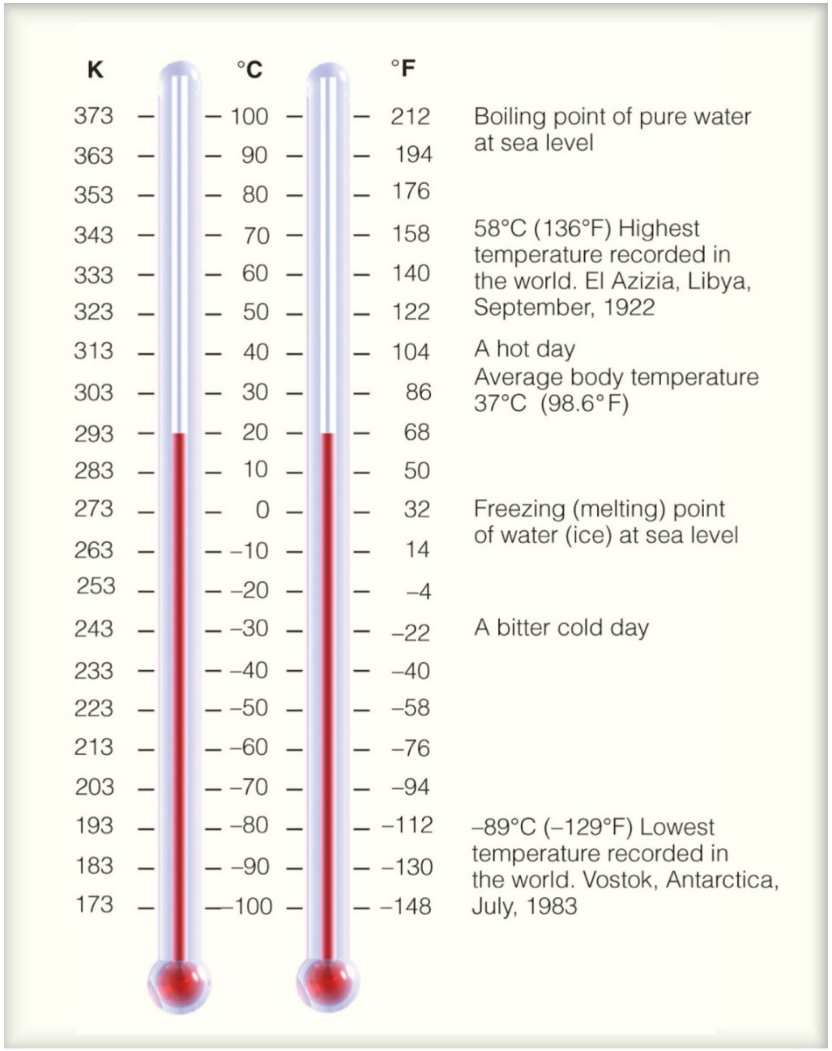


FIGURE 2.1 Air temperature is a measure of the average speed (motion) of the molecules. In the cold volume of air, the molecules move more slowly and crowd closer together. In the warm volume, they move faster and farther apart.

Energy, Temperature, and Heat

- **Temperature** a measure of the level of kinetic energy of the atoms in a substance, in form of gas, liquid, or solid.
- Substance receives a flow of radiant energy, such as sunlight, its temperature rises. If a substance loses energy, its temperature falls.
- Kelvin: absolute; 0K = -273°C



Specific Heat

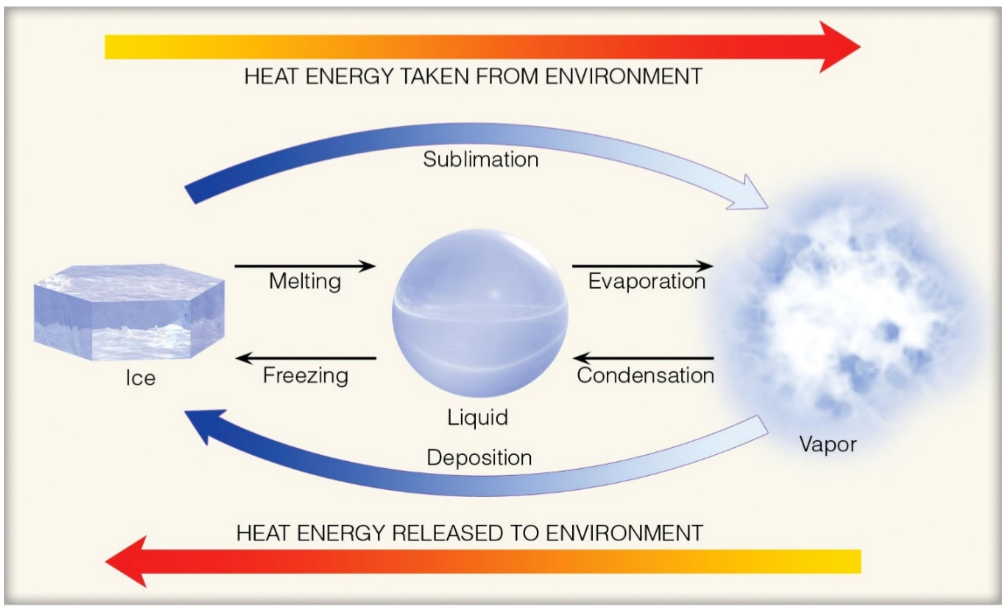
- **Heat capacity** is the heat energy absorbed to raise a substance to a given temperature
- **Specific heat** is the heat capacity divided by mass or the amount of energy required to raise one gram of a substance 1° C
  - High specific heat equals slow warming (and cooling); low specific heat equals fast warming (and cooling)

Table 2.1 Specific Heat of Various Substances

SUBSTANCE	SPECIFIC HEAT (Cal/g × °C)	J/(kg × °C)
Water (pure)	1	4186
Wet mud	0.6	2512
Ice (0°C)	0.5	2093
Sandy clay	0.33	1381
Dry air (sea level)	0.24	1005
Quartz sand	0.19	795
Granite	0.19	794

Latent Heat

- Change of state or phase change represents change between solid, gas, and liquid.
- Latent heat is the energy involved in the change of state.
- Ice to liquid to vapor: absorb energy, cool environment (melt, evaporation, sublimation)
- Vapor to liquid to ice: release energy, heat environment (freeze, condense, deposition)



Energy Transfer Mechanisms

- Conduction 傳導
  - Heat transfers from one molecule to another in a substance

$$F_H = \quad k \quad T$$

    - Heat flux 熱通量(W m^{-2})
    - Thermal conductivity 熱傳導係數 (W m^{-1} K^{-1})
    - Temperature gradient溫度梯度 (K m^{-1})

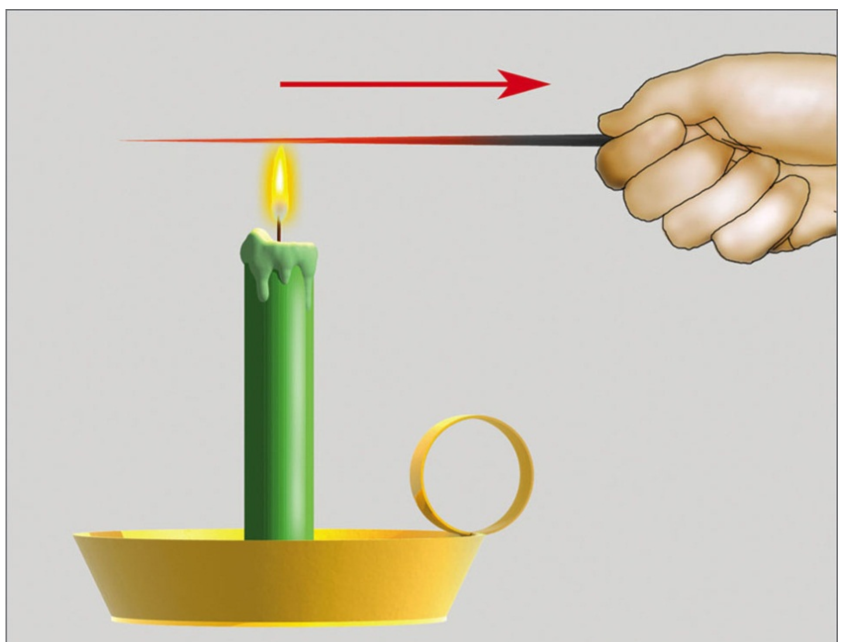


TABLE 2.2 Heat Conductivity* of Various Substances

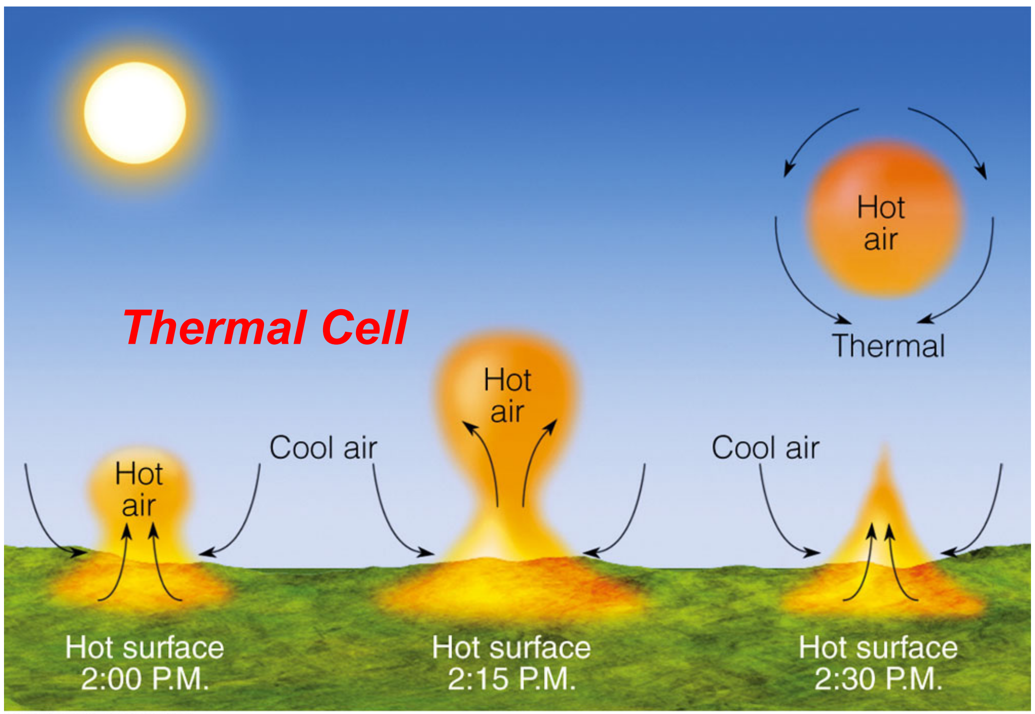
SUBSTANCE	HEAT CONDUCTIVITY (Watts† per meter per °C)
Still air	0.023 (at 20°C)
Wood	0.08
Dry soil	0.25
Water	0.60 (at 20°C)
Snow	0.63
Wet soil	2.1
Ice	2.1
Sandstone	2.6
Granite	2.7
Iron	80
Silver	427

*Heat (thermal) conductivity describes a substance's ability to conduct heat as a consequence of molecular motion.

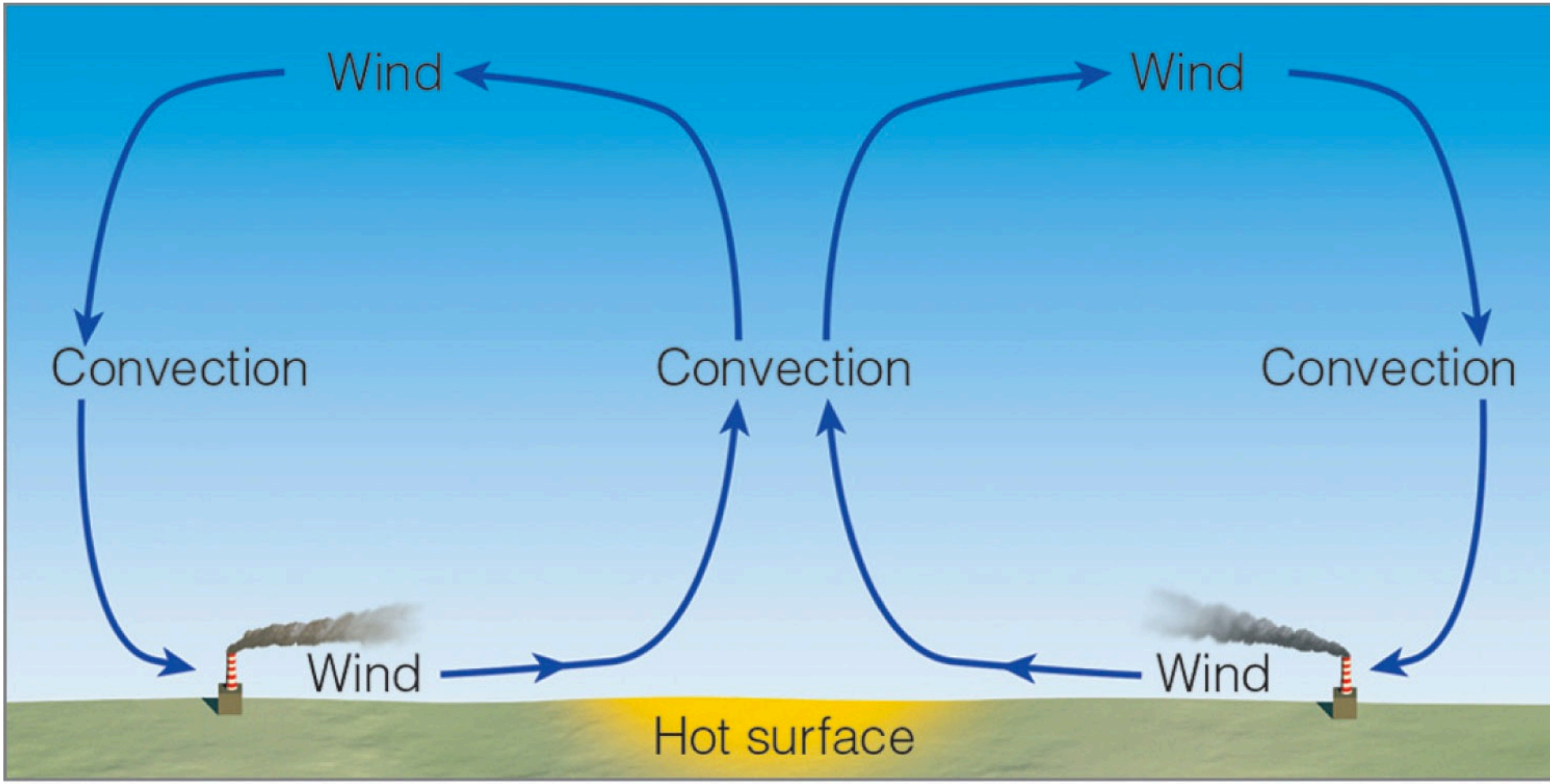
†A watt (W) is a unit of power where one watt equals one joule (J) per second (J/s). One joule equals 0.24 calories.

Energy Transfer Mechanisms

- Convection 對流
  - Energy transfer through fluids (gases, liquids)
  - Accomplished by movement of the liquid or gas
  - Convection circulation: warm air expands and rises then cools and sinks



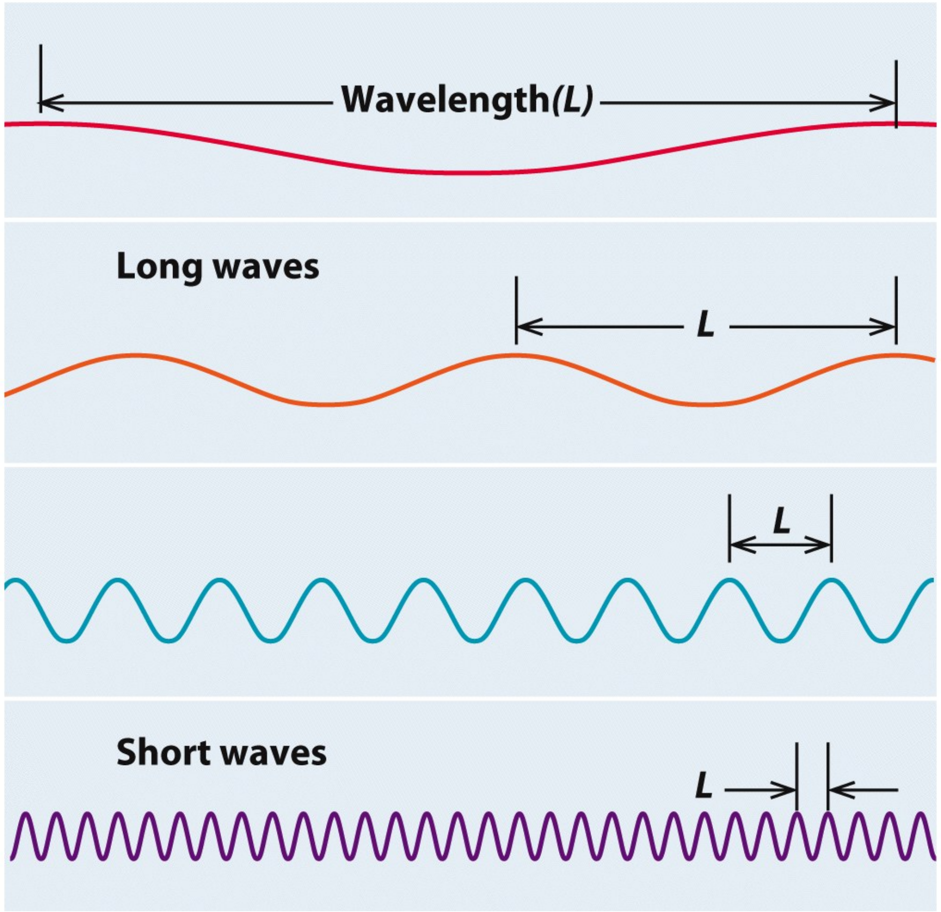
As air rises part of it s energy is lost as it expands and cools and when the air sinks it is compressed and the energy of molecules increase causing temperature to increase.

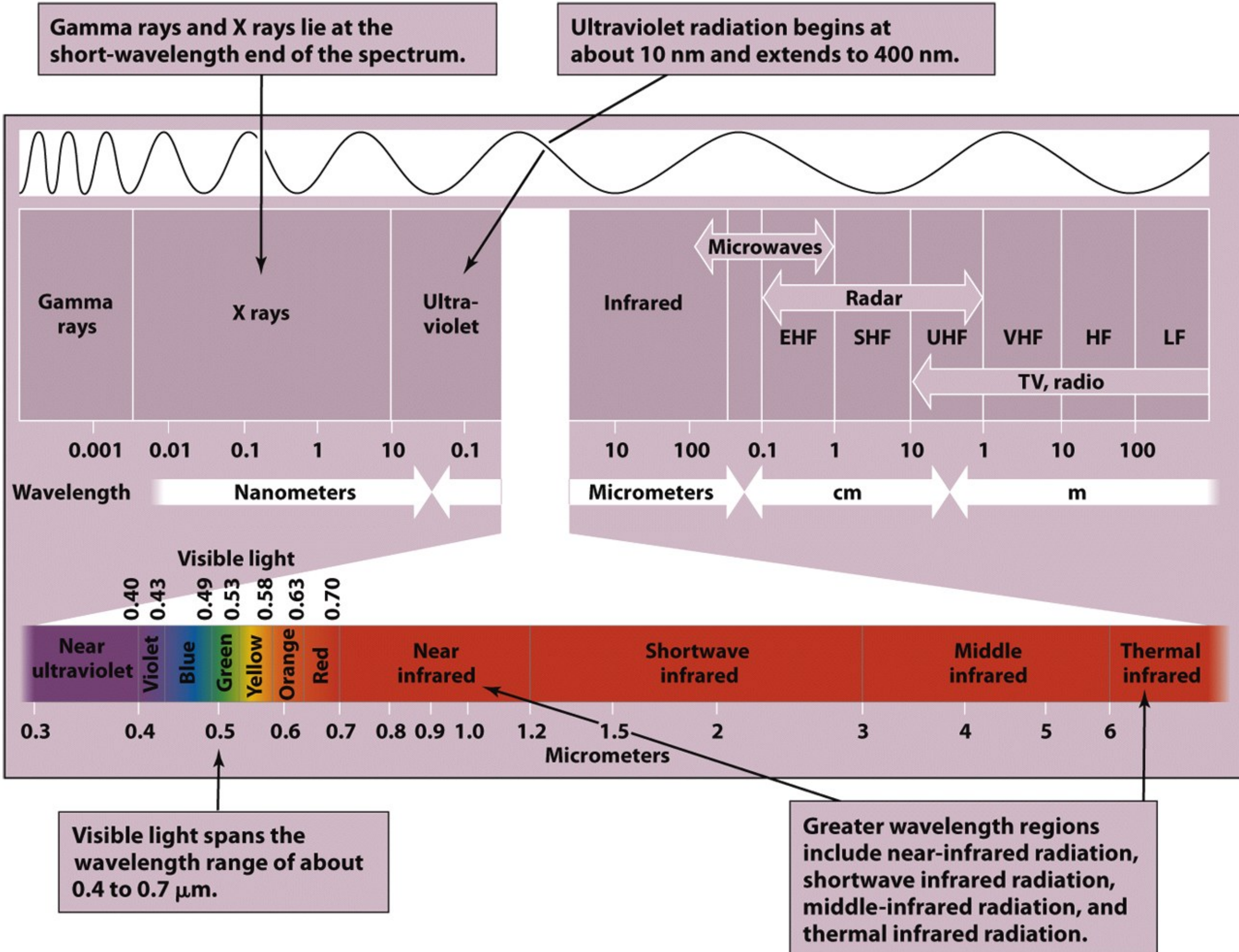


The rising of hot air and the sinking of cool air sets up a convective circulation. Normally, the vertical part of the circulation is called convection, whereas the horizontal part is called wind. Near the surface the wind is advecting smoke from one region to another.

Electromagnetic Radiation

- All surfaces emit radiation.
  - Hot objects - radiation in the form of light
  - Cooler objects - emit heat radiation.
- Electromagnetic Radiation –
  - collection of waves, wide range of wavelengths, travel away from the surface of an object.
  - Wavelength is the distance separating one wave crest from the next wave crest




Gamma rays and X rays lie at the short-wavelength end of the spectrum.
Ultraviolet radiation begins at about 10 nm and extends to 400 nm.
Gamma rays
X rays
Ultra-violet
Infrared
Microwaves
Radar
EHF
SHF
UHF
VHF
HF
LF
TV, radio
0.001
0.01
0.1
1
10
0.1
10
100
0.1
1
10
1
10
100
Wavelength
Nanometers
Micrometers
cm
m
Visible light
0.40
0.43
0.49
0.53
0.58
0.63
0.70
Near ultraviolet
Violet
Blue
Green
Yellow
Orange
Red
Near infrared
Shortwave infrared
Middle infrared
Thermal infrared
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.2
1.5
2
3
4
5
6
Micrometers
Visible light spans the wavelength range of about 0.4 to 0.7 µm.
Greater wavelength regions include near-infrared radiation, shortwave infrared radiation, middle-infrared radiation, and thermal infrared radiation.

Electromagnetic Radiation

- ***Gamma rays* and *X rays*** – short wavelength, high energies, hazardous to health.
- ***Ultraviolet*** - *10 nm to* 0.4 µm. Can damage living tissues.
- **Visible light** - *0.4 to* 0.7 µm. from violet blue, green, yellow, orange, to red.
- **N*ear-infrared*** - 0.7 to 1.2 µm. Similar to visible light. From the Sun. Cannot be seen because eyes not sensitive to radiation beyond 0.7 µm.
- ***Shortwave infrared*** - 1.2 and 3.0 µm. From the sun
- ***Middle-infrared*** - 3.0 µm to 6 µm. From Sun or hot sources on Earth (forest fires, gas well flames)
- **T*hermal infrared*** – 6 µm to 300 µm. Given off by bodies at temperatures found at the Earth's surface.

Radiation laws and definitions

- Electromagnetic Spectrum

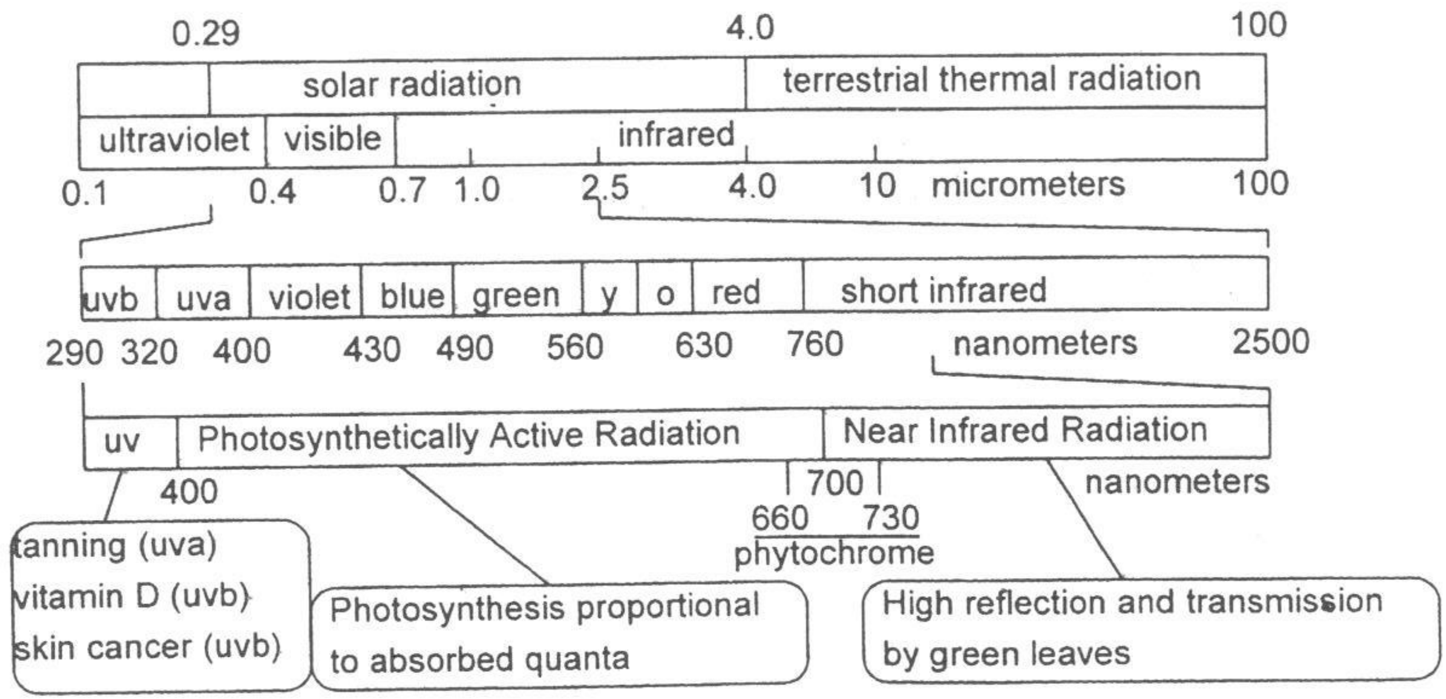


FIGURE 10.1. Part of the electromagnetic spectrum showing names of some of the wavebands and some of the biologically significant interactions with plants and animals.

Radiation

- Energy from the sun travels through the space and the atmosphere in the form of a wave (electromagnetic waves) and is called radiation.
- Radiation and Temperature
  - Black body
    - Black body is an object that absorbs all light that falls on it (perfect absorber). No electromagnetic radiation passes through it and none is reflected.
    - Any body with the temperature greater than absolute zero (0 K, the point at which molecules do not move) emits radiation.
  - As temperature of an object increases, the more total radiation that is emitted by an object (Stefan Boltzmann Law史坦芬-波茲曼定律).

Intensity and Wavelengths of Emitted Radiation

- Stefan-Boltzmann law (perfect radiator, black-body irradiance)

$$I = \quad T^4$$

  - I : the flux of the radiation W m^{-2}
  - σ: Stefan-Boltzmann constant: 5.67 x 10^{-8} W m^{-2} K^{-4}

- Graybodies emit a percentage of the maximum possible for a temperature

$$I = \quad T^4$$

  - ε: emissivity (長波輻射發散率)

Emissivity

32 3 Radiation Balance Near the Surface

Table 3.1 Radiative properties of natural surfaces.

Surface type	Other specifications	Albedo (a)	Emissivity (ε)
Water	Small zenith angle	0.03–0.10	0.92–0.97
	Large zenith angle	0.10–1.00	0.92–0.97
Snow	Old	0.40–0.70	0.82–0.89
	Fresh	0.45–0.95	0.90–0.99
Ice	Sea	0.30–0.45	0.92–0.97
	Glacier	0.20–0.40	
Bare sand	Dry	0.35–0.45	0.84–0.90
	Wet	0.20–0.30	0.91–0.95
Bare soil	Dry clay	0.20–0.40	0.95
	Moist clay	0.10–0.20	0.97
	Wet fallow field	0.05–0.07	
Paved	Concrete	0.17–0.27	0.71–0.88
	Black gravel road	0.05–0.10	0.88–0.95
Grass	Long (1 m)	0.16	0.90
	Short (0.02 m)	0.26	0.95
Agricultural	Wheat, rice, etc.	0.18–0.25	0.90–0.99
	Orchards	0.15–0.20	0.90–0.95
Forests	Deciduous	0.10–0.20	0.97–0.98
	Coniferous	0.05–0.15	0.97–0.99

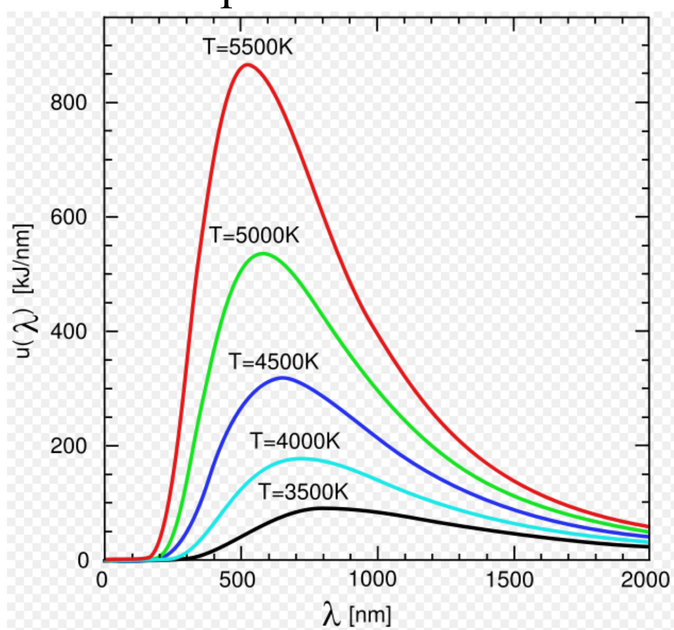
Compiled from Sellers (1965), Kondratyev (1969), and Oke (1987).

Radiation laws and definitions

- Wien's displacement law
  - Describe that there is an inverse relationship between the wavelength of the peak of the emission of a black body and its temperature

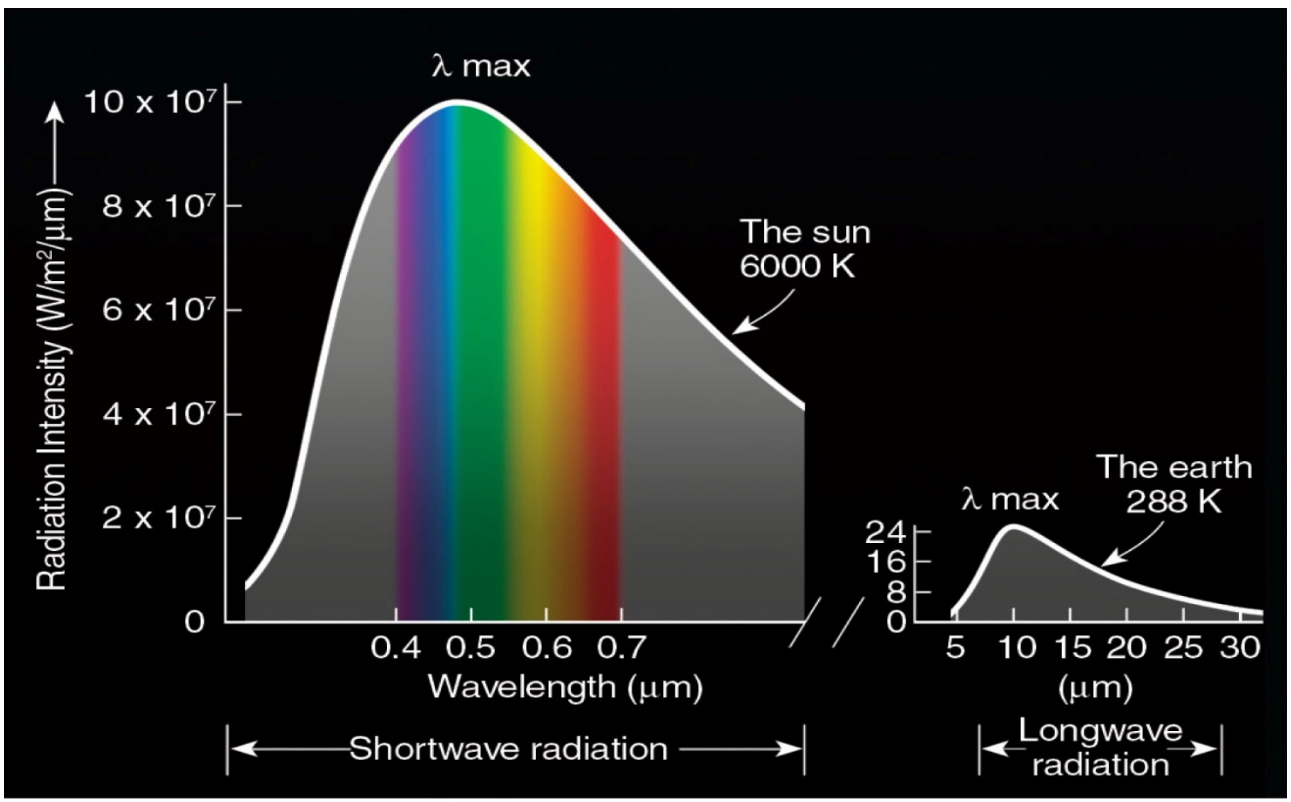
$$_{\max} = \frac{2900}{T} \qquad \text{(unit :} \quad m)$$

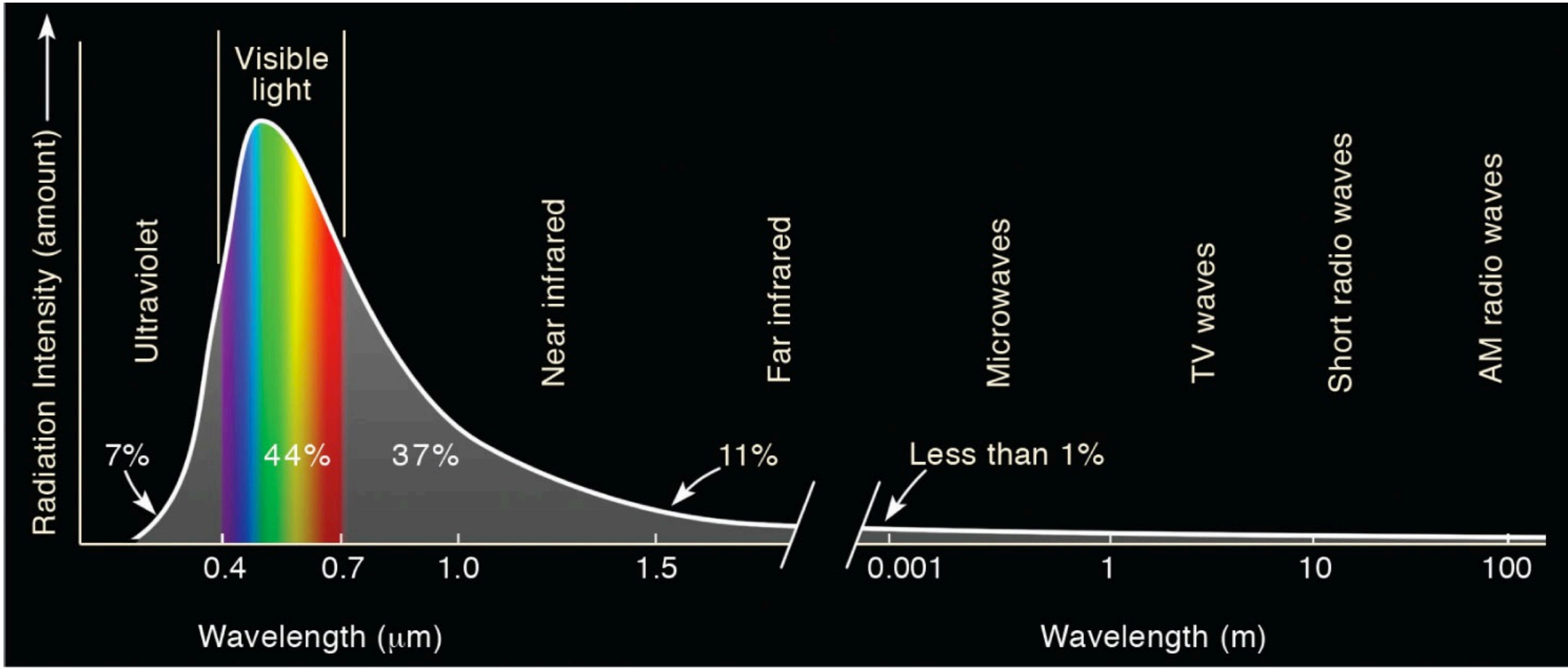
    - 2900 (μm K): Wien's displacement constant



Radiation

- Radiation of the Sun and Earth
  - Sun 6000k emits radiation, electromagnetic spectrum
  - Shortwave radiation (high energy) from the Sun (solar radiation)
  - Longwave radiation (low energy) from the Earth (terrestrial radiation)





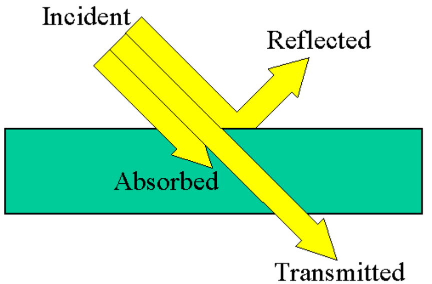
The sun's electromagnetic spectrum and some of the descriptive names of each region. The numbers underneath the curve approximate the percent of energy the sun radiates in various regions.

Absorption, Emission & Equilibrium

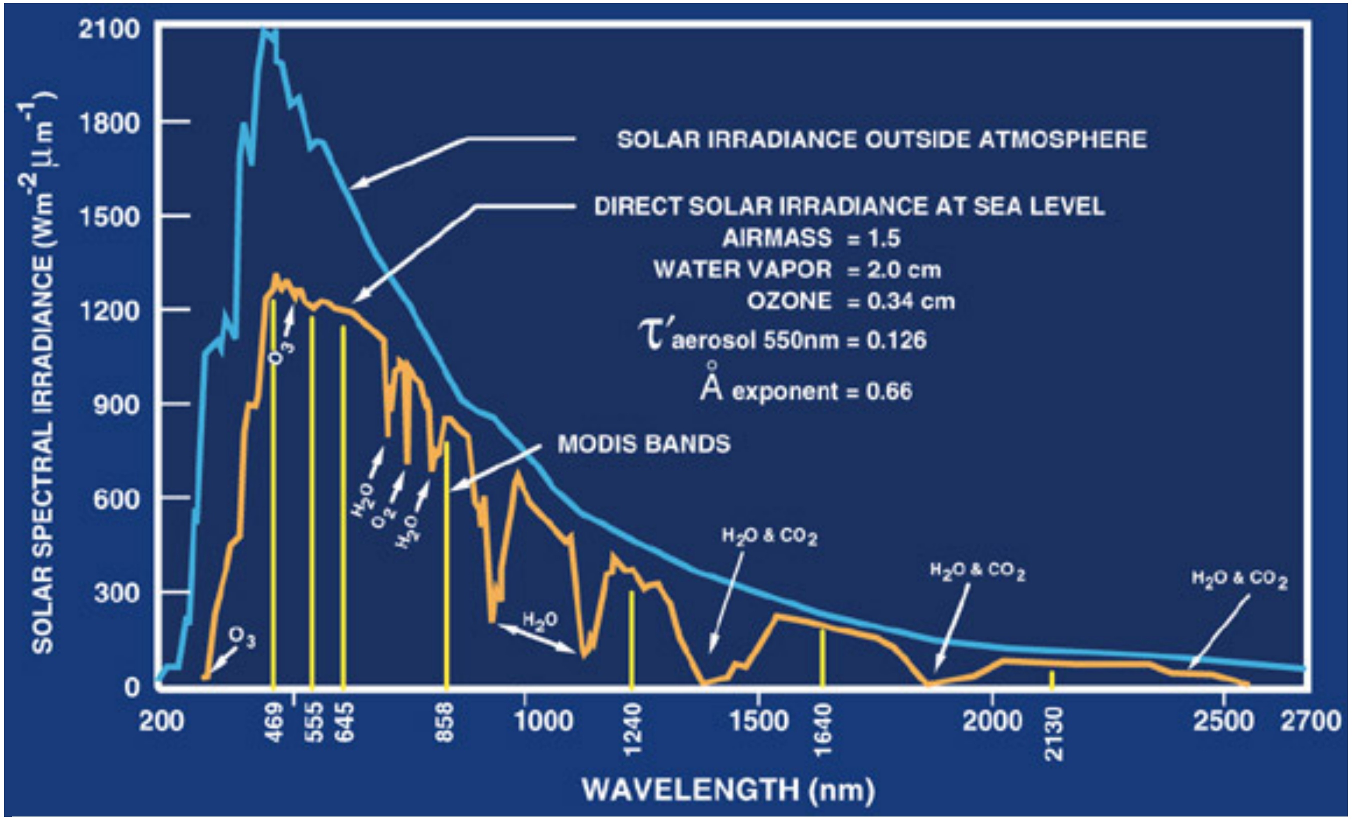
- Solar radiation is the atmosphere's heat source
- Radiative equilibrium
  - Absorb > emit = warm
  - Emit > absorb = cool
- The global energy budget
  - A balance between incoming solar radiation (insolation) and outgoing terrestrial radiation
  - If more energy is radiated than absorbed, the objects gets colder, and vice versa
  - Earth absorbs more energy than emitted during the day, and emits more energy than absorbed at night

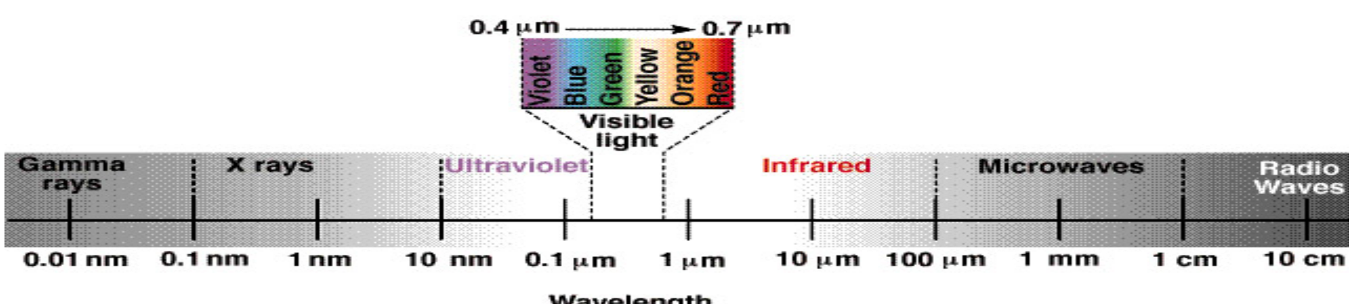
Atmospheric Influences on Insolation

- Radiant energy is absorbed, reflected, scattered, or transmitted
- Absorption吸收
  - Particular gases, liquids, and solids absorb energy
  - Heat increases
  - Gases are poor selective absorbers of energy
- Reflection 反射(specular reflection)
  - Redirection of energy
    - Does not increase heat
  - Albedo反照率 = percentage of reflected energy
- Scattering 散射(diffuse reflection)
  - Scattered energy diffuses radiation
    - Reduces intensity
    - Type determined by size of scattering agents



Solar spectral irradiance





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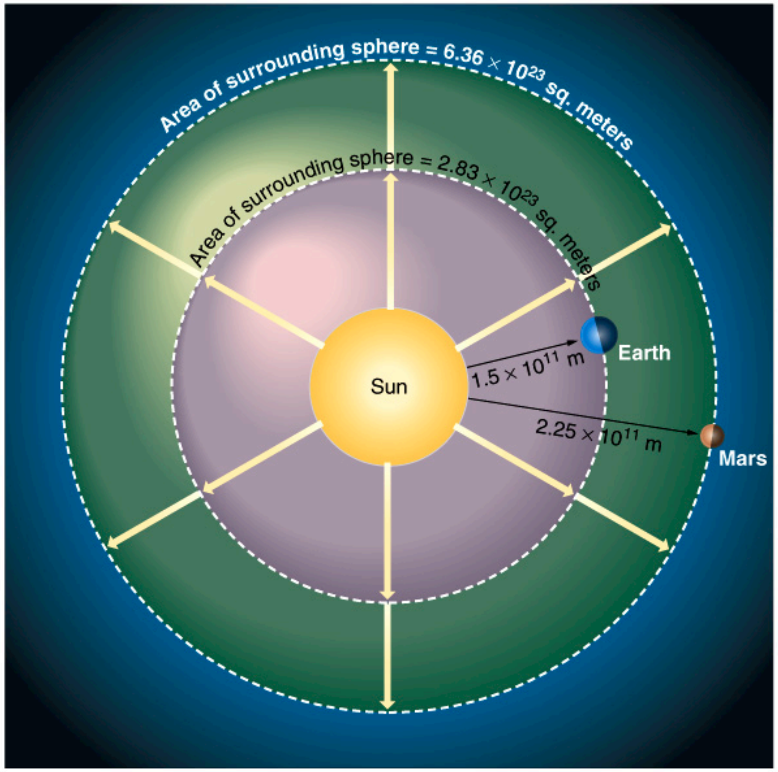
Solar Constant

- The Solar Constant
  - The amount of incoming solar electromagnetic radiation per unit area, measured on the outer surface of Earth's atmosphere in a plane perpendicular to the rays.

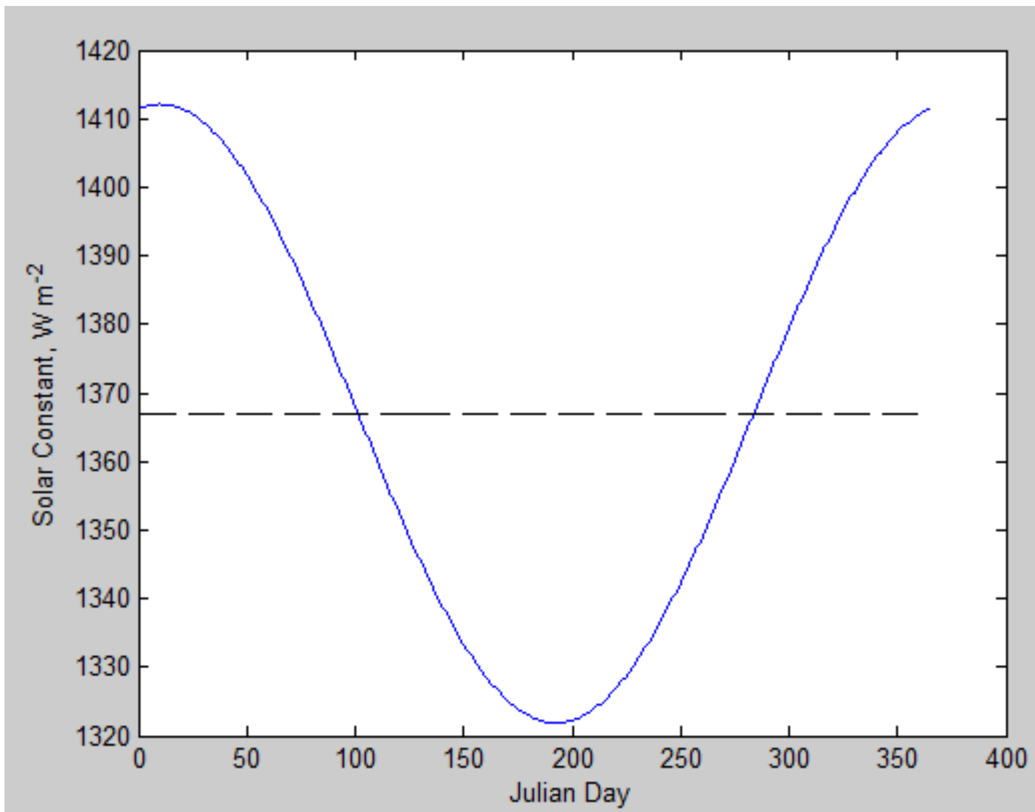
- Inverse square law

$$\frac{3.865 \cdot 10^{26} W}{4\pi \left(1.5 \cdot 10^{11} m\right)^2} = 1367\ \mathrm{W\ m^{-2}}$$



Solar constant

$$SC = 1367\ \mathrm{W\ m^{-2}}\quad 1 + 0.033\ \cos\frac{2\quad (day\quad 10)}{365}$$



Equilibrium temperature

- The solar constant for the Earth ~ 1367 W m^{-2}
- Solar radiation received outside atmosphere per unit area of sphere
  - $(1367) \cdot (\pi r_e^2)/(4 \pi r_e^2) = 342$ W m^{-2}
- Albedo of surface+atmosphere ~ 0.3
  - 30% of incoming solar energy is reflected by clouds, ice, etc.
- Energy absorbed by surface + atmosphere = 1-0.3 = 0.7
  - 70% of 342 W m^{-2} = 239.4 W m^{-2}
- Balanced by energy emitted by surface + atmosphere
  - Stefan-Boltzman law: Energy emitted = σT_e^4
  - $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}
- Solve $\sigma T_e^4 = 239.4$
  - Te = 255 K = -18^{o}C

Effective temperature of Earth

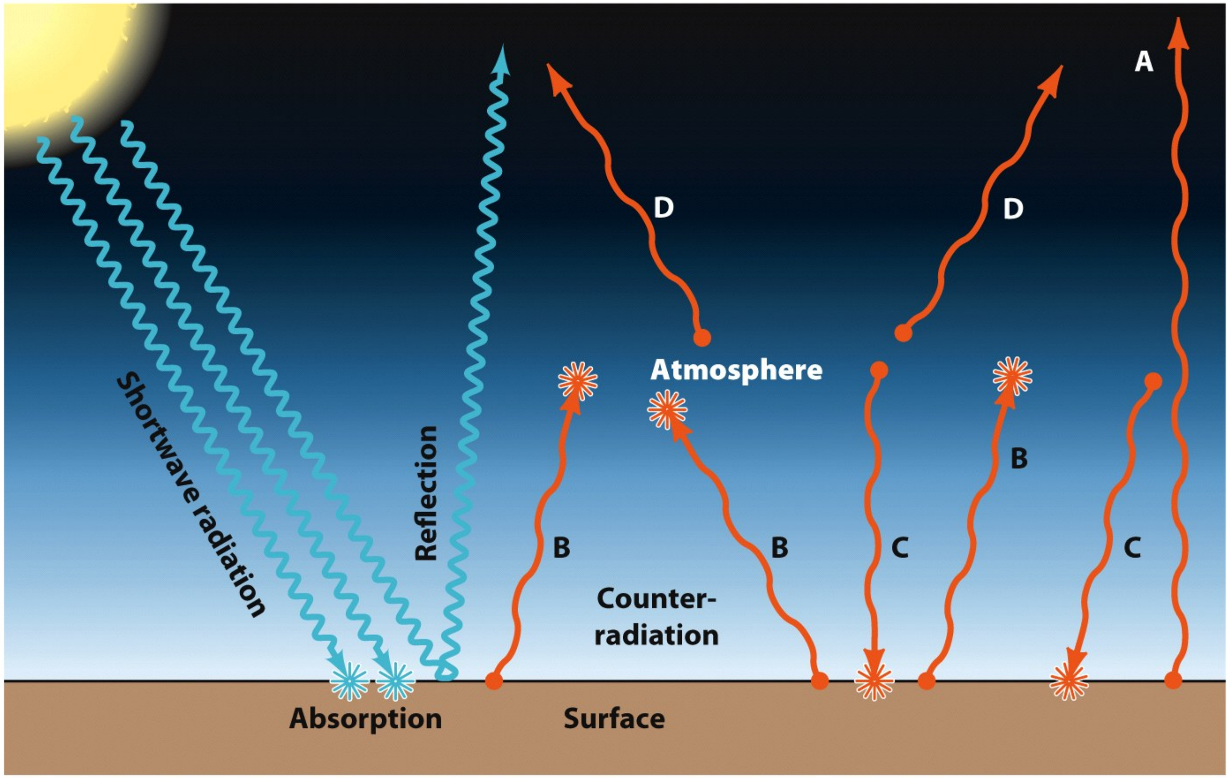
- Annual and global average temperature ~ 15 C, i.e. 288 K
  - Te = 255 K --> not representative of surface temp. of earth
- Why?

- Greenhouse effect: the atmosphere selectively absorbs infrared radiation from the Earth's surface but acts as a window and transmits shortwave radiation.

Counterradiation and the greenhouse effect

Shortwave radiation passes through atmosphere, absorbed and warms

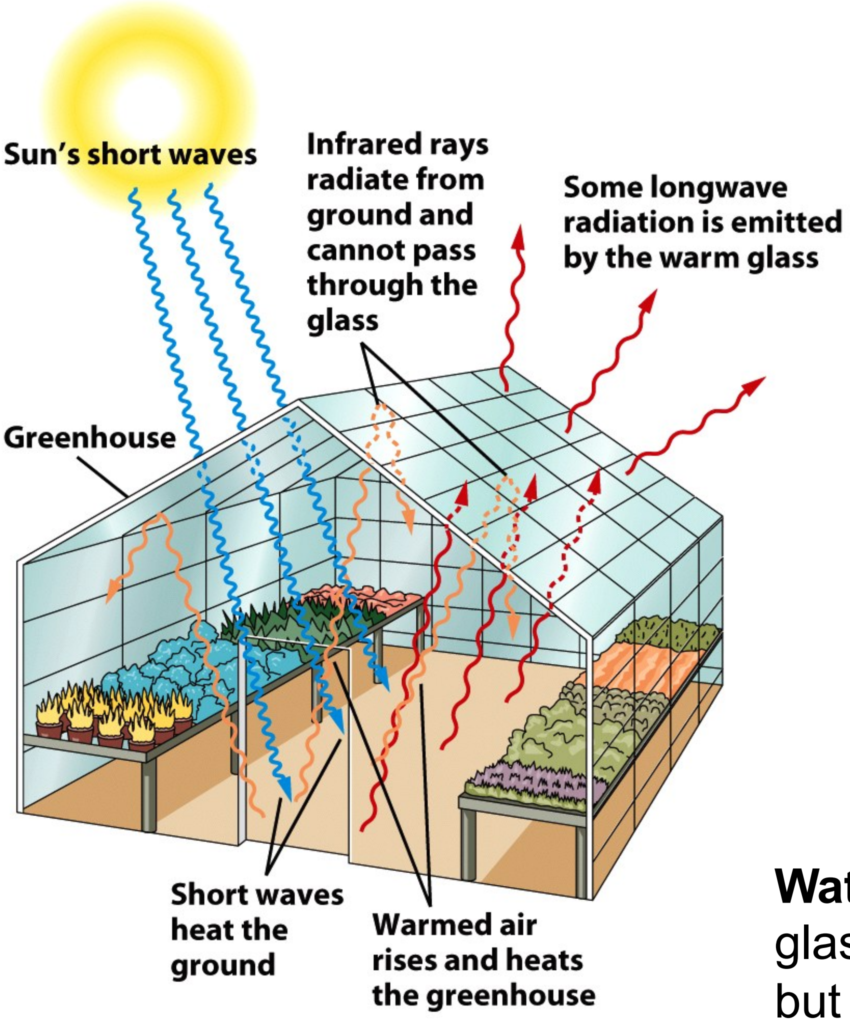
Surface emits longwave radiation which goes
(A) directly to space, or,
(B) absorbed by atmosphere

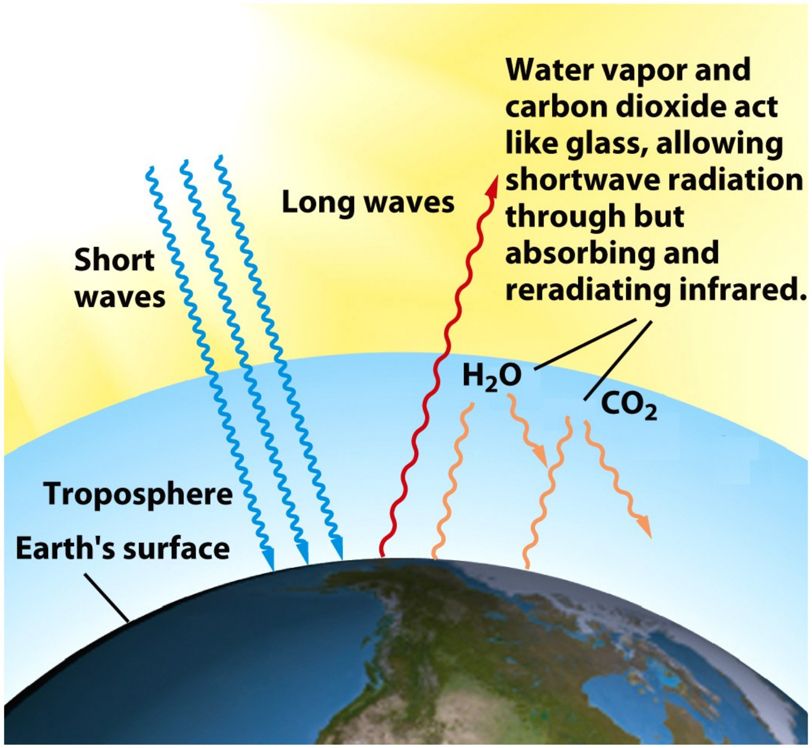


Atmosphere radiates longwave energy back to the surface and also to space as <u>counterradiation</u> (C & D)

Counterradiation produces the greenhouse effect.

Counterradiation and the greenhouse effect

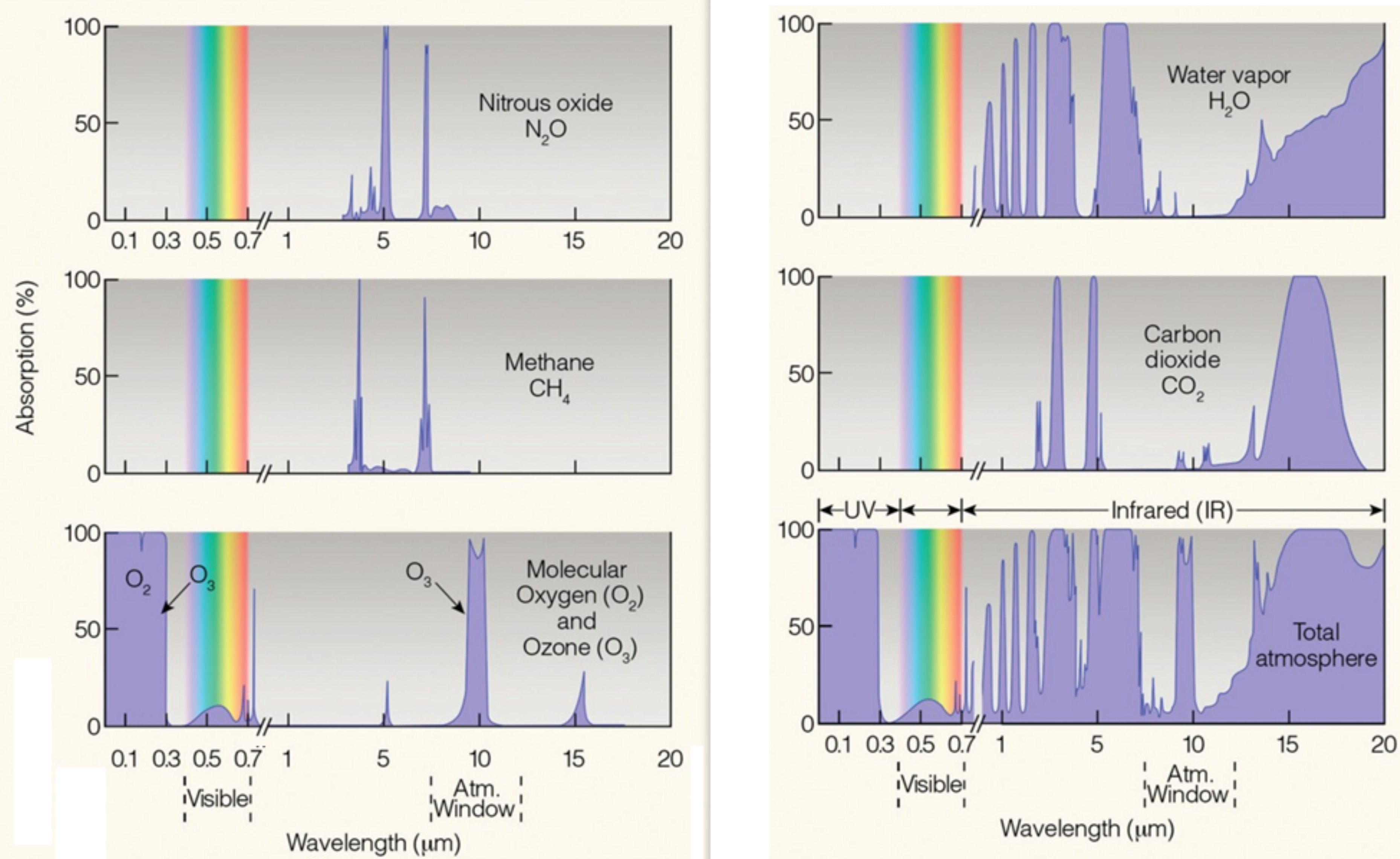




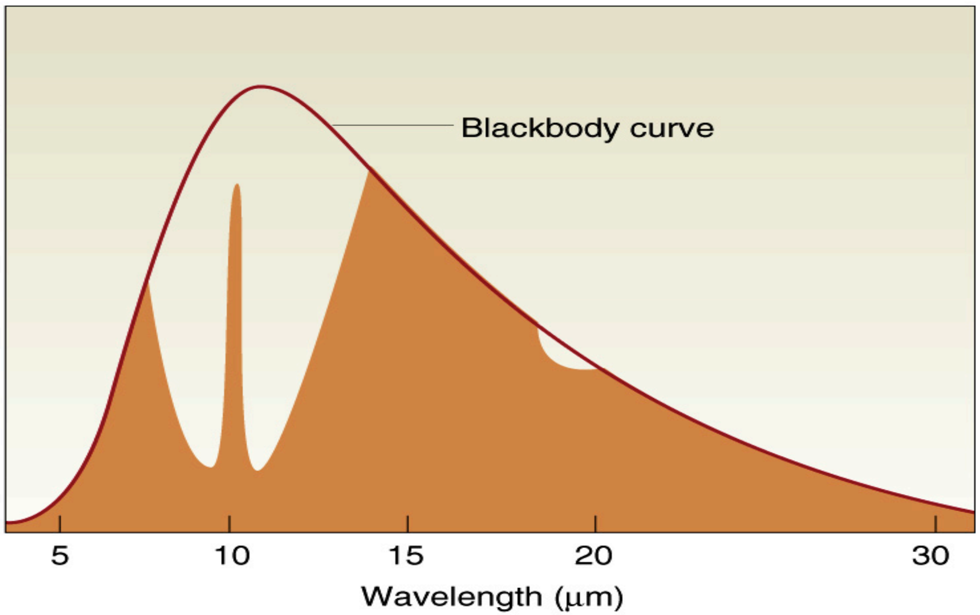
Water vapor and **carbon dioxide** act like glass allowing shortwave radiation through but absorbing and radiating longwave radiation.

Surface-Atmosphere Radiation Exchange

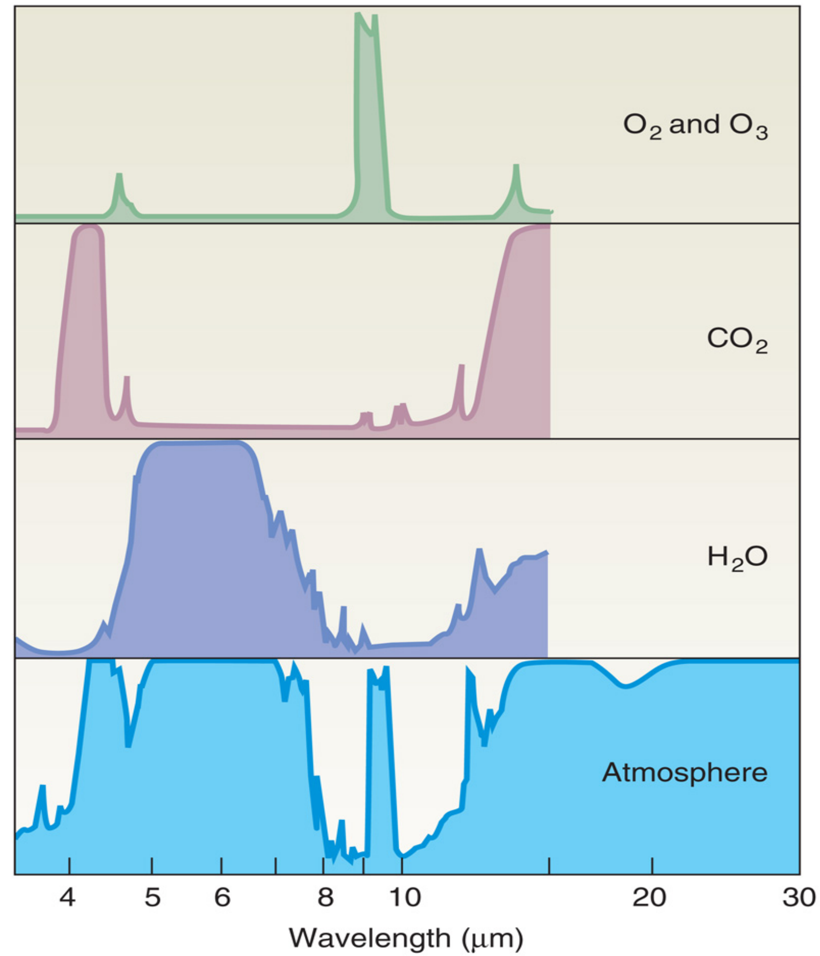
- Surface emission (terrestrial/longwave radiation)
  - Much is absorbed by atmospheric gases
    - H_2O and CO_2
  - Increases air temperature
- Some energy is reabsorbed at the surface
  - Additional surface heating
- Greenhouse gases absorb terrestrial radiation
- Global warming is occurring due to an increase in greenhouse gases
  - Carbon dioxide, Methane, Nitrogen Oxide, Chlorofluorocarbons, Ozone
  - Greenhouse effect: ~60% due to H2O; ~26% due to CO2; ~7% due to methane; ~7% due to remaining greenhouse gases



Absorption of radiation by gases in the atmosphere. The dark purple shaded area represents the percent of radiation absorbed by each gas. The strongest absorbers of infrared radiation are water vapor and carbon dioxide. The bottom Figure represents the percent of radiation absorbed by all of the atmospheric gases.



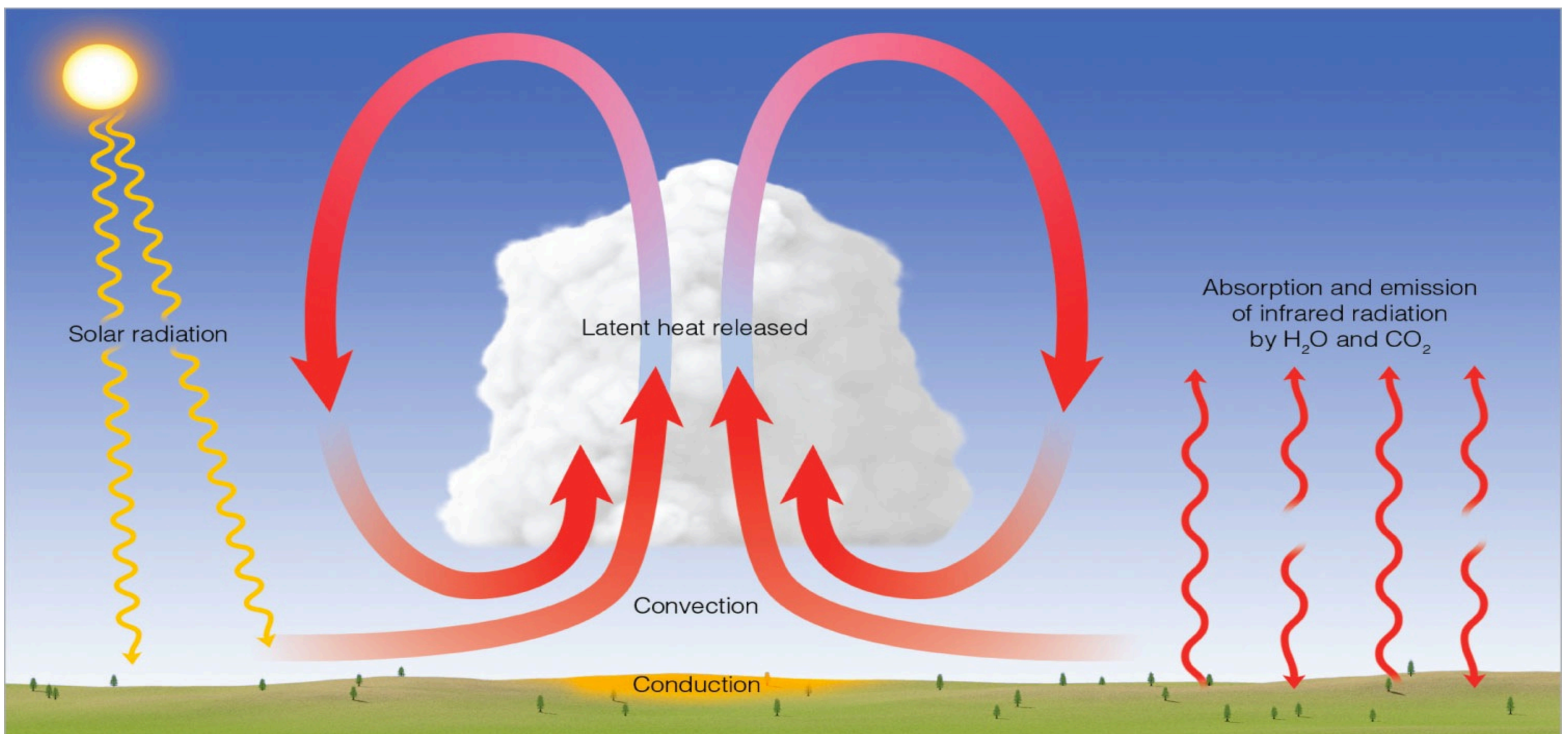
The atmospheric window - non-absorption of wavelengths between 8-15 μm



(b)

Incoming Solar Radiation

- Conduction, convection, and infrared radiation warm the atmosphere from below, not sunlight or insolation from above.
  - Scattering
  - Reflection, albedo

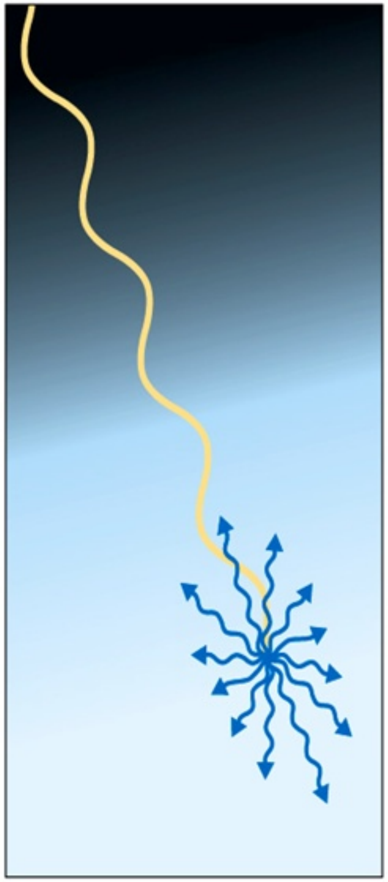


Incoming Solar Radiation

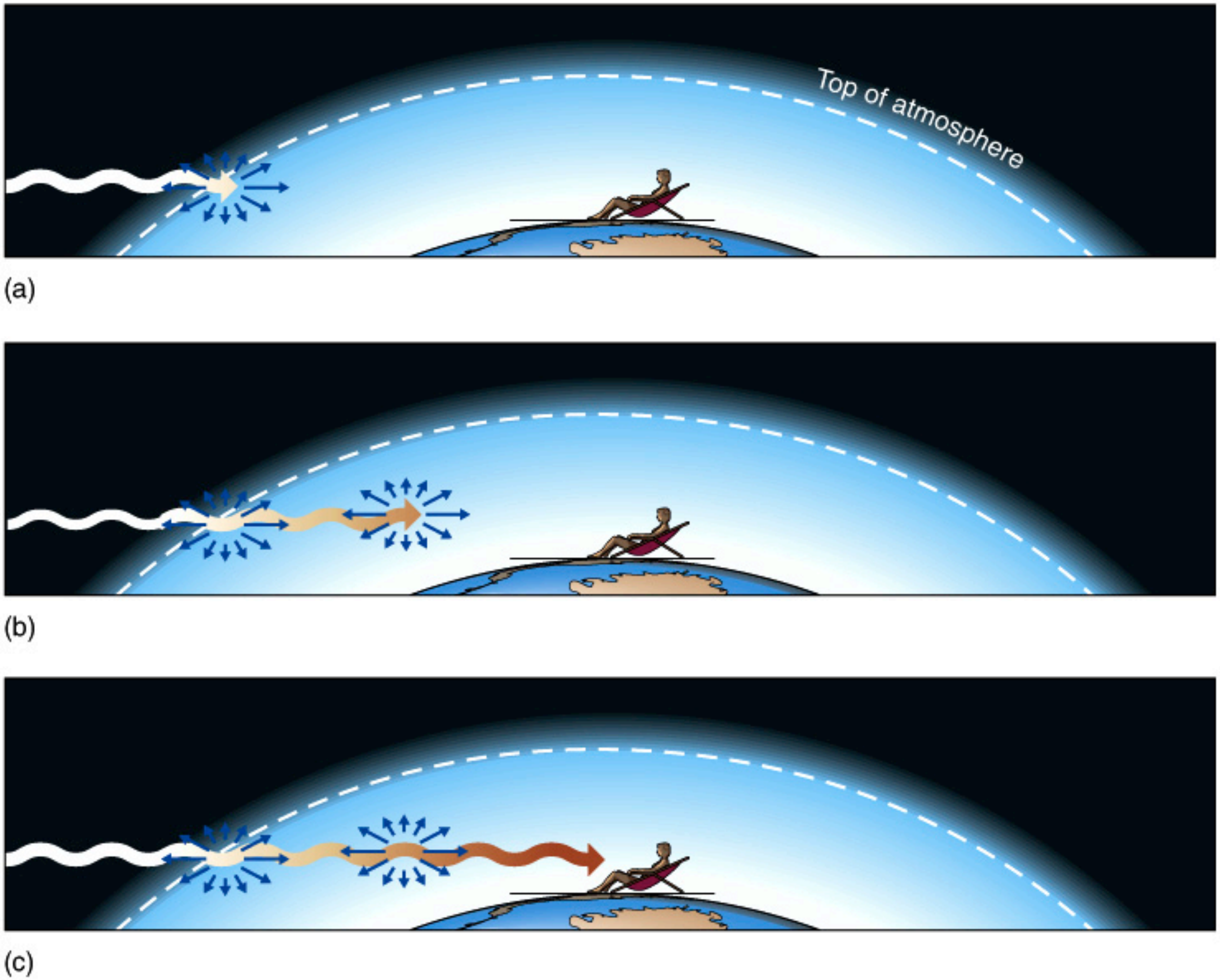
- Observation: Blue skies, red skies, and white clouds
  - Selective scattering of incoming solar radiation causes reflectance in portion of the electromagnetic spectrum that correspond with the colors our eyes detect.

Scattering- Selective scattering

- Selective scattering of incoming solar radiation causes reflectance in portion of the electromagnetic spectrum that correspond with the colors our eyes detect.
- Rayleigh Scattering
  - Scattering agent < 1/10 of the wavelength of incoming radiation
  - Effective for visible light
  - Partial to shorter wavelengths
- Mie Scattering
  - Larger scattering agents (aerosols)
  - Interacts with wavelengths across visible spectrum
    - Hazy, grayish skies
    - Sunrise/sunset color enhancement



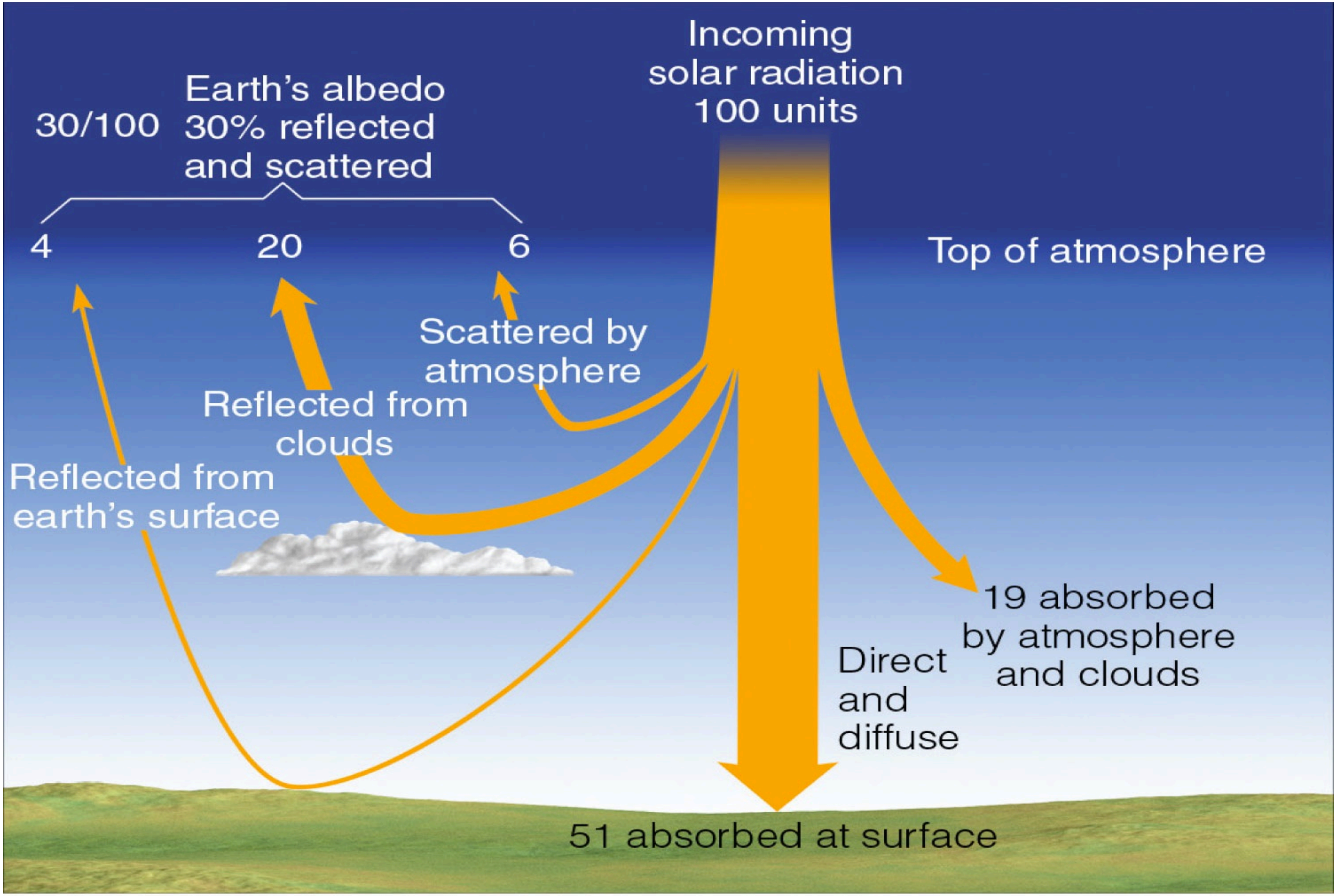
Scattering- Selective scattering



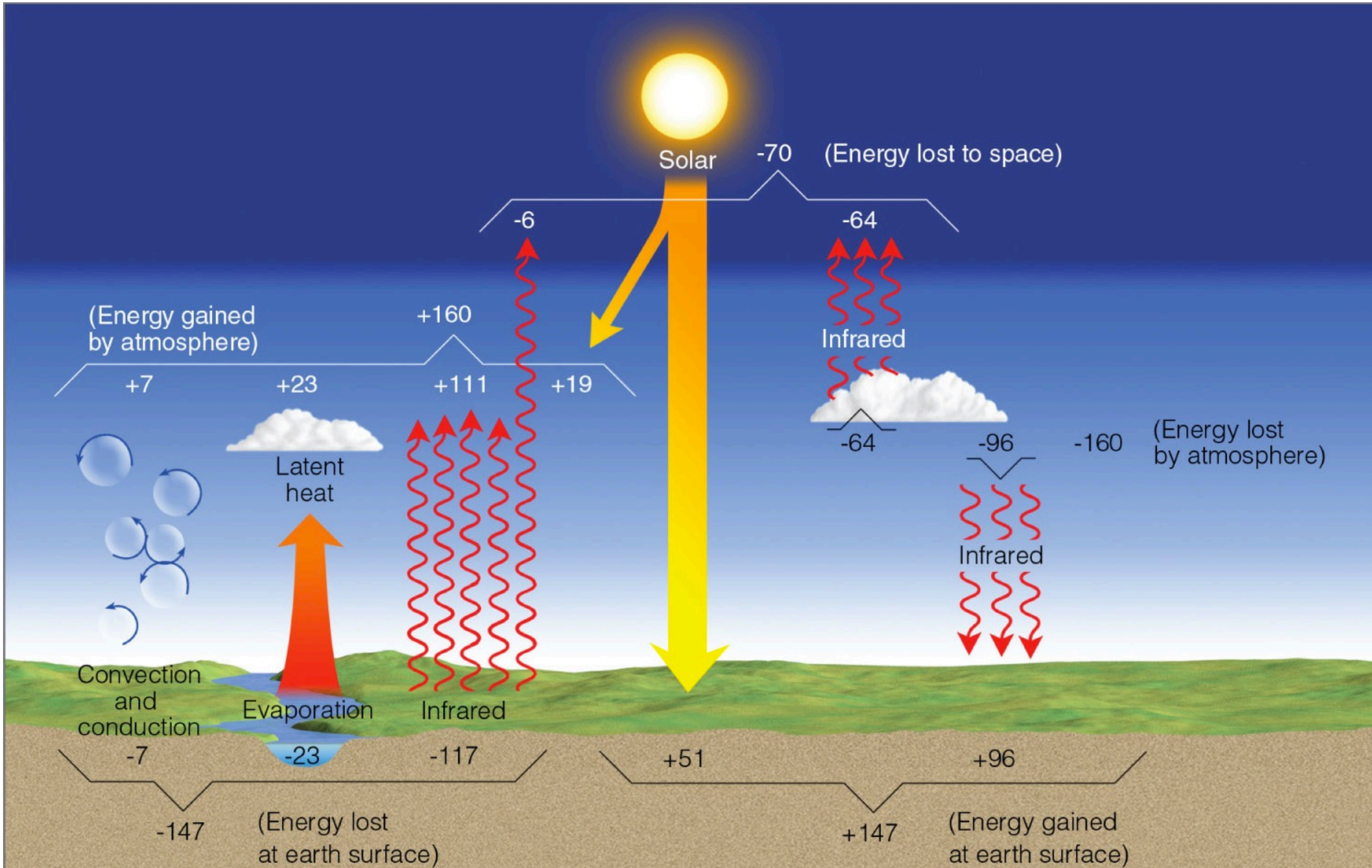
Scattering-Nonselective Scattering

- Nonselective Scattering
  - Very large scattering agents (water)
  - Scatter across the visible spectrum
    - White or gray appearance
  - Scattering by clouds: clouds reflect <u>all wavelengths</u> of incoming radiation about equally → nonselective

The Fate of Solar Radiation



The Fate of Solar Radiation



Surface-atmosphere radiation exchange

- Net radiation 淨輻射= difference between absorbed and emitted radiation
  - The atmosphere absorbs 19 units of solar radiation but undergoes a net loss of 49 units
    - net deficit 30 units
  - The surface absorbs 51 units of solar radiation but has a longwave deficit of 21
    - net surplus = 30 units
- Net radiation deficit equals net surplus
- Energy is transferred from the surface to the atmosphere
- The surplus and deficits offset

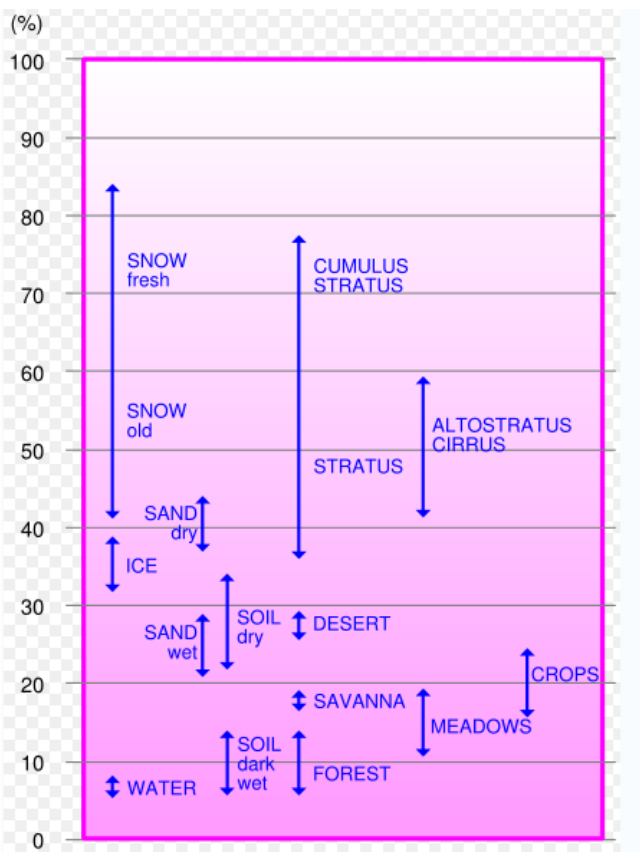
Albedo (地表反照率) and Emissivity （長波輻射發射率）over different land-use

- Surface albedo

$$= \frac{SW}{SW}$$

- Emissivity

$$LW = \quad T^4$$



32 **3 Radiation Balance Near the Surface**

Table 3.1 Radiative properties of natural surfaces.

Surface type	Other specifications	Albedo (a)	Emissivity (ε)
Water	Small zenith angle	0.03–0.10	0.92–0.97
	Large zenith angle	0.10–1.00	0.92–0.97
Snow	Old	0.40–0.70	0.82–0.89
	Fresh	0.45–0.95	0.90–0.99
Ice	Sea	0.30–0.45	0.92–0.97
	Glacier	0.20–0.40	
Bare sand	Dry	0.35–0.45	0.84–0.90
	Wet	0.20–0.30	0.91–0.95
Bare soil	Dry clay	0.20–0.40	0.95
	Moist clay	0.10–0.20	0.97
	Wet fallow field	0.05–0.07	
Paved	Concrete	0.17–0.27	0.71–0.88
	Black gravel road	0.05–0.10	0.88–0.95
Grass	Long (1 m)	0.16	0.90
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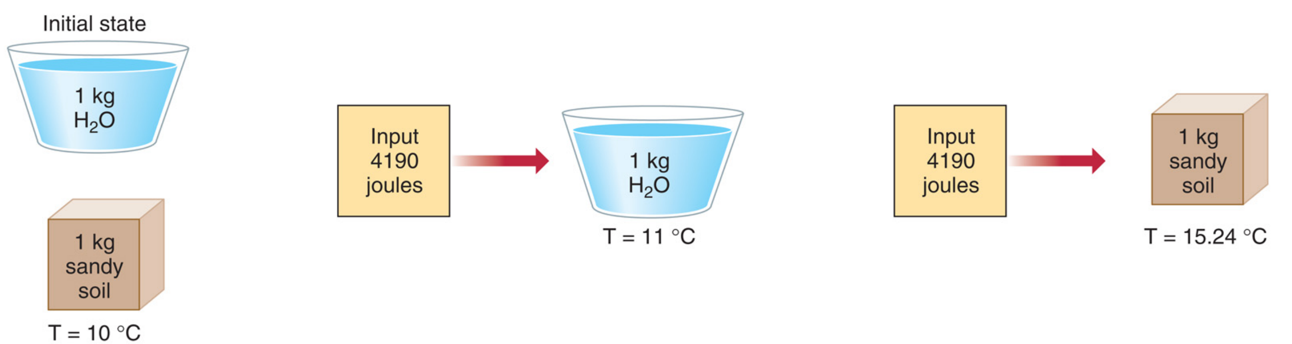
Agricultural	Wheat, rice, etc.	0.18–0.25	0.90–0.99
	Orchards	0.15–0.20	0.90–0.95
Forests	Deciduous	0.10–0.20	0.97–0.98
	Coniferous	0.05–0.15	0.97–0.99

Compiled from Sellers (1965), Kondratyev (1969), and Oke (1987).

Sensible Heat and Latent Heat

- Sensible Heat
  - Readily detected heat energy
  - Related to object’s specific heat and mass
  - 7 units transferred to the atmosphere as sensible heat

  - Specific heat
    - the measure of the heat energy required to increase the temperature of a unit quantity of a substance by a certain temperature interval.
    - Unit: *Joule* kg^{-1} K^{-1}



Sensible Heat and Latent Heat

- Latent Heat
  - Energy which induces a change of state (usually in water)
  - Redirects some energy which would be used for sensible heat
  - Latent heat of evaporation (蒸發潛熱 *Joule* kg^{-1}) is stored in water vapor
    - Released during condensation

*Latent heat of evaporation of water: ~2,500,000 J kg-1

*Latent heat of fusion of water: ~335,000 J kg-1

  - Globally, 23 units of energy are transferred to the atmosphere as latent heat

Surface energy balance

- Net Radiation淨輻射: the difference between the incoming and outgoing radiation (including long wave and short wave radiation)
  - Net short-wave radiation = short-wave down(incoming) - short-wave up(outgoing).
  - Net long-wave radiation = long-wave down(incoming) - long-wave up(outgoing).
  - Net radiation = net short-wave radiation + net long-wave radiation.

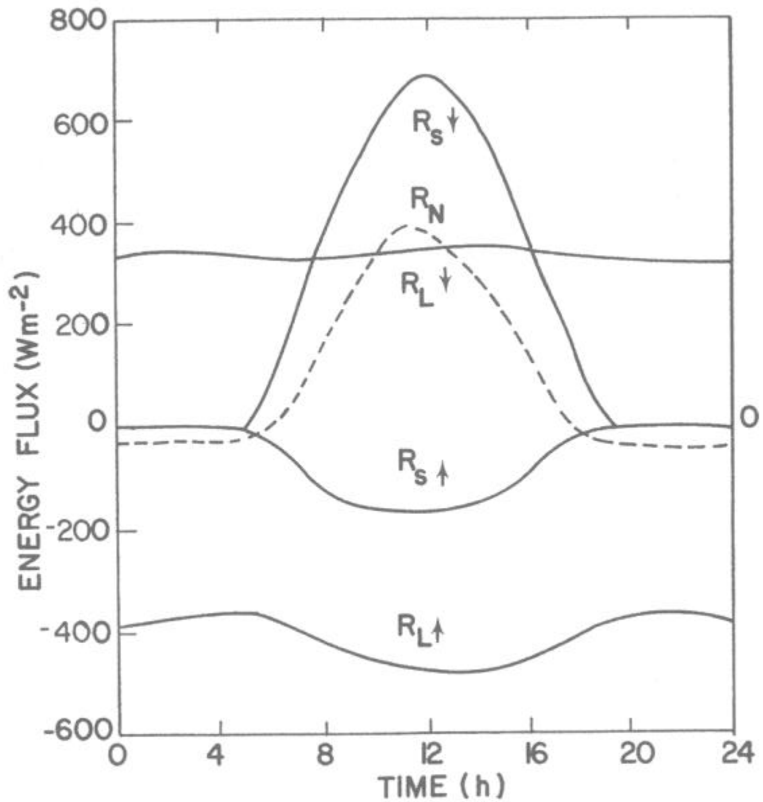


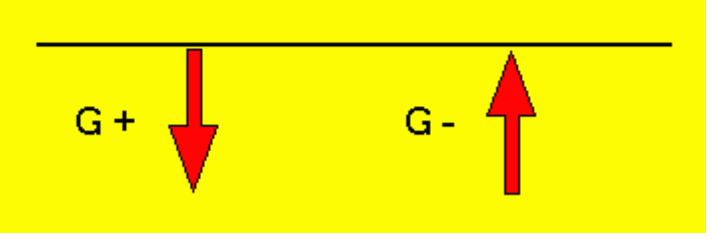
Figure 3.4 Observed radiation budget over a 0.2 m stand of native grass at Matador, Saskatchewan, on 30 July 1971. [From Oke (1987); after Ripley and Redmann (1976).]

Surface energy balance

- Sensible heat transfer 可感熱(H): the heat energy transferred between the surface and air when there is a difference in temperature

- Latent heat transfer 潛熱(LE, H_L): The heat used in the phase change from a liquid to a gas is called the latent heat of vaporization.

- Ground heat flux (G, H_G) : is to warm the subsurface of the Earth. Heat is transferred from the surface downwards via conduction.



Surface energy balance

- Surface energy balance
  - $R_N = H + H_L + H_G$

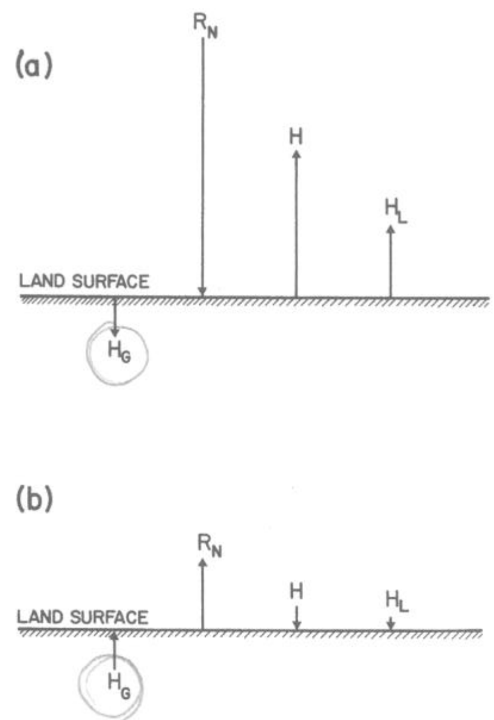


Figure 2.1 Schematic representation of typical surface energy budgets during (a) daytime and (b) nighttime.

  - Sometimes the term "storage" is used to quantify the difference between the net radiation and $H + H_L + H_G$

Surface energy balance

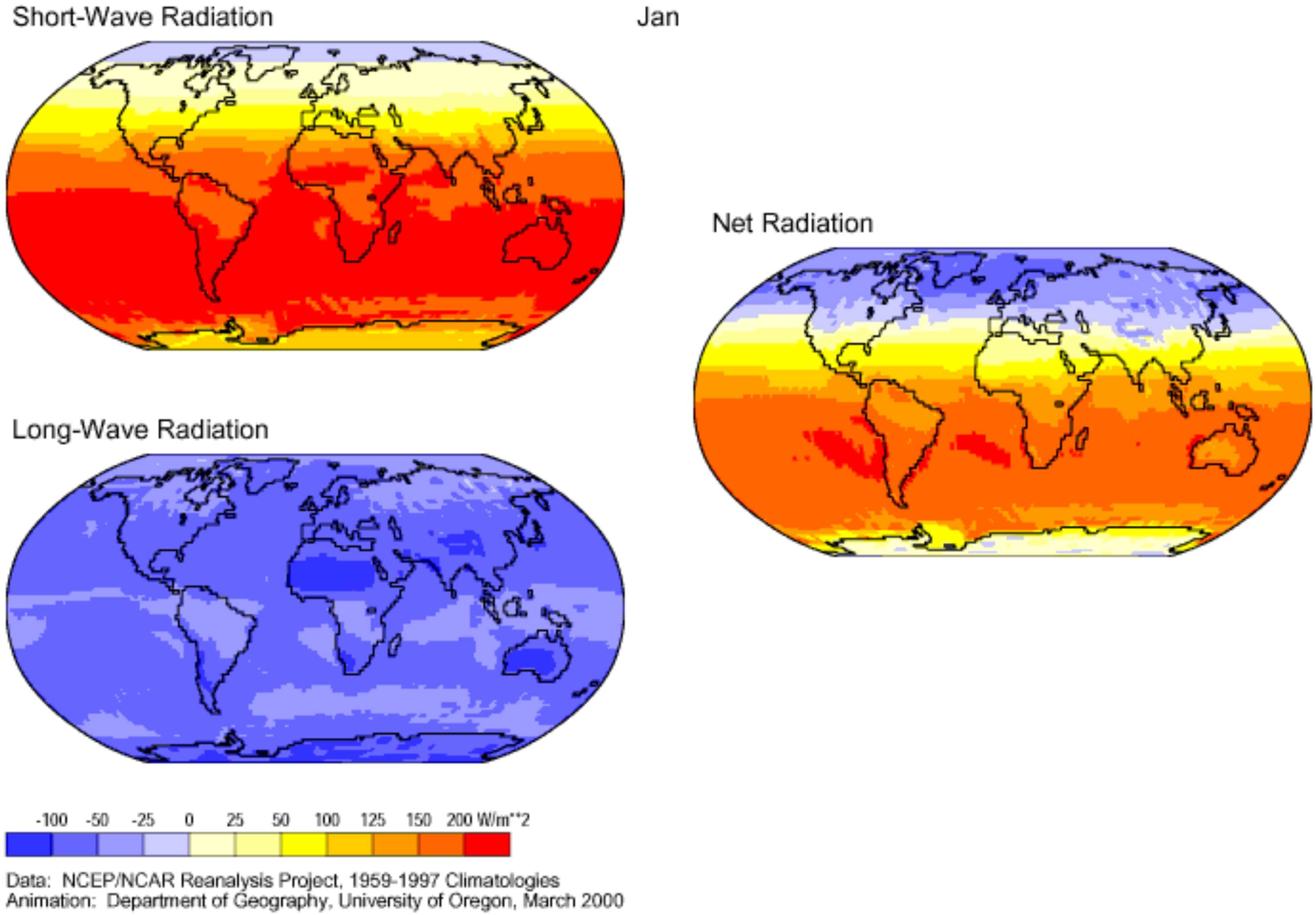
- Bowen ratio
  - ratio of energy fluxes from one medium to another by sensible and latent heating respectively. It is calculated by the equation

$$B = H / H_L$$

$$H = \frac{R_N \quad H_G}{1 \quad B^{1}}$$

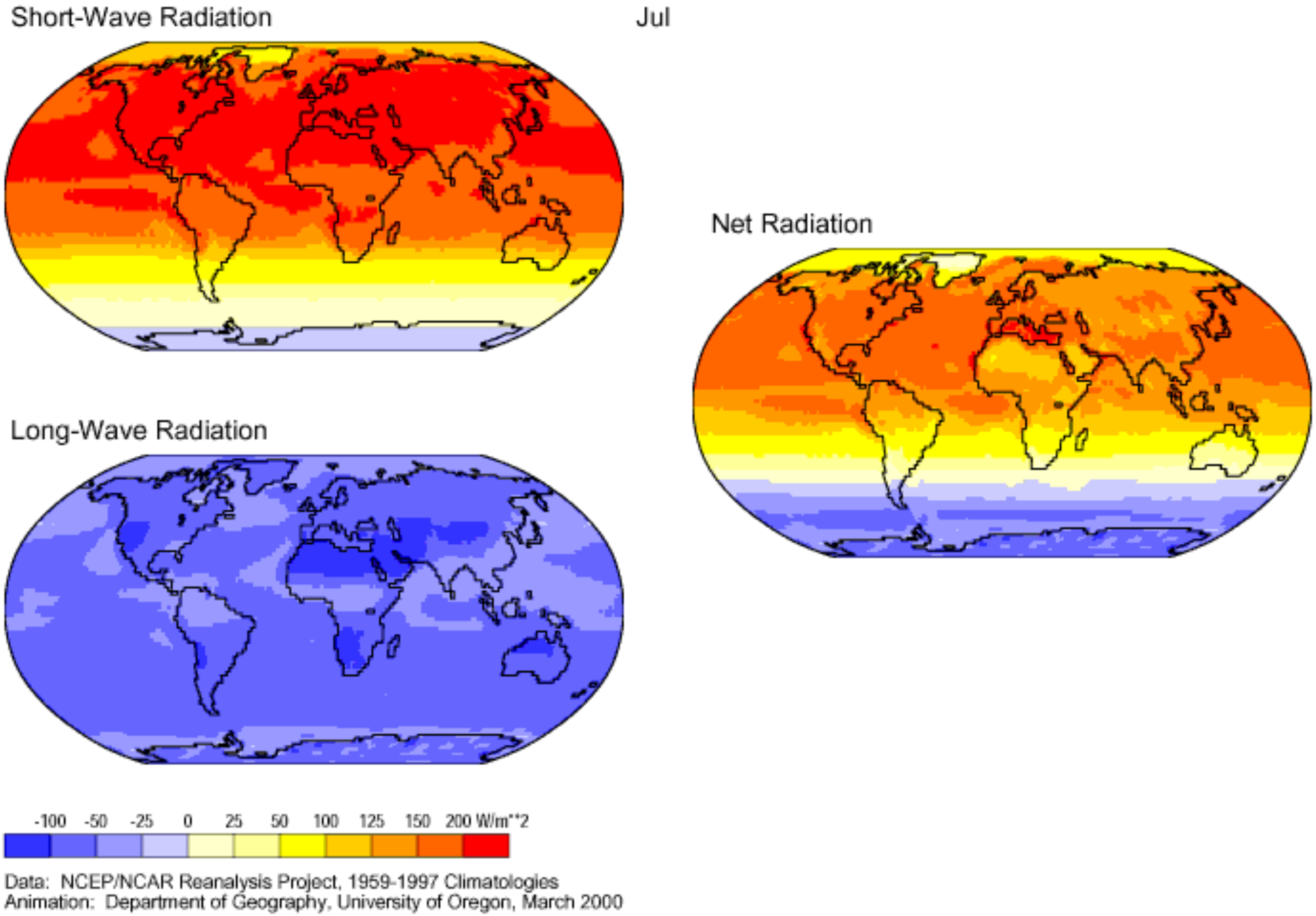
$$H_L = \frac{R_N \quad H_G}{1 \quad B}$$

Surface energy balance



http://geography.uoregon.edu/envchange/clim_animations/gifs/three_rads_web.gif

Surface energy balance



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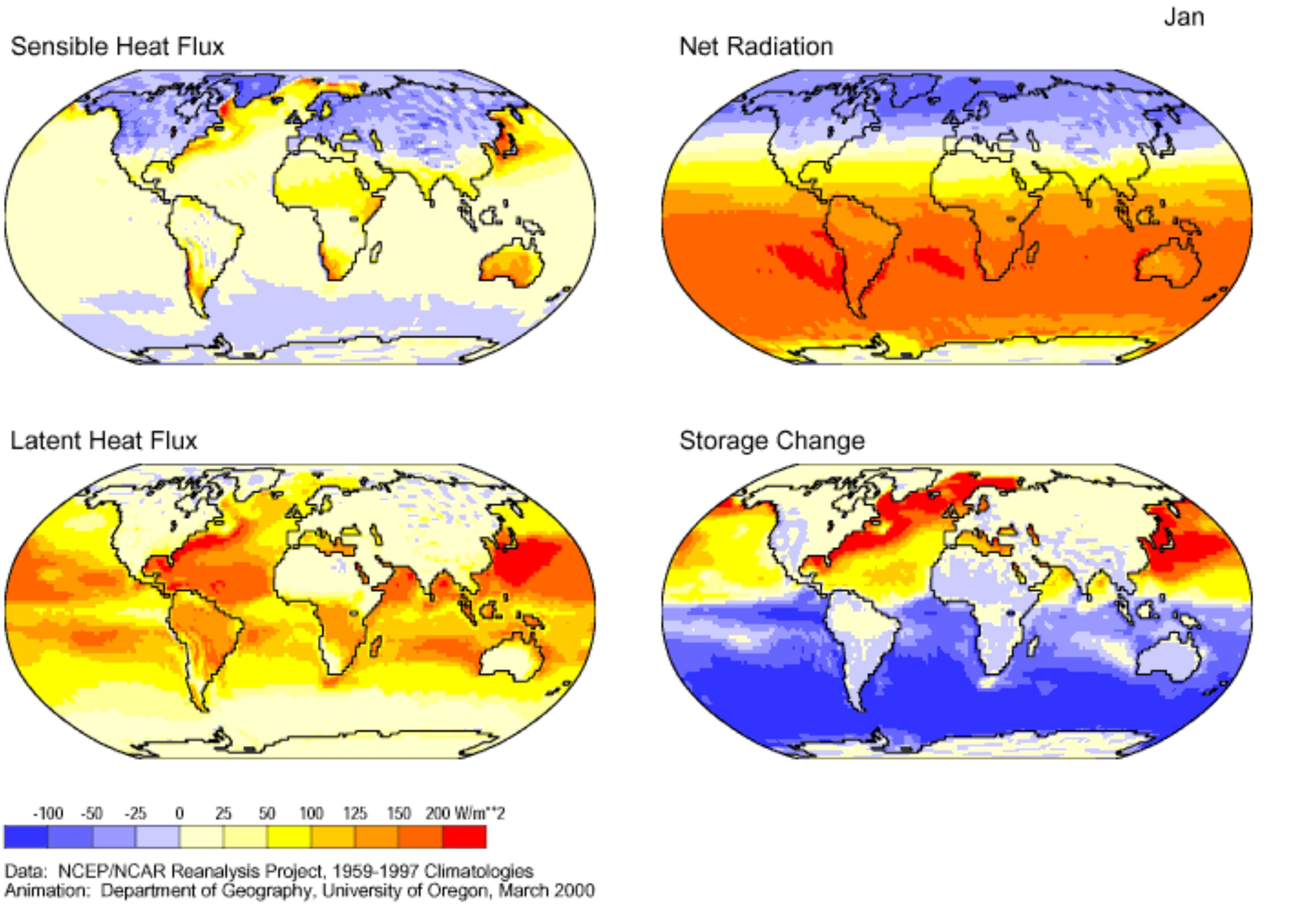
Surface energy balance



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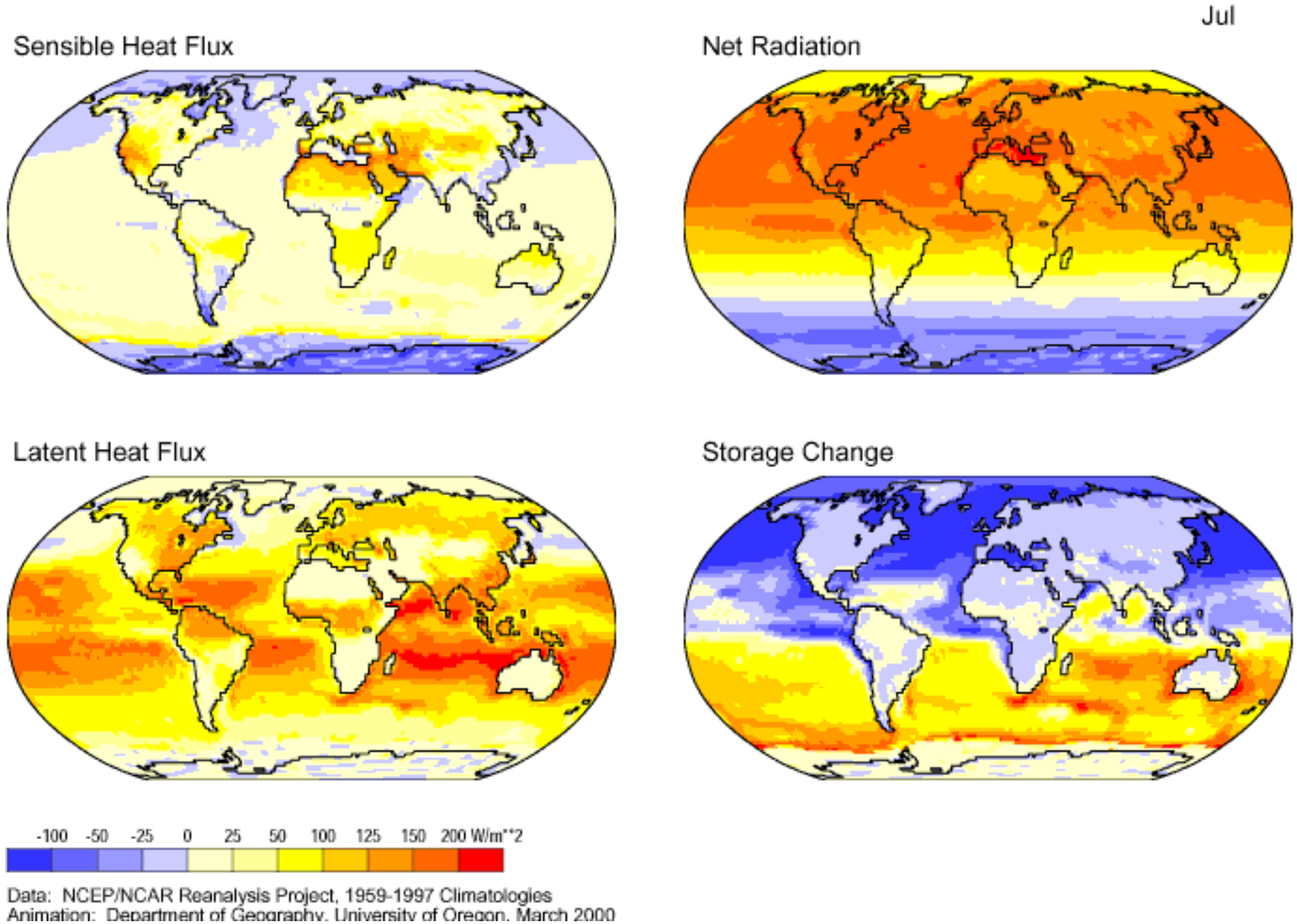
Surface energy balance

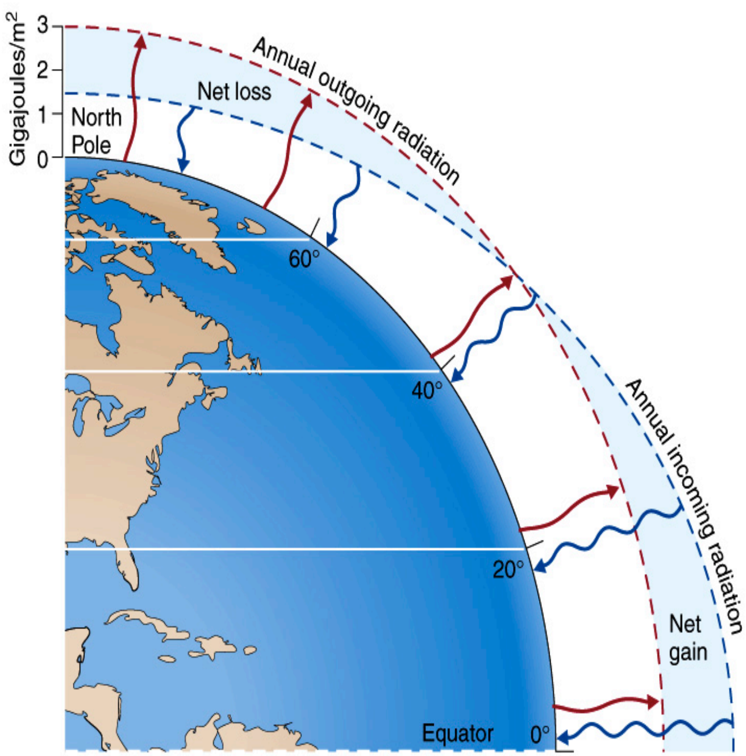


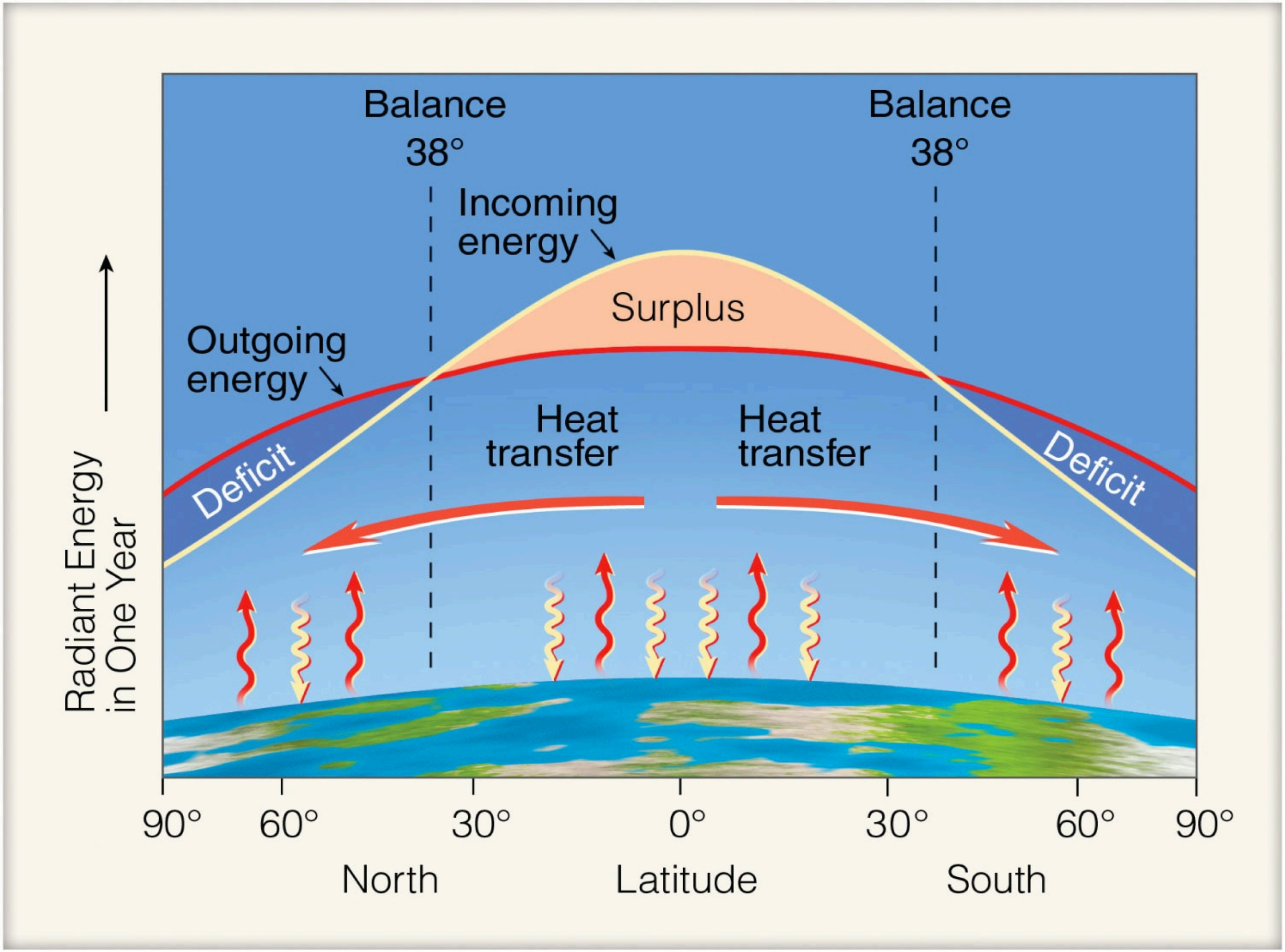
http://geography.uoregon.edu/envchange/clim_animations/gifs/four_storage_web.gif

Net Radiation and Temperature

- Energy balance
  - Incoming radiation balances with outgoing
  - If parameters are changed, a new equilibrium occurs

- Latitudinal Variations
  - Between 38°N and S = net energy surpluses
  - Poleward of 38° = net energy deficits
  - Winter hemispheres
    - Net energy deficits poleward of 15°





The average annual incoming solar radiation (yellow lines) absorbed by the earth and the atmosphere along with the average annual infrared radiation (red lines) emitted by the earth and the atmosphere.