Lecture 1: Global Energy Balance

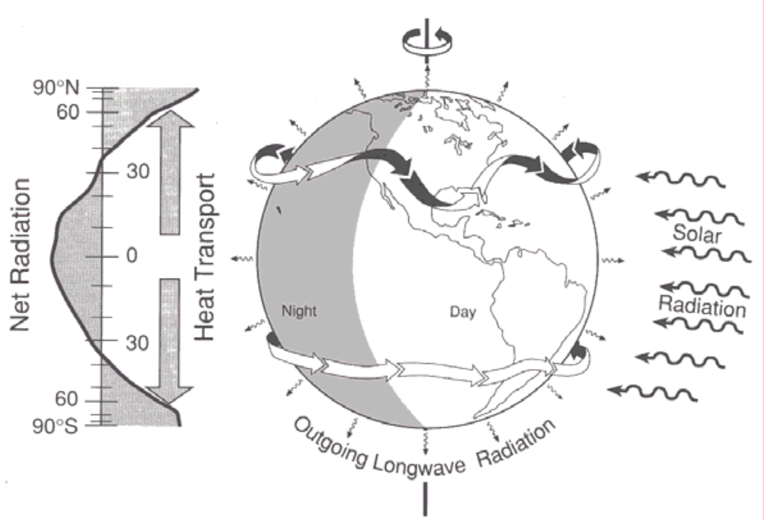


Figure 1.2: The incoming solar radiation (right) illuminates only part of the Earth while the outgoing long-wave radiation is distributed more evenly. On an annual mean basis, the result is an excess of absorbed solar radiation over the outgoing long-wave radiation in the tropics, while there is a deficit at middle to high latitudes (far left), so that there is a requirement for a poleward heat transport in each hemisphere (arrows) by the atmosphere and the oceans. This radiation distribution results in warm conditions in the tropics but cold at high latitudes, and the temperature contrast results in a broad band of westerlies in the extra-tropics of each hemisphere in which there is an embedded jet stream (shown by the "ribbon" arrows) at about 10 km above the Earth's surface. The flow of the jetstream over the different underlying surface (ocean, land, mountains) produces waves in the atmosphere and adds geographic spatial structure to climate. The excess of net radiation at the equator is 68 Wm^{-2} and the deficit peaks at −100 Wm^{-2} at the South Pole and −125 Wm^{-2} at the North Pole; from Trenberth and Solomon (1994).

(from *Climate Change 1995*)

- **Planetary energy balance**

  Energy absorbed by Earth = Energy emitted by Earth

- **Role of the atmosphere**

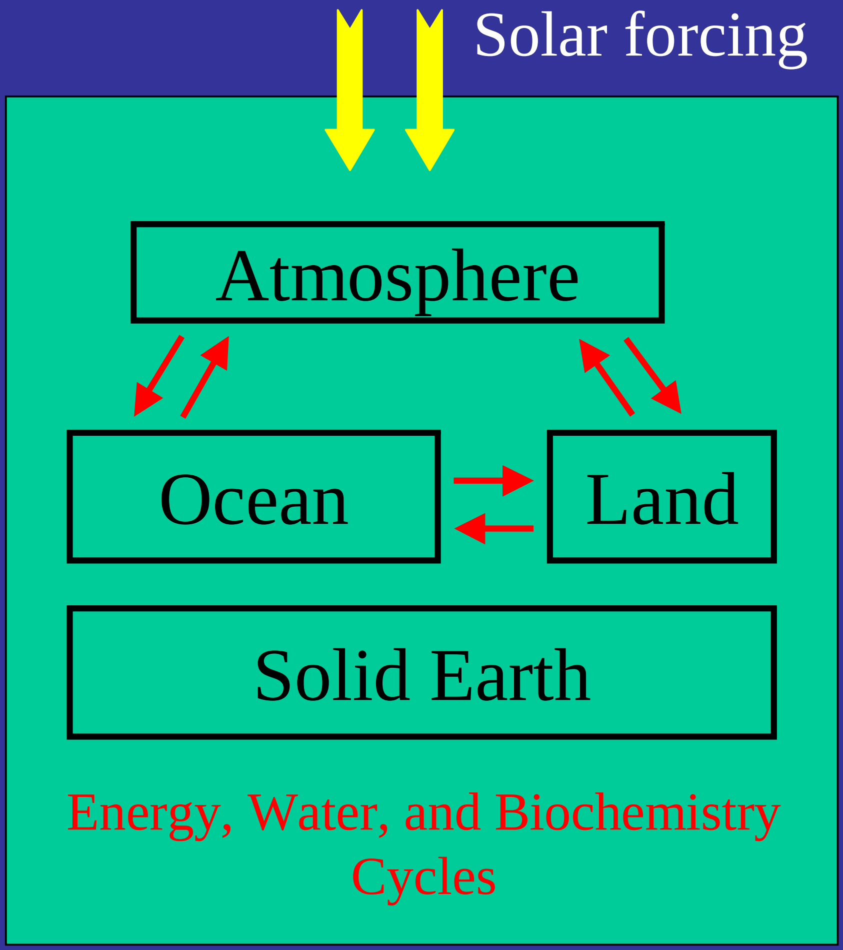
  Greenhouse effect

- **Role of oceans**

  Polarward energy transport

- **Role of land surface**

  not significant due to its low heat capacity



Solar forcing

Atmosphere

Ocean

Land

Solid Earth

Energy, Water, and Biochemistry Cycles

Global View of the Energy Balance

Solar Flux and Flux Density

☐ Solar Luminosity (*L*)

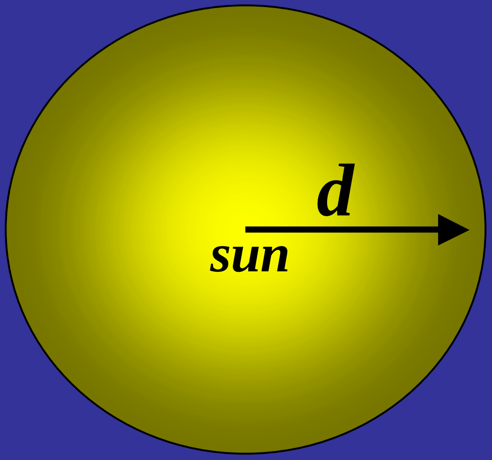
the constant flux of energy put out by the sun

$$L = 3.9 \times 10^{26} \quad \mathrm{W}$$

☐ Solar Flux Density (S_d)

the amount of solar energy per unit area on a sphere centered at the Sun with a distance ***d***

$$S_d = L / (4 \pi d^2) \quad \mathrm{W/m^2}$$



Solar Flux Density Reaching Earth

- Solar Constant (*S*)

  The solar energy density at the mean distance of Earth from the sun (1.5×10^{11} m)

$$S = L / (4 \pi d^2)$$
$$= (3.9 \times 10^{26}\ \mathrm{W}) / [4 \times 3.14 \times (1.5 \times 10^{11}\ \mathrm{m})^2]$$
$$= 1370\ \mathrm{W/m^2}$$

Solar Energy Incident On the Earth

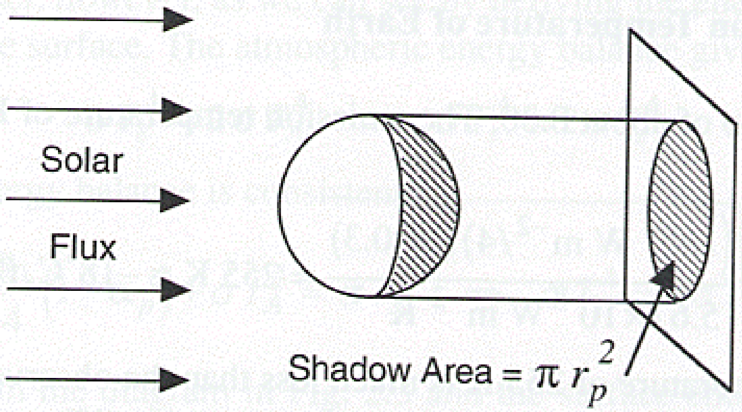
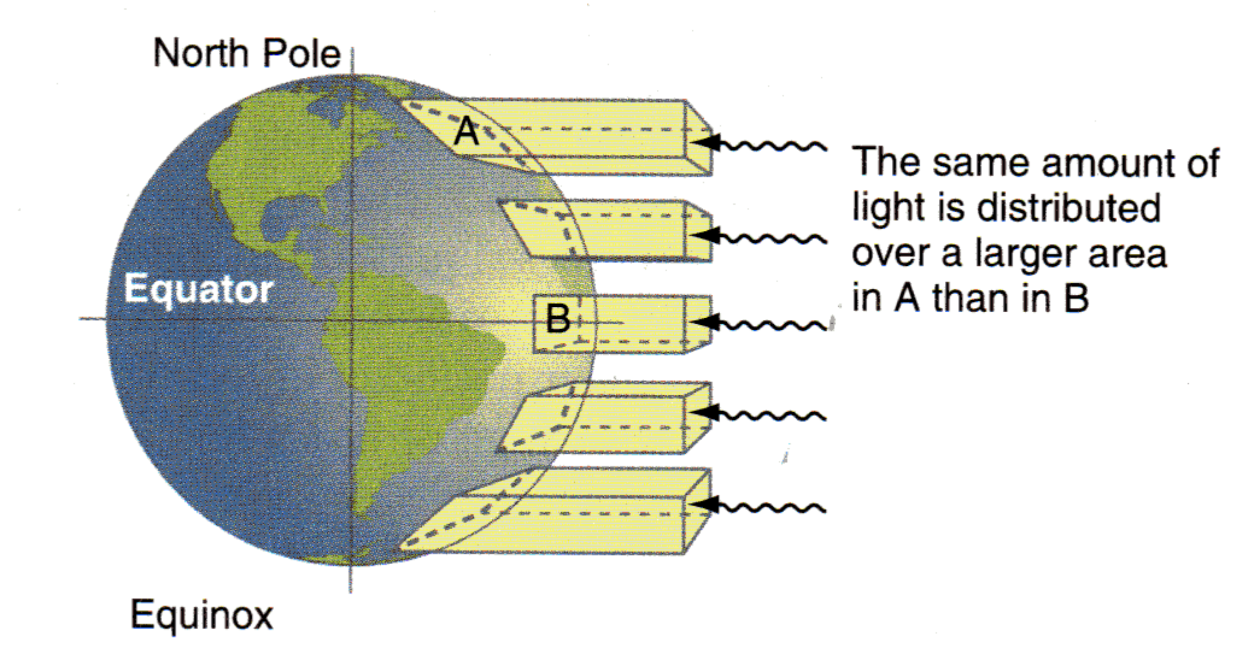


Fig. 2.2 Diagram showing the shadow area of a spherical planet.

- Solar energy incident on the Earth
  - = total amount of solar energy **can be** absorbed by Earth
  - = (Solar constant) x (Shadow Area)
  - = $S \text{ x } \pi R^2_{Earth}$

Zenith Angle and Insolation

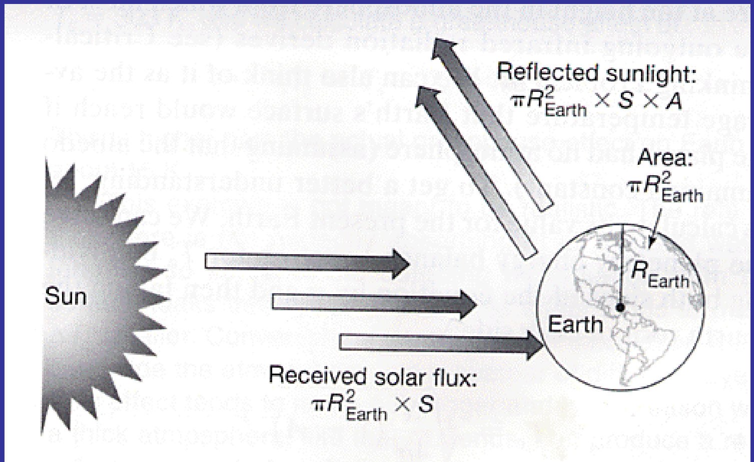


The same amount of light is distributed over a larger area in A than in B

(from *Meteorology: Understanding the Atmosphere*)

- The larger the solar zenith angle, the weaker the insolation, because the same amount of sunlight has to be spread over a larger area.

Solar Energy Absorbed by Earth



BOX FIGURE 3-1

The amount of sunlight received by and reflected by Earth.

(from *The Earth System*)

- **Solar Constant (S)**

  = solar flux density reaching the Earth

  = 1370 W/m^2

- **Solar energy incident on the Earth**

  = S x the "flat" area of the Earth

  = $S \times \pi R^2_{Earth}$

- **Solar energy absorbed by the Earth**

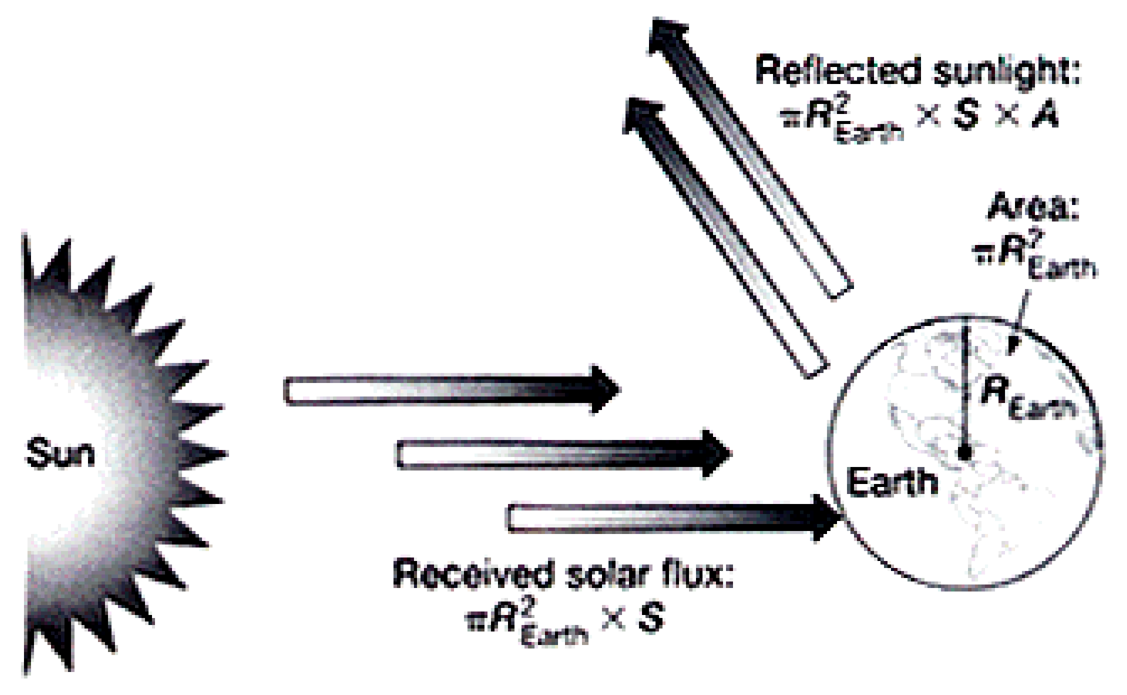
  = (received solar flux) – (reflected solar flux)

  = $S \pi R^2_{Earth} - S \pi R^2_{Earth} \times A$

  = $\mathbf{S \pi R^2_{Earth} \times (1-A)}$

A is the *planetary albedo* of the Earth, which is about 0.3.

Albedo = [Reflected] / [Incoming] Sunlight



Albedo is the percentage of the sunlight that is reflected back to the space by the planet.

What Happens After the Earth Absorbs Solar Energy?

- The Earth warms up and has to emit radiative energy back to the space to reach a equilibrium condition.

- The radiation emitted by the Earth is called “terrestrial radiation” which is assumed to be like blackbody radiation.

Blackbody Radiation

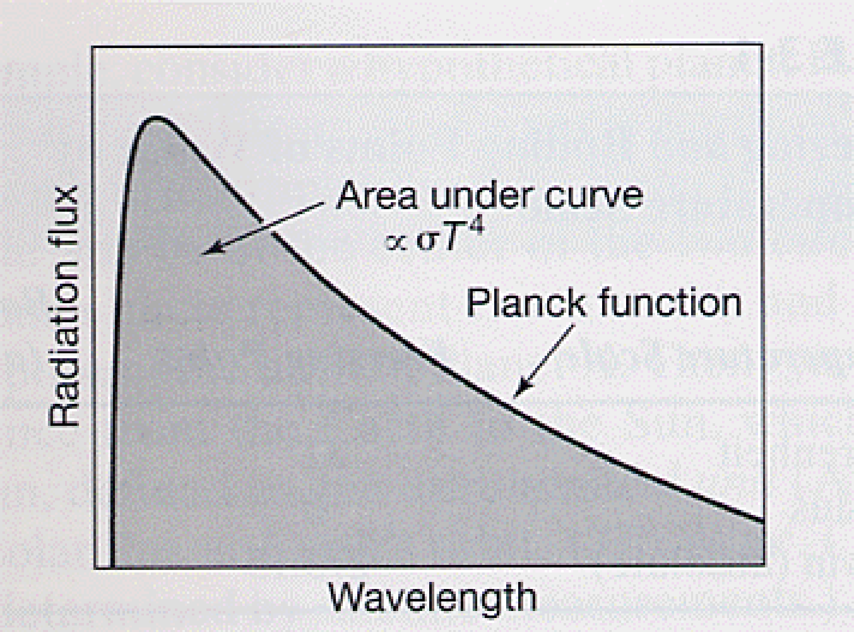
- Blackbody

  A blackbody is something that emits (or absorbs) electromagnetic radiation with 100% efficiency at all wavelength.

- Blackbody Radiation

  The amount of the radiation emitted by a blackbody depends on the absolute temperature of the blackbody.

Energy Emitted from Earth



(from *The Earth System*)

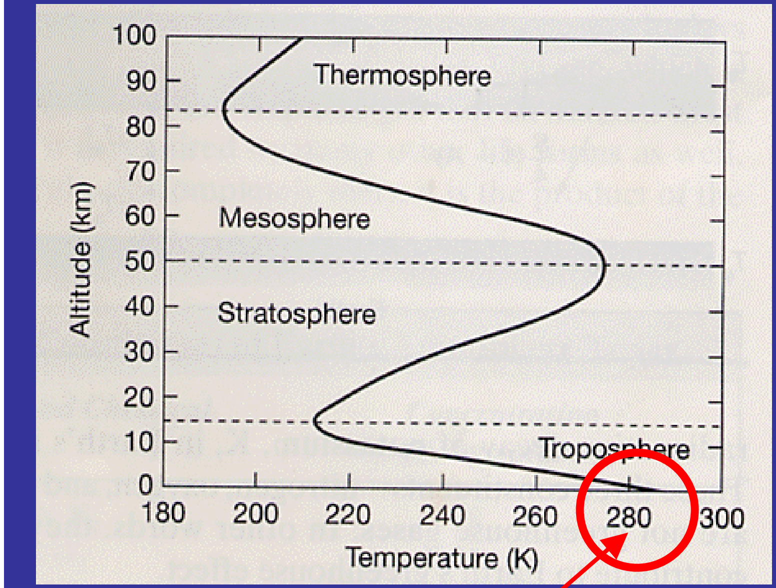
- **The Stefan-Boltzmann Law**

  The energy flux emitted by a blackbody is related to the fourth power of the body's absolute temperature

  $\mathbf{F = \sigma T^4}$ where σ is $5.67\text{x}10^{-8}$ $\text{W/m}^2\text{/K}$

- **Energy emitted from the Earth**
  = (blackbody emission) x (total area of Earth)
  = $(\sigma T_e^{\ 4})$ x $(4\pi\, R^2_{\text{Earth}})$

Planetary Energy Balance



(from *Global Physical Climatology*)

- **Energy emitted by Earth = Energy absorbed by Earth**

$$\sigma T_e^4 \times (4\pi R^2_{\text{Earth}}) = S \pi R^2_{\text{Earth}} \times (1-A)$$

$$\sigma T_e^4 = S/4 * (1-A)$$

$$= 1370/4 \text{ W/m}^2 * (1-A)$$

$$= 342.5 \text{ W/m}^2 * (1-A)$$

$$= 240 \text{ W/m}^2$$

- **Earth's *blackbody* temperature**

T_e = 255 K (-18C)

Earth's *surface* temperature

T_S = 288 K (15C)

greenhouse effect (33C) !!

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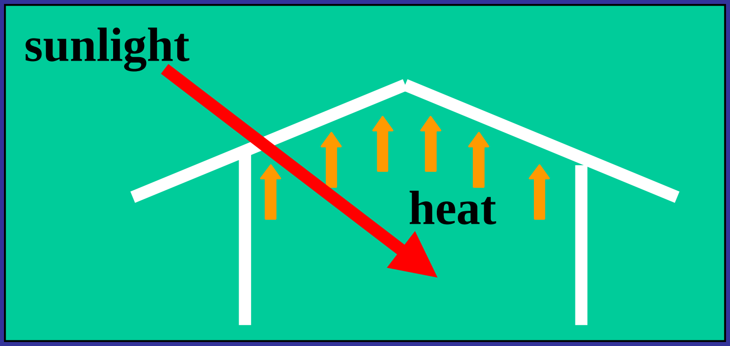
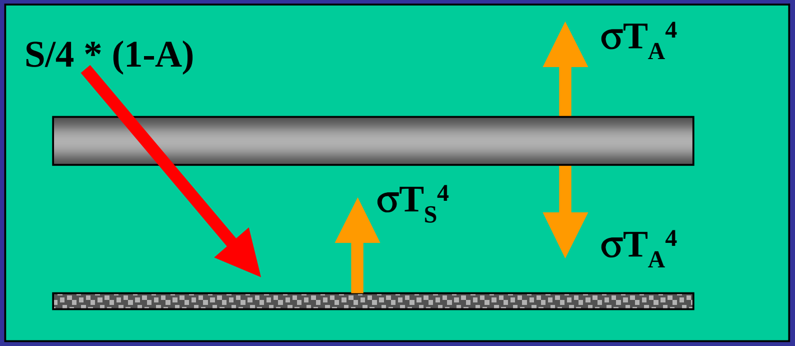
Greenhouse Effect

Greenhouse



- allow sunlight to come in
- trap heat inside the house

Atmosphere



At the top of the atmosphere:

$S/4*(1-A) = \sigma T_A^4$ ➔ $T_A = T_e =$ **255K**

For Earth's surface:

$S/4*(1-A) + \sigma T_A^4 = \sigma T_S^4$

➔ $T_S = 1.19 T_A =$ **303K**

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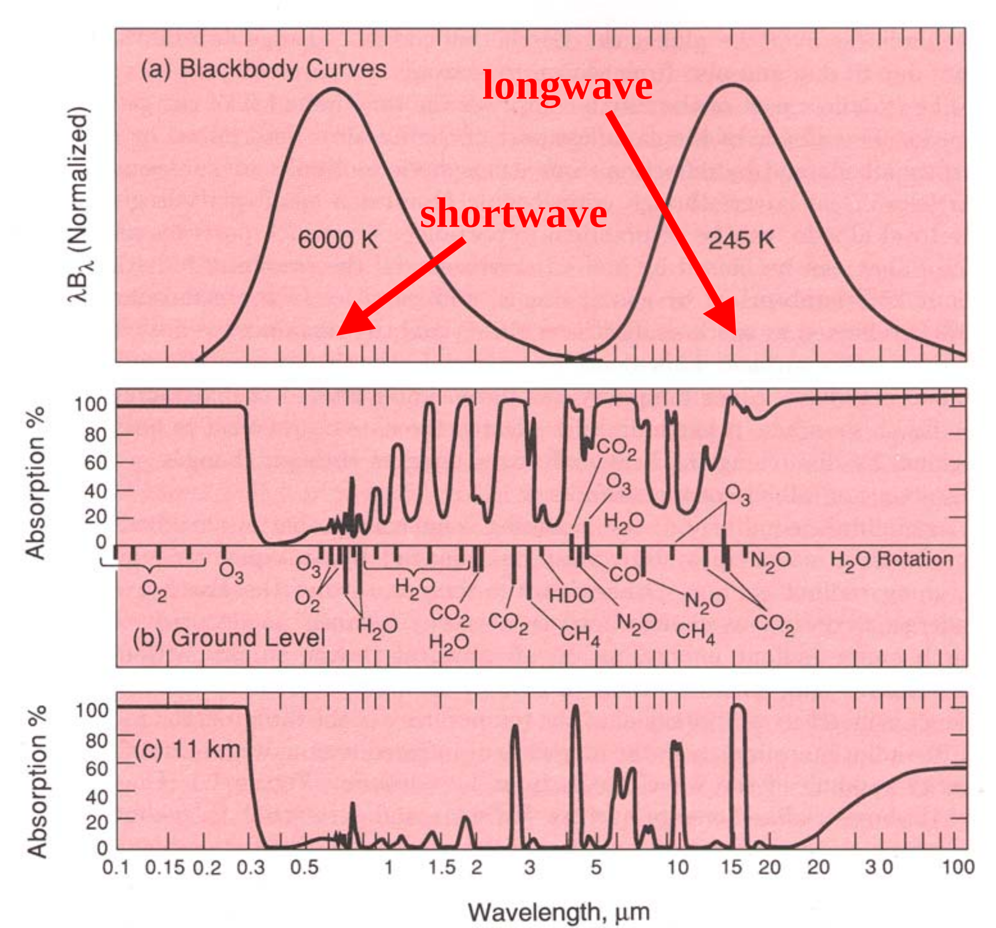
Different Wavelengths of Solar and Earth’s Radiation

Normalized Planck Function



longwave

shortwave

(from *Climate System Modeling*)

Planck Function

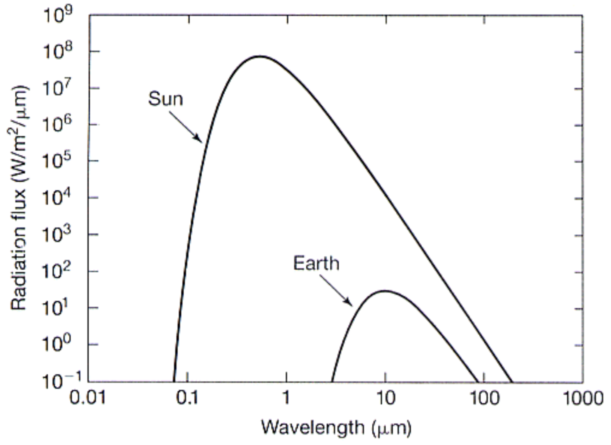


FIGURE 3-8

Blackbody emission curves for the Sun and Earth. The Sun emits more energy at all wavelengths.

(from *The Earth System*)

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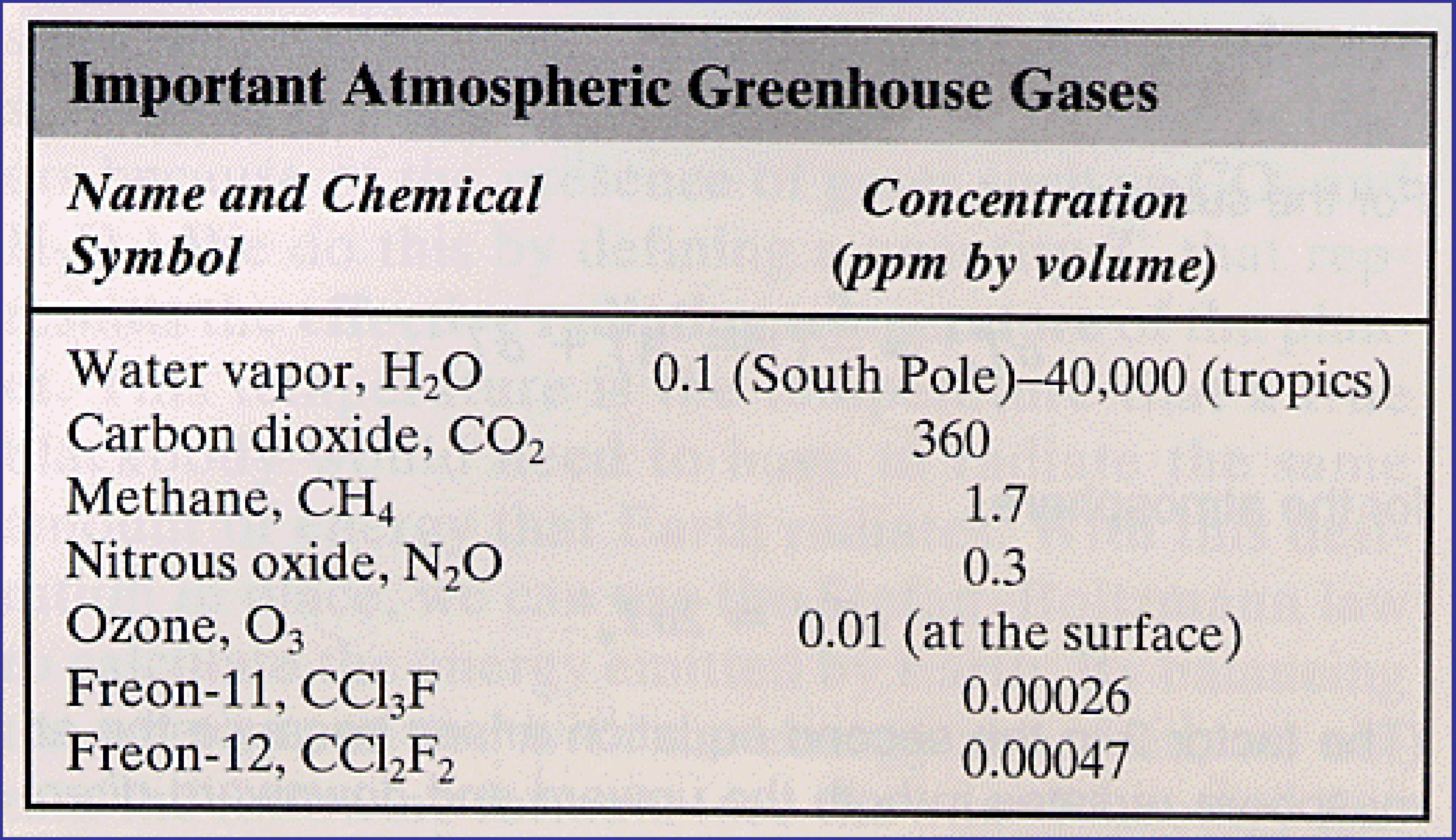
Greenhouse Gases



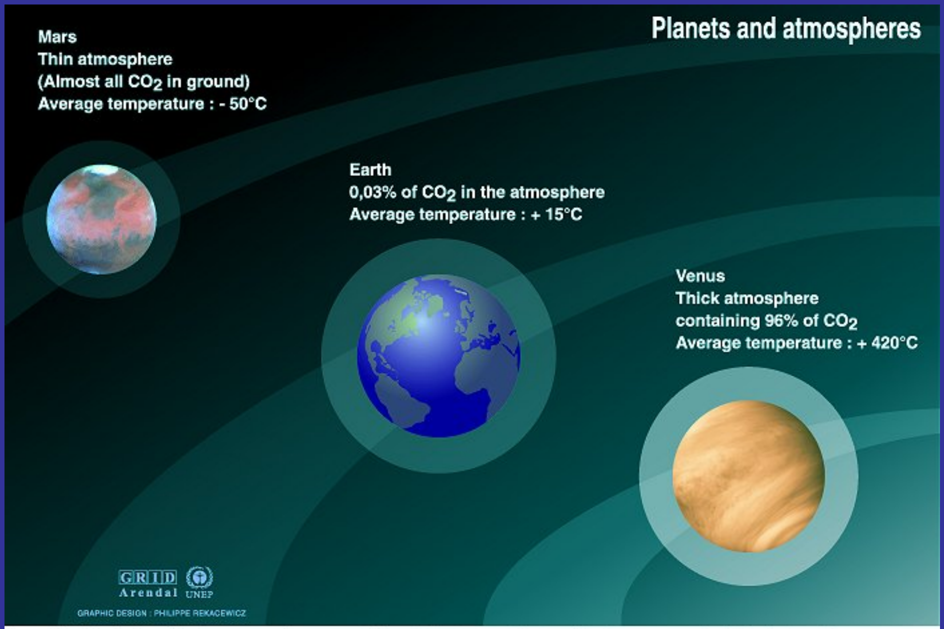
Important Atmospheric Greenhouse Gases

Name and Chemical Symbol	*Concentration (ppm by volume)*
Water vapor, H_2O	0.1 (South Pole)–40,000 (tropics)
Carbon dioxide, CO_2	360
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	0.00047

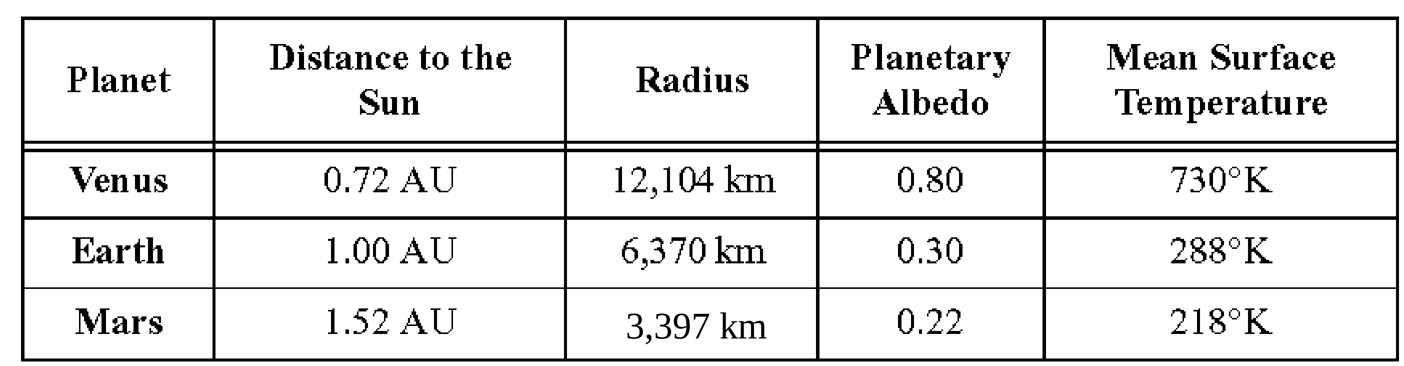
Three Factors To Determine Planet Temperature

- Distance from the Sun
- Albedo
- Greenhouse effect

Earth, Mars, and Venus

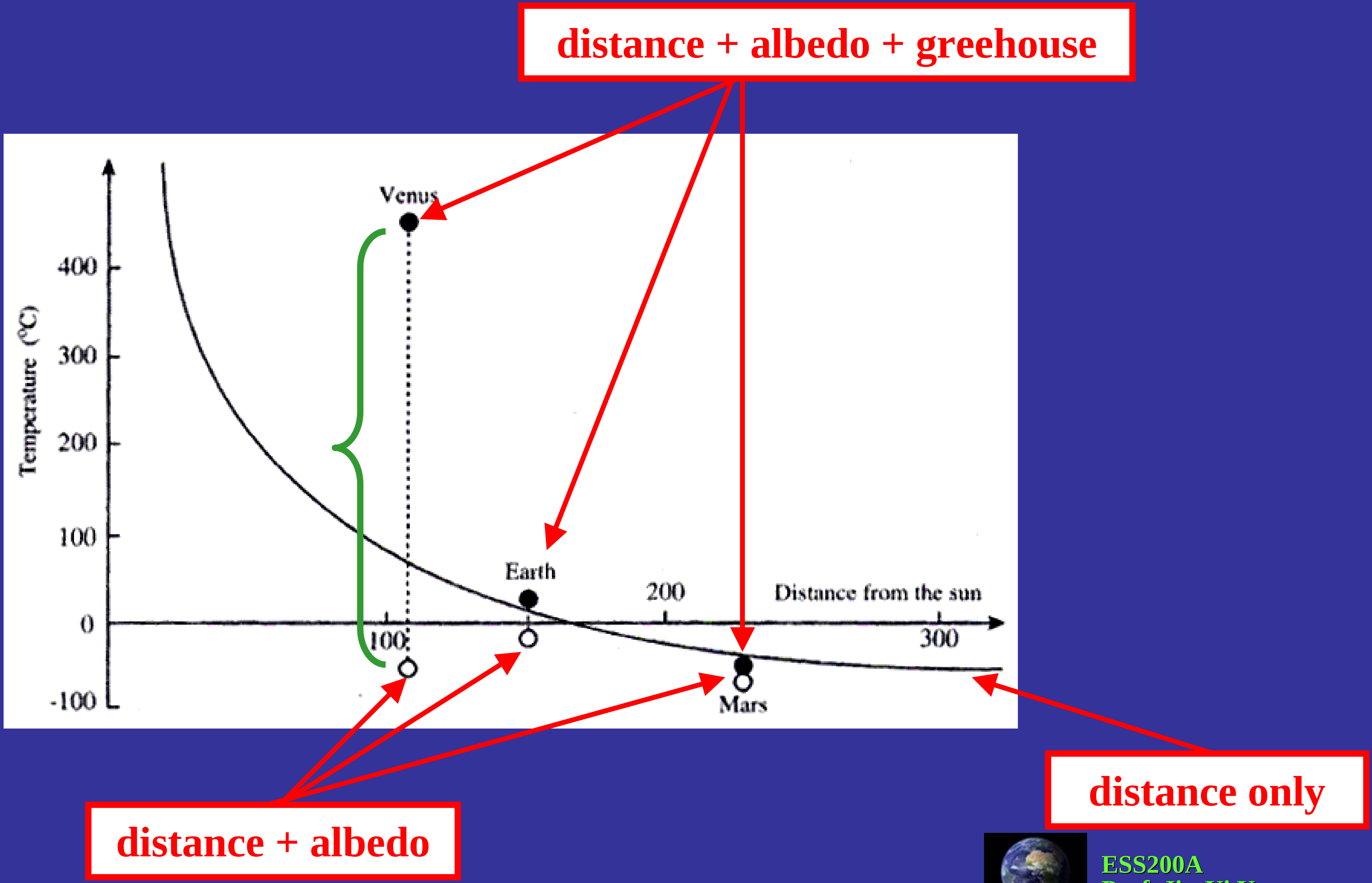


Sources: Calvin J. Hamilton, Views of the solar system, www.planetscapes.com; Bill Arnett , The nine planets, a multimedia tour of the solar system, www.seds.org/billa/tnp/nineplanets.html



Planet	Distance to the Sun	Radius	Planetary Albedo	Mean Surface Temperature
Venus	0.72 AU	12,104 km	0.80	730°K
Earth	1.00 AU	6,370 km	0.30	288°K
Mars	1.52 AU	3,397 km	0.22	218°K

Global Temperature



Greenhouse Effects

- On Venus → 510°K (very large!!)
- On Earth → 33°K
- On Mars → 6°K (very small)

Why Large Greenhouse Effect On Venus?

❑ **Venus is too close to the Sun**

➔ Venus temperature is very high

➔ Very difficult for Venus’s atmosphere to get saturated in water vapor

➔ Evaporation keep on bringing water vapor into Venus’s atmosphere

➔ Greenhouse effect is very large

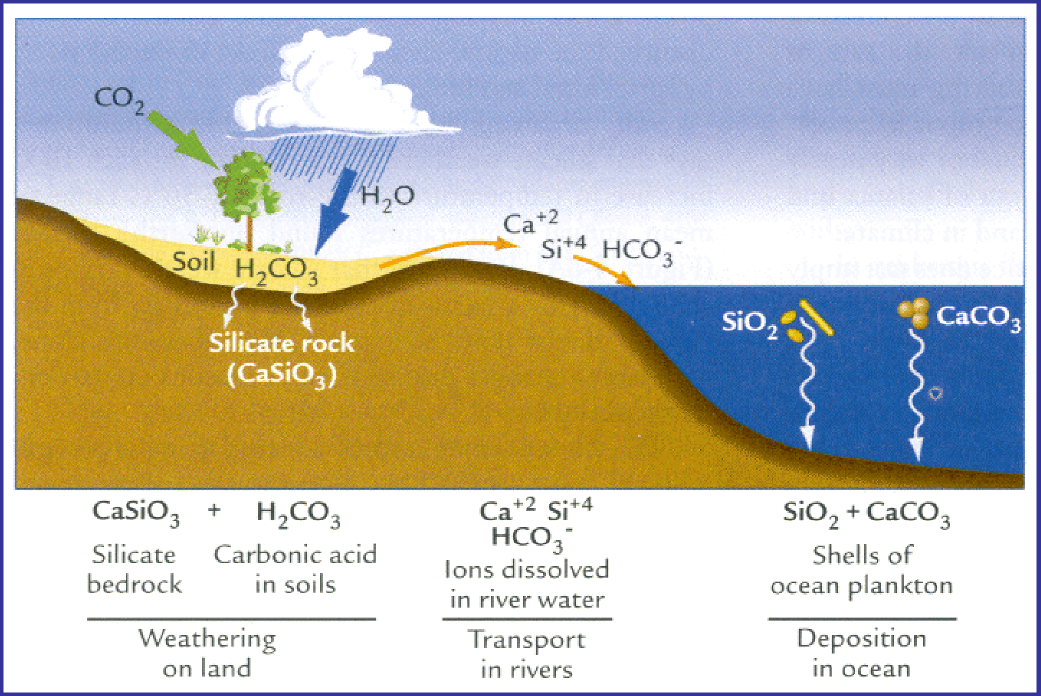
➔ A “run away” greenhouse happened on Venus

➔ Water vapor is dissociated into hydrogen and oxygen

➔ Hydrogen then escaped to space and oxygen reacted with carbon to form carbon dioxide

➔ **No water left on Venus (and no more chemical weathering)**

Chemical Weathering

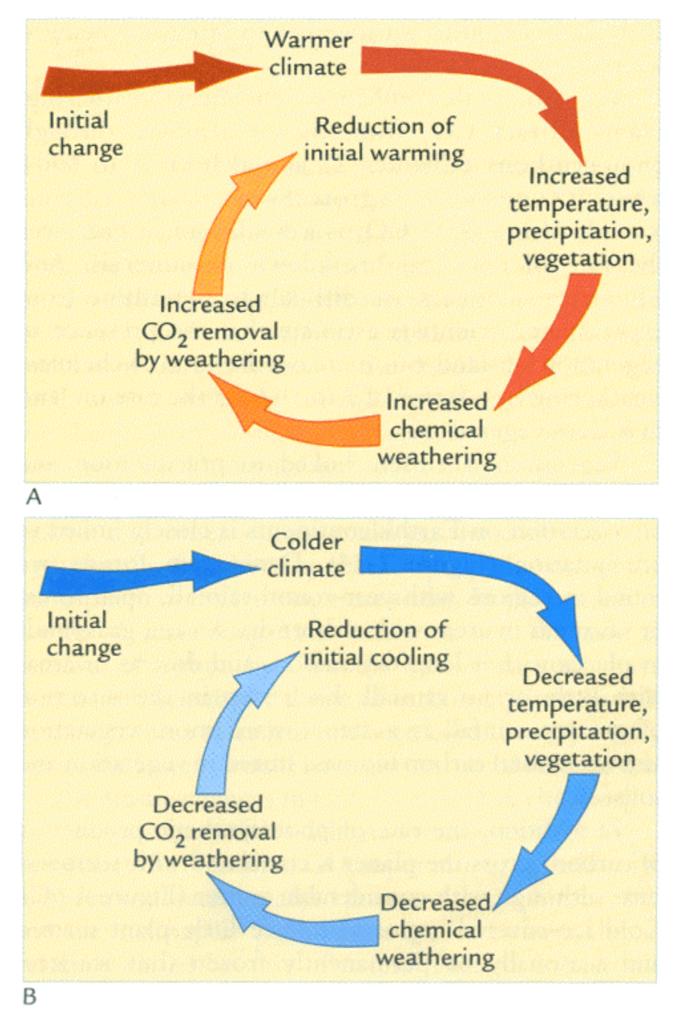


(from *Earth's Climate: Past and Future*)

- The precipitation process in the atmosphere dissolve and remove CO_2 from the atmosphere.
- Rocks exposed at Earth's surface undergo chemical attack from this rain of dilute acid.
- This whole process is known as ***chemical weathering***.
- The rate of chemical weathering tend to increase as temperature increases.
- Weathering requires water as a medium both for the dissolution of minerals and for the transport of the dissolved materials to the ocean

➔ The rate of chemical weathering increases as precipitation increases.

Negative Feedback From Chemical Weathering

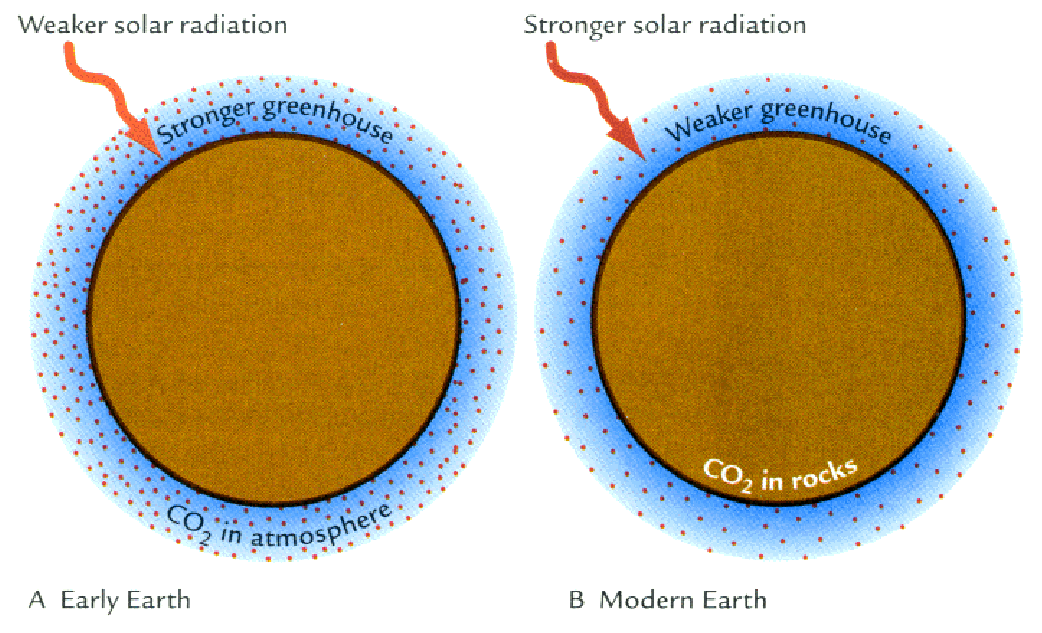


(from *Earth's Climate: Past and Future*)

- The chemical weathering works as a negative feedback that moderates long-term climate change.

- This negative feedback mechanism links CO_2 level in the atmosphere to the temperature and precipitation of the atmosphere.

Earth’s Thermostat – Chemical Weathering



(from *Earth’s Climate: Past and Future*)

- ☐ Chemical weathering acts as Earth’s thermostat and regulate its long-term climate.
- ☐ This thermostat mechanism lies in two facts:

  (1) the average global rate of chemical weathering depends on the state of Earth’s climate,

  (2) weathering also has the capacity to alter that state by regulating the rate which CO_2 is removed from the atmosphere.

Why Small Greenhouse Effect on Mars?

❑ **Mars is too small in size**

➔Mars had no large internal heat

➔Mars lost all the internal heat quickly

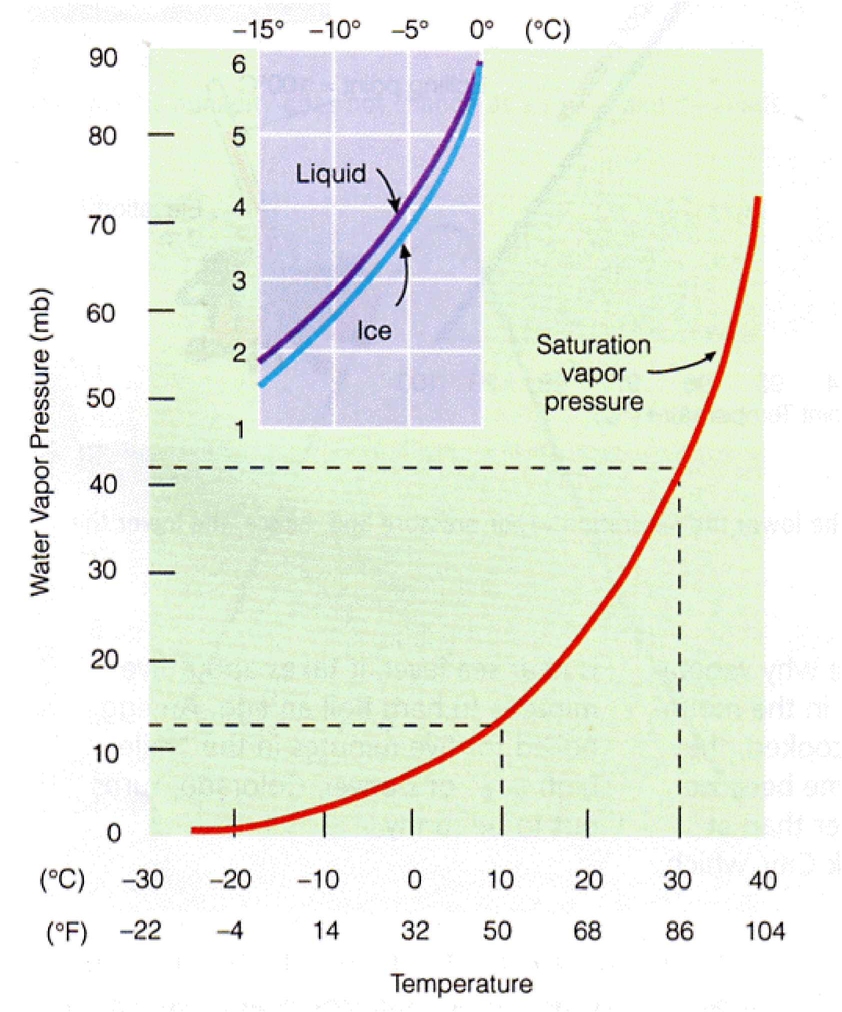
➔No tectonic activity on Mars

➔Carbon can not be injected back to the atmosphere

➔Little greenhouse effect

➔**A very cold Mars!!**

Saturation Vapor Pressure



- Saturation vapor pressure describes how much water vapor is needed to make the air saturated at any given temperature.
- Saturation vapor pressure depends primarily on the air temperature in the following way:

$$\boxed{\frac{de_s}{dT} = \frac{L}{T(\alpha_v - \alpha_l)}}$$

The Clausius-Clapeyron Equation

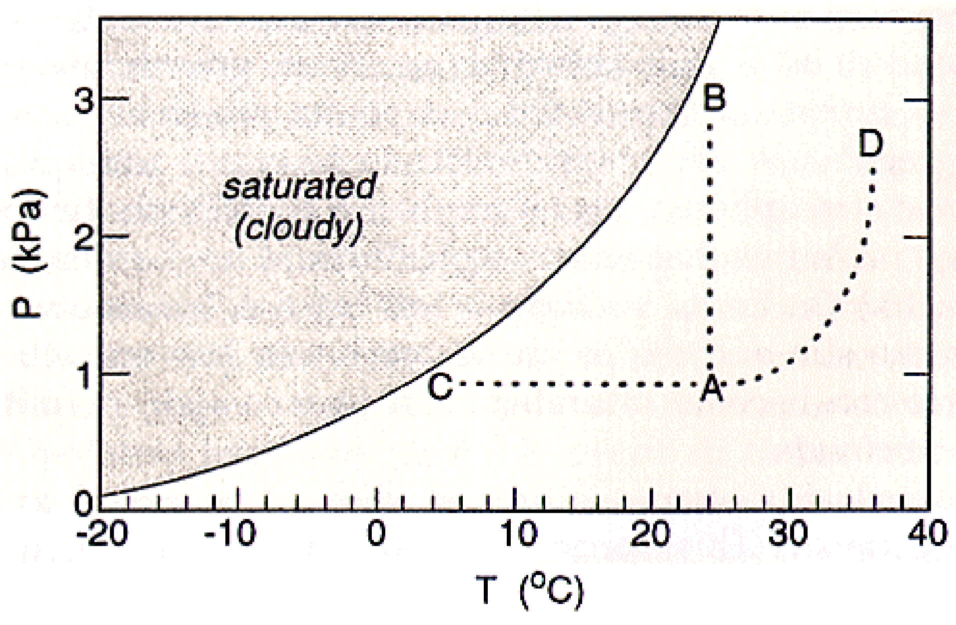
➔

$$\boxed{e_s \cong 6.11 \bullet \exp\left\{\frac{L}{R_v}\left(\frac{1}{273} - \frac{1}{T}\right)\right\}}$$

- Saturation pressure increases exponentially with air temperature.

L: latent heat of evaporation; α: specific volume of vapor and liquid

How to Saturate the Air?



(from "*IS The Temperature Rising*")

- ☐ Two ways:

(1) Increase (inject more) water vapor to the air (A→ B).

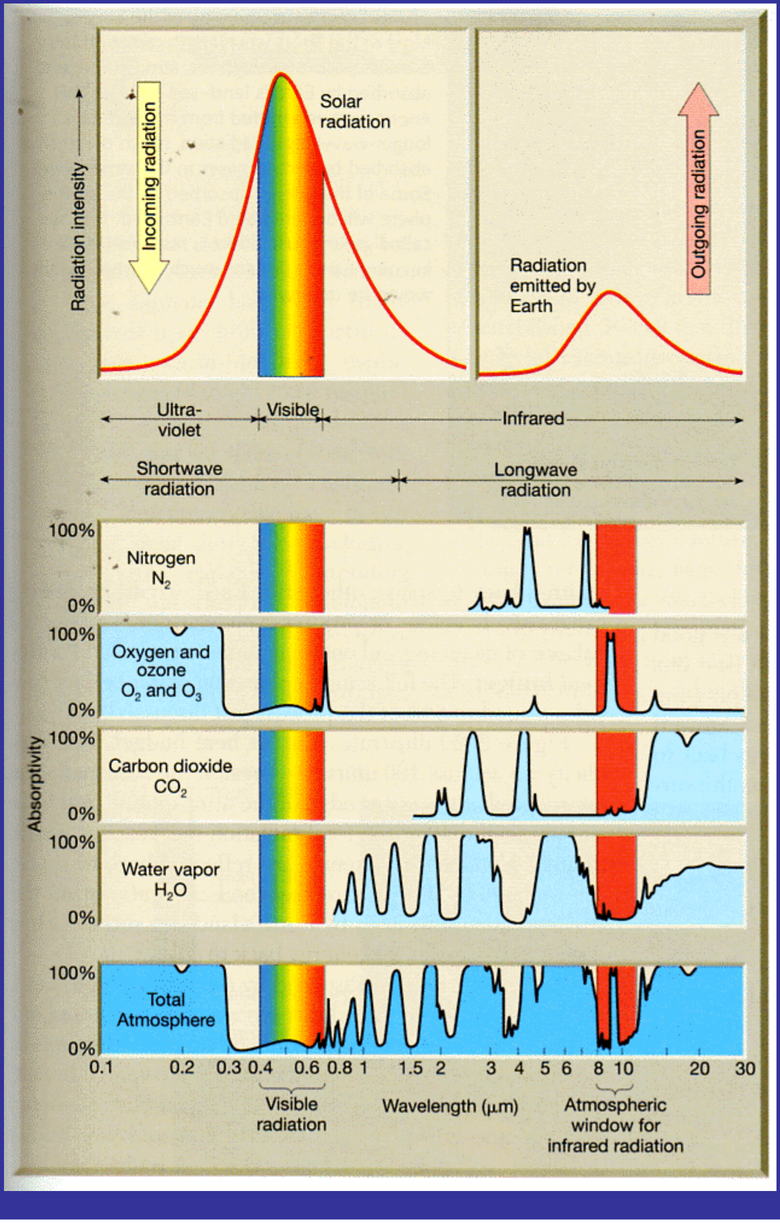
(2) Reduce the temperature of the air (A → C).

Two Key Reasons for the Greenhouse Effect

- Solar and terrestrial radiations are emitted at very different wavelengths.

- The greenhouse gases selectively absorb certain frequencies of radiation.

Selective Absorption and Emission

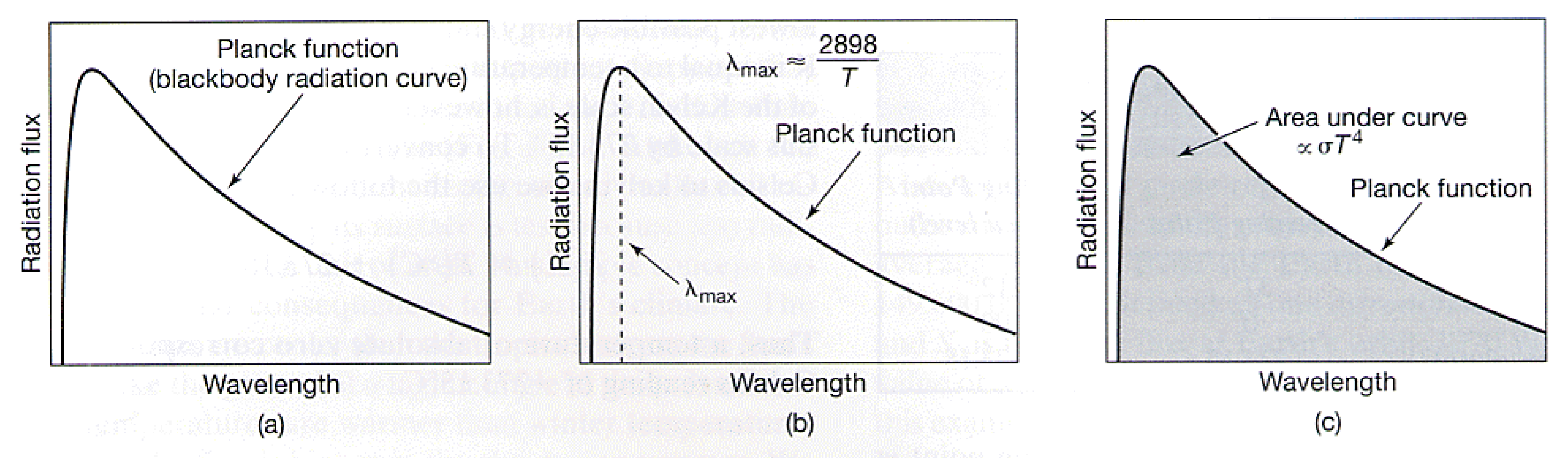


- The atmosphere is not a perfect blackbody, it absorbs some wavelength of radiation and is transparent to others (such as solar radiation). ➔ Greenhouse effect.
- Objective that selectively absorbs radiation usually selectively emit radiation at the same wavelength.
- For example, water vapor and CO2 are strong absorbers of infrared radiation and poor absorbers of visible solar radiation.

(from *The Atmosphere*)

Planck Function

- The Planck function relates the intensity of radiation from a blackbody to its wavelength.



(from *The Earth System*)

Wien’s Law

$$\lambda_{max} = w/T$$

λ_{max} = wavelength (micrometers)

W = 2897 μm K

T = temperate (K)

- Wien’s law relates an objective’s maximum emitted wavelength of radiation to the objective’s temperature.

- It states that the wavelength of the maximum emitted radiation by an object is inversely proportional to the objective’s absolute temperature.

Apply Wien's Law To Sun and Earth

- **Sun**

  λ_{max} = 2898 μm K / 6000K

  = 0.483 μm

- **Earth**

  λ_{max} = 2898 μm K / 300K

  = 9.66 μm

- Sun radiates its maximum energy within the visible portion of the radiation spectrum, while Earth radiates its maximum energy in the infrared portion of the spectrum.

Stefan-Boltzmann Law

$$E = \sigma T^4$$

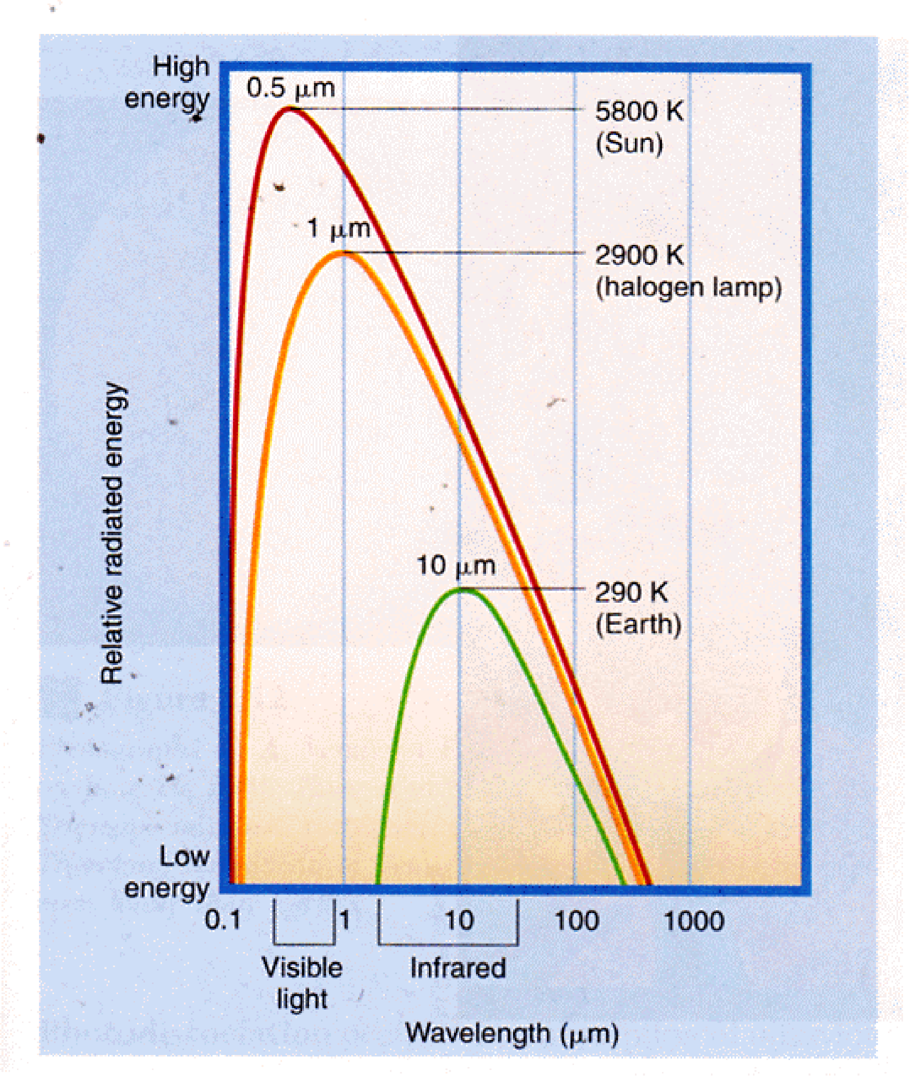
E = radiation emitted in W/m^2

σ= 5.67 x 10^{-8} W/m^2 * K *sec

T = temperate (K)

- The single factor that determine how much energy is emitted by a blackbody is its temperature.
- The intensity of energy radiated by a blackbody increases according to the fourth power of its absolute temperature.
- This relationship is called the Stefan-Boltzmann Law.

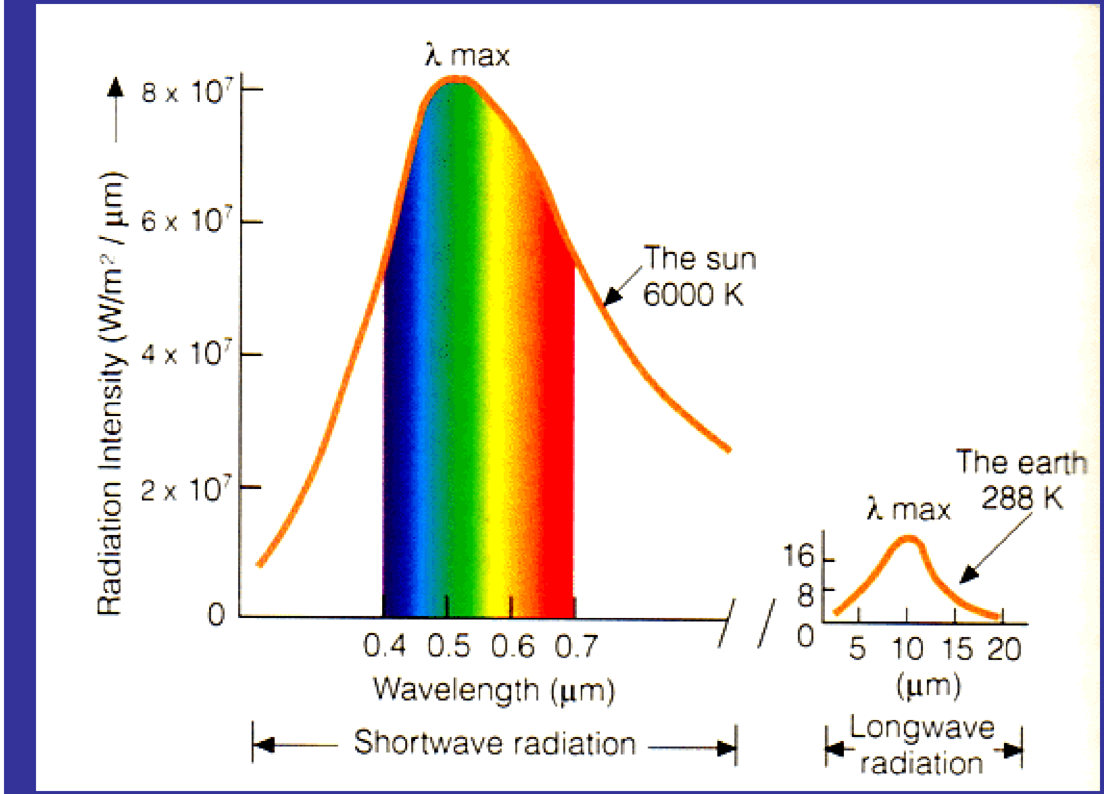
Wavelength and Temperature



(from *Meteorology: Understanding the Atmosphere*)

- ❑ The hotter the objective, the shorter the wavelength of the peak radiation.

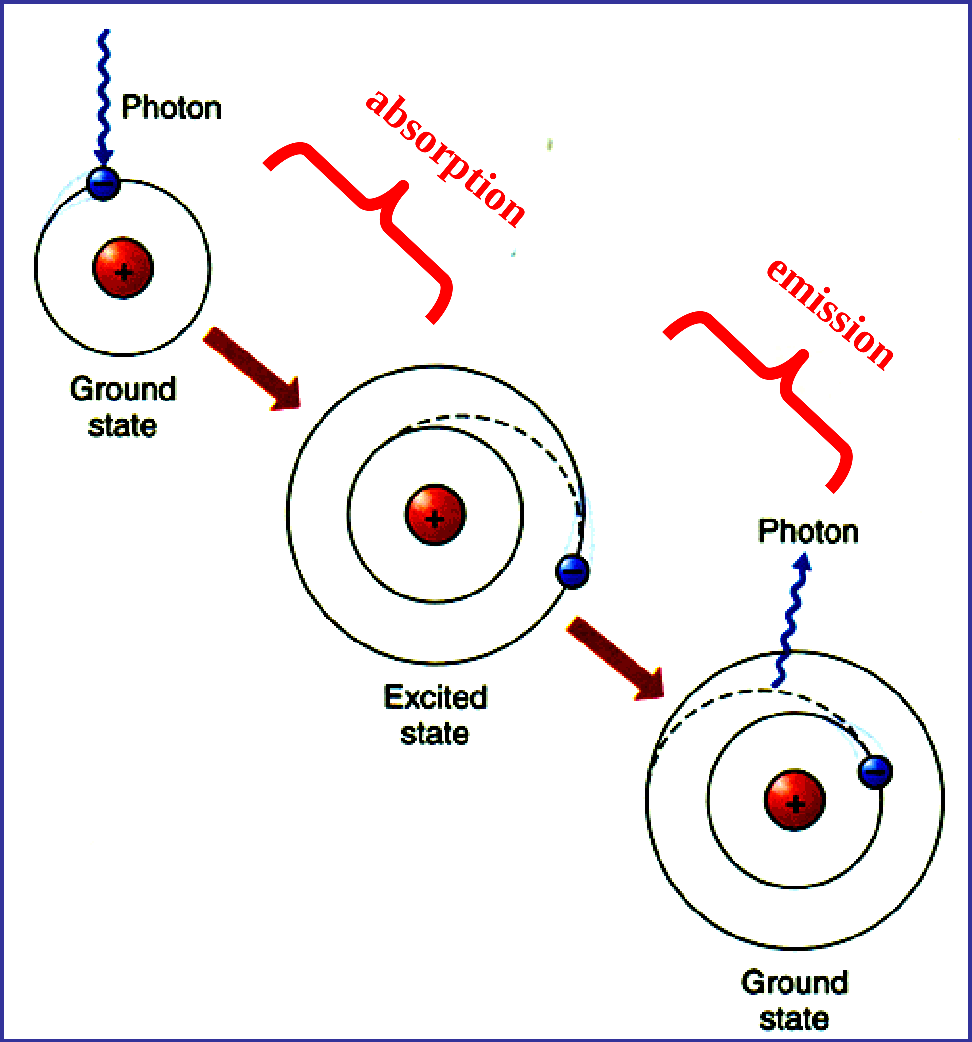
Shortwave and Longwave Radiations



(from *Meteorology: Understanding the Atmosphere*)

- Solar radiation is often referred to as “shortwave radiation”.
- Terrestrial radiation is referred to as “longwave radiation”.

Why Selective Absorption/Emission?

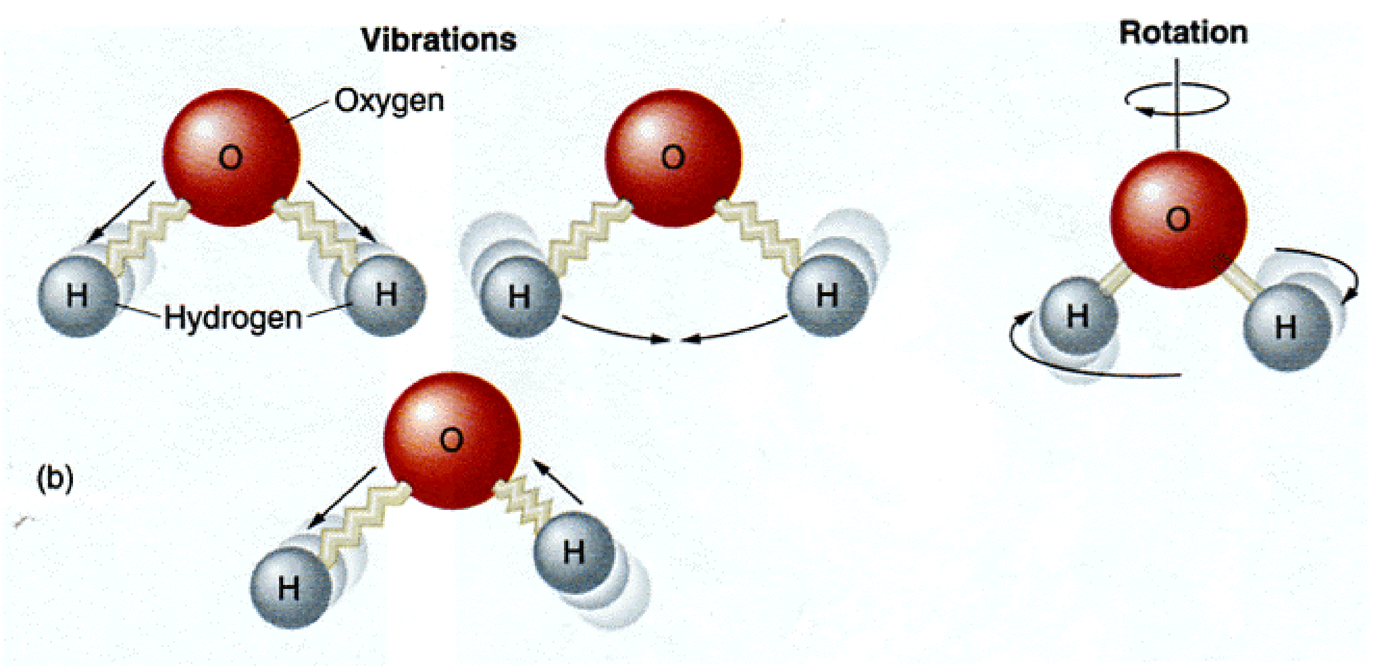


(from *Understanding Weather & Climate*)

- ❑ Radiation energy is absorbed or emitted to change the energy levels of atoms or molecular.
- ❑ The energy levels of atoms and molecular are discrete but not continuous.
- ❑ Therefore, atoms and molecular can absorb or emit certain amounts of energy that correspond to the differences between the differences of their energy levels.

➔ Absorb or emit at selective frequencies.

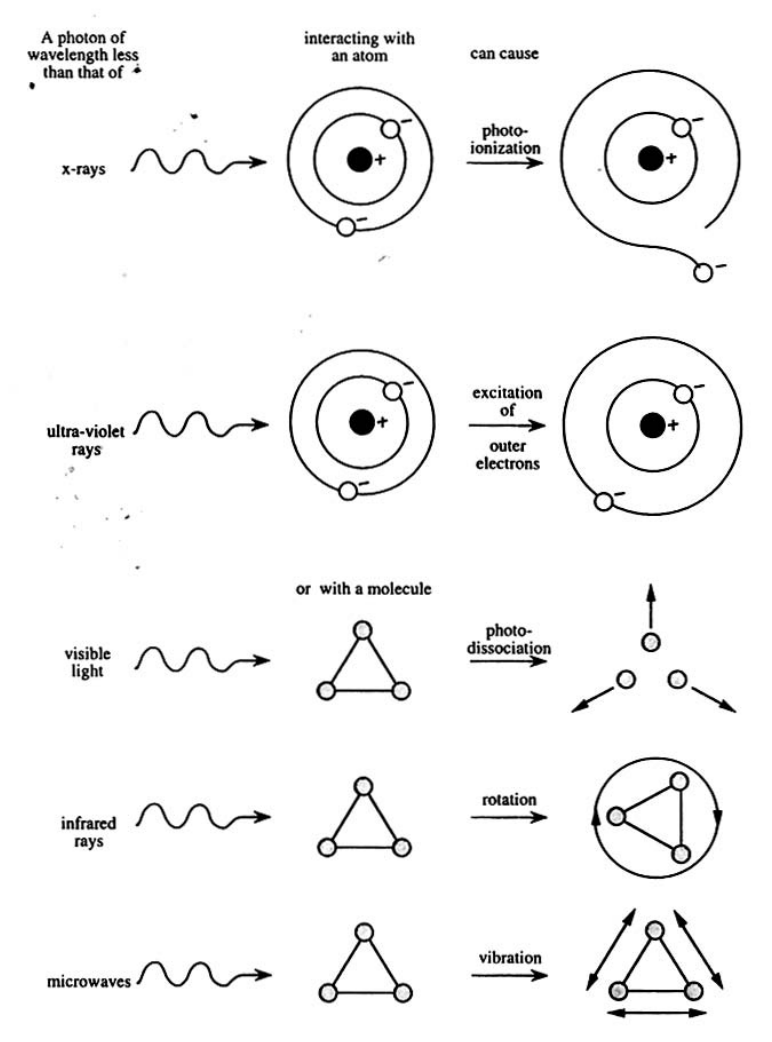
Different Forms of Energy Levels



(from *Understanding Weather & Climate*)

- The energy of a molecule can be stored in (1) translational (the gross movement of molecules or atoms through space), (2) vibrational, (3) rotational, and (4) electronic (energy related to the orbit) forms.

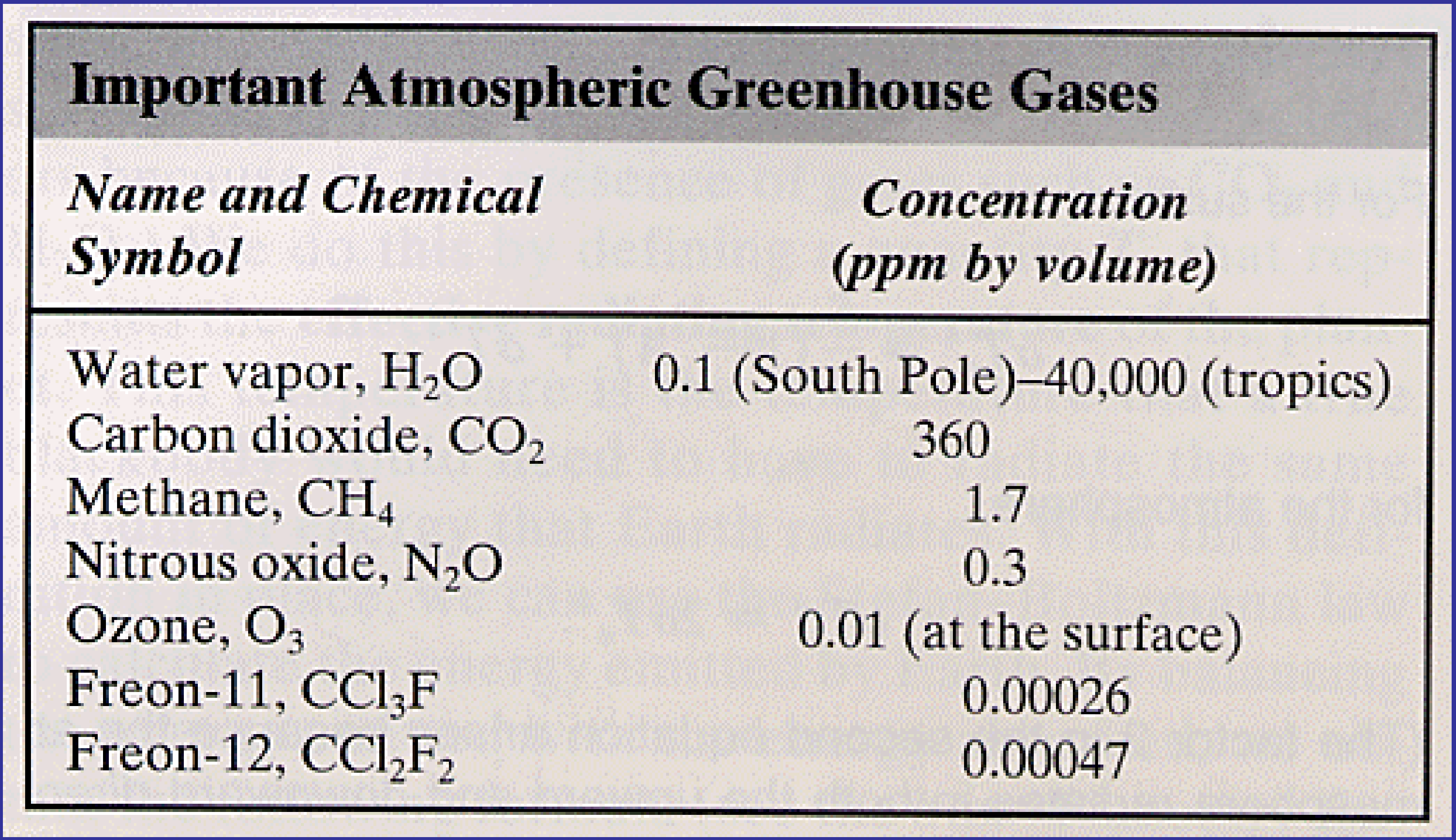
Energy Required to Change the Levels



- ☐ The most energetic photons (with shortest wavelength) are at the top of the figure, toward the bottom, energy level decreases, and wavelengths increase.

(from *Is The Temperature Rising?*)

Greenhouse Gases



Important Atmospheric Greenhouse Gases

Name and Chemical Symbol	*Concentration (ppm by volume)*
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Ozone, O_3	0.01 (at the surface)
Freon-11, CCl_3F	0.00026
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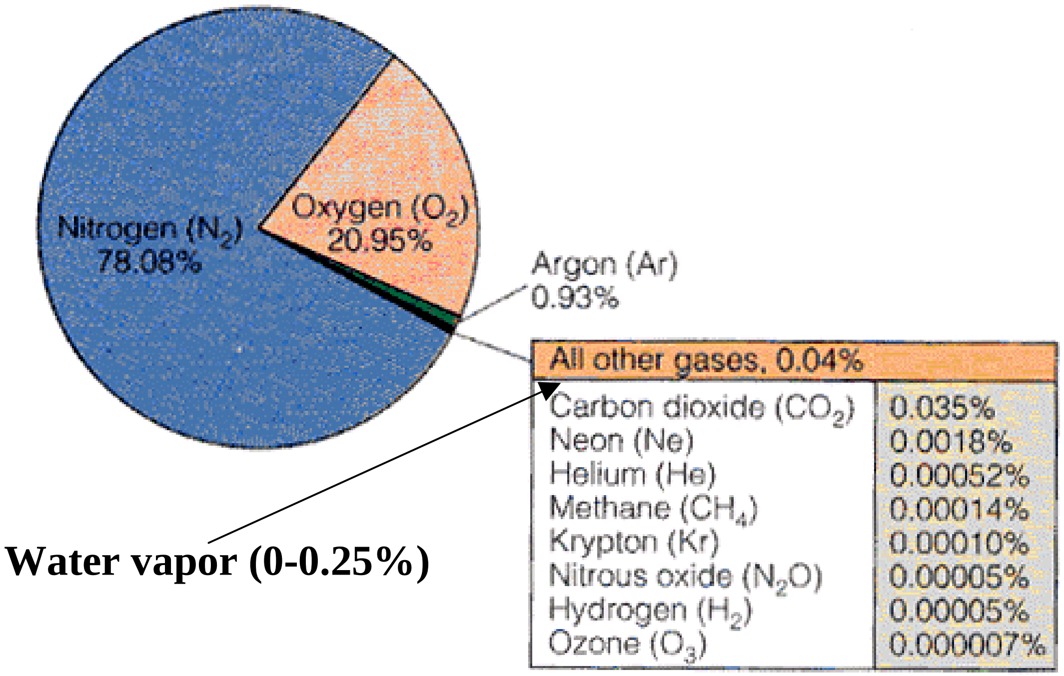
Composition of the Atmosphere

(inside the DRY homosphere)



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%

Figure 12.2 Composition of dry, aerosol-free air in volume percent. Three gases—nitrogen, oxygen, and argon—make up 99.96 percent of the air.

(from *The Blue Planet*)

Origins of the Atmosphere

❑ The release of gases from rock through volcanic eruption (so-called **outgassing**) was the principal source of atmospheric gases.

➔ The primeval atmosphere produced by the outgassing was mostly carbon dioxide (**CO_2**) with some Nitrogen (**N_2**) and water vapor (**H_2O**), and trace amounts of other gases.

What Happened to H_2O?

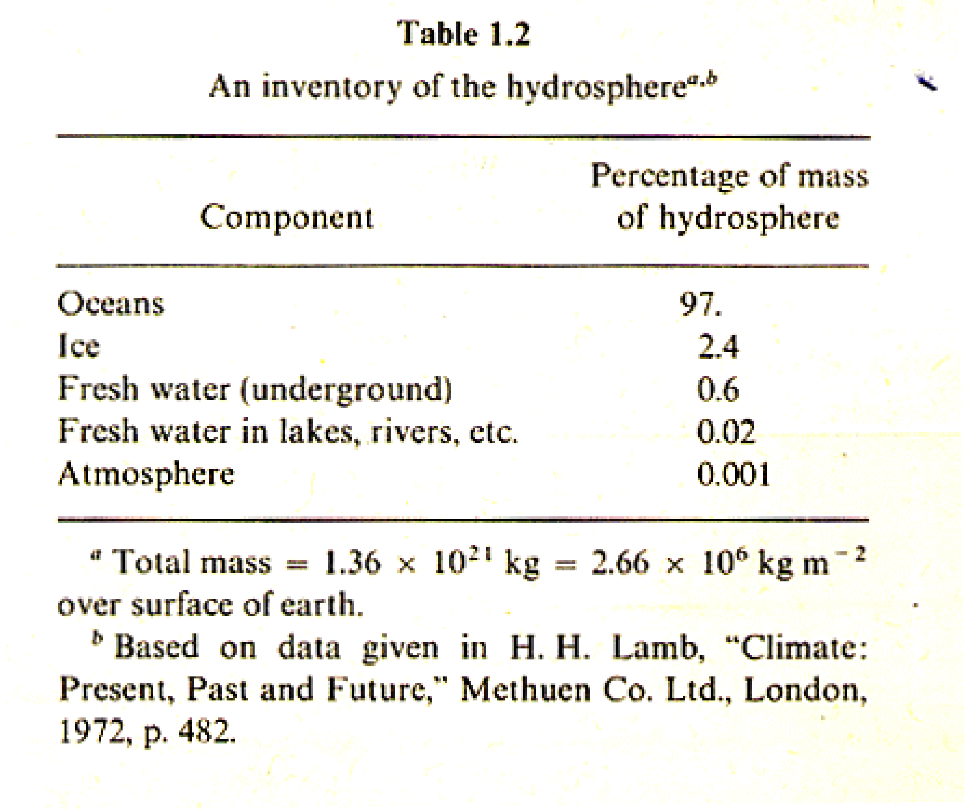


Table 1.2

An inventory of the hydrosphere[a,b]

Component	Percentage of mass of hydrosphere
Oceans	97.
Ice	2.4
Fresh water (underground)	0.6
Fresh water in lakes, rivers, etc.	0.02
Atmosphere	0.001

[a] Total mass = 1.36×10^{21} kg = 2.66×10^{6} kg m^{-2} over surface of earth.

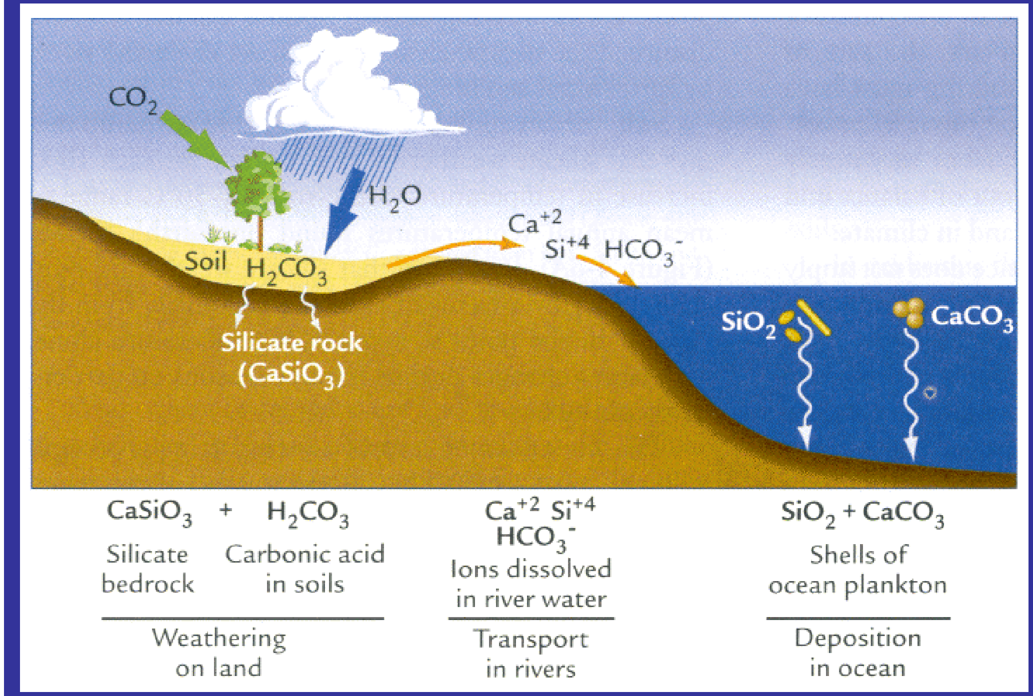
[b] Based on data given in H. H. Lamb, "Climate: Present, Past and Future," Methuen Co. Ltd., London, 1972, p. 482.

(from *Atmospheric Sciences: An Introductory Survey*)

- ☐ The atmosphere can only hold small fraction of the mass of water vapor that has been injected into it during volcanic eruption, most of the water vapor was condensed into clouds and rains and gave rise to rivers, lakes, and oceans.

➔ The concentration of water vapor in the atmosphere was substantially reduced.

What happened to CO_2?

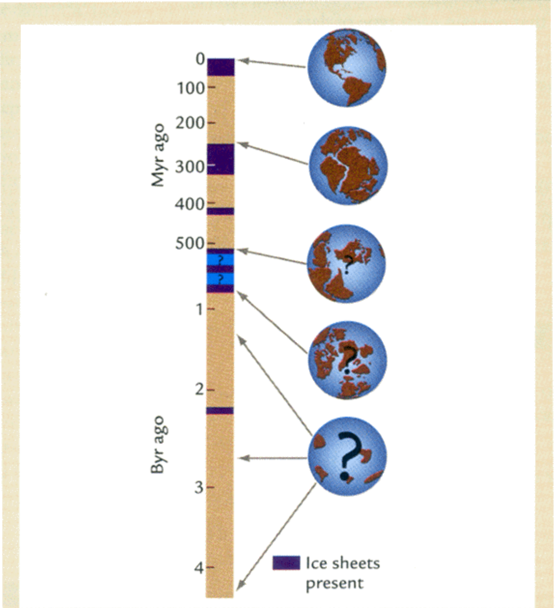


(from *Earth's Climate: Past and Future*)

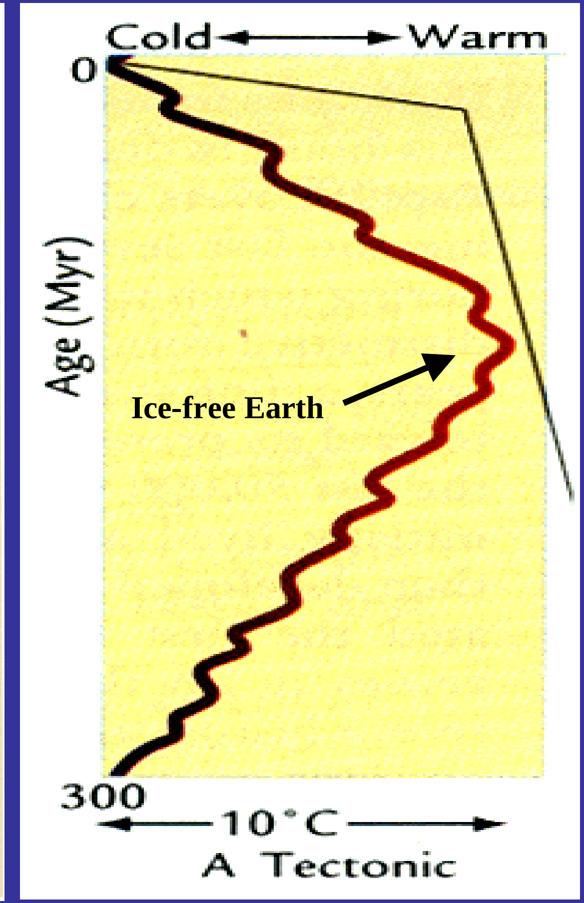
- Chemical weather is the primary process to remove CO2 from the atmosphere.
- ➔ In this process, CO2 dissolves in rainwater producing weak carbonic acid that reacts chemically with bedrock and produces carbonate compounds.

- This biogeochemical process reduced CO2 in the atmosphere and locked carbon in rocks and mineral.

Tectonic-Scale Climate Change



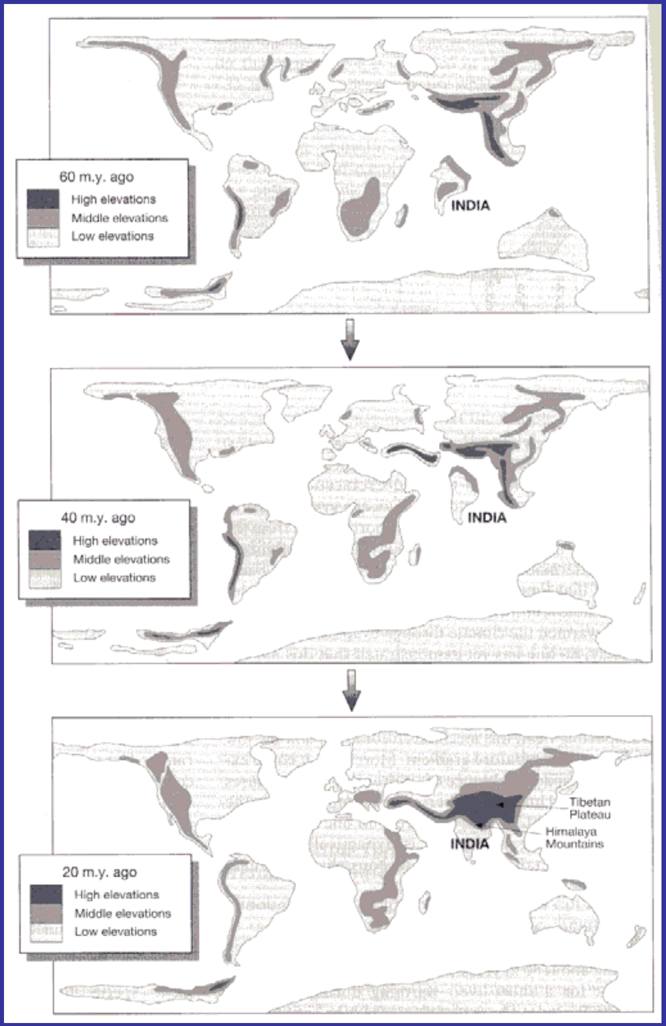
Past glaciations and continental positions. During Earth's 4.55-billion-year history, intervals when large continental ice sheets were present alternated with times when they were not (left). The earliest history of these changes is poorly defined because few ancient records are preserved. The movements of continents in relation to ocean basins are well known only for the last several hundred million years (right). (Globes adapted from D. Merritts et al., *Environmental Geology*, © 1997 by W. H. Freeman and Company.)



(from *Earth's Climate: Past and Future*)

- The faint young Sun paradox and its possible explanation.
- Why was Earth ice-free even at the poles 100 Myr ago (the Mesozoic Era)?
- What caused Earth's climate to cool over the last 55 Myr (the Cenozoic Era)?

Why the Cooling over the Last 50 Myr?



(from *The Earth System*)

- The collision of Indian and Asia happened around 40 Myr ago.
- The collision produced the Himalayas and a huge area of uplifted terrain called the Tibetan Plateau.
- The Himalayas Mountains provided fresh, readily erodable surfaces on which chemical weathering could proceed rapidly.
- At the same time, the uplifting of the Tibetan Plateau create seasonal monsoon rainfalls, which provided the water needed for chemical weathering.
- Therefore, the collision of India and Asia enhanced the chemical weathering process and brought down the atmospheric CO2 level to the relatively low values that prevail today.
- This reduced the greenhouse effect and cooled down the climate over the last 50 Myr.

What Happened to N_2?

- Nitrogen (N2):
  (1) is inert chemically,
  (2) has molecular speeds too slow to escape to space,
  (3) is not very soluble in water.

➔ The amount of nitrogen being cycled out of the atmosphere was limited.

➔ Nitrogen became the most abundant gas in the atmosphere.

Where Did O_2 Come from?

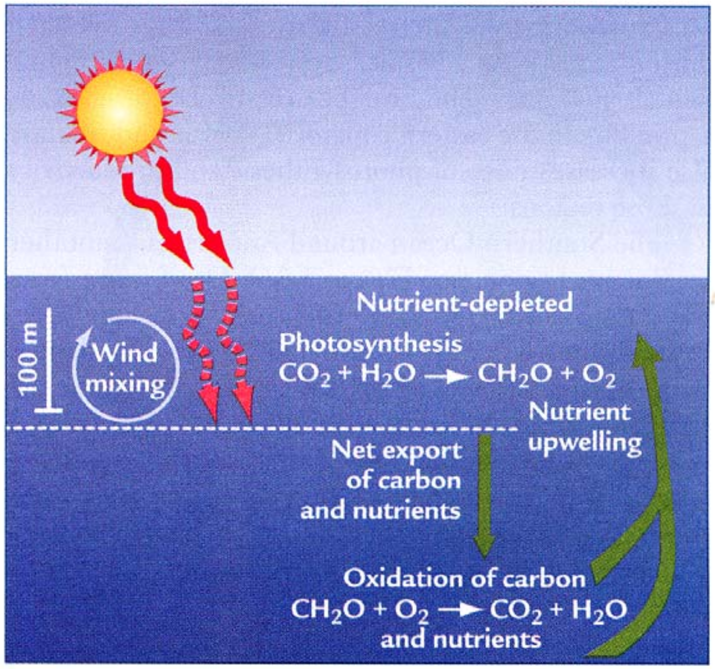


FIGURE 2-35 Photosynthesis in the ocean Sunlight penetrating the surface ocean causes photosynthesis by microscopic plants. As they die, their nutrient-bearing organic tissue descends to the seafloor. Oxidation of this tissue at depth returns nutrients and inorganic carbon to the surface ocean in regions of upwelling.

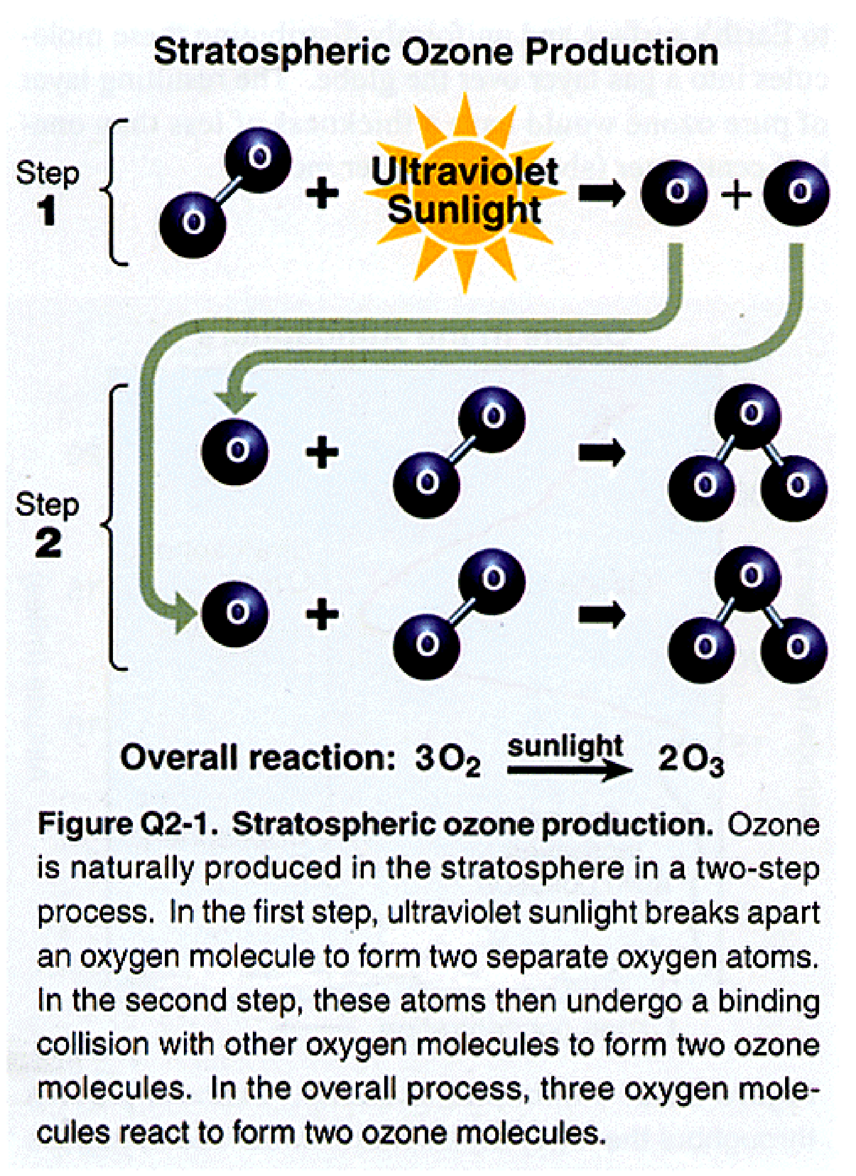
(from *Earth's Climate: Past and Future*)

❑ Photosynthesis was the primary process to increase the amount of oxygen in the atmosphere.

➔ Primitive forms of life in oceans began to produce oxygen through photosynthesis probably 2.5 billion years ago.

➔ With the concurrent decline of CO2, oxygen became the second most abundant atmospheric as after nitrogen.

Formation of Ozone (O_3)



Stratospheric Ozone Production

Overall reaction: $3O_2 \xrightarrow{\text{sunlight}} 2O_3$

Figure Q2-1. Stratospheric ozone production. Ozone is naturally produced in the stratosphere in a two-step process. In the first step, ultraviolet sunlight breaks apart an oxygen molecule to form two separate oxygen atoms. In the second step, these atoms then undergo a binding collision with other oxygen molecules to form two ozone molecules. In the overall process, three oxygen molecules react to form two ozone molecules.

(from *WMO Report 2003*)

- ❑ With oxygen emerging as a major component of the atmosphere, the concentration of ozone increased in the atmosphere through a photodissociation process.

Where Did Argon Come from?

❑ Radioactive decay in the planet’s bedrock added argon (**Ar**) to the evolving atmosphere.

➔ Argon became the third abundant gas in the atmosphere.

Permanent and Variable Gases

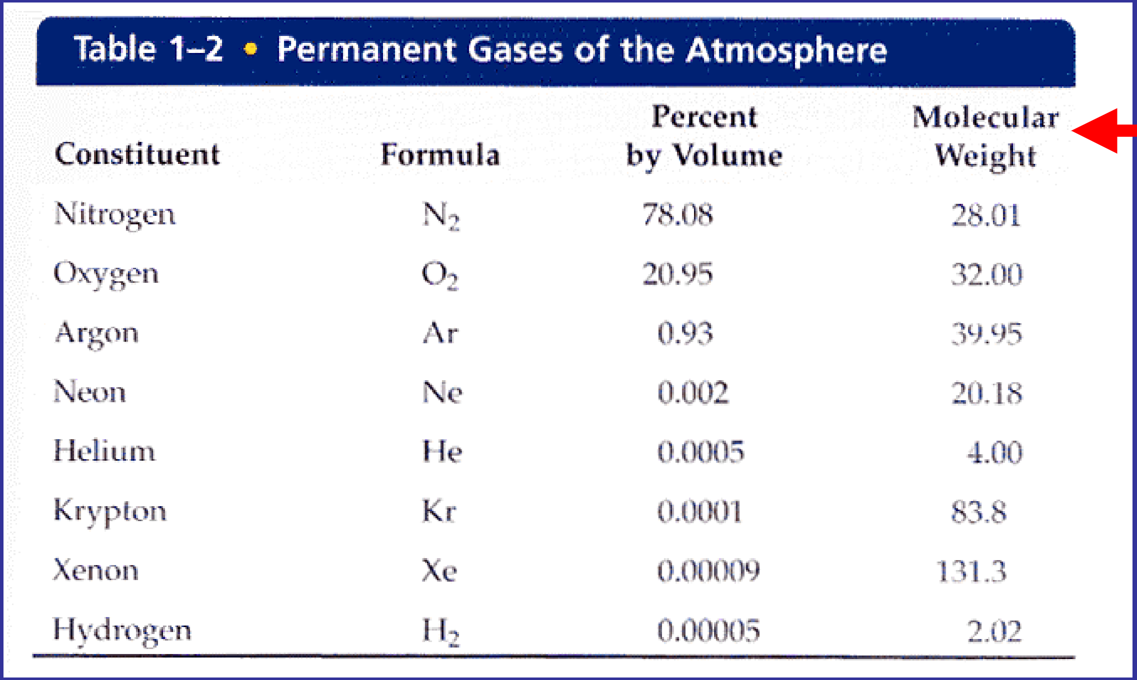


Table 1–2 • Permanent Gases of the Atmosphere

Constituent	Formula	Percent by Volume	Molecular Weight
Nitrogen	N_2	78.08	28.01
Oxygen	O_2	20.95	32.00
Argon	Ar	0.93	39.95
Neon	Ne	0.002	20.18
Helium	He	0.0005	4.00
Krypton	Kr	0.0001	83.8
Xenon	Xe	0.00009	131.3
Hydrogen	H_2	0.00005	2.02

Those gases that form a constant portion of the atmospheric mass.

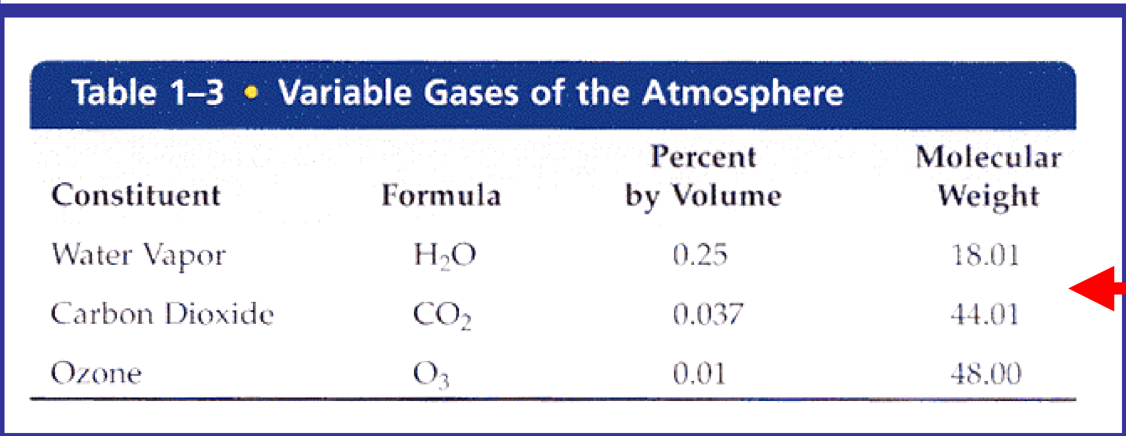


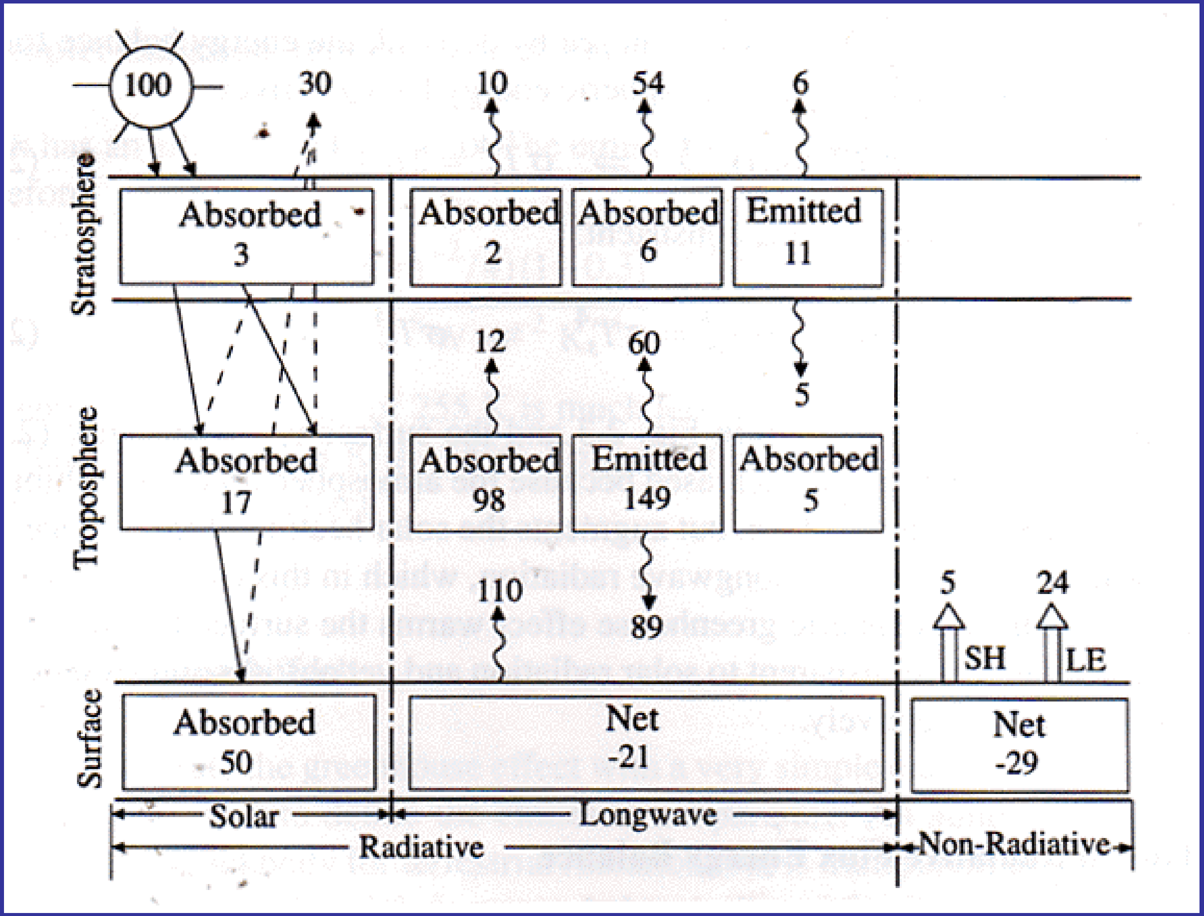
Table 1–3 • Variable Gases of the Atmosphere

Constituent	Formula	Percent by Volume	Molecular Weight
Water Vapor	H_2O	0.25	18.01
Carbon Dioxide	CO_2	0.037	44.01
Ozone	O_3	0.01	48.00

Those gases whose concentrations changes from time to time and from place to place, and are important to weather and climate.

Vertical View of the Energy Balance

Vertical Distribution of Energy

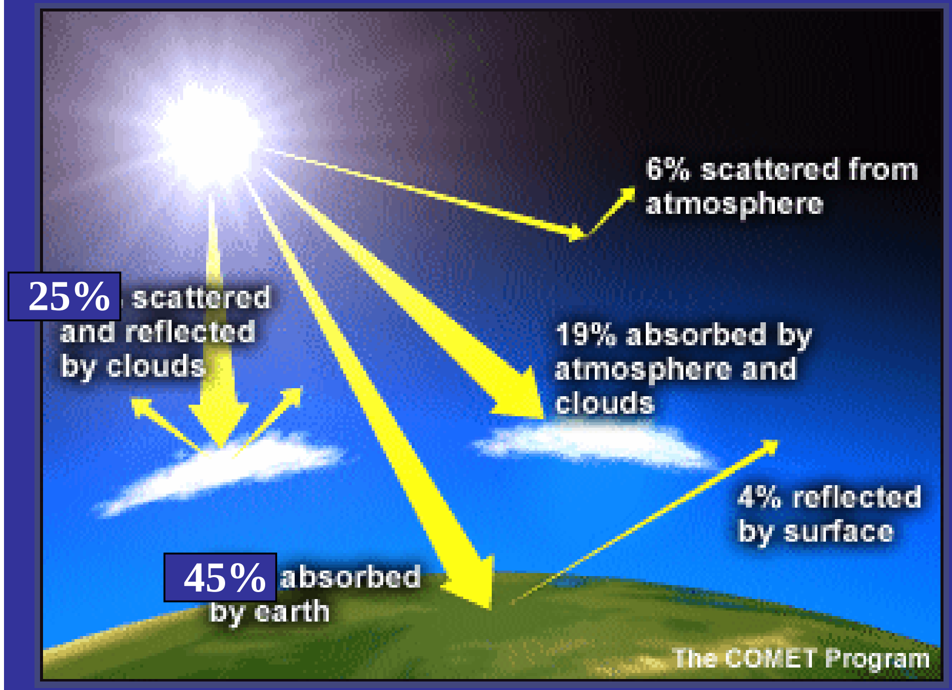


(from *Global Physical Climatology*)

Incoming solar energy (100)

- 70% absorbed
  - 50% by Earth's surface
  - 20% by atmosphere
    - 3% in stratosphere (by ozone and O_2)
    - 17% in troposphere (water vapor & cloud)
- 30% reflected/scattered back
  - 20% by clouds
  - 6% by the atmosphere
  - 4% by surface

Where Does the Solar Energy Go?



(from NCAR/COMET website)

Incoming solar energy (100)

- 70% absorbed

  50% by Earth’s surface (ocean + land)

  20% by the atmosphere and clouds

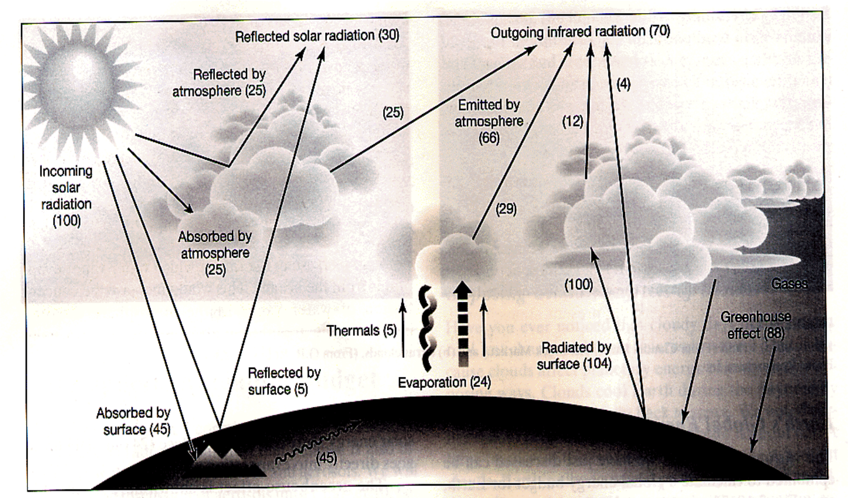
- 30% reflected and scattered back

  20% by clouds

  6% by the atmosphere

  4% by surface

Where Is Earth's Radiation Emitted From?



(from *The Earth System*)

Radiation back to Space (70 Units)

- 70 (units) radiation back to space

  60% by the atmosphere

  10% by surface (through clear sky)

- Greenhouse emission (back to surface)

  89% (of solar radiation)

Greenhouse Effect and Diurnal Cycle

- The very strong downward emission of terrestrial radiation from the atmosphere is crucial to main the relatively small diurnal variation of surface temperature.

- If this large downward radiation is not larger than solar heating of the surface, the surface temperature would warm rapidly during the day and cool rapidly at the night.

  ➔ a large diurnal variation of surface temperature.

- The greenhouse effect not only keeps Earth’s surface warm but also limit the amplitude of the diurnal temperature variation at the surface.

Important Roles of Clouds In Global Climate

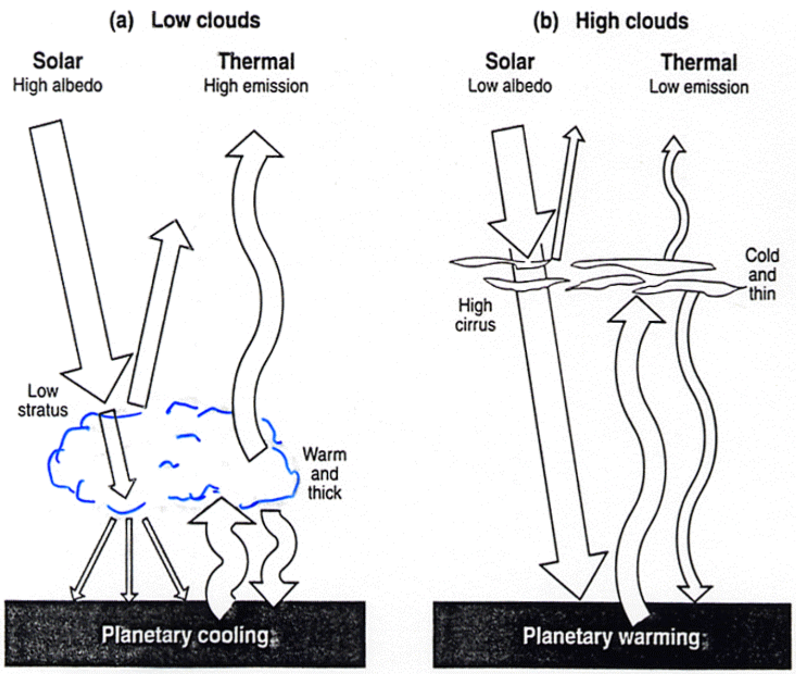
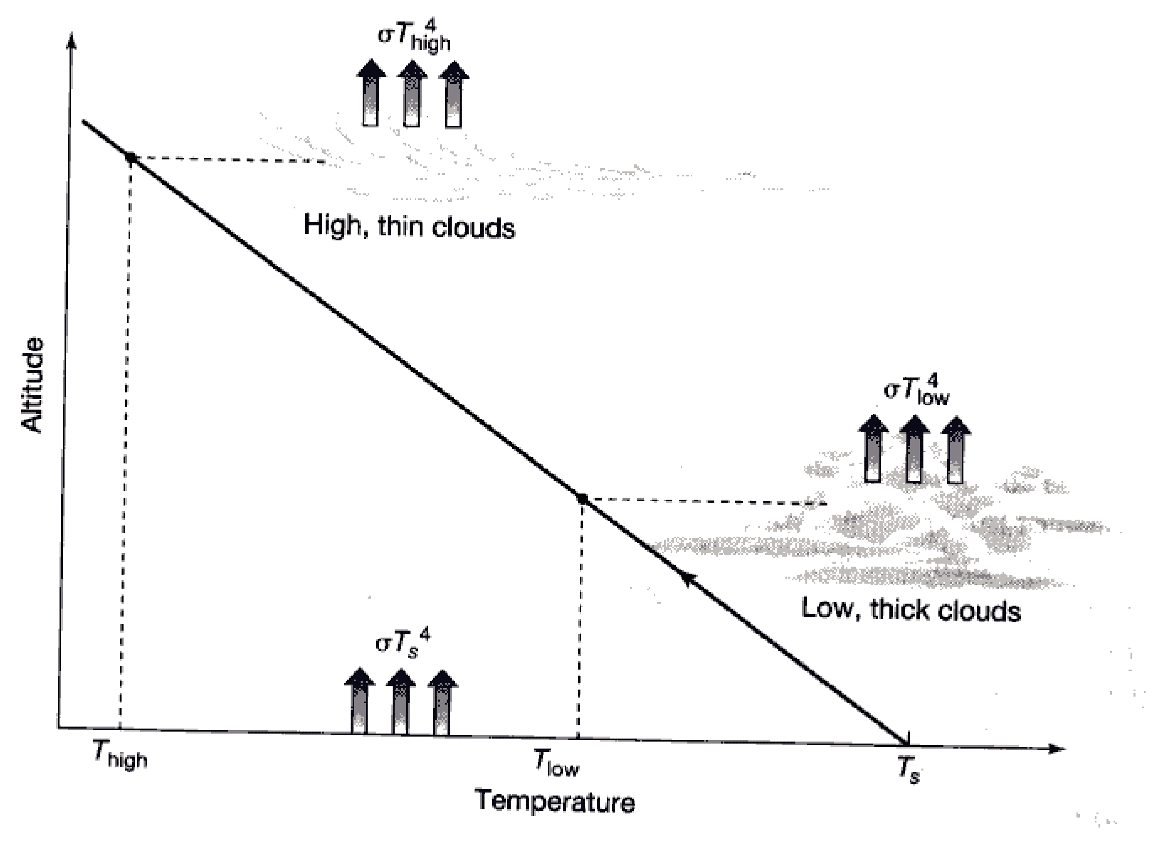


Figure 11.13 The effects of clouds on the flow of radiation and energy in the lower atmosphere and at the surface. Two cases are shown: (a) low clouds, with a high solar albedo and high thermal emission temperature; and (b) high clouds, with a low solar albedo and low thermal emission temperature. The solar components are shown as straight arrows, and the infrared components, as curved arrows. The relative thicknesses of the arrows indicate the relative radiation intensities. The expected impact on surface temperature in each situation is noted along the bottom strip.

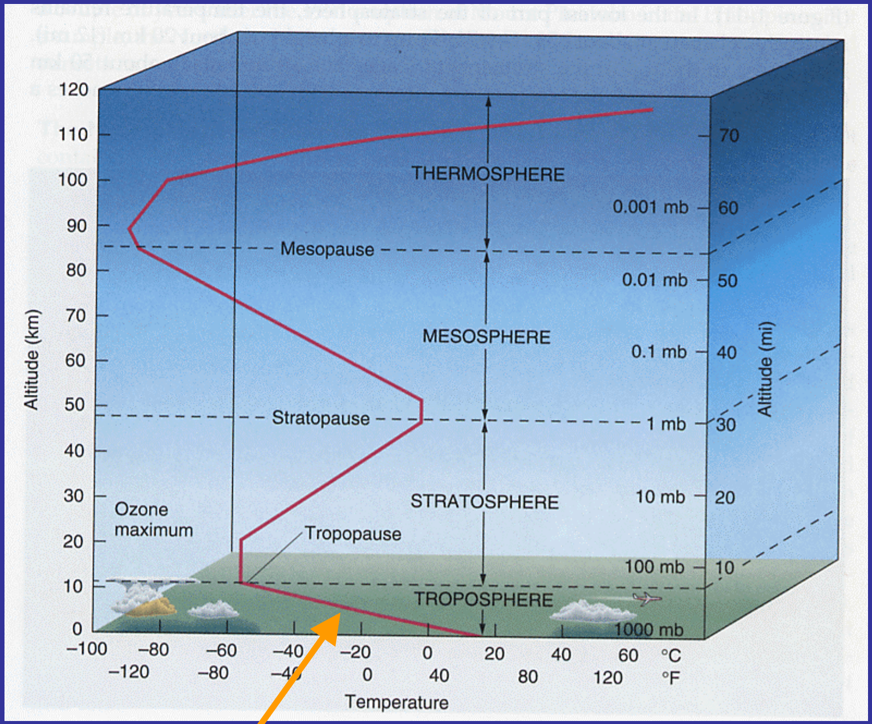
Important Roles of Clouds In Global Climate



(from The Earth System)

Vertical Thermal Structure

Standard Atmosphere



(from *Understanding Weather & Climate*)

lapse rate = 6.5 C/km

Troposphere (“overturning” sphere)
- contains 80% of the mass
- surface heated by solar radiation
- strong vertical motion
- where most weather events occur

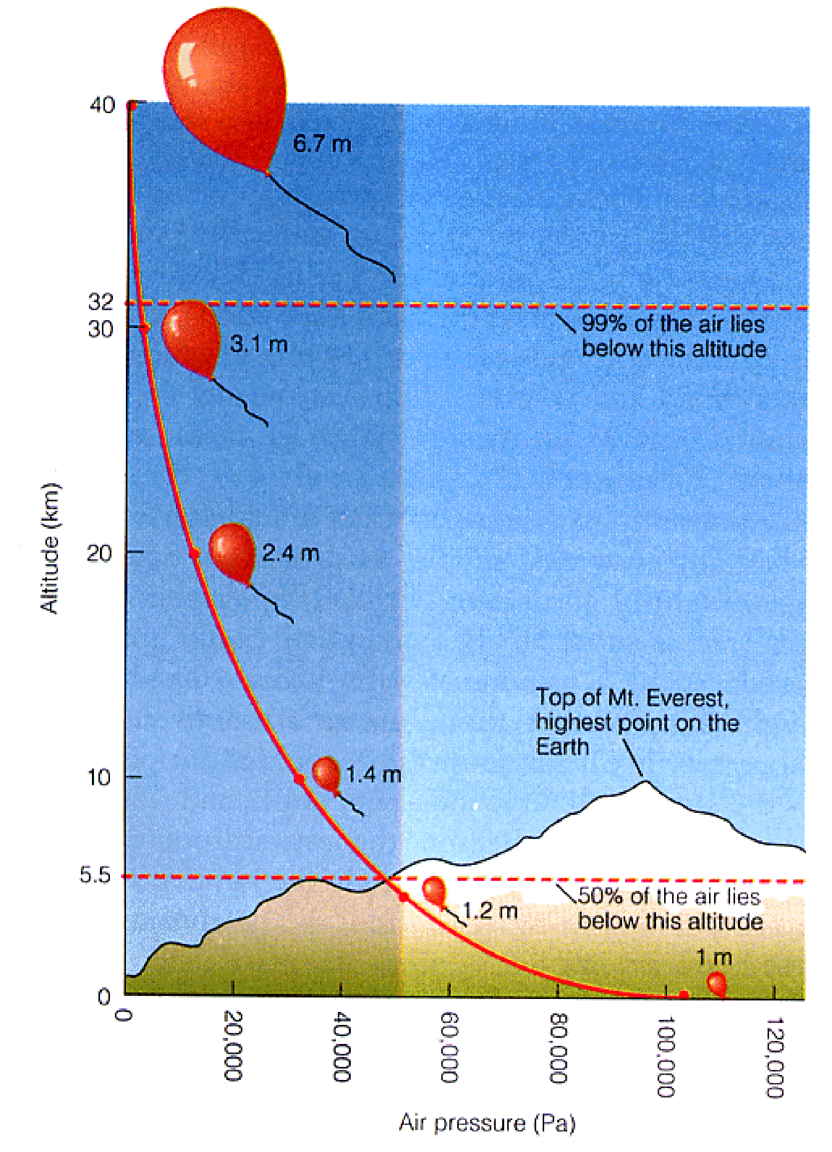
Stratosphere (“layer” sphere)
- weak vertical motions
- dominated by radiative processes
- heated by ozone absorption of solar ultraviolet (UV) radiation
- warmest (coldest) temperatures at summer (winter) pole

middle atmosphere

Mesosphere
- heated by solar radiation at the base
- heat dispersed upward by vertical motion

Thermosphere
- very little mass

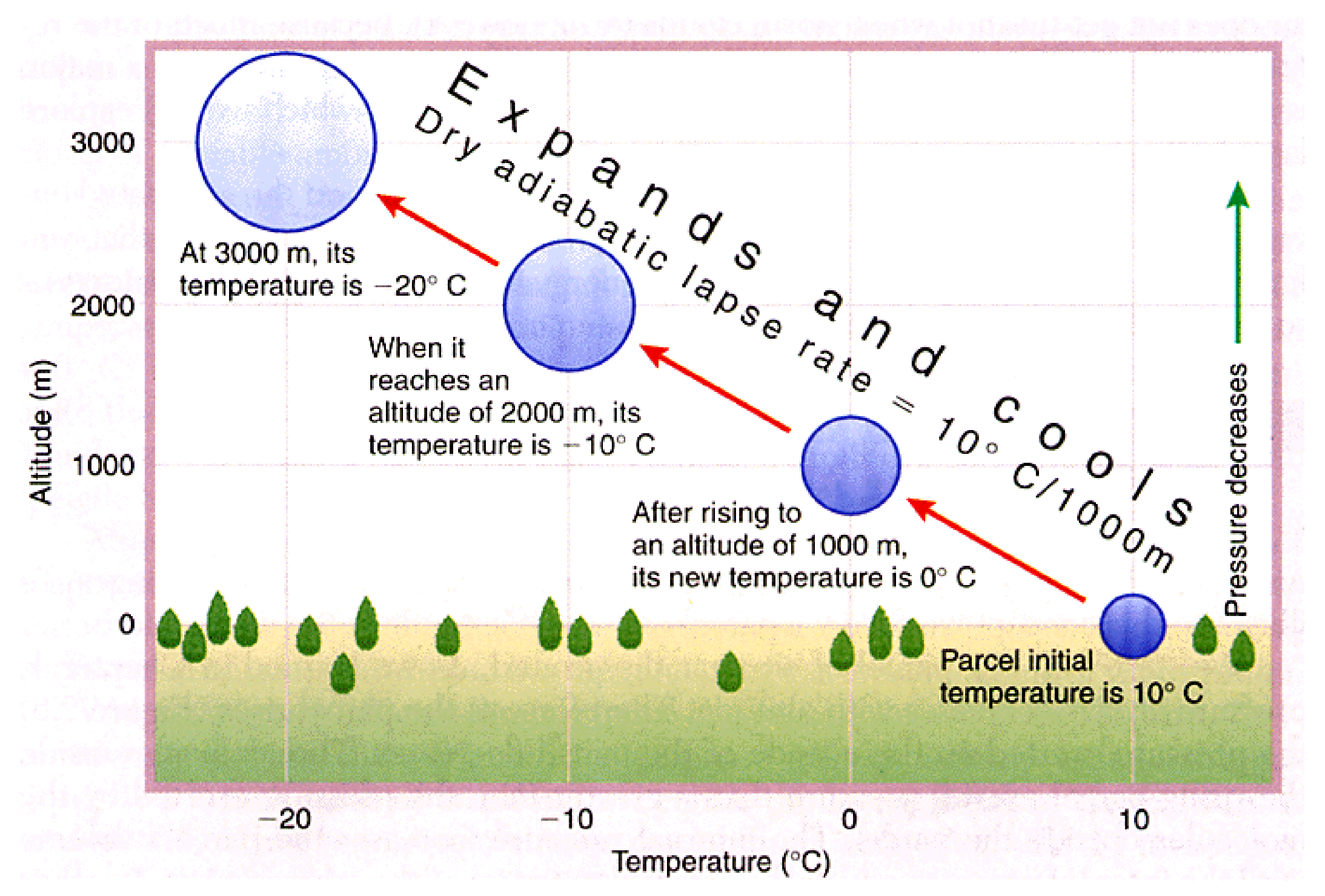
Air Parcel Expands As It Rises…



(from *The Blue Planet*)

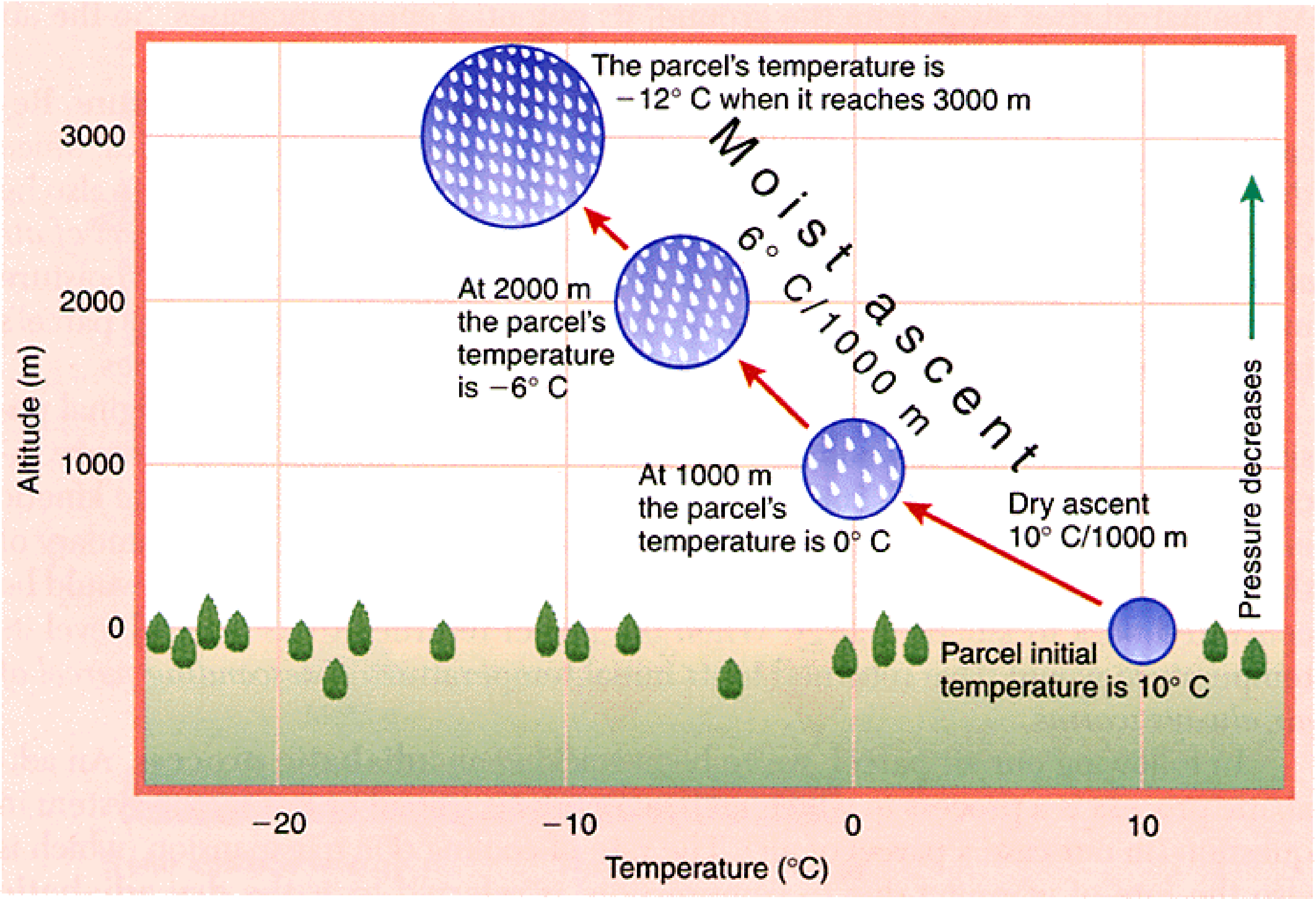
- ☐ Air pressure decreases with elevation.
- ☐ If a helium balloon 1 m in diameter is released at sea level, it expands as it floats upward because of the pressure decrease. The balloon would be 6.7 m in diameter as a height of 40 km.

Dry Adiabatic Lapse Rate



(from *Meteorology: Understanding the Atmosphere*)

Moist Adiabatic Lapse Rate



(from *Meteorology: Understanding the Atmosphere*)

Variations in Tropopause Height

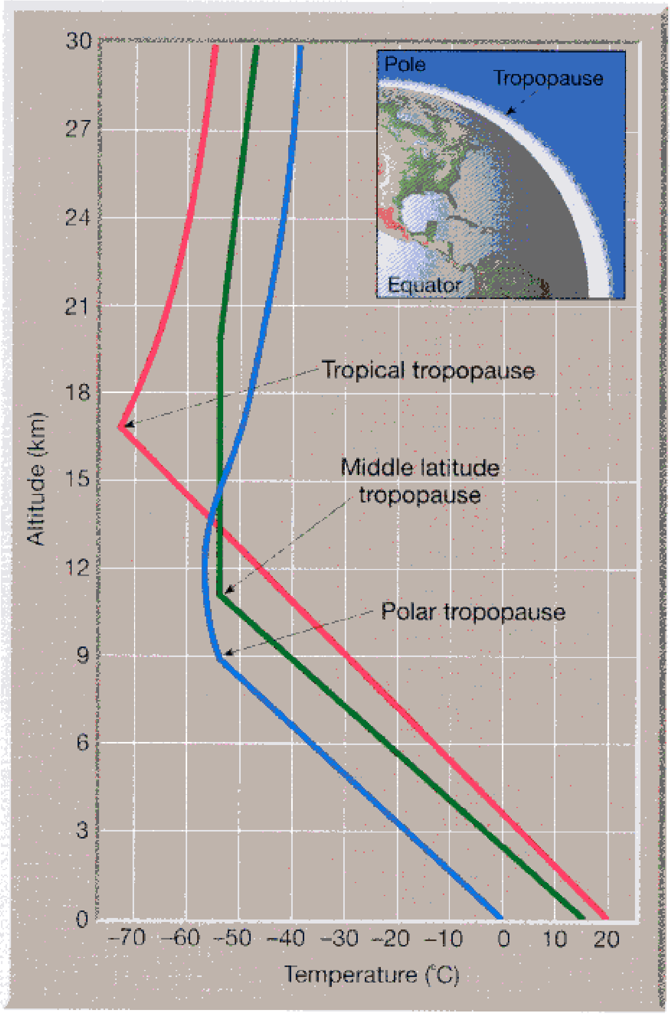
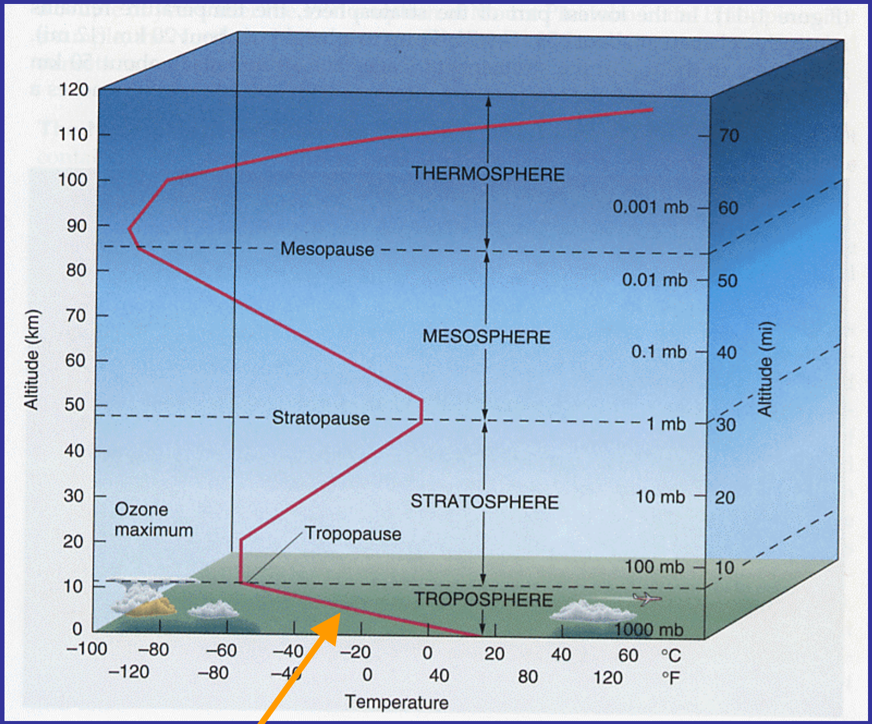


FIGURE 1-23 Differences in the height of the tropopause. The variation in the height of the tropopause, as shown on the small inset diagram, is greatly exaggerated.

(from *The Atmosphere*)

Stratosphere

Standard Atmosphere

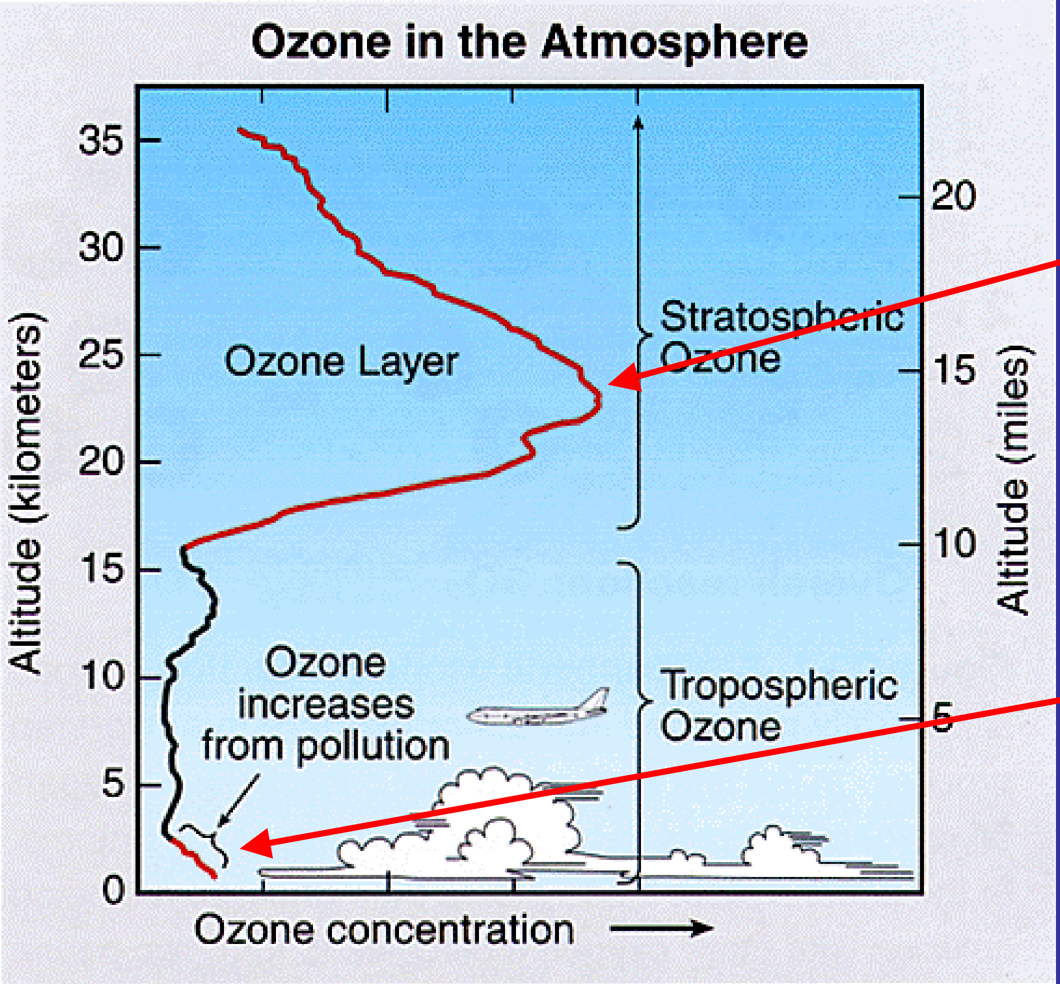


(from *Understanding Weather & Climate*)

lapse rate = 6.5 C/km

- The reasons for the inversion in the stratosphere is due to the ozone absorption of ultraviolet solar energy.
- Although maximum ozone concentration occurs at 25km, the lower air density at 50km allows solar energy to heat up temperature there at a much greater degree.
- Also, much solar energy is absorbed in the upper stratosphere and can not reach the level of ozone maximum.

Ozone (O_3)



"good" ozone
~ 15ppm

"bad" ozone
~ 0.15ppm

(from WMO Report 2003)

ESS200A
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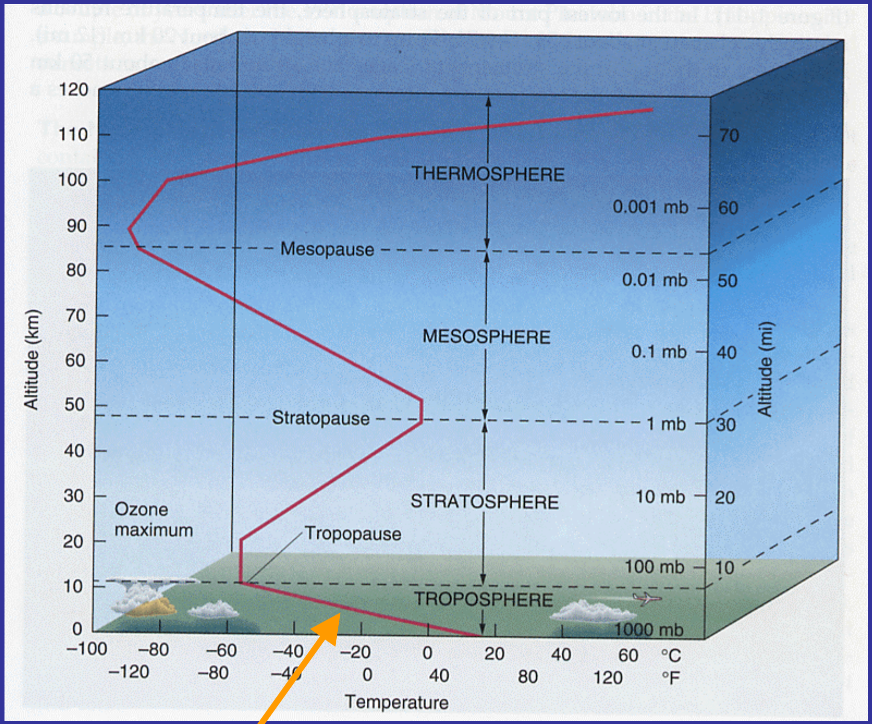
Mesosphere

Standard Atmosphere



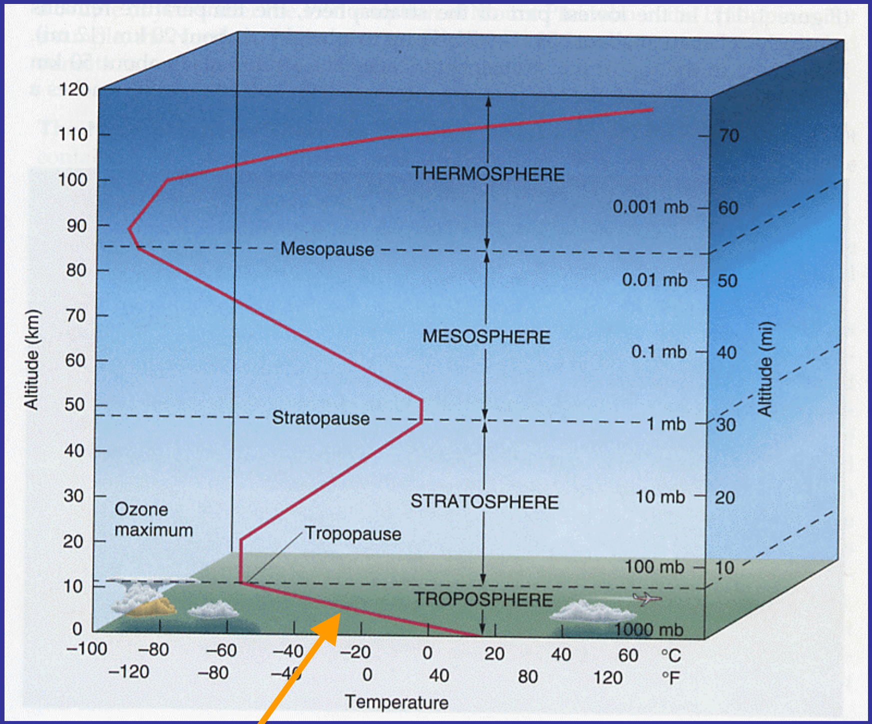
(from *Understanding Weather & Climate*)

lapse rate = 6.5 C/km

- ❑ There is little ozone to absorb solar energy in the mesosphere, and therefore, the air temperature in the mesosphere decreases with height.
- ❑ Also, air molecules are able to lose more energy than they absorb. This cooling effect is particularly large near the top of the mesosphere.

Thermosphere

Standard Atmosphere

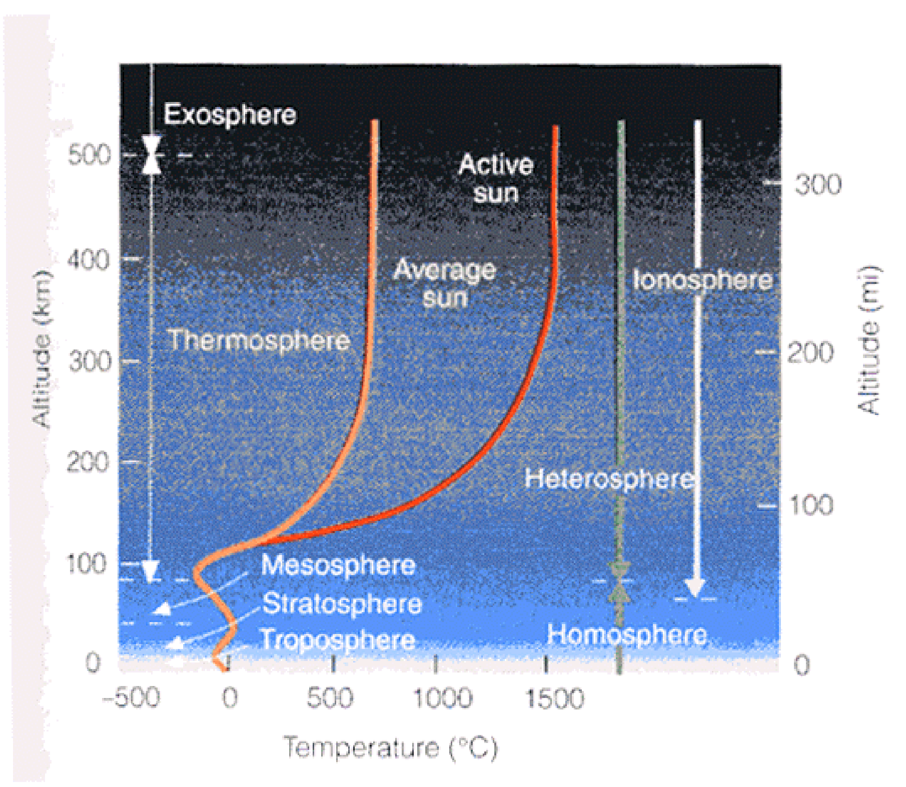


(from *Understanding Weather & Climate*)

lapse rate = 6.5 C/km

- In thermosphere, oxygen molecules absorb solar rays and warms the air.
- Because this layer has a low air density, the absorption of small amount of solar energy can cause large temperature increase.
- The air temperature in the thermosphere is affected greatly by solar activity.

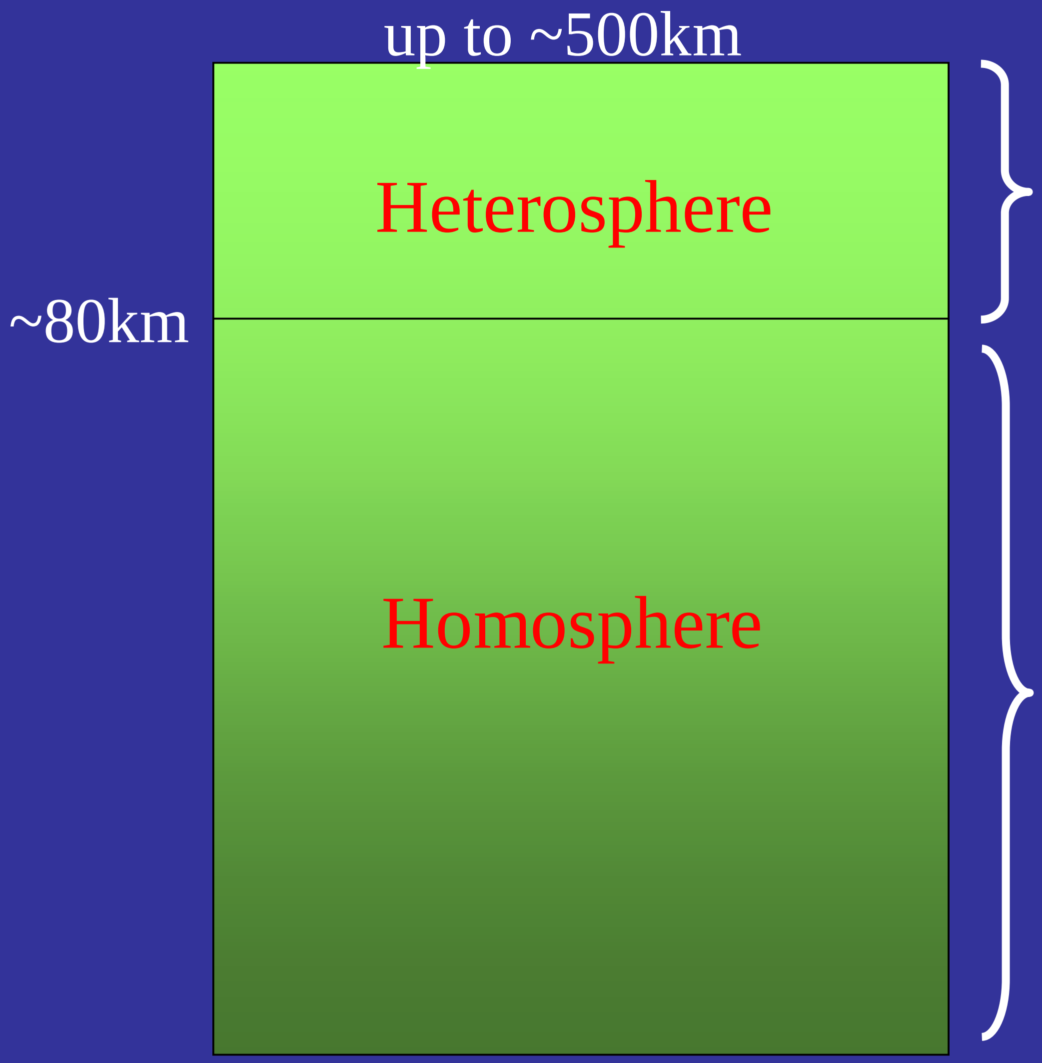
Ionosphere



(from *Meteorology Today*)

- ☐ The ionosphere is an electrified region within the upper atmosphere where large concentration of ions and free electrons exist.
- ☐ The ionosphere starts from about 60km above Earth's surface and extends upward to the top of the atmosphere. Most of the ionosphere is in the thermosphere.
- ☐ The ionosphere plays an important role in radio communication.

Vertical Structure of Composition



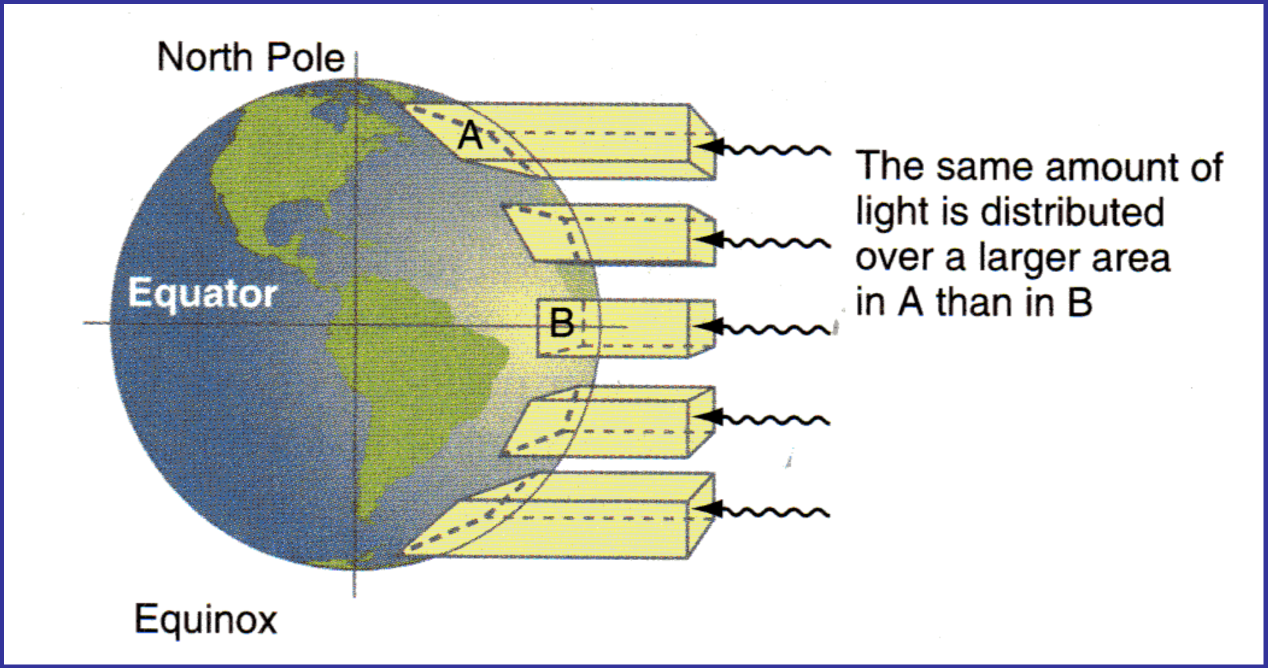
Dominated by lighter gases with increasing altitude, such as hydrogen and helium.

This part of the atmosphere continually circulates, so that the principal atmospheric gases are well mixed.

➔ For most purpose, we consider the homosphere virtually the entire atmosphere.

Latitudinal View of the Energy Balance

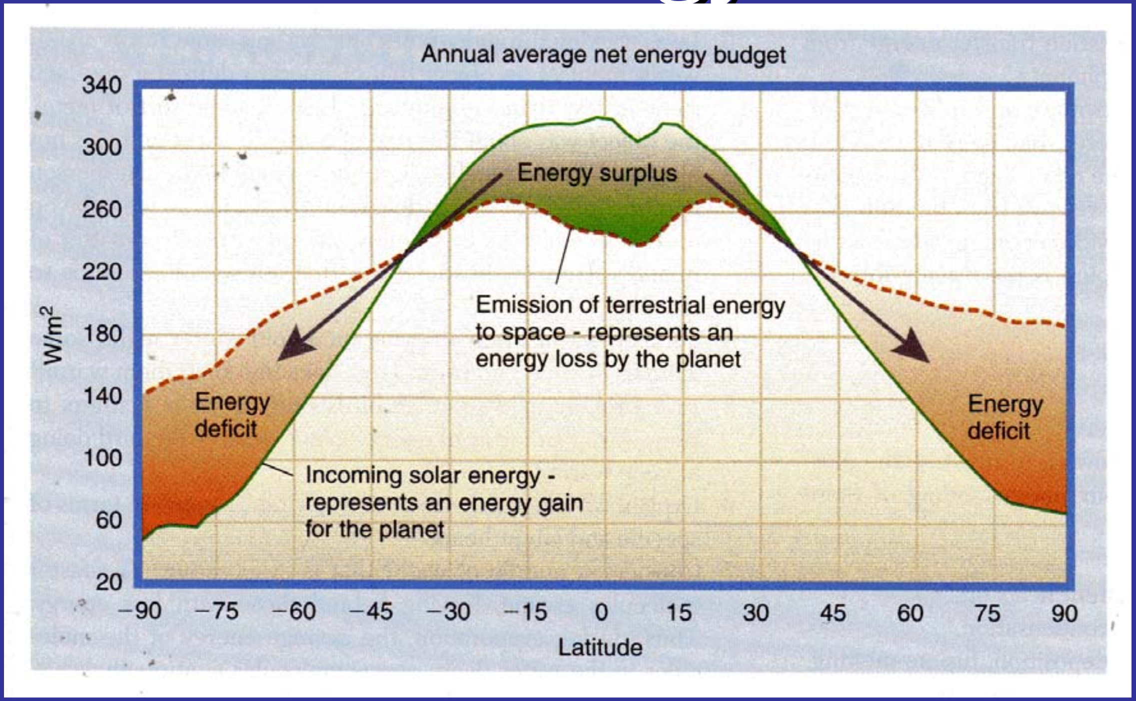
Zenith Angle and Insolation



(from *Meteorology: Understanding the Atmosphere*)

☐ The larger the solar zenith angle, the weaker the insolation, because the same amount of sunlight has to be spread over a larger area.

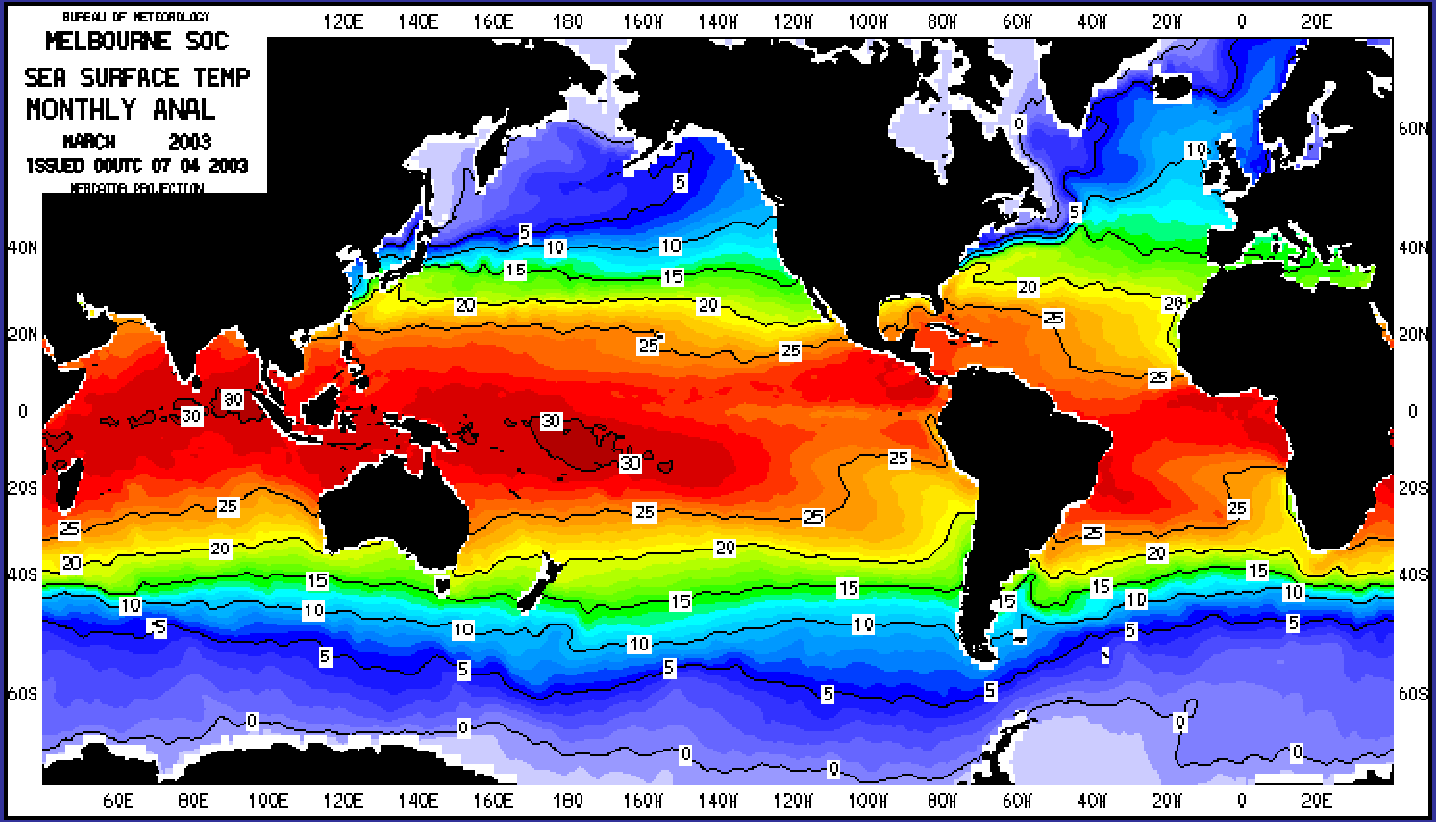
Latitudinal Variations of Net Energy



(from *Meteorology: Understanding the Atmosphere*)

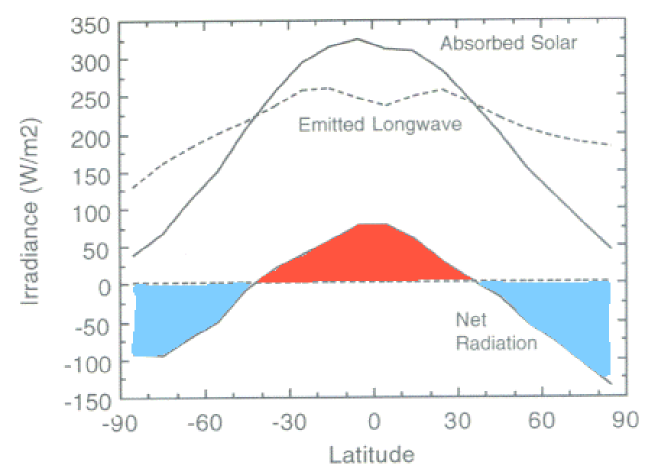
- ❑ Polarward heat flux is needed to transport radiation energy from the tropics to higher latitudes.

Sea Surface Temperature

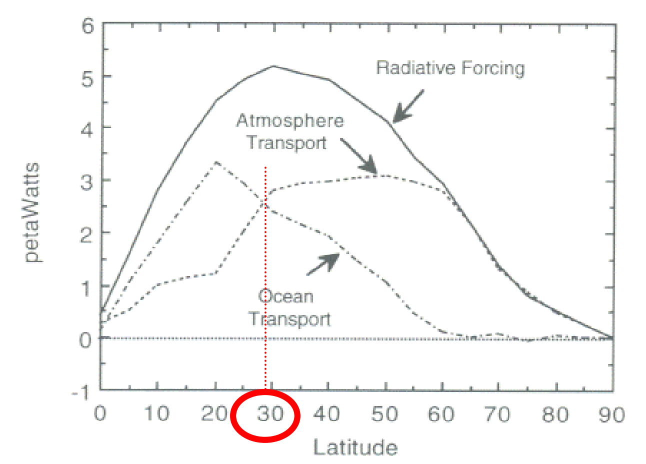


Polarward Energy Transport

Annual-Mean Radiative Energy



Polarward Heat Flux



Polarward heat flux is needed to transport radiative energy from the tropics to higher latitudes

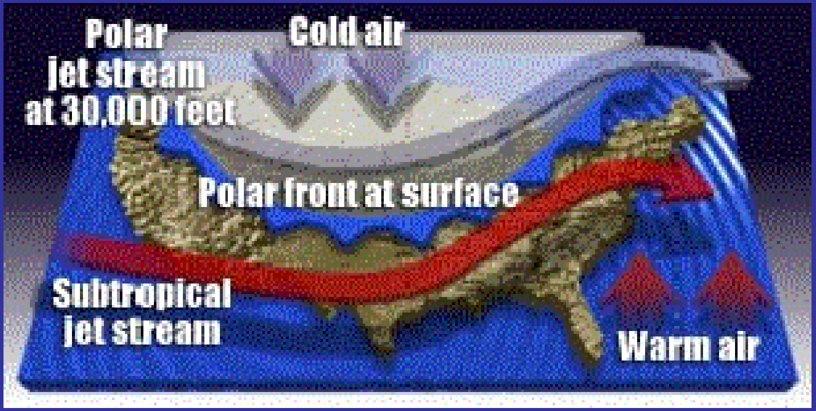
The atmosphere dominates the polarward heat transport at middle and high latitudes. The ocean dominates the transport at lower latitudes.

(1 petaWatts = 10^{15} W)

(figures from *Global Physical Climatology*)

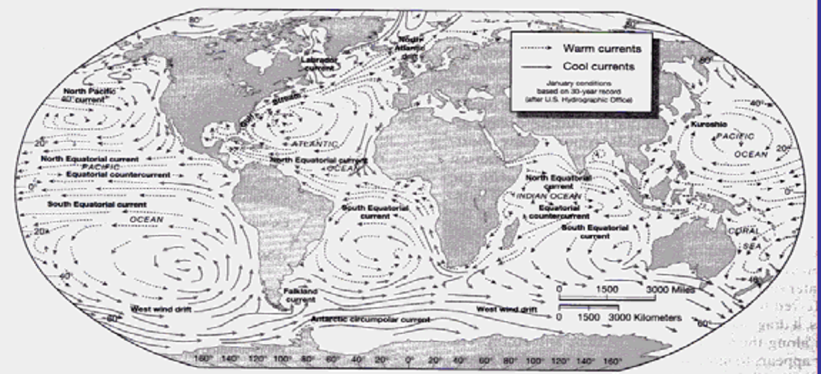
How Do Atmosphere and Ocean Transport Heat?

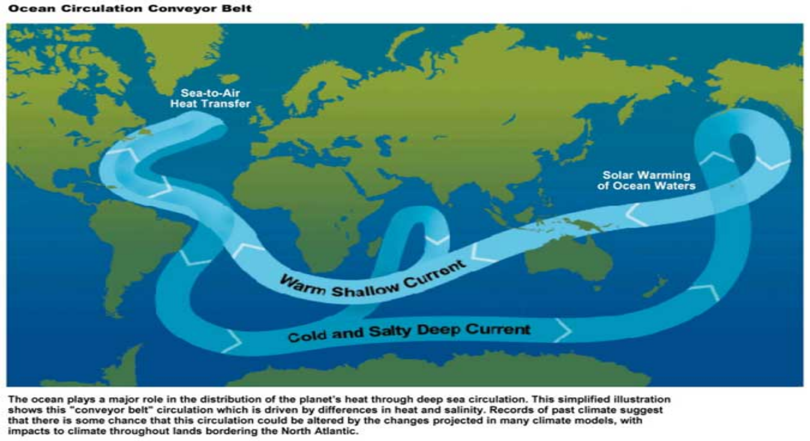
Atmospheric Circulation



(from USA Today)

Ocean Circulation





Ocean Circulation Conveyor Belt

The ocean plays a major role in the distribution of the planet's heat through deep sea circulation. This simplified illustration shows this "conveyor belt" circulation which is driven by differences in heat and salinity. Records of past climate suggest that there is some chance that this circulation could be altered by the changes projected in many climate models, with impacts to climate throughout lands bordering the North Atlantic.

(top from *The Earth System*)
(bottom from USGCRP)

ESS200A
Prof. Jin-Yi Yu

Global Temperature Distribution

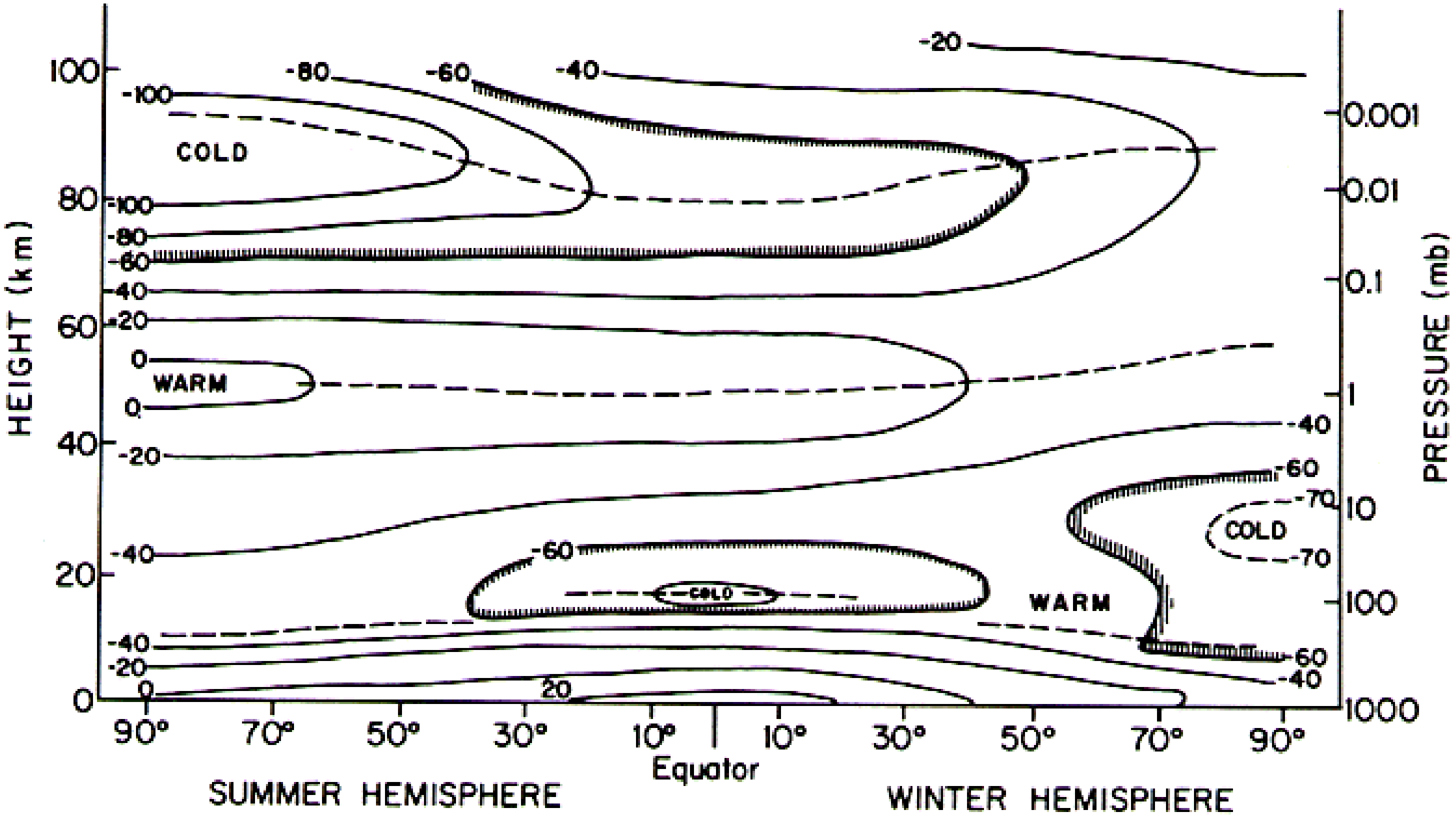
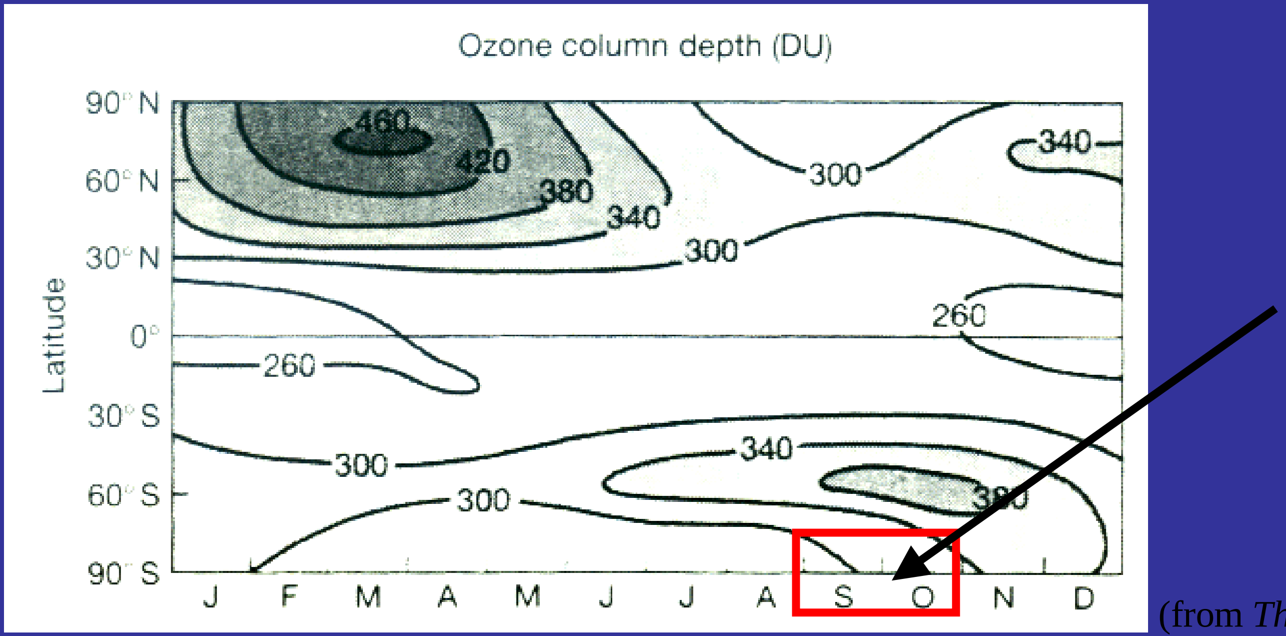


Fig. 1.3. Schematic latitude–height section of zonal mean temperatures (°C) for solstice conditions. Dashed lines indicate tropopause, stratopause, and mesopause levels. (Courtesy of R. J. Reed.)

Ozone Distribution

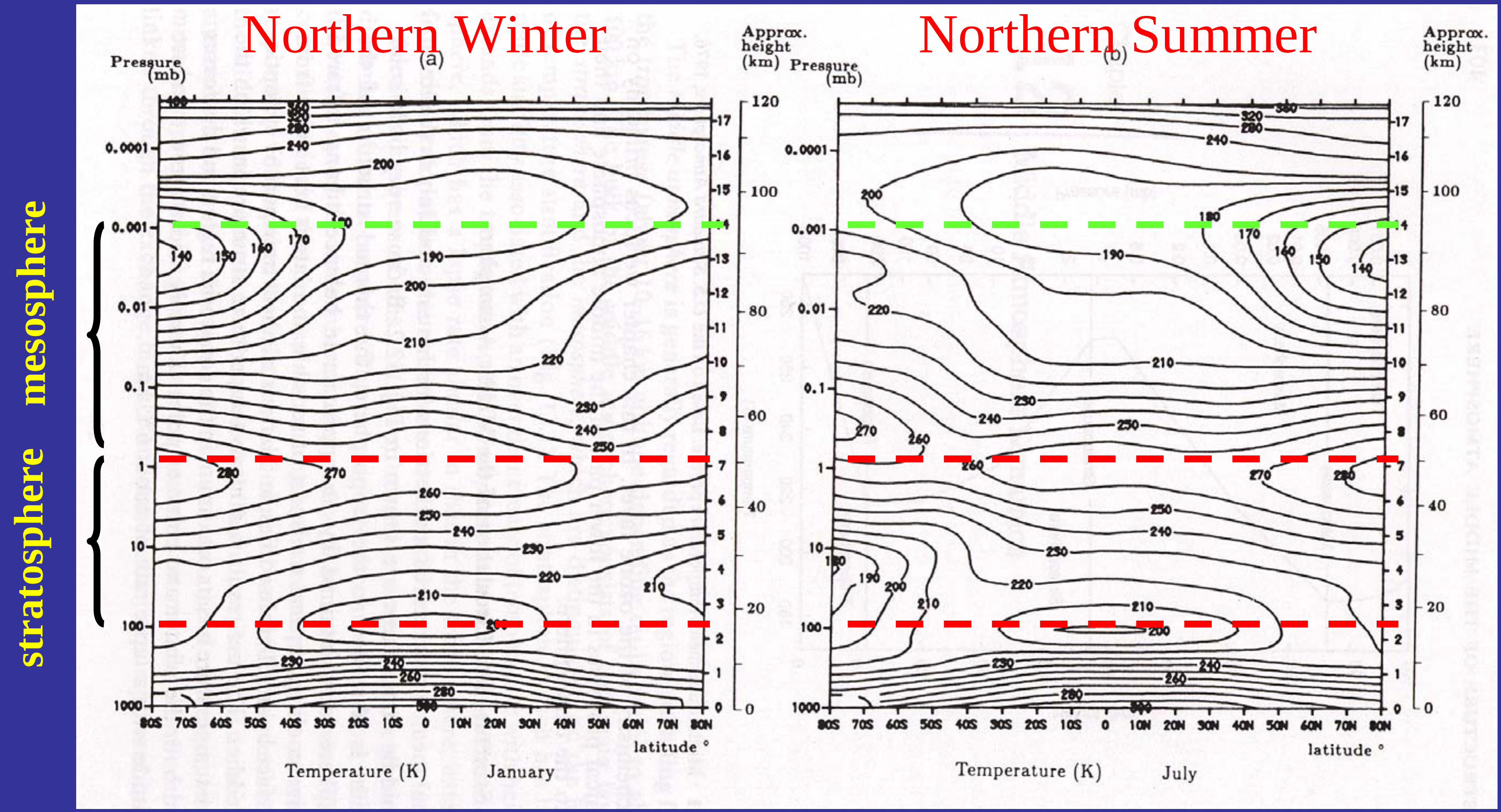


Antarctic Ozone Hole

(from *The Earth System*)

- The greatest production of ozone occurs in the tropics, where the solar UV flux is the highest.
- However, the general circulation in the stratosphere transport ozone-rich air from the tropical upper stratosphere to mid-to-high latitudes.
- Ozone column depths are highest during springtime at mid-to-high latitudes.
- Ozone column depths are the lowest over the equator.

Temperatures in Stratosphere



(from *Dynamic Meteorology*)