Global energy balance I

Reading: GPC Ch2

- Outline:
- Orbital characteristics and insolation
- Blackbody radiation
- Emission temperature
- Greenhouse effect
- Global radiative budget
- Distribution of radiation

Global energy balance

Sun:

Table 2.1

Characteristics of the Sun

Mass	1.99×10^{30} kg
Radius	6.96×10^{8} m
Luminosity	3.9×10^{26} J s^{-1}
Mean distance from Earth	1.496×10^{11} m

Energy source is nuclear fusion (hydrogen, mainly)

Luminosity increased about 30% over earth lifetime
Projected lifetime: ~ 11 billion years
Sun is about middle age

Energy balance:

Energy from the Sun =
energy returned to space by Earth’s radiative emission

The absorpion of solar radiation takes place mostly at the surface of the Earth.

The emission to space takes place mostly in the atmosphere.

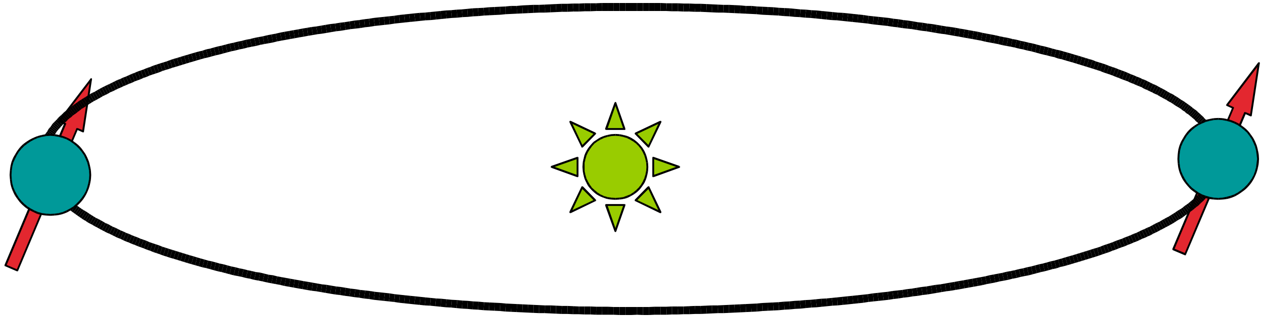
Because its atmosphere efficiently absorbs and emits IR radiation, the surface of the Earth is much warmer than it would be in the absence of the atmosphere (*greenhouse effect*).

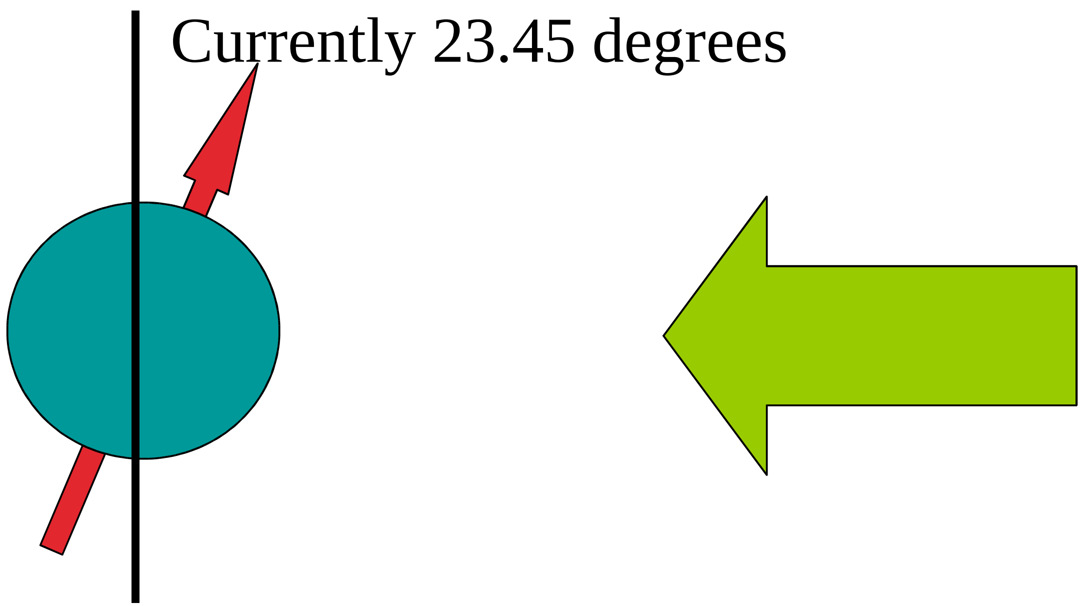
In one year, the solar energy absorbed near the equator is greater than the solar energy absorbed near the poles.

Therefore the atmosphere and the oceans transport energy poleward to reduce the effects of this heating gradient on surface temperature.

Much of the character of the **Earth's** evolution and climate has been determined by its **position within the solar system**.

Define obliquity (tilt) as the angle between the rotation axis of the planet and the plane of the orbit around the sun





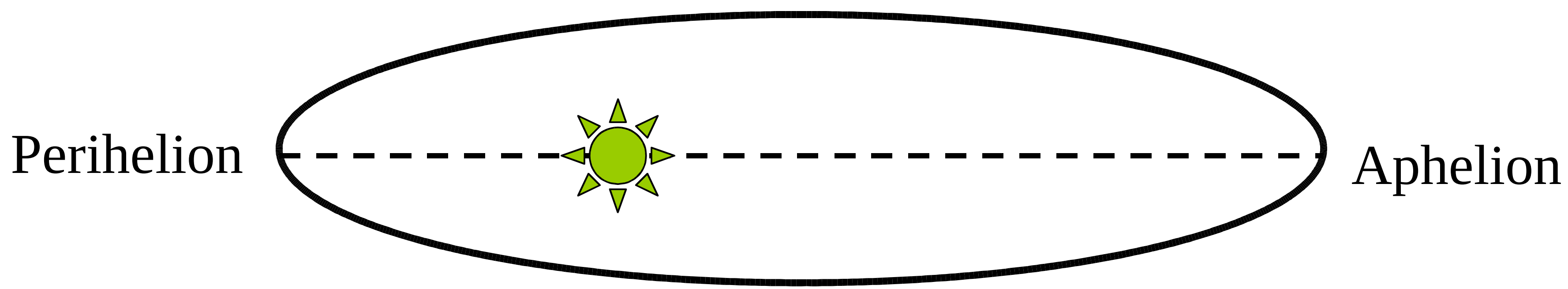
Eccentricity

Mean distance: **1.496 x 10^{11}m = 1AU**

Max (aphelion): 1.521 x 10^{11}m = 1.017AU

Min (perihelion): 1.471 x 10^{11}m = 0.983 AU

Define eccentricity (e) by $r_{aphelion} = (1+e)\, r_{mean}$;   e ~ 0.0167 today



Phase of the seasons relative to the Earth's position in the orbit

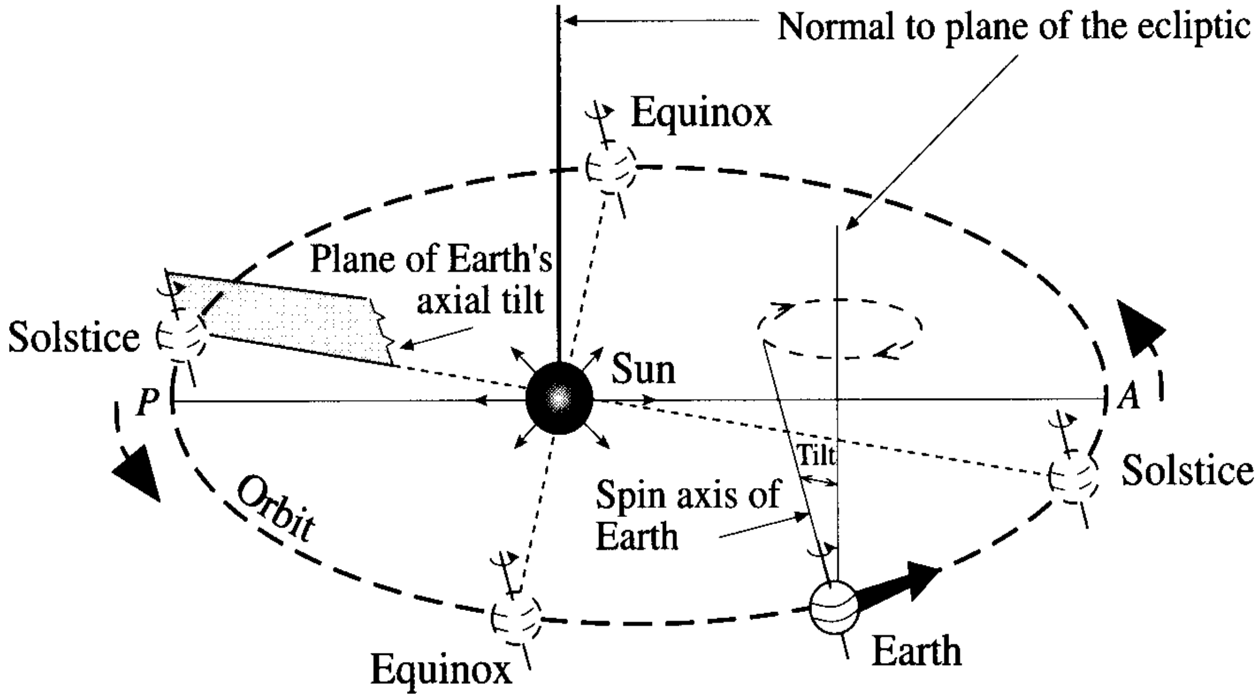


Figure 1.2 Geometry of the Earth–Sun system. The Earth's orbit, the large ellipse with major axis AP and the Sun at one focus, defines the plane of the ecliptic. The plane of the Earth's axial tilt (obliquity) is shown passing through the Sun corresponding to the time of the southern summer solstice. The Earth moves around its orbit in the direction of the solid arrow (period one year) whilst spinning about its axis in the direction shown by the thin curved arrows (period one day). The broken arrows shown opposite the points of aphelion (A) and perihelion (P) indicate the direction of the very slow rotation of the orbit

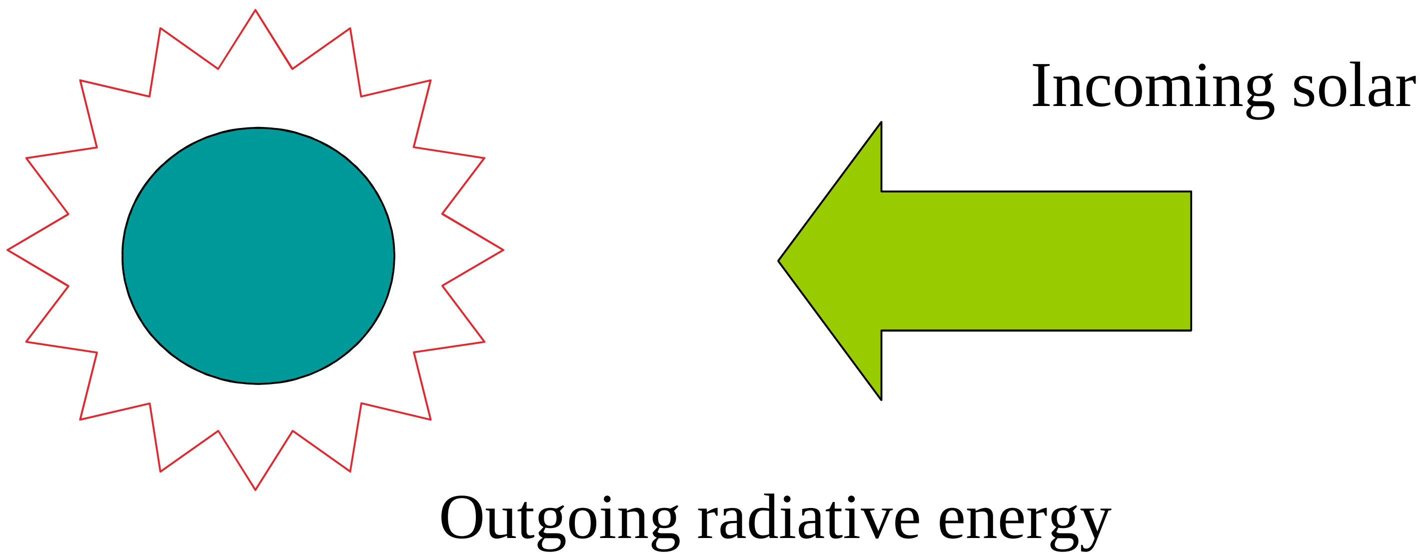
(source: Wells, "The atmosphere and ocean")

Energy balance of the earth

First law of thermodynamics:

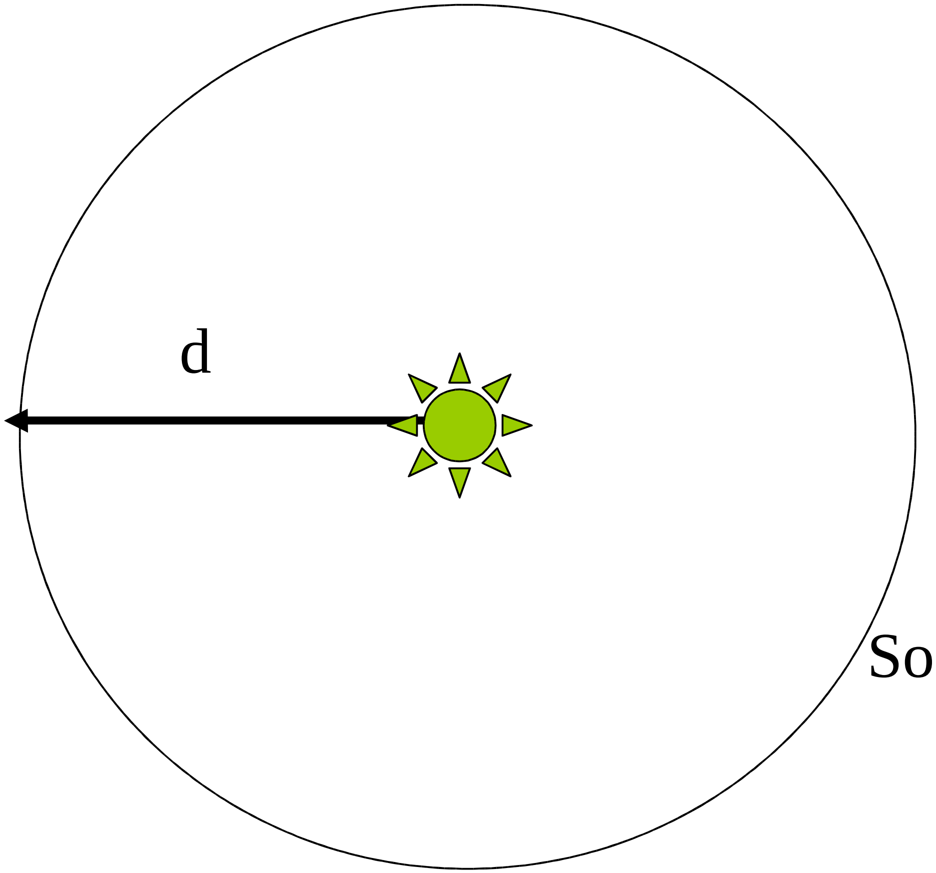
$dQ = dU - dW$ for a closed system

Work done by the Earth on its environment: negligible



Incoming solar radiation = outgoing planetary radiation

Flux, Flux density, solar constant



Sun's energy output

$L_o = 3.9 \times 10^{26}$W

Assume radiative flux is spherically uniform

DEF: **flux density** (S_d) = energy per unit area

So: L_o = flux density x area of sphere

$= S_d \times 4 \pi d^2$

Solar constant (S_o) = flux density at earth-sun distance

$= L_o / 4 \pi d^2 = 1367$ W/m^2

Cavity Radiation = radiation field within a closed cavity in thermodynamic equilibrium

DEF: a **blackbody** is a hypothetical body consisting of a sufficient number of molecules absorbing and emitting electromagnetic radiation over all frequencies so that

2. All incident radiation completely absorbed
3. In all wavelength bands and in all directions the maximum possible emission is realized

Stefan-Boltzmann Law for blackbody radiation:

$E_{BB} = \sigma T^4$ σ = Stefan-Boltzmann constant

$= 5.67 \times 10^{-8} W m^{-2} K^{-4}$

DEF: **Emmissivity (**ε) describes how ‘far’ or ‘close’ it is to being a blackbody:

$$E_R = \varepsilon \sigma T^4 \qquad (2.6)$$

Emission temperature

DEF: Emission temperature is the blackbody temperature required for the planet to get rid of the solar flux it absorbs by blackbody radiation

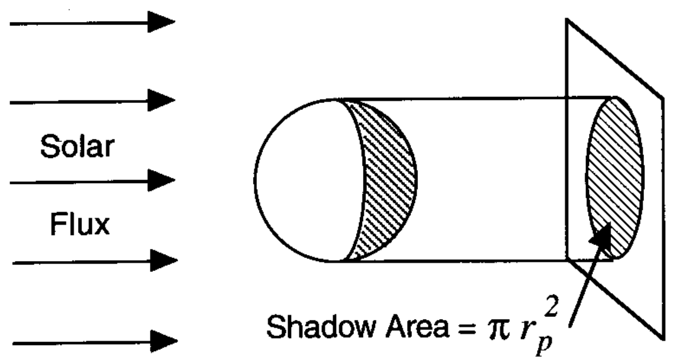


Fig. 2.2 Diagram showing the shadow area of a spherical planet.

Absorbed solar rad = $S_o(1-\alpha_p)\,\pi\, r_p^2$

DEF: **albedo (α_p) = fraction of solar radiation reflected**

Emitted terrestrial rad = $\sigma T_e^4\, 4\,\pi\, r_p^2$

Equate to get $\mathbf{(S_o/4)(1-\alpha_p) = \sigma T_e^4}$

So /4=1367/4=342 W/m²

Globally averaged insolation at TOA

Greenhouse effect

Add a 'slab' atmosphere with the properties:

ii) Lets SW through (transparent)

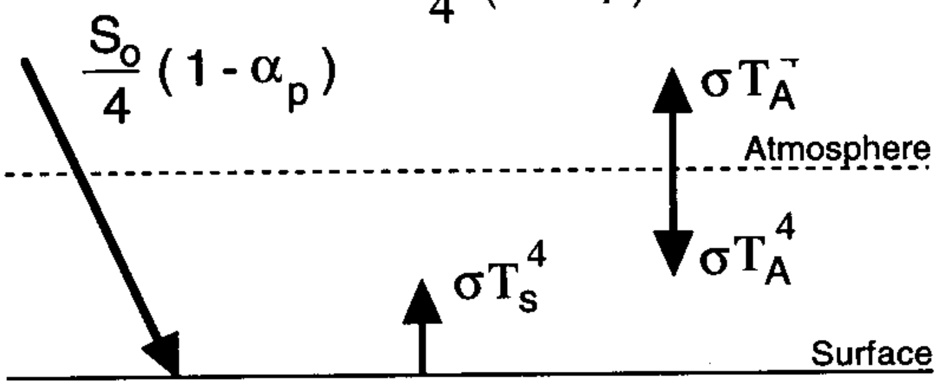
iii) But blackbody for terrestrial radiation

Top of Atmosphere (TOA) balance: $$\frac{S_0}{4}\left(1-\alpha_p\right)=\sigma T_A^4=\sigma T_e^4$$

Atmospheric balance: $$\sigma T_s^4=2\sigma T_A^4 \quad\Rightarrow\quad \sigma T_s^4=2\sigma T_e^4$$

Surface balance:

$$\frac{S_0}{4}\left(1-\alpha_p\right)+\sigma T_A^4=\sigma T_s^4 \quad\Rightarrow\quad \sigma T_s^4=2\sigma T_e^4$$



NOTE: $T_e=T_A<T_S$

Fig. 2.3 Diagram of the energy fluxes for a planet with an atmosphere that is transparent for solar radiation but opaque to terrestrial radiation.

Example: what is T_s for earth parameters?

$$\sigma T_s^4 = 2\,\sigma\,T_e^4 \quad \text{or} \quad T_s = (2\,T_e^4\,)^{0.25}$$

Since T_e = 255K from before, T_s = 303K or 30 degrees C!

Example: what albedo α^* do I need to get a surface temperature comparable to observed mean earth surface temperature of 288K?

Note that from the surface energy balance and the TOA energy balance that

$$(S_o/4)(1-\alpha^*) + \sigma\,T_A^4 = 2\,(S_o/4)(1-\alpha^*) = \sigma\,T_s^4 \quad \text{or}$$

$$\alpha^* = 1 - (2\,\sigma\,T_s^4)/S_o = 1 - (2 \times 5.67\text{x}10^{-8}\text{Wm}^{-2}\text{K}^{-4} \times (288\text{K})^4)/1367\text{Wm}^{-2}$$

$$= 0.42$$

Global radiative flux energy budget

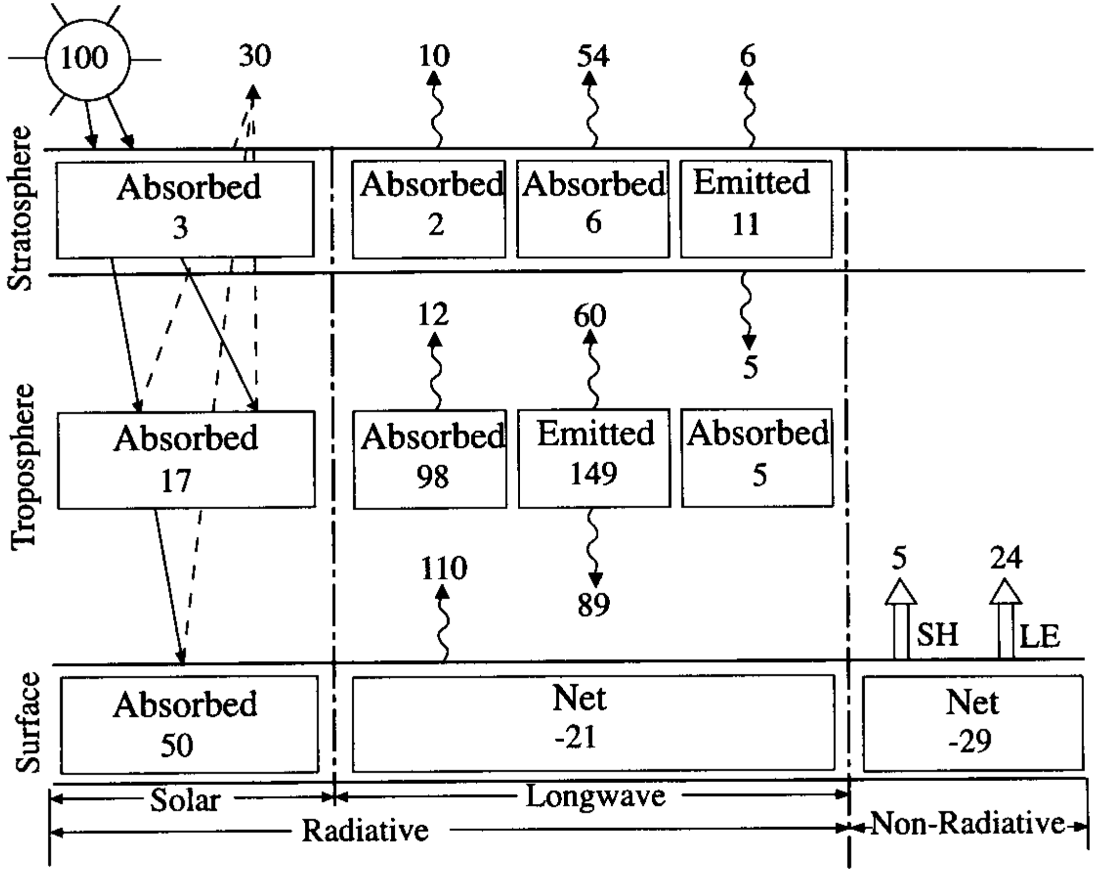


Fig. 2.4 Radiative and nonradiative energy flow diagram for Earth and its atmosphere. Units are percentages of the global-mean insolation (100 units = 342 W m^{-2}).

Distribution of radiation

Radiation at TOA depends on **latitude, season, time of day**

DEF: ***solar zenith angle*** θ_s: angle between normal to earth's surface and line between earth and sun (incident SW radiation)

$$Q = S_0 \left(\frac{\bar{d}}{d} \right)^2 \cos\ \theta_s$$

Solar flux per unit area

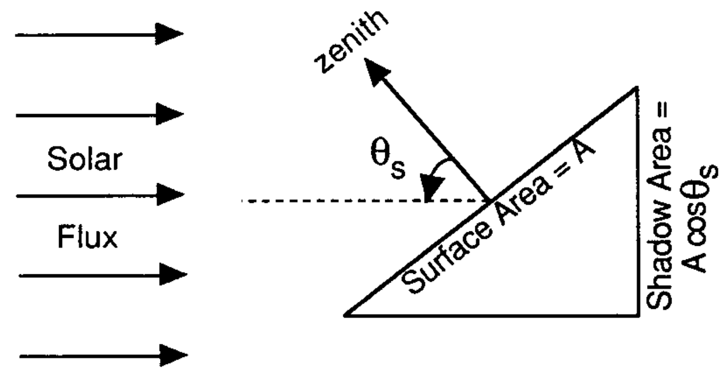


Fig. 2.5 Diagram showing the relationship of solar zenith angle to insolation on a plane parallel to e surface of a planet.

Solar zenith angle is calculated from:

Latitude (***angle*** ϕ: from -90 to 90 degrees)

Season (DEF: ***declination angle*** δ of the sun = latitude of the point of the sfc of the earth directly under the sun at noon - can be written as a function of the day of the year)

Time of day (DEF: ***hour angle*** h, defined as the longitude of the subsolar point relative to its position at noon)

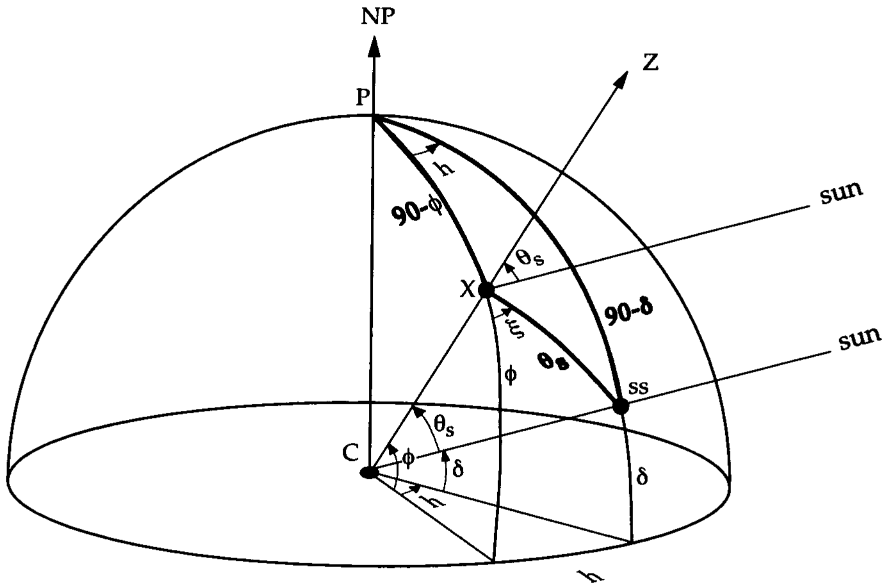


Fig. A.1 Spherical geometry for solar zenith angle calculation.

Cos θ_s = sin ϕ sin δ + cos ϕ cos δ cos h

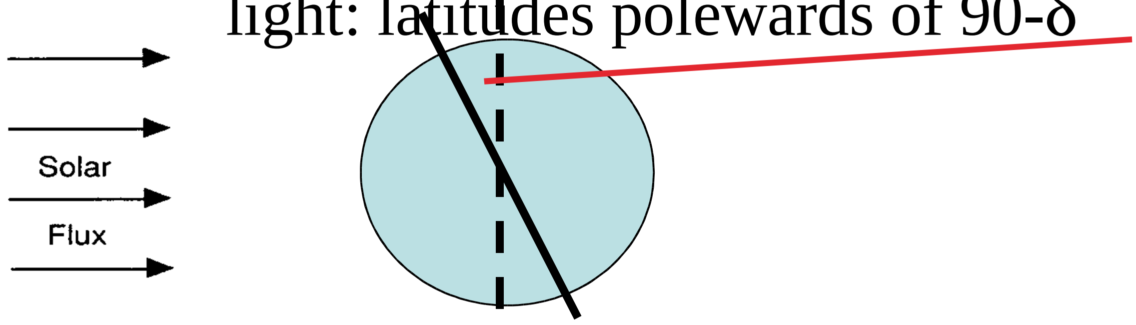
Special cases:

•Night: Cos θ_s < 0

•Sunrise or sunset: Cos θ_s = 0 so that cos h_0 = -tan ϕ tan δ

(I.e. time of sunrise/sunset depends on latitude and season)

light: latitudes polewards of 90-δ



Insolation $$Q = S_0 \left(\frac{\bar{d}}{d} \right)^2 \cos \theta_s$$

Average daily insolation (function of latitude and season):

$$\overline{Q}^{\text{day}} = \frac{S_0}{\pi} \left(\frac{\bar{d}}{d} \right)^2 \left[h_0 \sin\phi \sin\delta + \cos\phi \cos\delta \sin h_0 \right]$$