Chapter two: Atmospheric Energy Budget

Main Objectives

At the end of this chapter, students will understand the following concept.

- **How energy can cause to generate atmospheric circulation**
- **Latitudinal variation of incoming solar radiation and meridional heat transport**
- **Impact of orbital parameters of the Earth to seasonal formation**
- **Types of energy in the atmosphere**

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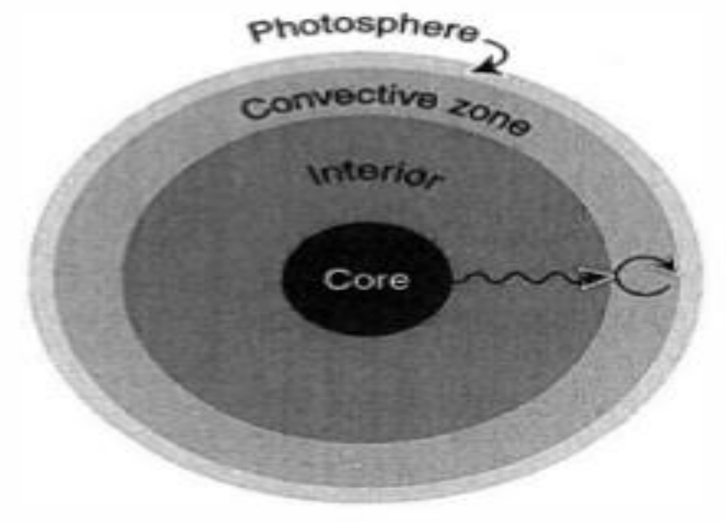
Introductions:

Solar physics: The sun is large star and its radius of 696,000 km is a little more than 100 times that of the Earth. In mass terms, the Sun weighs in at 2x10^30 kg which is 300million times more than the Earth.

Consisting mostly of hydrogen (91.2%) and helium (8.7 %).The sun has three spheres, Interior, convective zone and photosphere.



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- The temperature of photosphere is important for climate studies
- photosphere; about 6,000K
- The sun produces a vast amount of energy.
- The energy emitted by the sun is called solar energy or solar radiation
- Solar radiation is the earth primary natural source of energy
- Other sources are: the geothermal heat flux generated by the earth interior, natural terrestrial radioactivity, and cosmic radiation, which are all negligible relative to solar radiation.
- The solar radiation influences many aspects of the earth, including weather and climate, ocean, life on earth, agronomy and horticulture, forestry, ecology, oenology, energy, architecture and building engineering, or materials weathering

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Terms:

ANGLES:

- Solar declination: The angle formed by the direction to the centre of the sun and the terrestrial equatorial plane.
- Solar zenithal angle: The angle formed by the direction of the sun and the local vertical.
- Solar elevation angle: The angle formed by the direction of the sun and the horizon.
- Solar azimuthal angle, solar azimuth: The angle formed by the projection of the direction of the sun on the horizontal plane and the north.

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Radiations:

- **Broadband irradiance**: The irradiance integrated over a large spectrum
- **Irradiance**: The power received per area; unit is W m-2.
- **Irradiation**: The energy received per area; unit is J m-2.
- **Radiant energy**: The amount of energy that is transferred by radiation. It is expressed in J (Joule)
- **Radiant flux**: The time rate of flow of the radiant energy. It is expressed in W (Watt).
- **Spectral distribution of the irradiance**: The distribution of the irradiance as a function of the wavelength.
- **Total irradiance, irradiation**: The irradiance, irradiation, integrated over the whole spectrum

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RADIATION AT THE TOP OF THE ATMOSPHERE

- Extra-terrestrial radiation: the amount of incoming radiation that reaches on a horizontal surface located at the top of the atmosphere

RADIATION AT GROUND LEVEL

- Diffuse irradiation: the downward scattered shortwave irradiation, irradiance, coming from the whole hemisphere,
- Global irradiation, irradiance: The shortwave irradiation, irradiance, received at ground level; it is the sum of the direct, diffuse and reflected irradiations.

TIME AND TIME SYSTEMS

Time – legal time, local time, standard time, civil time, local clock time: The time used legally in a given country

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Time – mean solar time: The time determined locally by dividing the average duration of a rotation by 24 h. The mean solar time is equal to 12 h when the sun is at its highest, i.e. at zenith, as an annual average.

Time – true solar time: The time for which the sun is actually at its highest when it is 12 h. It depends on the day of the year and longitude of the site.

Time – Universal Time (UT): The mean solar time for the longitude 0°.

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planetary orbits; For most planets in the solar system, the eccentricity (deviation from circular) is relatively small, meaning the orbits are nearly circular. Kepler found that the time period Y of each orbit is related to the distance R of the planet from the sun by:

$$Y = a_1 \cdot R^{3/2}$$

Parameter a1 ≈ 0.1996 d·(Gm)–3/2, where d is Earth days, and Gm is gigameters = 106 km.

Verify the above equation gives the correct orbital period of one Earth year.
Solution: Given: R = 149.6 Gm avg. distance sun to Earth.

Find: Y = ? days, the orbital period for Earth.

Y = (0.1996 d·(Gm)–3/2) · [(149.6 Gm)1.5] = 365.2 days.

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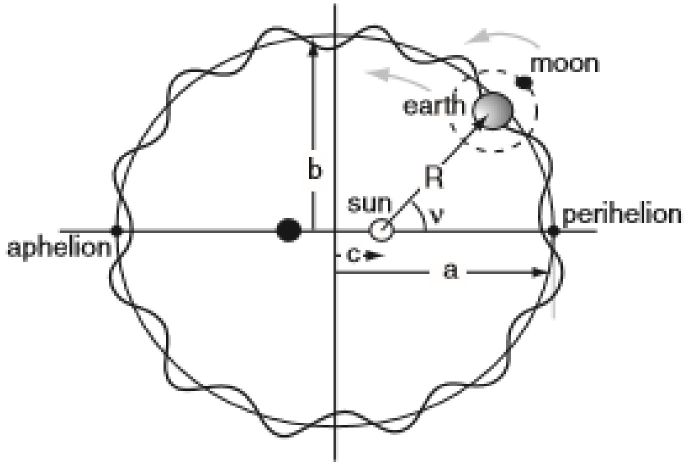
Length of the semi-major axis (half of the longest axis) of the ellipse is a = 149.457 Gm, which is the definition of one astronomical unit (au).

Semi-minor axis (half the shortest axis) length is b = 149.090 Gm.

The closest distance of earth to the sun(4January) is called perihelion

The farthest distance of earth to the sun(5juley) is called (aphelion)



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Julian Day calendar begins from 1 January; For example, For 5 February, Julian day (d) is =36 (which includes 31 days in January plus 5 days in February

Exercises

Given distances R between the sun and planets compute the orbital periods (Y) of: a. Mercury (R = 58 Gm) b. Venus (R = 108 Gm) c. Mars (R = 228 Gm) d. Jupiter (R = 778 Gm) e. Saturn (R = 1,427 Gm) f. Uranus (R = 2,869 Gm) g. Neptune (R = 4,498 Gm) h. Pluto (R = 5,900 Gm)

What is the relative Julian day for: a. 10 Jan b. 25 Jan c. 10 Feb d. 25 Feb e. 10 Mar f. 25 Mar g. 10 Apr h. 25 Apr

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LAWS OF RADIATION

Kirchoff's law: Kirchoff's law states that a body which is a good absorber of radiation in certain wavelengths is also a good emitter in the same wavelengths.

Stefan-Boltzmann's law: The Steffan-Boltzmann law states that the amount of energy radiated per unit time and wavelength from a unit surface area of an ideal black body is proportional to the fourth power of the absolute temperature of the body. It is expressed as

$$I = \sigma T^4$$

Wein's law: The Wein law states that the wavelength of maximum intensity (m) in black body radiation is inversely proportional to the absolute temperature (T),

$$\lambda_m = \frac{2897}{T}$$

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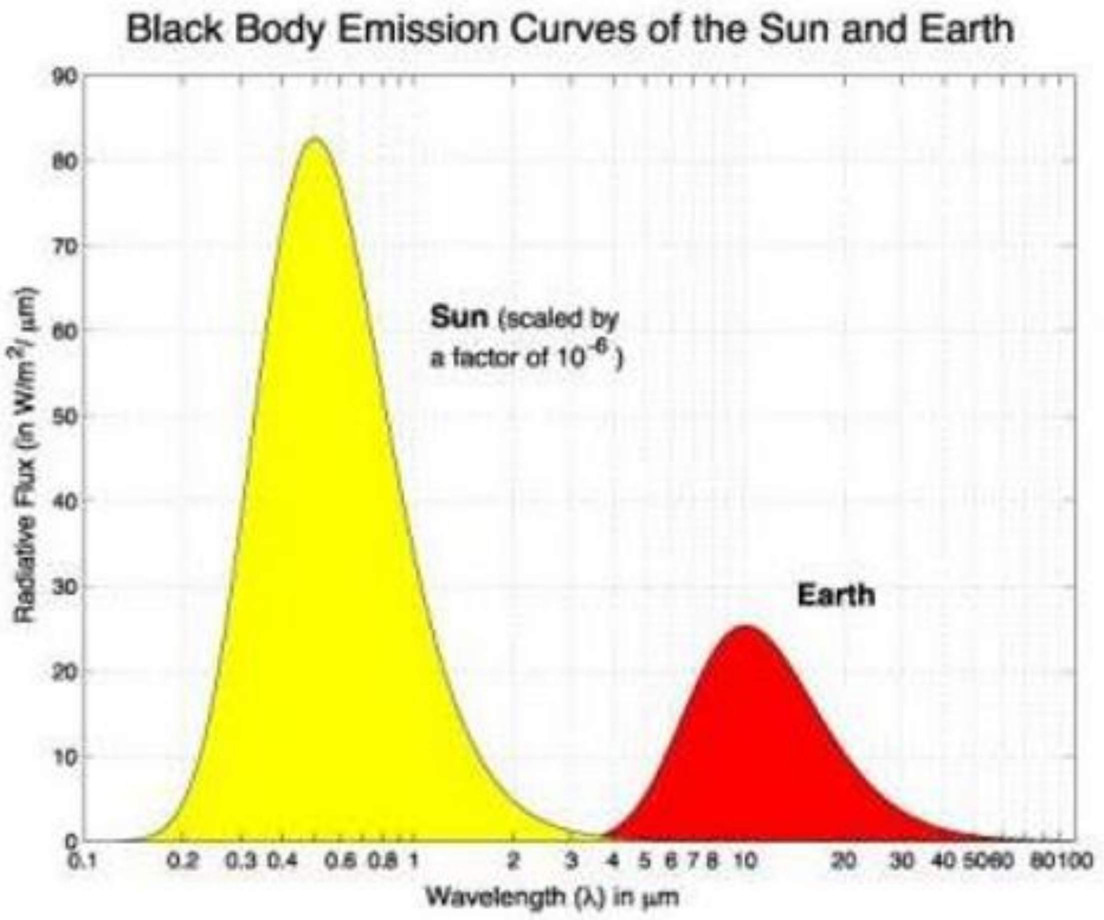
$$\lambda_{\max} = \frac{2897}{T}\,\mu m$$

$$\lambda_{sun} = \frac{2897}{6000}\,\mu m = 0.48\,\mu m$$

$$\lambda_{earth} = \frac{2897}{280}\,\mu m = 10.4\,\mu m$$



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It shows that higher the temperature of the black body the shorter is the wavelength of the radiation

Planck's law: Planck's law gives the relationship between radiation energy, temperature and wavelength of the electromagnetic radiation, and is given by

$$I_\lambda = \frac{C^1}{\lambda^5} \frac{1}{e^{c/(\lambda T)} - 1}$$

Calculate the energy radiated in one minute by a perfectly black body sphere of 5 cm radius maintained at 127 ºC.

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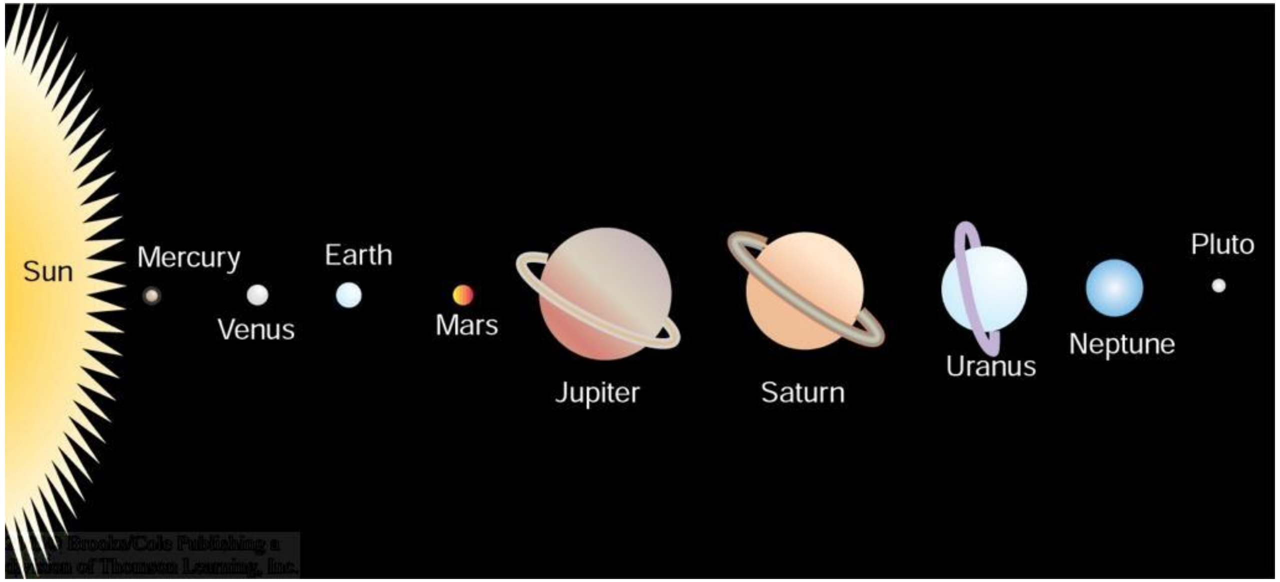
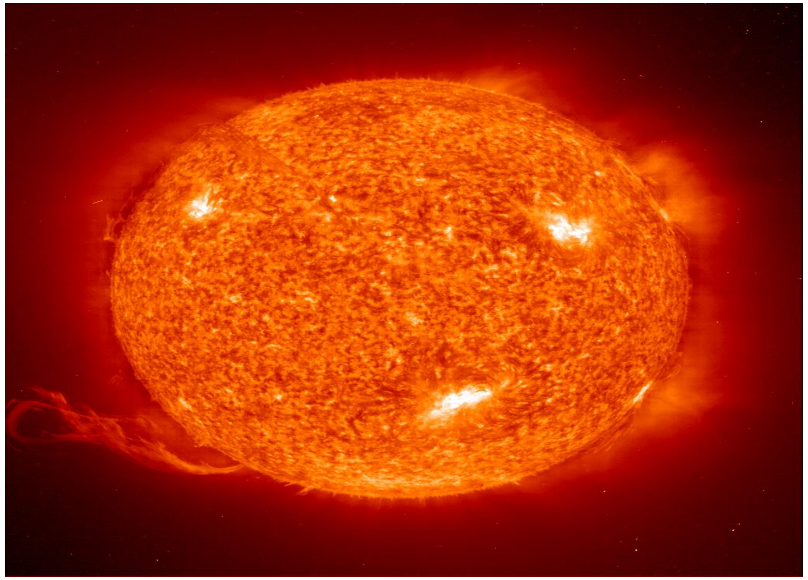
2.1 Incoming and outgoing radiation

The incoming solar radiation (ISR) at the Earth's orbit is determined by solar evolution on timescales of billions of years.





Nearly 150 million kilometers separate the sun and earth, yet solar radiation drives earth's weather

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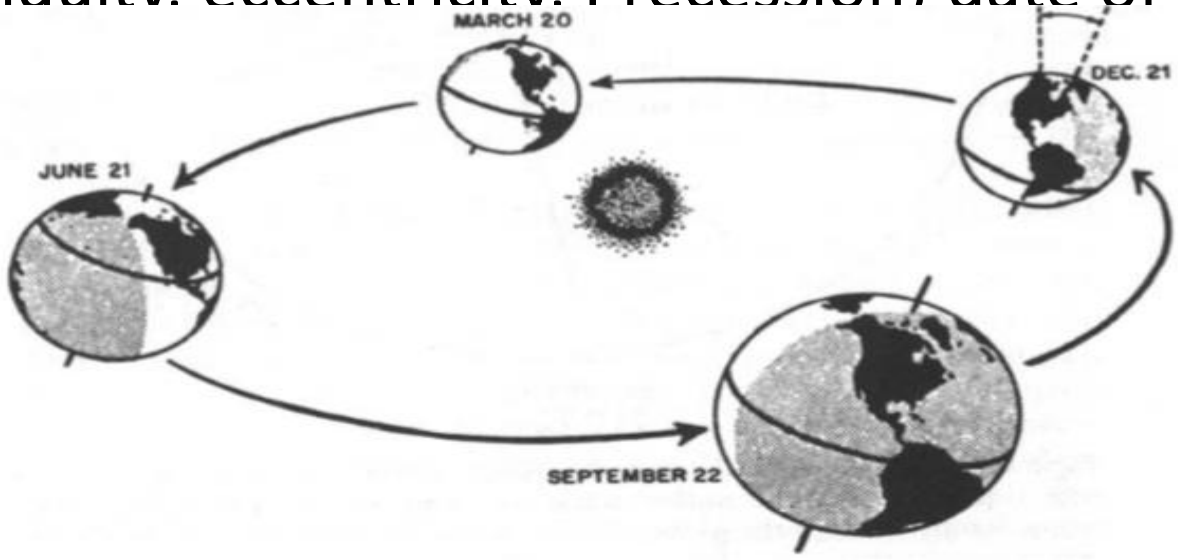
Radiation is the only mechanism by w/c the earth can exchange energy with the rest universes. Solar energy flux at mean earth radius orbit is about 1370 w/m2.The distribution of solar energy determined by earth's orbital parameters(obliquity, eccentricity, Precession) date of equinox and earth rotation



Which orbital parameter is responsible to cause seasons?

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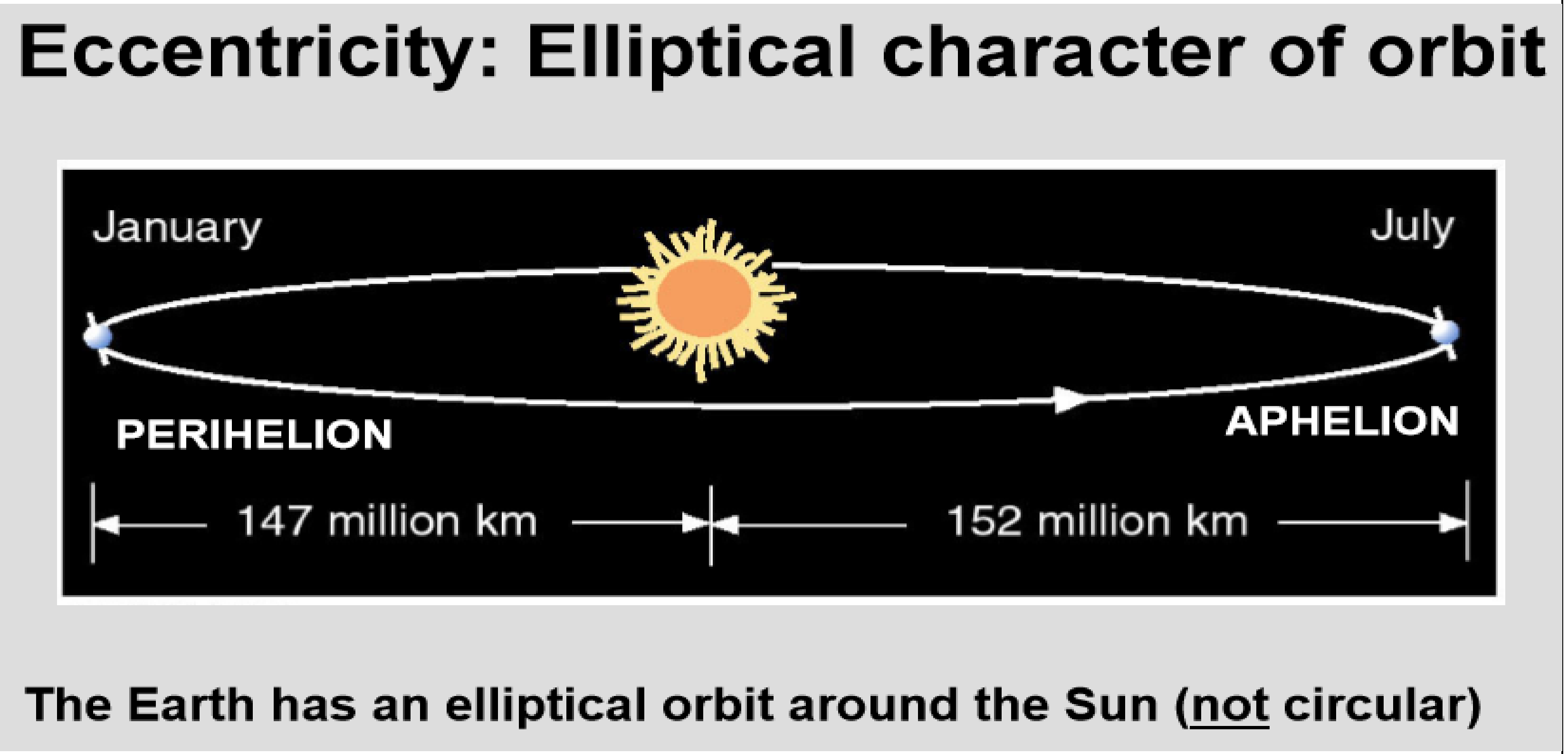
Which one orbital parameters of the Earth is responsible for the occurrence of the seasons?

Eccentricity

Precession

Obliquity



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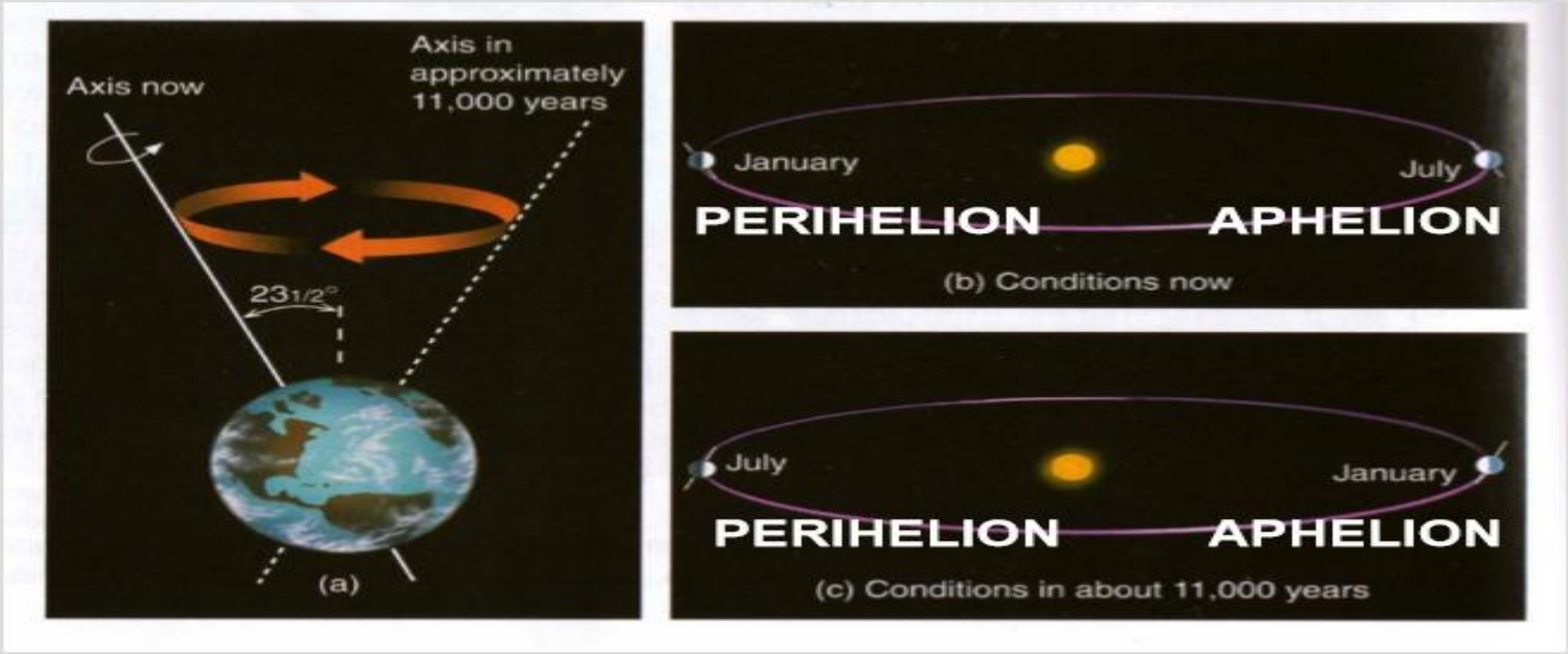
Precession: Change in Time of Perihelion and Aphelion



Position of perihelion and aphelion reverse

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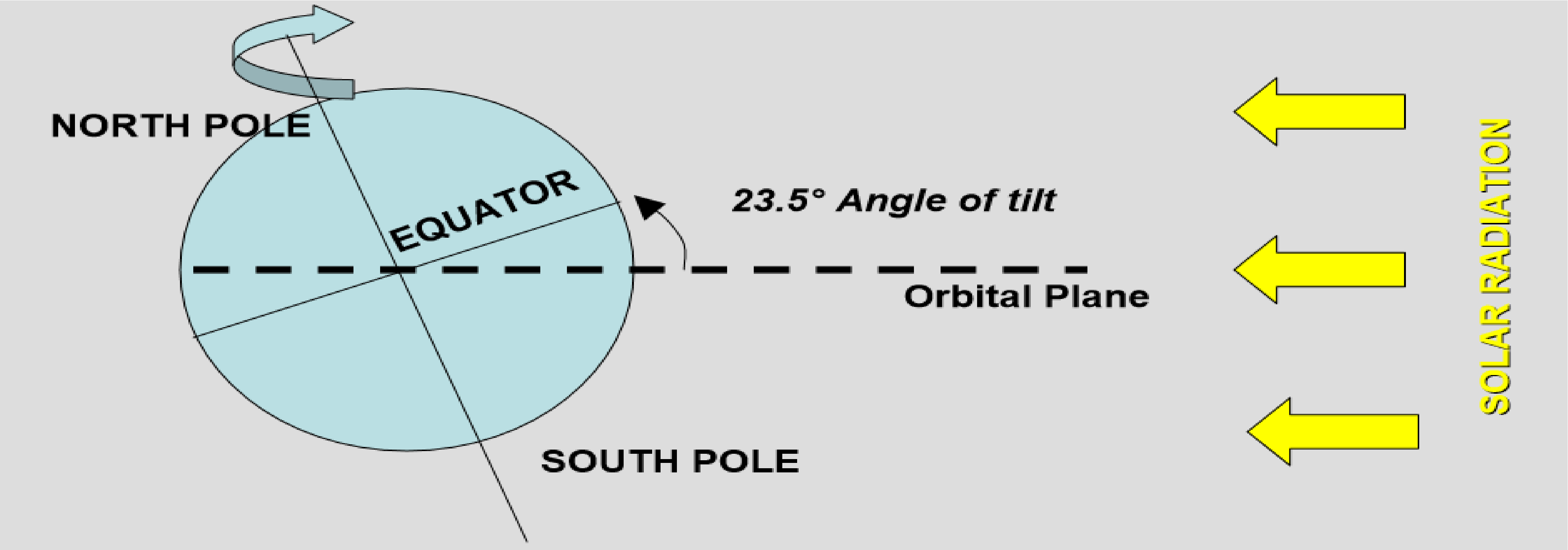
Obliquity: Tilt of the Earth with respect to its orbital plane



As the Earth rotates around the sun, it's axis of rotation is tilted at an angle of 23.5°.

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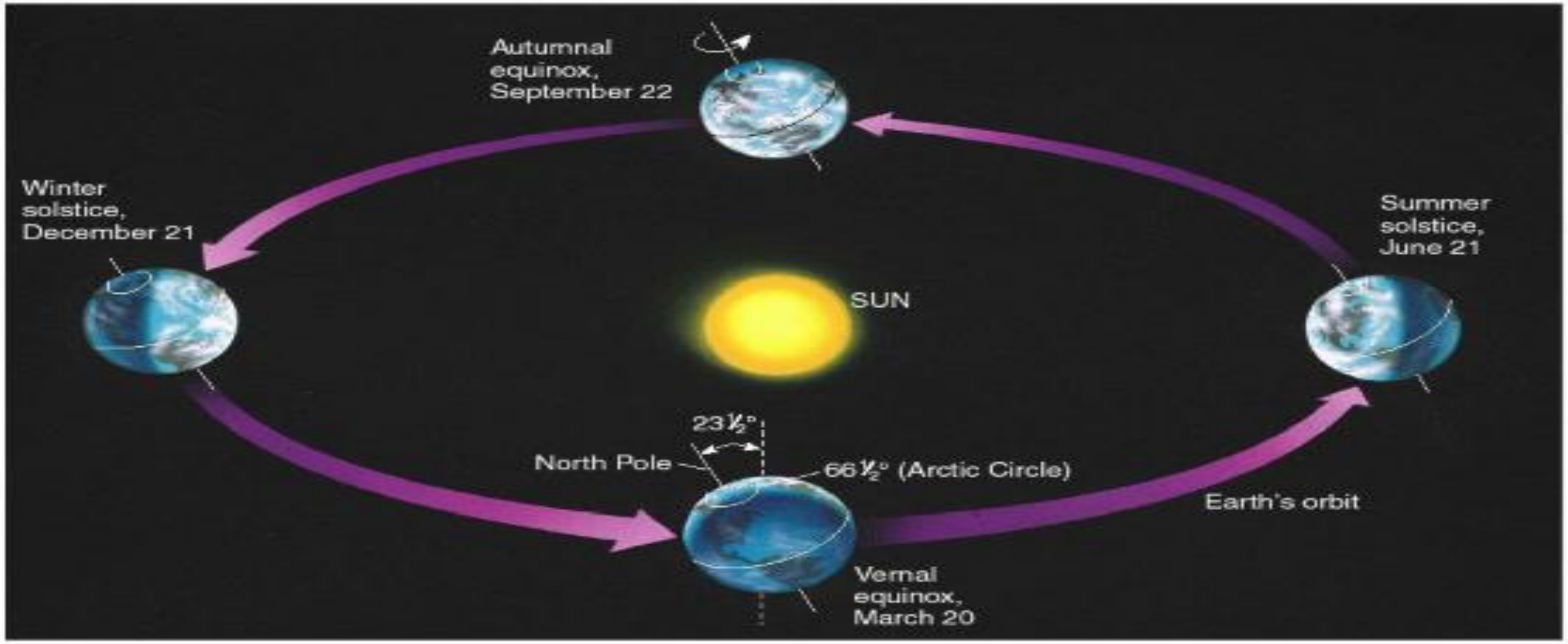
Obliquity and Seasonal Cycle



The variation in the amount of solar radiation through the year due to the obliquity of the Earth is what causes the seasons

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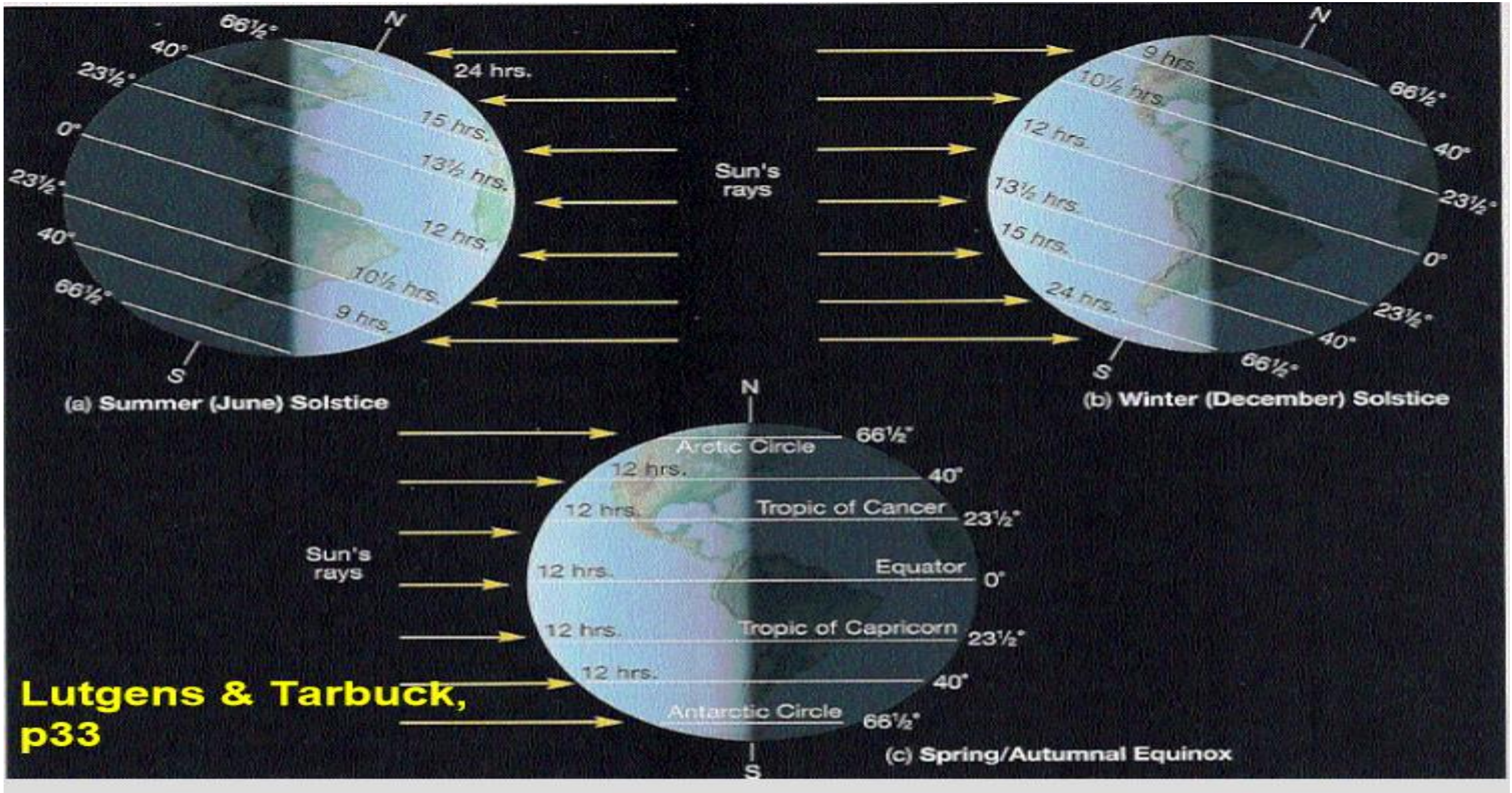

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The Earth's rotation about its axis causes a daily cycle of sunrise, increasing solar radiation until solar noon, then decreasing solar radiation, and finally sunset.

- Seasonal variation in solar radiation is caused by the inclination of the earth's axis.
- The largest variation occurs at the poles
- The global atmospheric circulation and its seasonal variability is driven by the uneven solar heating of the Earth's atmosphere and surface.
- A secondary maximum occurs near latitude 40º at the summer solstice
- The solar radiation at any latitude depends on the day of the year
- The latitudinal variation is small close to the summer solstice

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The interactions between radiation and matter may take various forms such as absorption, scattering, diffuse reflection and transmitted processes are conducted.

1. Scattering: When the incoming solar radiation encounters small particles (air molecules, dust, aerosols, and water droplets) of the atmosphere, the radiation energy is diffusely scattered in all directions from the particles

2. Absorption: The solar radiation can be absorbed by O_3 and partly by O_2 in the stratosphere.

3. Diffuse reflection: Clouds can reflect much incoming solar radiation to space

4. Transmission: incoming radiation can pass through atmosphere and reach ground surface

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TERRESTRIAL RADIATION:

The amount of solar energy absorbed by the earth-atmosphere system is (1–A)S/4

The incoming solar r alanced by the long wave terrestrial radiation:

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

The solar radiation which is received by the entire earth's surface of area 4pir^2 (r is radius of earth) is, on average.

At any given time of the year, when the atmosphere over a place is continually heated (cooled) relative to its surrounding, the differential heating creates a heat source (sink) over the place.

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Heat Sources and Sinks in the atmosphere

$dH/dt = 0$, $\nabla^2 dH/dt < 0$, Heat source

$dH/dt = 0$, $\nabla^2 dH/dt > 0$, Heat sink

Where H denotes the steady-state heat content of the air at a given place at time t, and ∇ is a Del operator. Here, $H = \rho c_p T$, where ρ is density, c_p is specific heat at constant pressure p, and T is temperature determined by local heat balance.

Thus, to maintain a steady-state, a heat source must give up its excess heat to the environment, and a heat sink must make up its deficit heat by acquiring heat from the environment.

Accordingly, low latitude is heat source and high latitudes heat sink

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Diabatic/Adiabatic Heat Sources/Sinks

Diabatic heating or cooling process is one in which a working sample of the atmosphere is free to exchange heat with its environment.

There are three important processes of diabatic heating or cooling process:

- Absorption or emission of short- and long-wave radiation
- Latent heat released by condensation of water vapour, or lost through evaporation
- Sensible and latent heat gained from, or lost

Adiabatic Heating/Cooling: any change that occurs in its temperature is due to its own expansion or compression

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Example of the Hadley Circulations - Meridional Circulation with Heat Source at the Equator and Heat Sinks in Higher Latitudes

Trade winds diverging from the high pressure belt were assumed to travel equatorward, converge at the equator and rise in penetrative convection producing cloud and rain and thereby releasing latent heat of condensation of water vapour carried by the trade winds.

The rising currents from equator are assumed to diverge in the upper troposphere and flow poleward an till sup tropic (30^0) then sink

Observation shows that the equatorial tropopause with a temperature of about –80◦C at a height of about 16 km above sea level is the coldest place in the tropical atmosphere.

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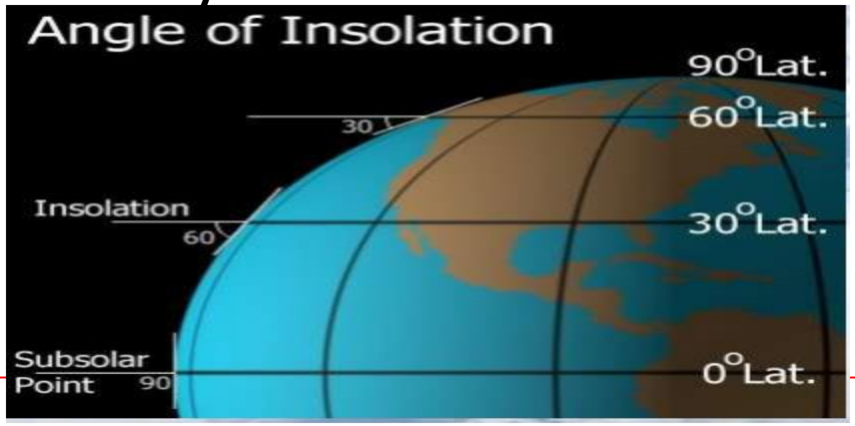
Factors Affecting Insolation – there are six main factors that affect the intensity of radiation received at the Earth's surface

Angle of Insolation

The intensity of insolation increases, as the angle of insolation gets closer to 90 degrees

The intensity of insolation decreases with an increase in latitude

The angle of insolation varies throughout the day



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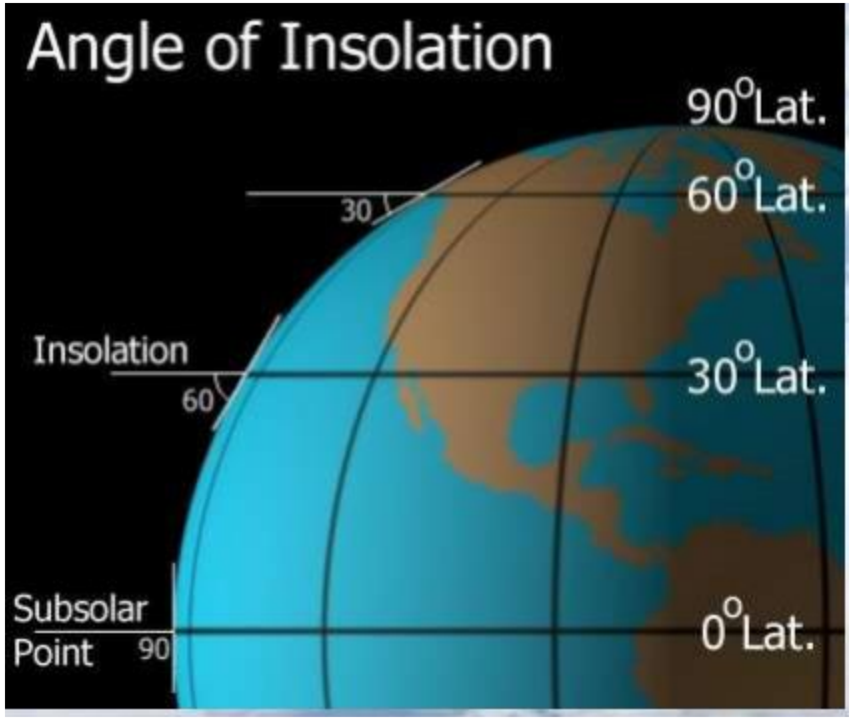
Angle of insolation



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Duration of Insolation – the length of time that Earth's surface receives insolation

The surface temperature at a particular location on the Earth is directly related to the duration of insolation

The duration of insolation varies with latitude and the season of the year. Maximum insolation occurs in the Northern Hemisphere around June 21st

Maximum Surface temperature occur at the Earth's surface after the maximum duration of insolation

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Absorption of Insolation – Approximately 19% of incoming solar radiation is absorbed by the atmosphere

Approximately 47% of insolation is absorbed by the Earth's surface.

Reflection of Insolation – Approximately 34% of insolation received by the Earth is reflected back into space by clouds (25%), snow, ice caps, and water.

Scattering of Insolation – Insolation can be scattered by molecules of gas, water, or dust in the Earth's Atmosphere. This is why the sky is blue

Solar Constant (S) The solar energy density at the mean distance of Earth from the sun (1.5 x 1011m)

$S = L / (4 \, Pi d^2)$

$(3.9 \times 10^{26} W) / [4 \times 3.14 \times (1.5 \times 10^{11} m)^2] = 1370 \ W/m2$

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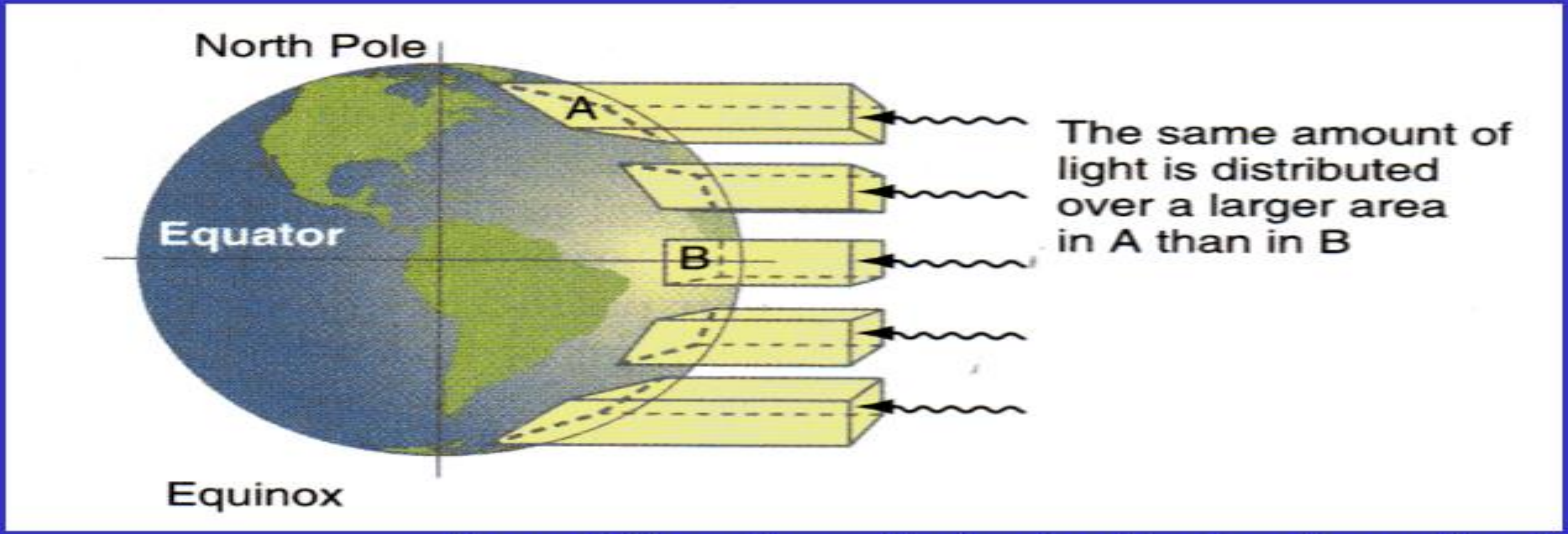
Zenith Angle and Insolation



(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.

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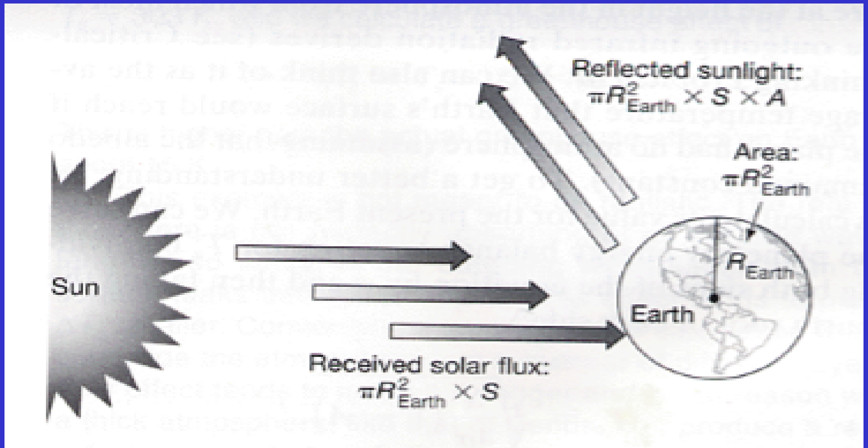
Solar Energy Absorbed by Earth



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.

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Blackbody Radiation

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

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

The single factor that determir energy is emitted by a blackbody is its temperature

$$E = \sigma T^4$$

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

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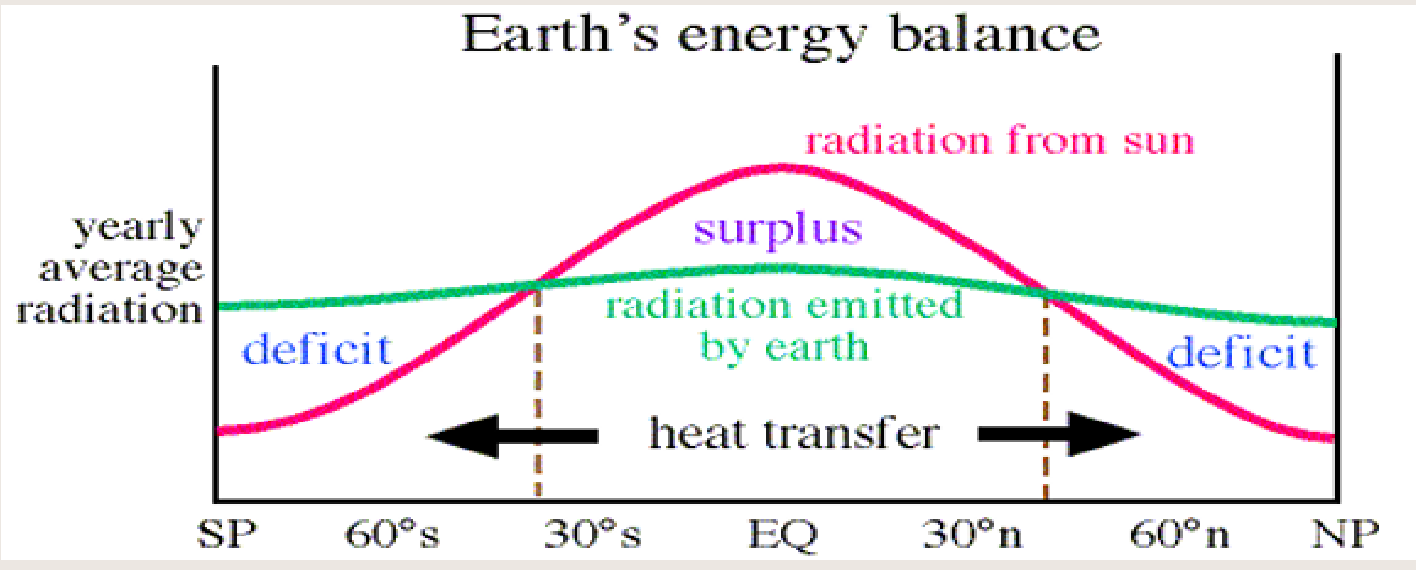
Long Wave Radiation: It is emission from the surface of the earth

The mean surface temperature of the earth is 288º K (15º C). The radiation emitted (I) per unit area of the surface per unit time is given by the Stefan-Boltzmann formula as $I = \sigma T_E^4$

HEAT BALANCE: is the difference between the total incoming radiation and the total outgoing radiation



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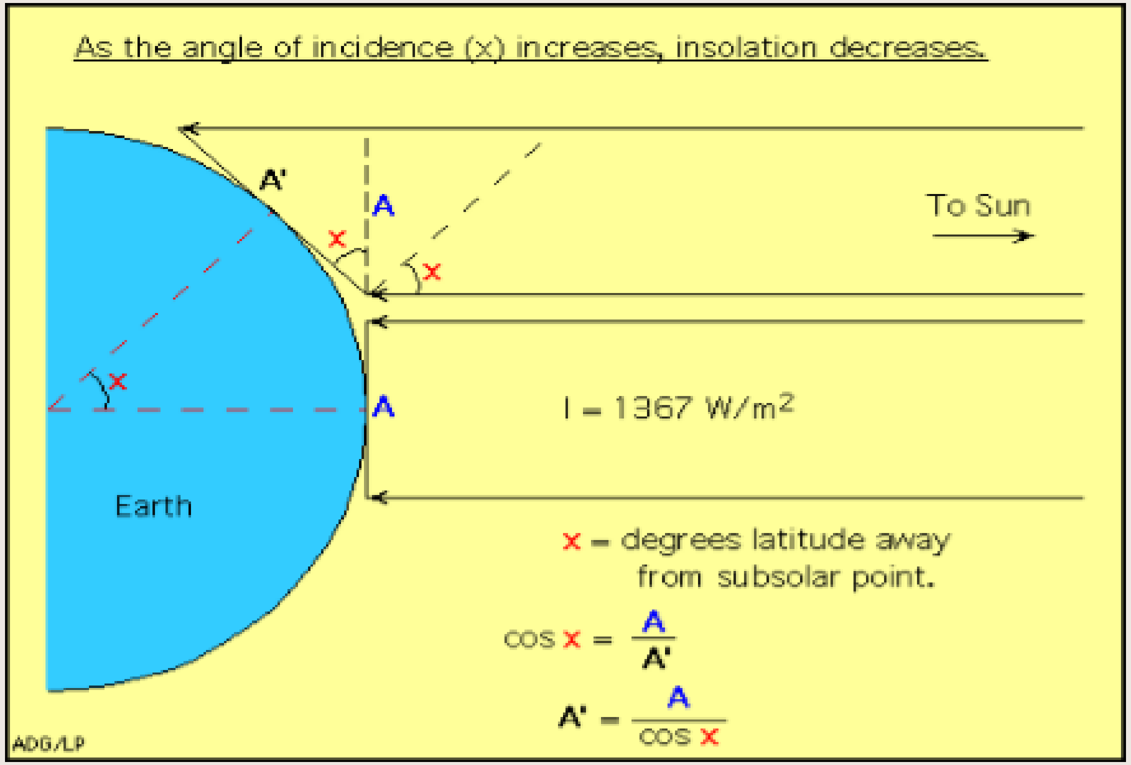
2.2 Latitudinal distribution of earth radiation

1. Earth's curvature: the energy within a given solar radiation beam is spread over a larger area as the latitude increases.



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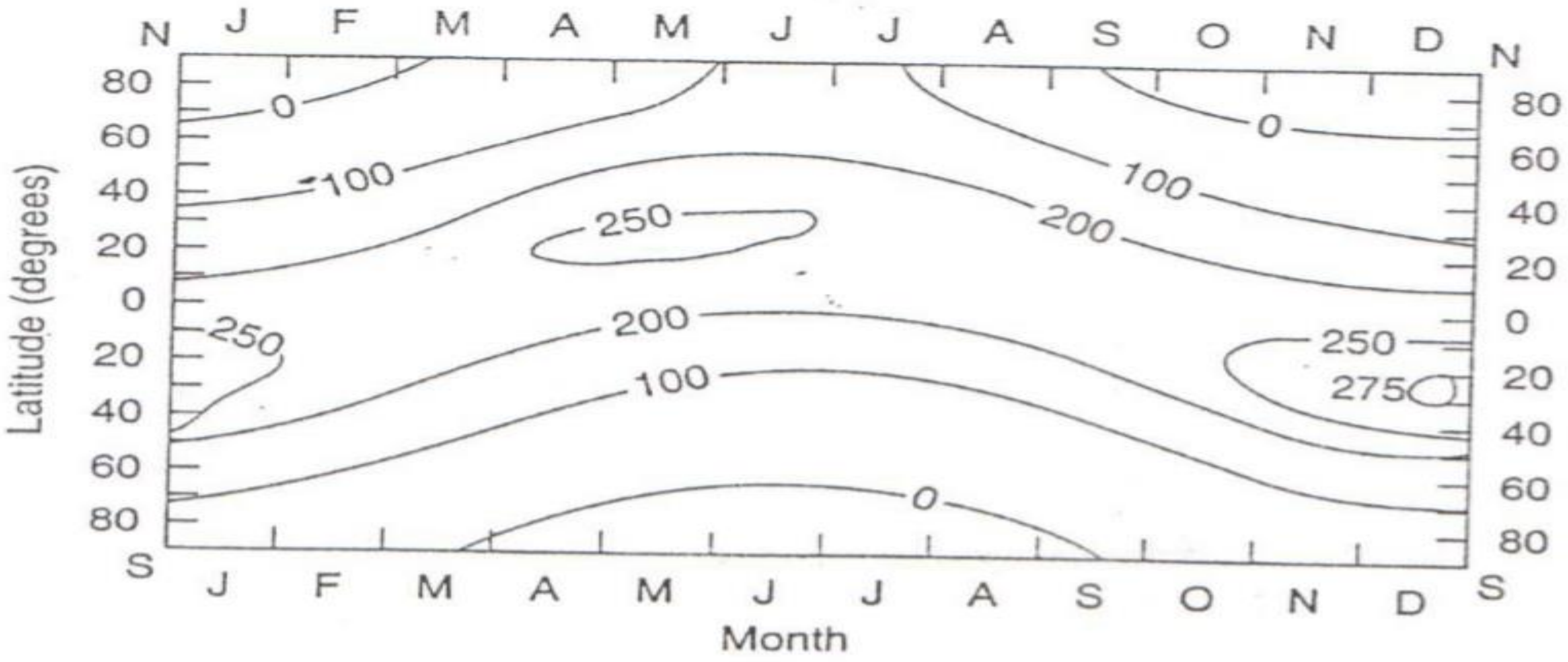
Solar insolation at the surface as a function of latitude and season



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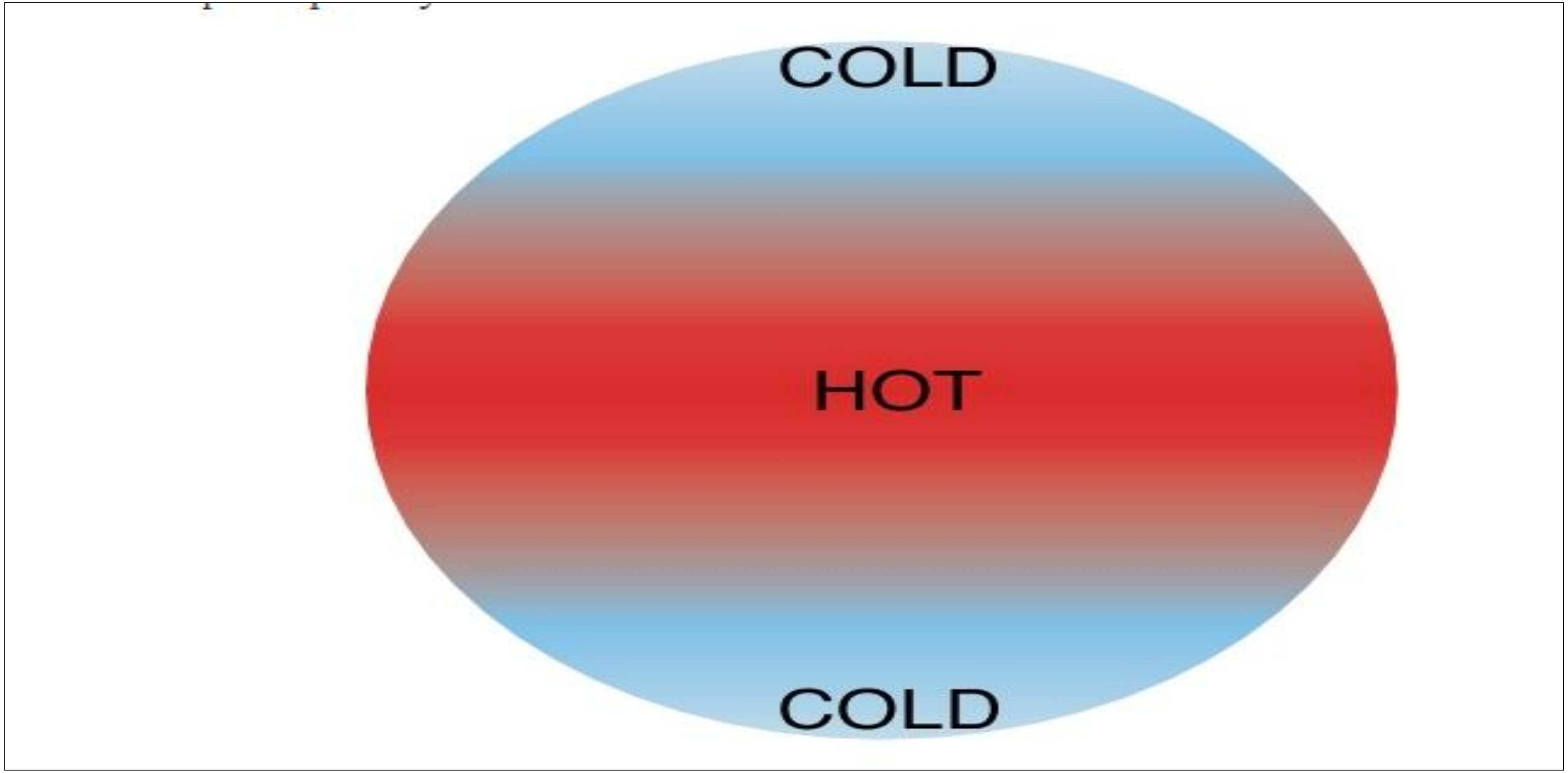

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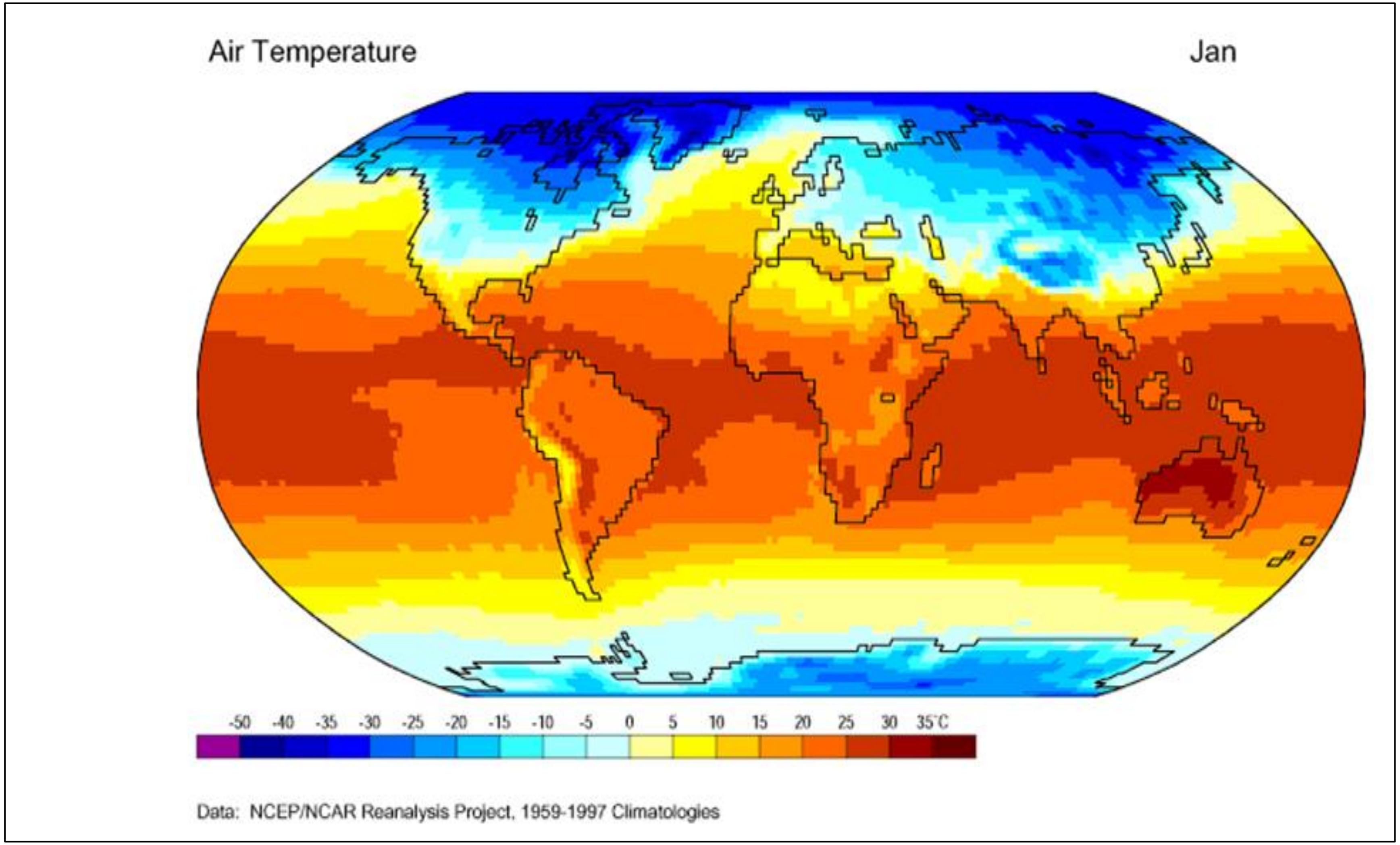

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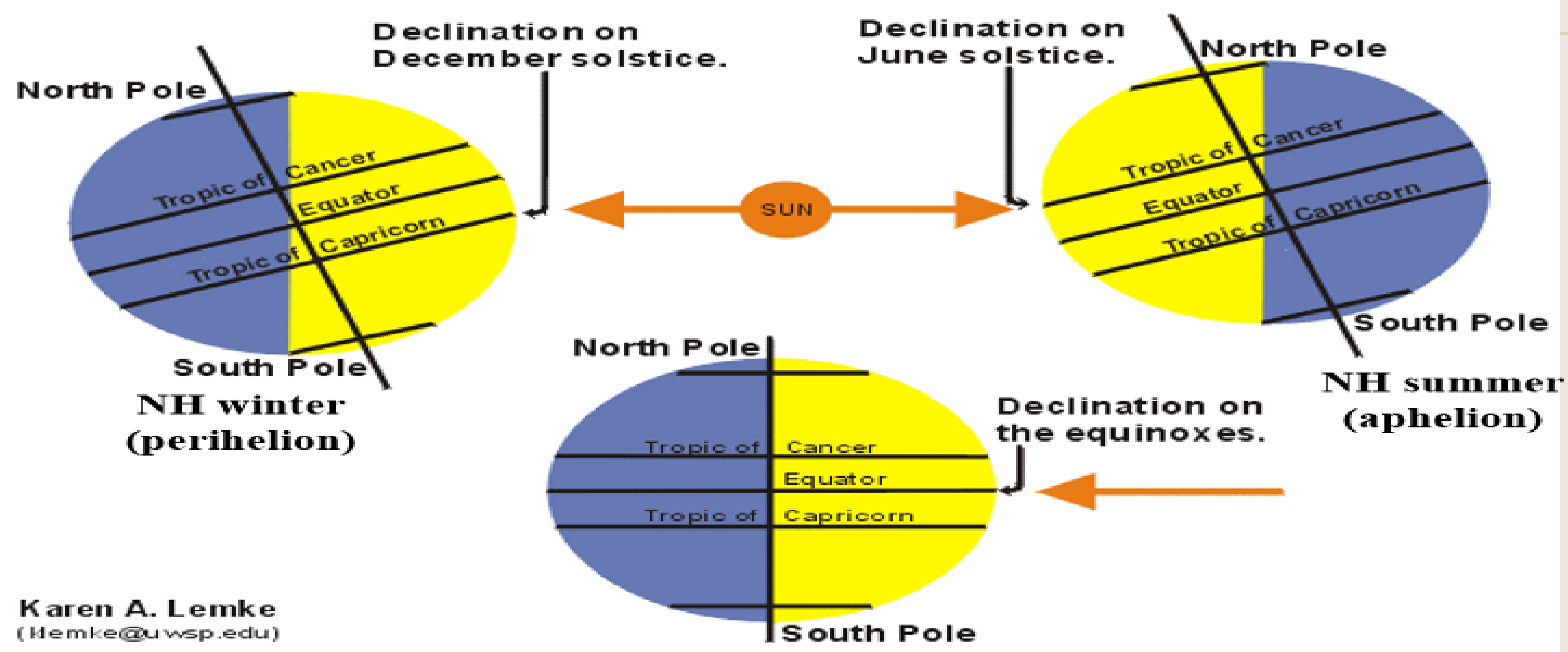
2. The tilt of the axis deprives the portion of the earth poleward of $90° - 23.5° = 66.5°$ latitude in the winter hemisphere of sunlight.



Note: the earth is closest to the sun (perihelion) in the NH winter at the current time.

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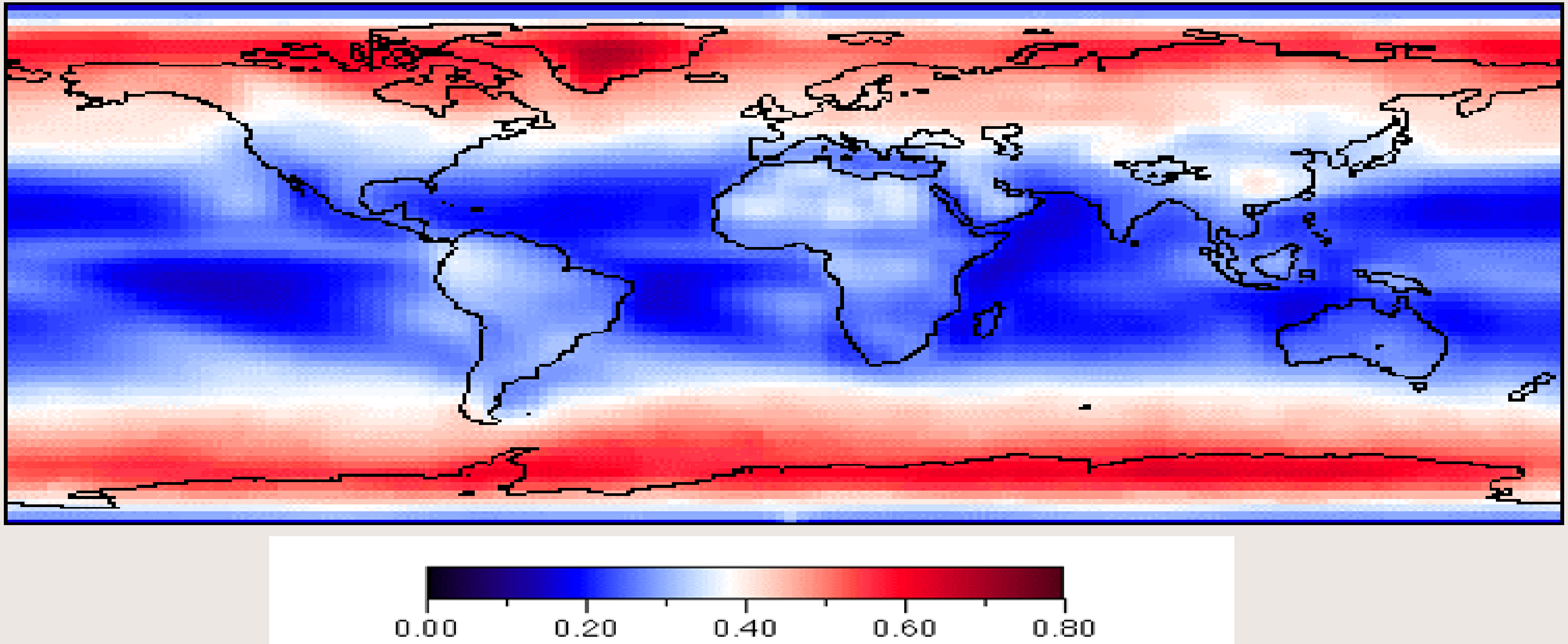
3. Albedo varies with latitude; snow and ice occur at high latitudes, water has a higher albedo at higher latitudes (zenith angle effect). At lower latitudes, clouds dominate the planetary albedo.



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2.3 Atmospheric Energetics

Energy type

The form of energy that play significant role in the general circulation are:

(1) Internal energy(IE)

(2) Potential energy (PE)

(3) Kinetic energy (KE)

(4) Latent energy(LE)

During atmospheric motions KE can convert to PE or reverse

KE is immediate source of PE or Sink of PE

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Internal Energy

The internal energy of a system is the energy contained within the system, excluding the kinetic energy and the potential energy of the system as a whole due to external force fields.

Internal energy per unit mass of an ideal gas is just given by:

$$I = CvT$$

Then, by definition, internal energy of unit cross section

$dI=\rho cvTdz$

Integrating from the earth's surface to the top of the atmosphere gives the

total internal energy, I, as $I = cv \int_0^\infty \rho T dz$

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Potential energy

Potential Energy is any type of stored energy, can be chemical, gravitational, mechanical or nuclear energy.

The potential energy P per unit mass is defined as: $P = gz = \Phi$.

Thus, gravitational potential energy, dP, of the same vertical section as the above

Potential energy at a height z above the earth surface is given by: dP=ρgzdz

Integrating through the atmosphere gives the total potential energy of the column is given by $P = g\int_0^{\infty} \rho z dz$

Or by introducing hydrostatic $P = -\int_{p0}^{0} z dp$

By introducing ideal gas law $P = R\int_0^{\infty} \rho T dz$

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Kinetic energy

The kinetic energy of the atmosphere is produced by vortex stretching and twisting associated with turbulent eddies.

$$K = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2} + \overline{\omega'^2}\right)$$

Where $\overline{u'^2}$, $\overline{v'^2}$ and $\overline{\omega'^2}$ are variances of components of wind vector.

The total energy of the atmosphere is always conserved. Hence, I+P+K = constant.

If the atmosphere is at rest initiall, $I_i+P_i=I_f+P_f+K_f$.

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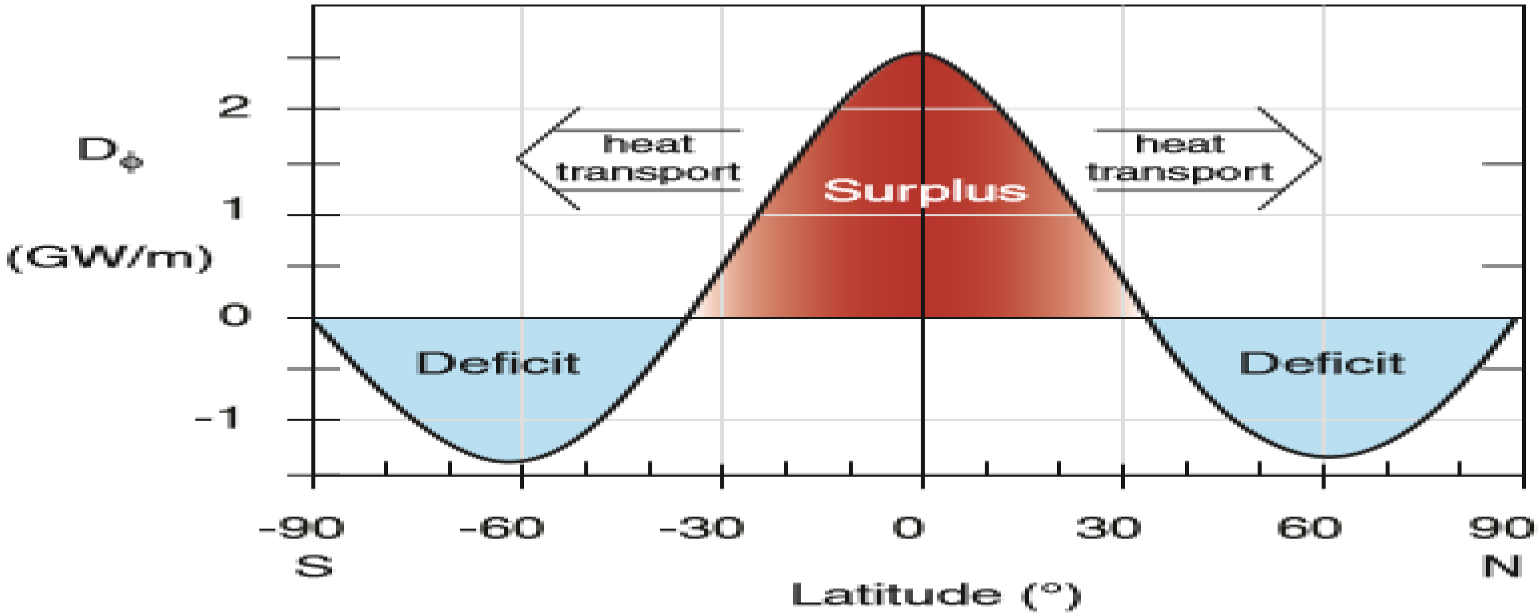
2.4 Meridional heat exchanges

The resulting incoming, outgoing, and net radiative forcings vs. latitude

In both poles experiences heat deficit whereas in the tropic heat surplus



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Net (incoming minus outgoing) zonally-integrated radiative forcing on the Earth. Surplus balances deficits.

This differential heating imposed on the Earth must be compensated by heat transport through the global circulation; otherwise, the tropics would keep getting hotter and the polar regions colder.

We can define E_{net} as differential heating Dφ :

$$D_\phi = E_{\phi\,net} = E_{\phi\,in} - E_{\phi\,out}$$