EMS717U/EMS717P

Renewable Energy Sources

Solar Energy

Content

- **Effect of greenhouse gases**
- **Air mass**
- **Estimation of solar irradiance at the top of atmosphere**
- **Estimation of solar irradiance at the Earth's surface**

Introduction to Solar Energy – Solar Irradiation

<u>Overveiw:</u>

1. Nature of solar radiation
2. Effect of Earth's atmosphere – greenhouse effect
3. Estimation of solar irradiance at the top of atmosphere

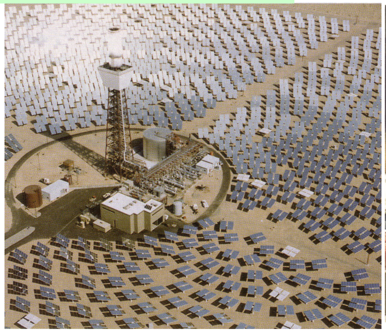
    Example problem 1

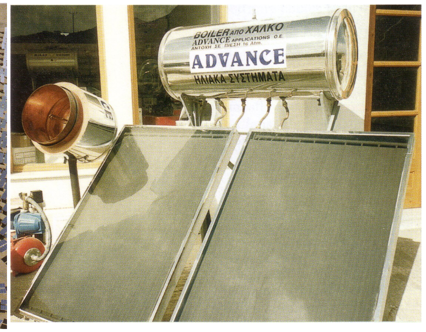
4. Quantifying atmospheric effects
5. Solar irradiance at Earth's surface
6. Irradiance on inclined surfaces

    Example problem 2

Solar Energy Capture

Solar thermal systems – capturing the sun’s heat. Applications include simple hot water and domestic space heating and solar engines for electricity generation





Solar Photovoltaics – conversion of sun’s energy to electricity. Can be local small scale installations to large scale plants

Solar Photovoltaics/Thermal – Use of thermal energy to reduce the panel temperature to increase electrical conversion efficiency

Biomass and biofuels – capture of sun’s energy as organic matter. Subsequent processing can produce liquid fuels such as biodiesel for automotive and energy production applications

Note - Design of any solar energy system relies on careful assessment of available solar radiation at the site

Solar radiation and greenhouse effect

1. Nature of Solar Radiation

Particle-wave duality:

1905 – Einstein proposed that light consisted of discrete particles or quanta of energy, described by

$$E = hf = \frac{hc}{\lambda} \qquad (1)$$

where light, of frequency f or wavelength λ, occurs in photon of energy E.

h is Plank's constant (6.626×10^{-34} Js) and c is the speed of light (3×10^{8} m/s)

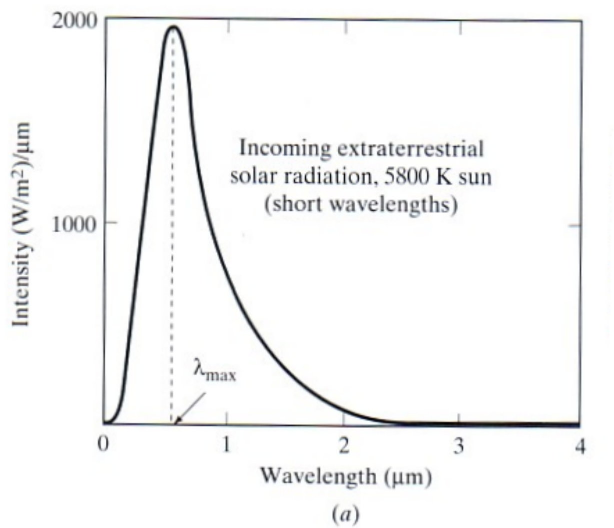
Note: In considering the design characteristics and performance of solar installations, such as photovoltaic panels and solar thermal hot water heaters, light is sometimes treated as waves and other times as photons

'Blackbody' radiation:

A 'Blackbody' – defined as an ideal absorber and emitter of radiation.

As material is heated and temperature increases it emits radiation of higher energy/shorter wavelength

The emitted radiation from the sun can be approximated to a 'blackbody' at 5800 K



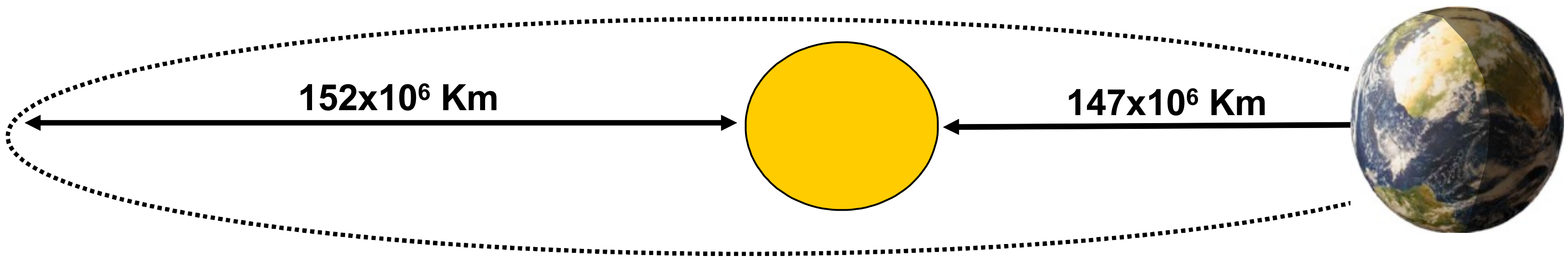
Source: Masters, G., Introduction to Environmental Engineering

Intensity of Radiation - The Solar Constant

The level of radiation emitted from the surface of the sun is fairly constant and at the distance of the Earth has a mean value of I_{SC} = 1370 W/m^2

Variation due to Earth-Sun distance:

The actual amount reaching Earth does vary due to eccentricity in the Earth's orbit



The extraterrestrial radiation flux can be predicted from

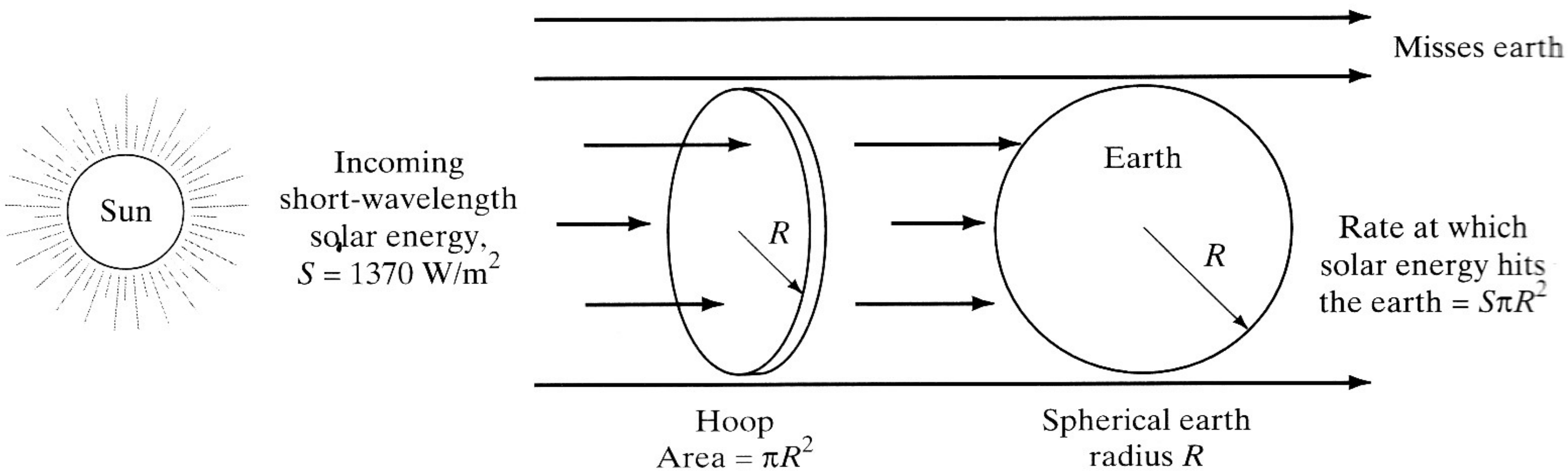
$$I_o \equiv I_{SC}\left[1 + 0.033\mathrm{Cos}\left(\frac{360 d_n}{370}\right)\right] \qquad (2)$$

where d_n is the day number (Jan 1st = 1 and Dec 31st = 365)

The result is that Jan is ~3.5% higher than *I*sc and June ~3.5% lower

Intensity of Radiation – Estimation for Earth

For the spherical body of Earth we can estimate the average amount of radiation available



Surface area of sphere is 4πR², therefore

Earth's collected solar energy = $\dfrac{S\pi R^2}{4\pi R^2} = \dfrac{S}{4} = 342\left(\text{W/m}^2\right)$

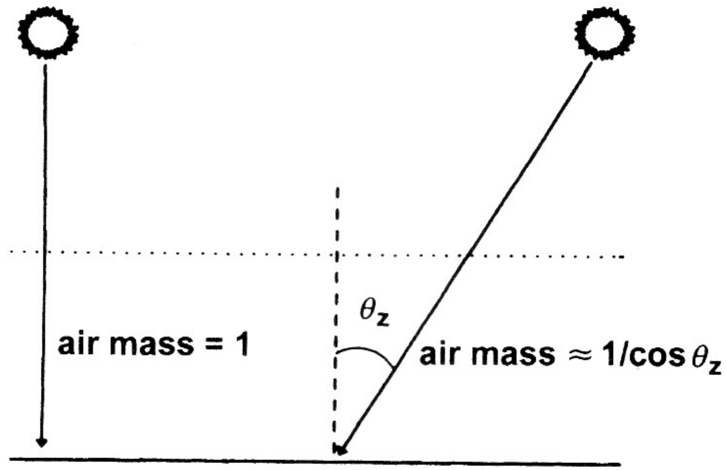
Solar Radiation – Air Mass

<u>What happens to the radiation as it passes through the atmosphere</u>

On a clear day maximum radiation reaches the Earth's surface when the Sun is directly overhead – when it travels the shortest distance through atmosphere

This condition corresponds to an *Air Mass* (AM) = 1.

Standard test condition of solar cells is specified as **AM1.5** which would be the spectral power distribution when the sun has a zenith angle of 48.2º.



The AM can also be estimated at any location using the formula

$$AM = \sqrt{1 + \left(\frac{s}{h}\right)^2} \qquad (3)$$

where *s* is the length of shadow cast by a vertical post of height *h*.

What about extraterrestrial AM value?

Solar Radiation – Air Mass

<u>What happens to the radiation as it passes through the atmosphere?</u>

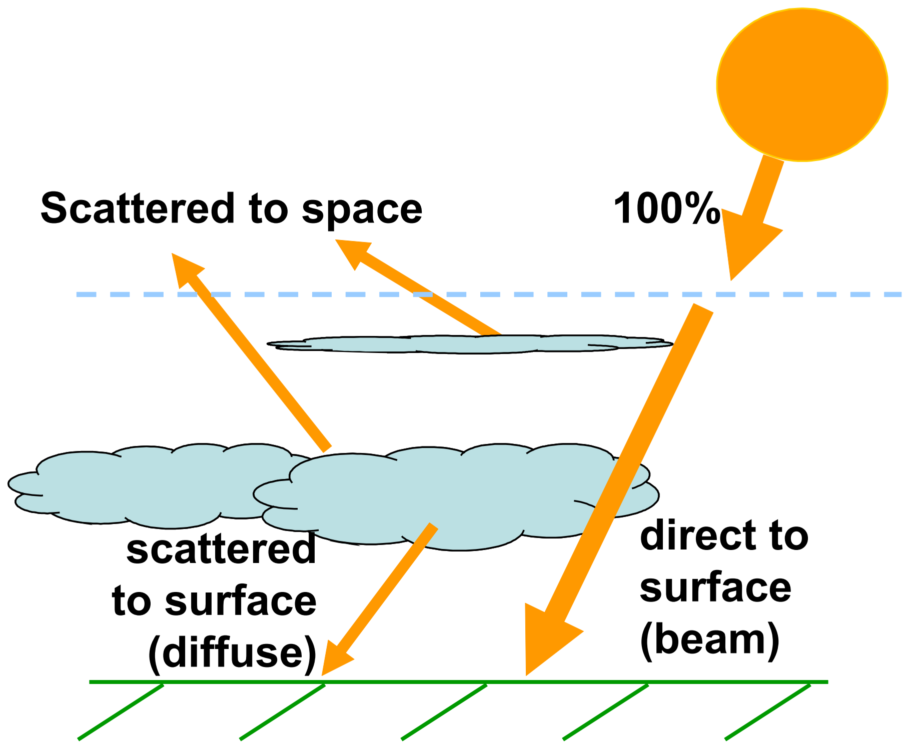
It is attenuated by particles, vapours and gases in the Earth's atmosphere due to the following effects

1. Rayleigh scattering by molecules in the atmosphere
2. Scattering by aerosols and dust particles
3. Absorption by atmospheric gases such as oxygen, ozone, water vapour and carbon dioxide.

The first two effects cause a proportion of the incoming solar radiation to be scattered either back into space or to eventually reach the Earth's surface – known as diffuse radiation

Radiation reaching the surface directly is called direct or **<u>beam radiation</u>**, *B*

Scattered radiation that reaches the ground is called **<u>diffuse radiation</u>**, *D*

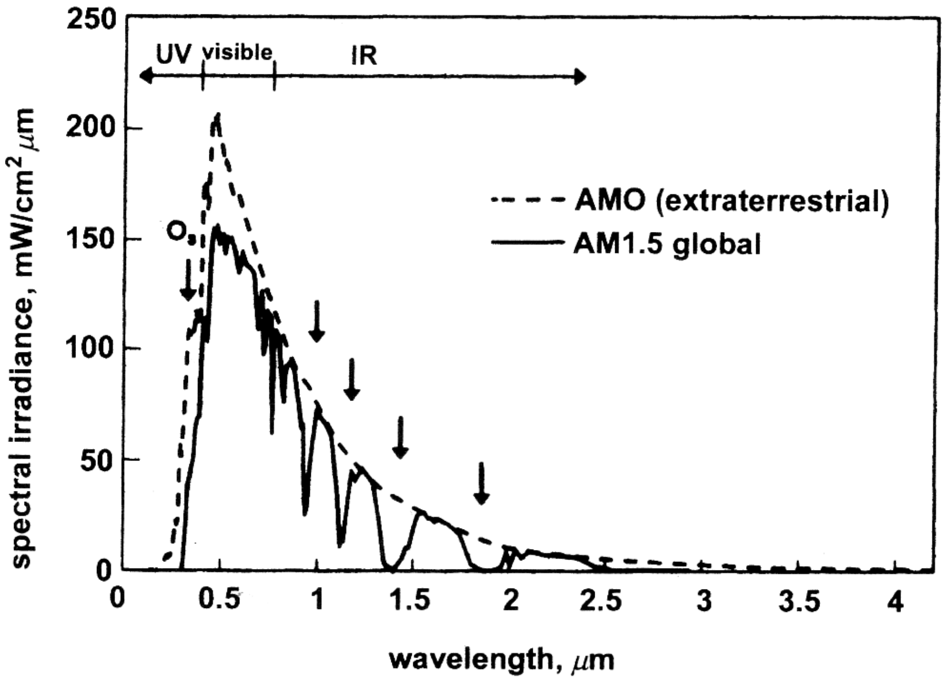


Solar Radiation – Air Mass

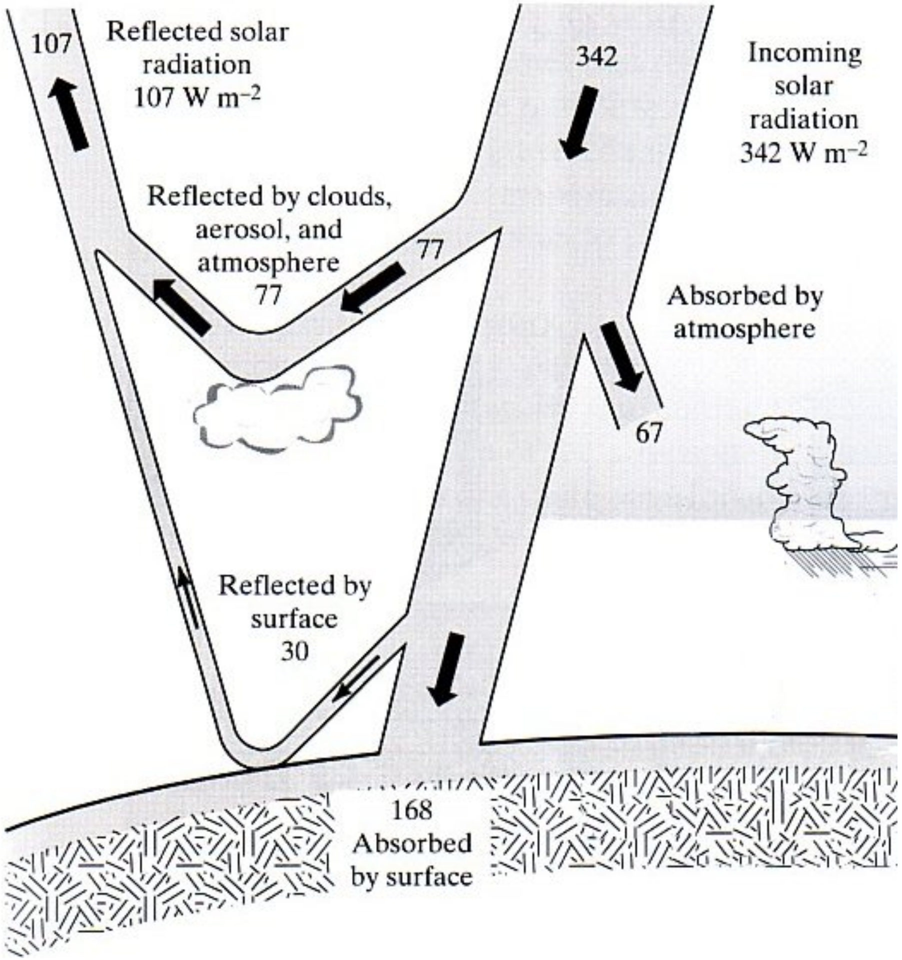
<u>What happens to the radiation as it passes through the atmosphere?</u>

The absorption by atmospheric gases varies with wavelength.

Most significant for life on Earth is the strong absorption of short wavelength/high energy UV (ultraviolet) radiation by ozone.



Earth Energy Balance



Earth's Energy Balance:-

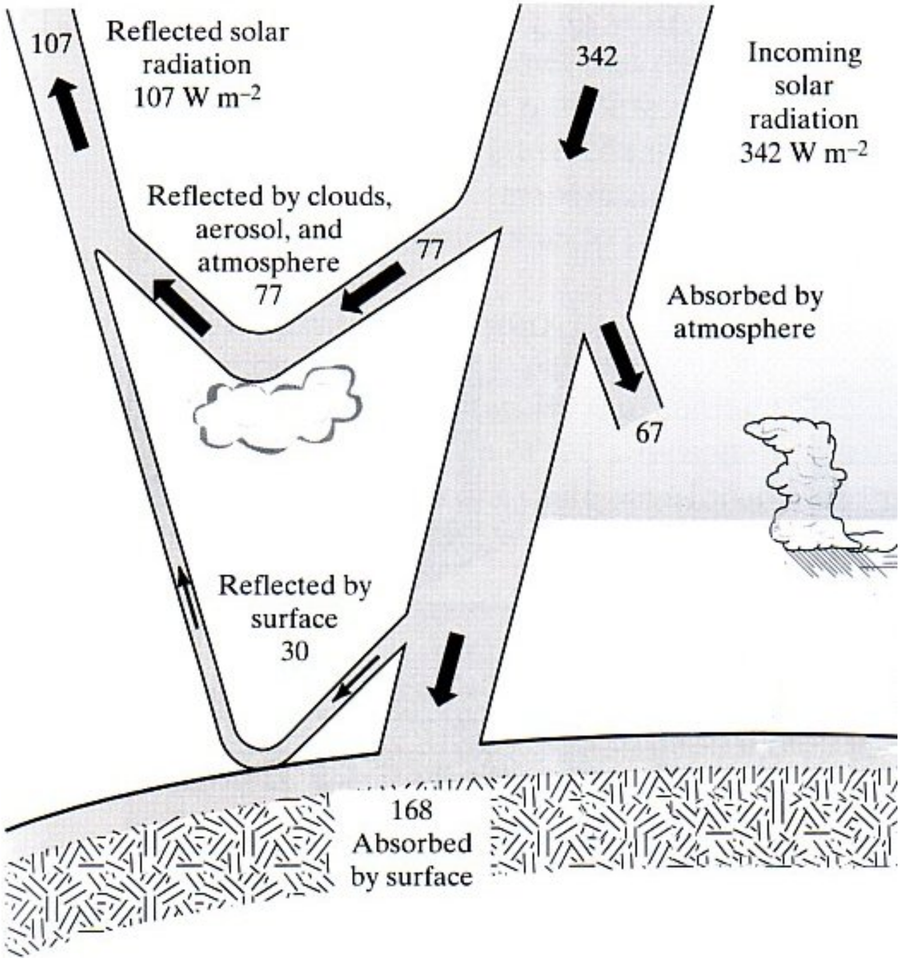
342 W/m^2 = (77 + 30) W/m^2 + 235 W/m^2

Total Incident — Reflected — Absorbed

$$Q_{abs} = \frac{S\pi R^2(1-\alpha)}{4\pi R^2} = 235\ \text{W/m}^2$$

where α is the Earth's albedo, currently assumed to have a value of 0.31.

Earth Energy Balance



Assuming steady-state conditions

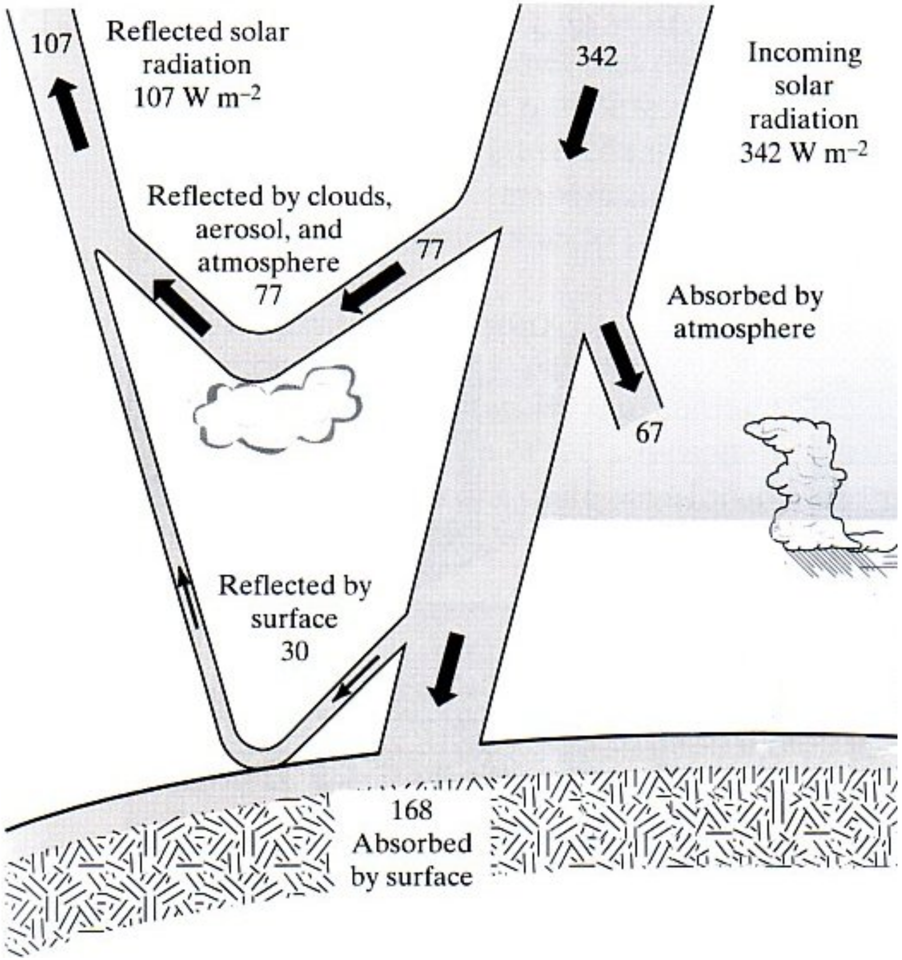
$$S\pi R^2(1-\alpha) = \sigma 4\pi R^2 T_e^4$$

where σ is the Stefan-Boltzmann constant
$\sigma = 5.67 \times 10^{-8}$ W/m^2.K^4

solving to find the Earth's "effective" black body temperature T_e,

$$T_e = \left[\frac{S\pi R^2(1-\alpha)}{4\pi R^2\sigma}\right]^{0.25} = \left[\frac{S(1-\alpha)}{4\sigma}\right]^{0.25}$$

Earth Energy Balance



solving to find the Earth's "effective" black body temperature T_e,

$$T_e = \left[\frac{S\pi R^2(1-\alpha)}{4\pi R^2\sigma}\right]^{0.25} = \left[\frac{S(1-\alpha)}{4\sigma}\right]^{0.25}$$

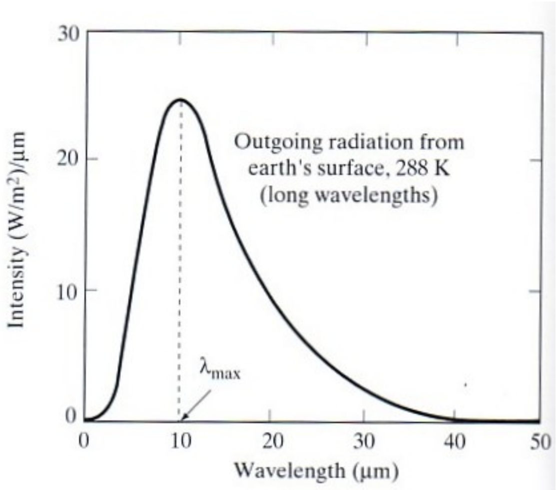
Therefore, $T_e = \left[\frac{1370\ \mathrm{Wm^{-2}}\,(1-0.31)}{4\times5.67\times10^{-8}\ \mathrm{Wm^{-2}K^{-4}}}\right]^{0.25}$

Therefore, T_e = 254 K = -19 ^{o}C

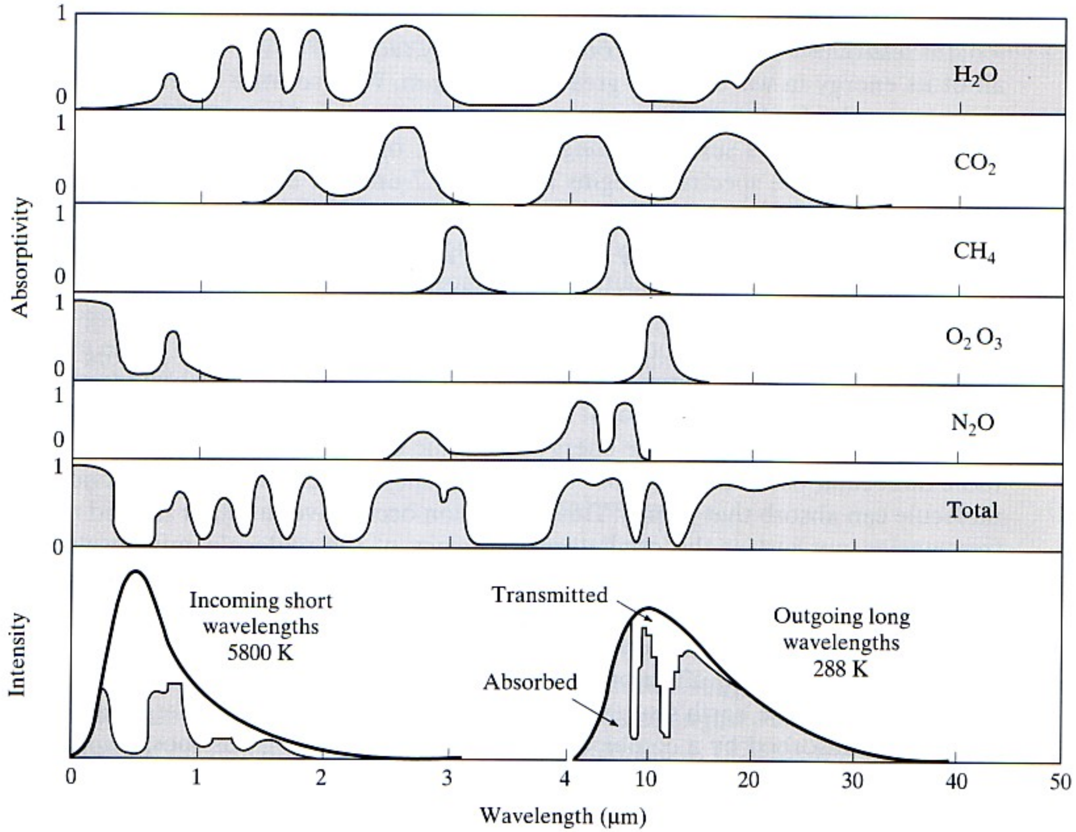
Earth Energy Balance – Greenhouse Effect

The Earth emits it's own radiation but due to the much lower temperature (relative to that of the Sun) of 288K the radiation is lower energy/longer wavelength infra-red radiation.

A number of gases and vapours in the atmosphere absorb this emitted radiation before it reaches space – these are known as greenhouse gases

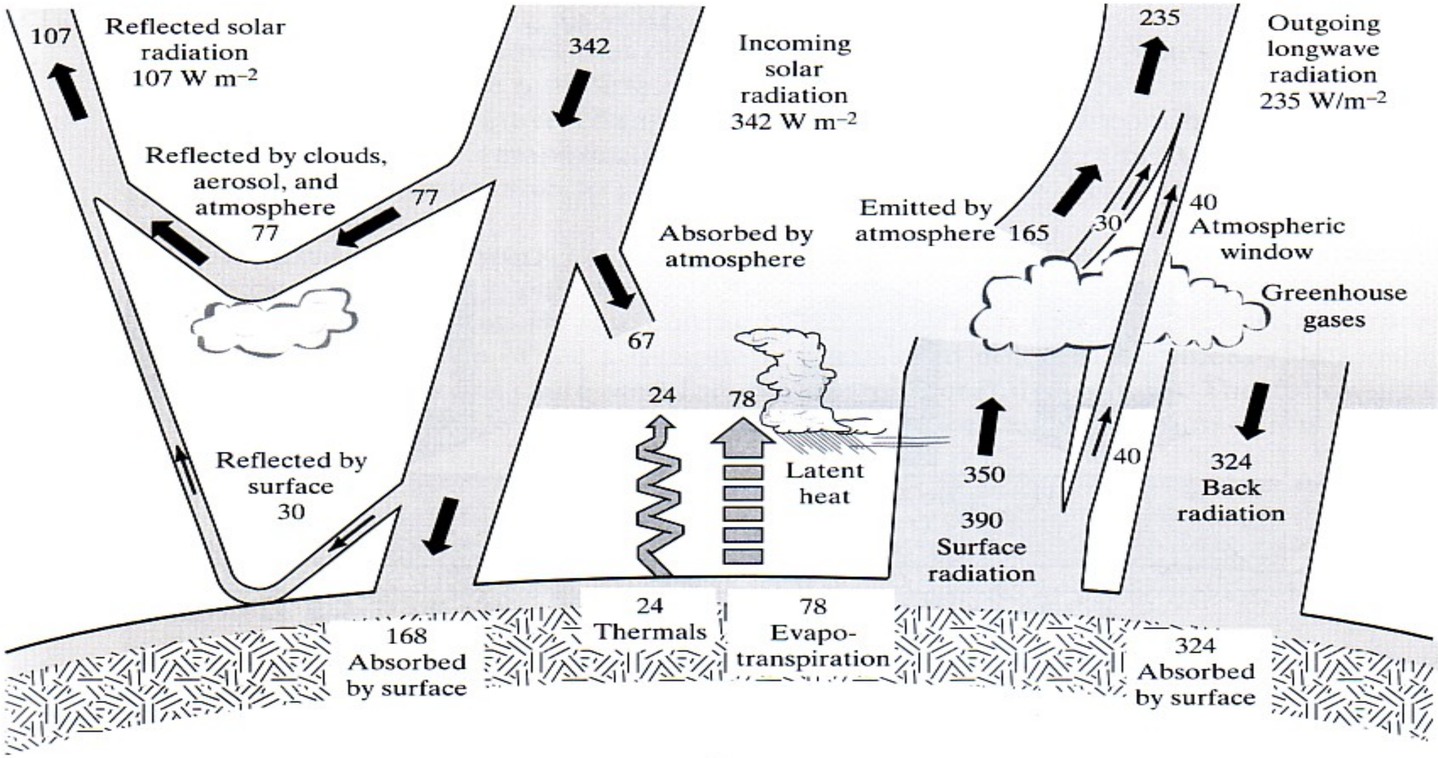


Black body radiation at 288 K has a maximum at 10 µm.



Absorptivity as a function of wavelength for most significant gases in atmosphere

Earth Energy Balance – With Greenhouse Effect

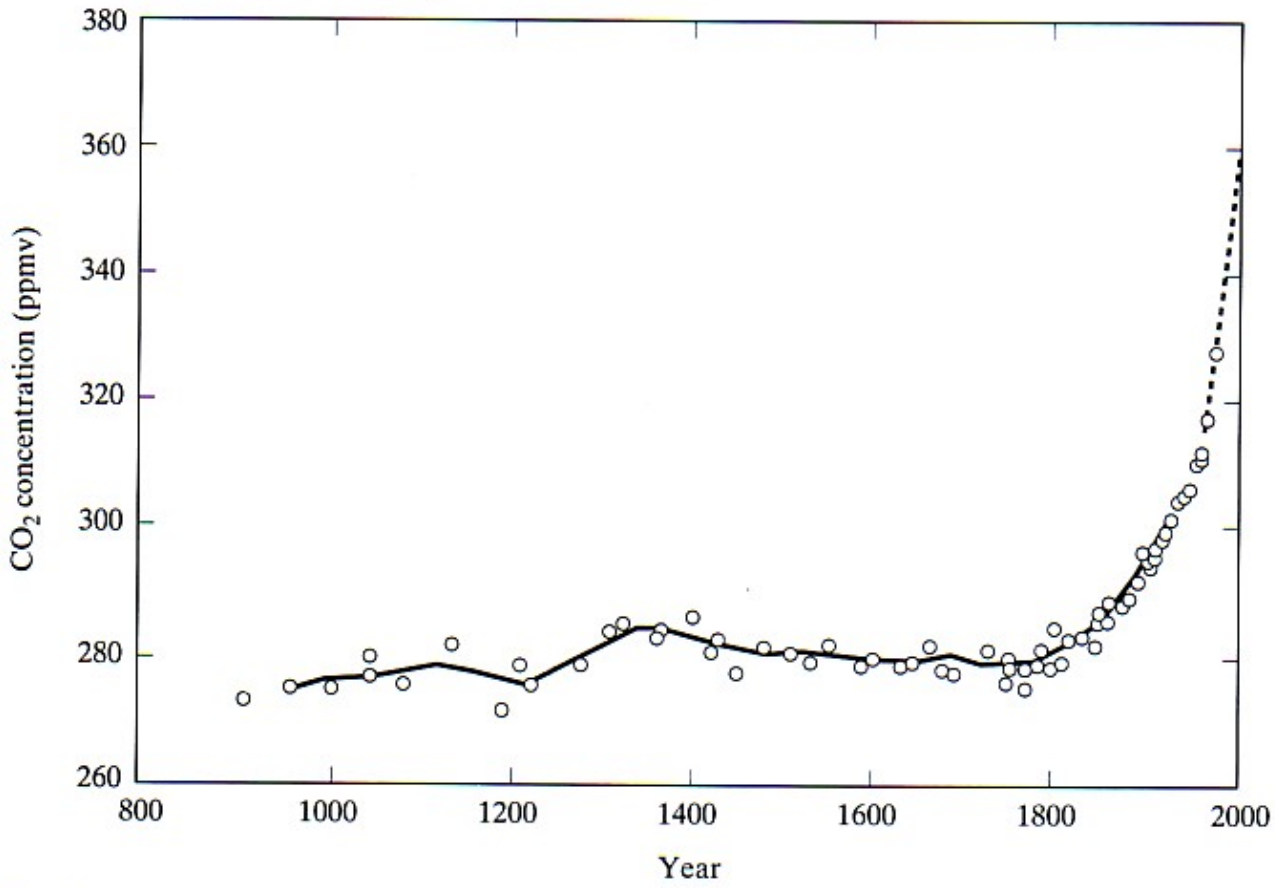


Global average energy flows between space, the atmosphere, and the earth's surface

Planet	Distance to sun (10^6 km)	Atmosphere pressure (atm)	Solar constant $S(\mathrm{W/m^2})$	Albedo α (%)	Effective temperature T_e (K)	Surface temperature T_s (K)	Greenhouse warming (°C)
Venus	108	90	2620	76	229	750	521
Earth	150	1	1370	31	254	288	34
Mars	228	0.006	589	25	210	218	8

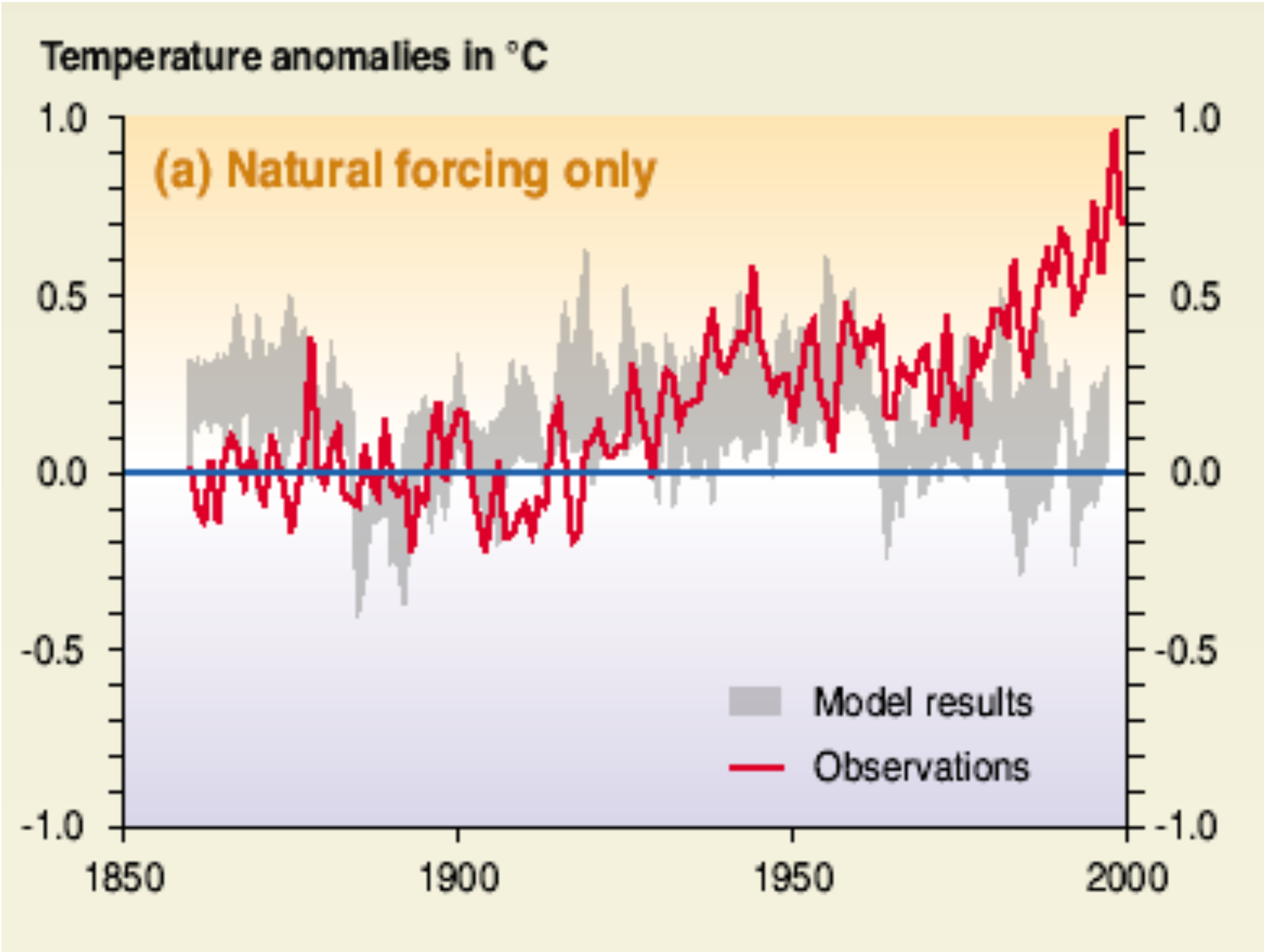
Note: Mars, with little atmosphere, shows almost no greenhouse effect, while on Venus it is quite pronounced.
Source: Hoffert, 1992

Carbon dioxide (CO_2) – the story so far



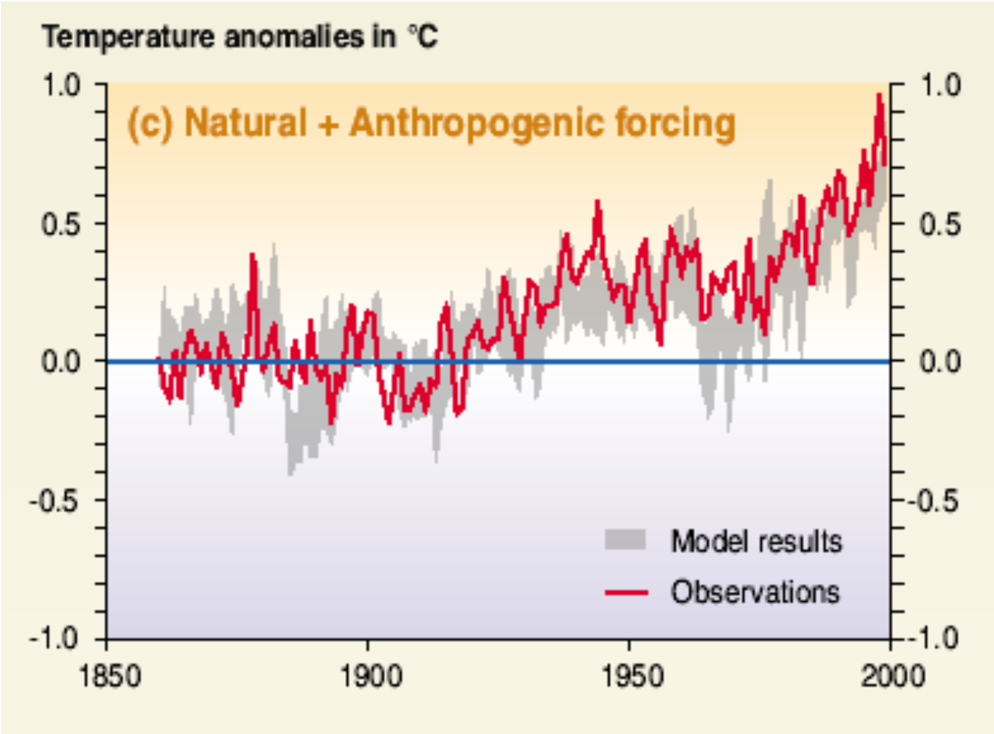
Combined ice core data and direct measurements of carbon dioxide concentration over past 1000 years

Evidence for human induced climate change



Comparison between modeled and observed temperature changes since 1860 - natural forcing only. (Source: IPCC 2001)

Evidence for human induced climate change – cont.

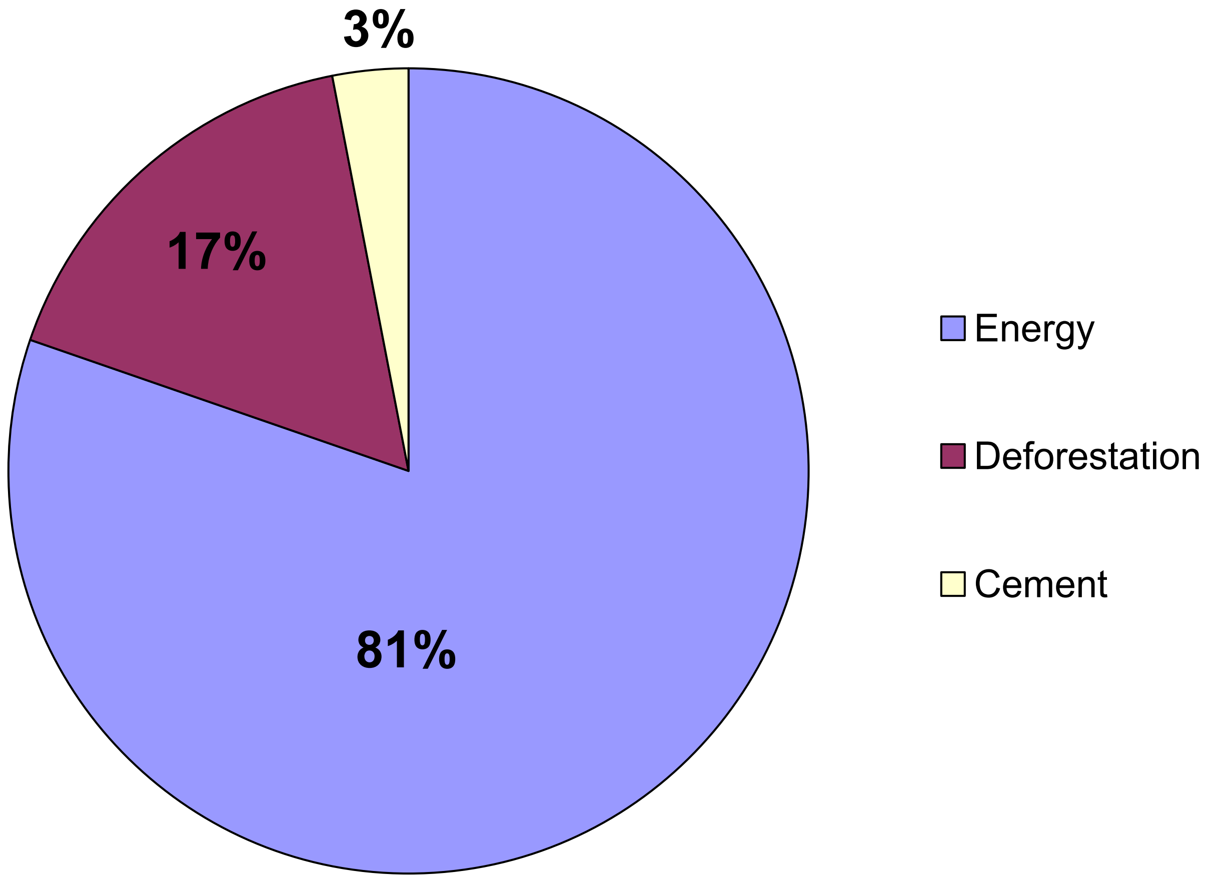


Comparison between modeled and observed temperature changes since 1860 - combined forcing

Conclusions

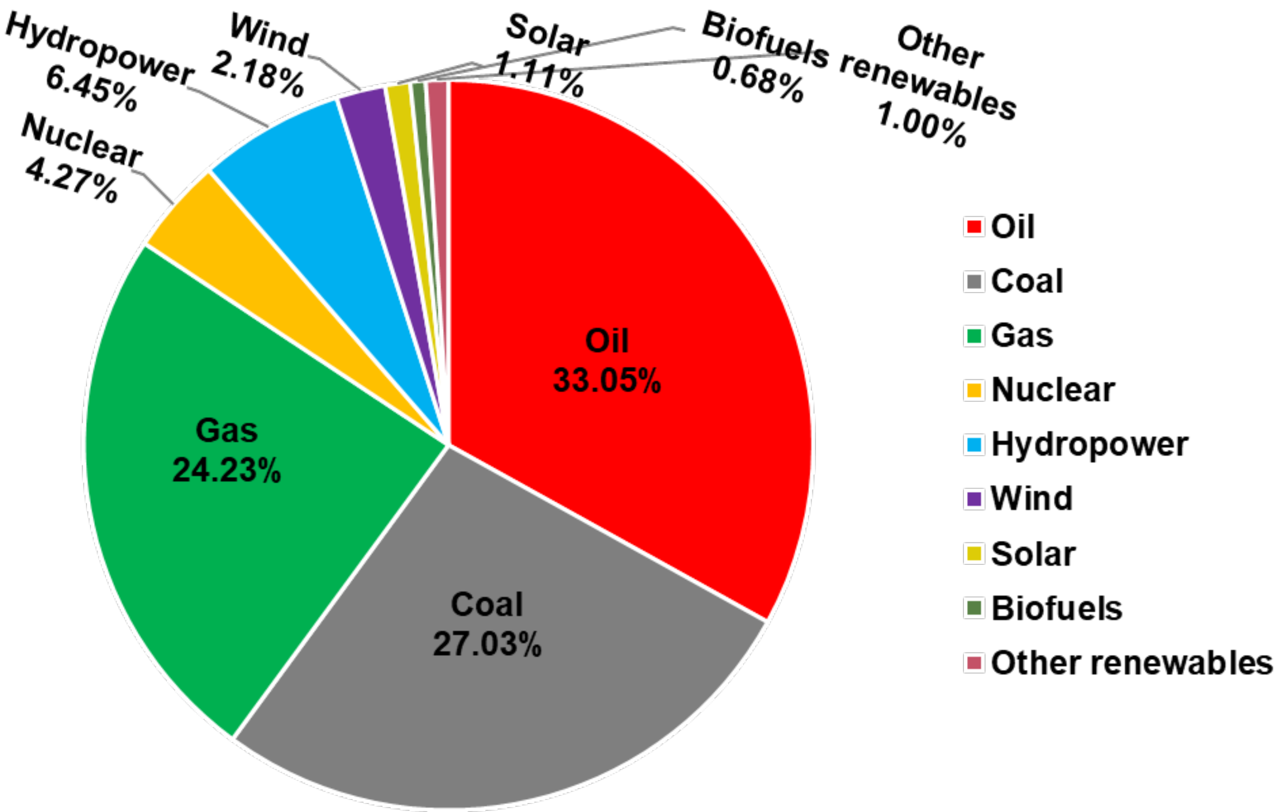
- Inclusion of anthropogenic forcings provides a plausible explanation for a substantial part of the temperature changes over the past century
- Strong evidence for human induced climate change

Man's Influence on the Environment



Anthropogenic Carbon dioxide emissions from differing sources

Energy Sources to Meet Global Demand

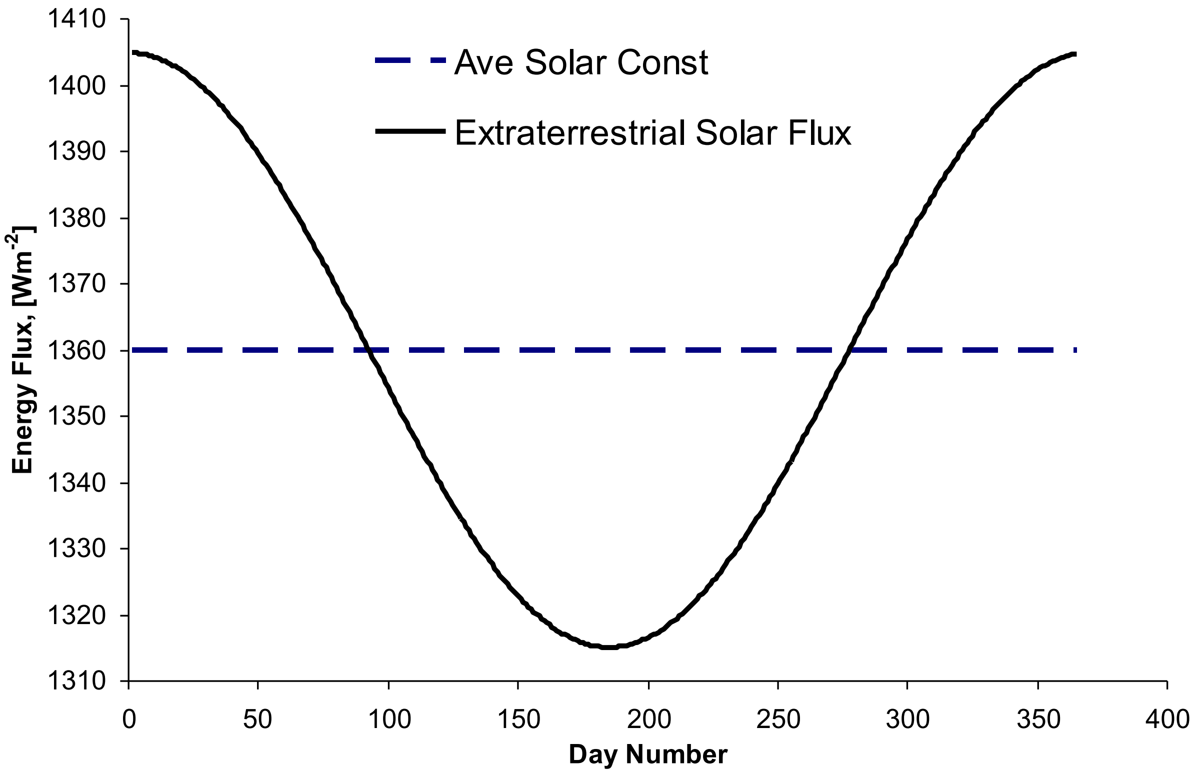


Percentage contributions of different energy sources to global primary energy consumption in 2019

Estimation of solar irradiance at the top of atmosphere

Variation Due to Earth-Sun Distance

$$I_o \equiv I_{SC}\left[1 + 0.033\mathrm{Cos}\left(\frac{360 d_n}{370}\right)\right]$$



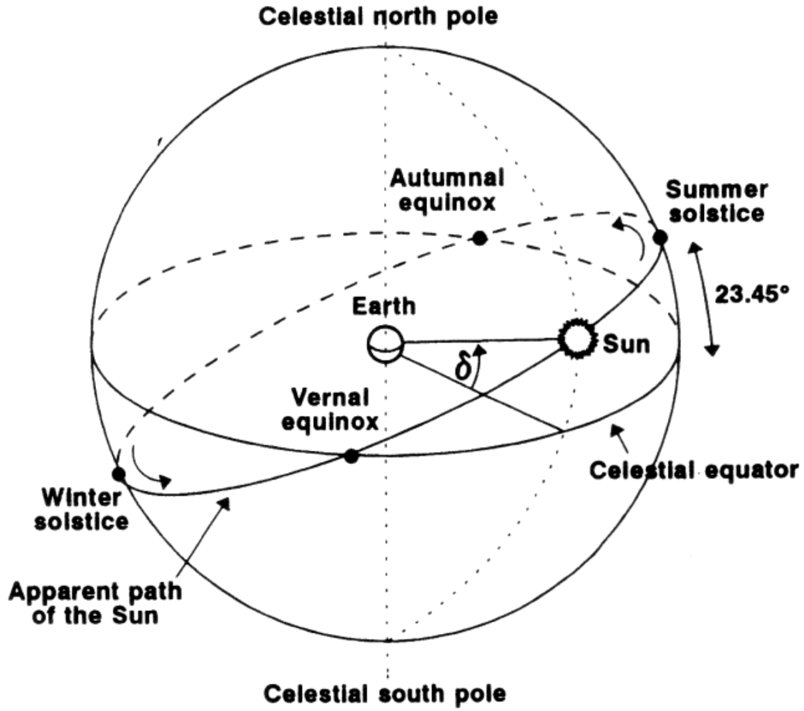
Variation Due to Seasonal Declination

More significant change in apparent extraterrestrial radiation due to seasonal variation in daily sun's path through sky. This is due to inclination of the Earth's axis of rotation of 23.45º to the plane normal to the Earth's orbit around the sun

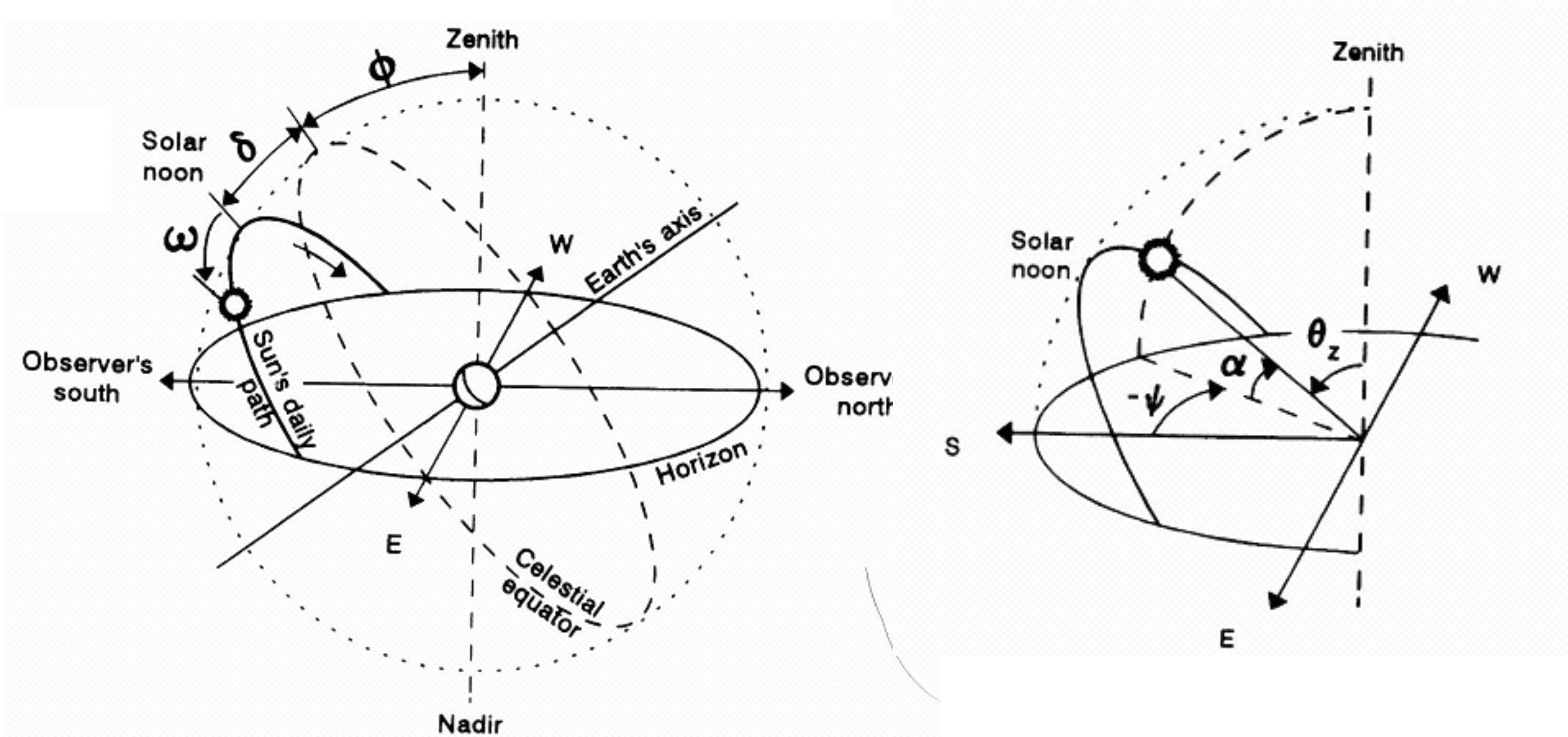
Due to this all regions, especially the poles, receive more light in the summer than the winter

Declination angle (in degrees) can be calculated by

$$\delta \equiv 23.45^{\circ} \sin\left[\left(\frac{d_n - 80}{370}\right) \times 360\right] \qquad (4)$$



Variation Due to Daily Motion of Sun



Solar elevation α or zenith angle θ_Z,

$$\sin\alpha \equiv \sin\delta \sin\phi + \cos\delta \cos\phi \cos\omega \equiv \cos\theta_Z \qquad (5)$$

where ω is the suns hour angle (zero at solar noon)

Variation Due to Daily Motion of Sun

Solar elevation α or zenith angle θ_Z,

$$\sin\alpha \equiv \sin\delta\sin\phi + \cos\delta\cos\phi\cos\omega \equiv \cos\theta_Z$$

Solar Azimuth

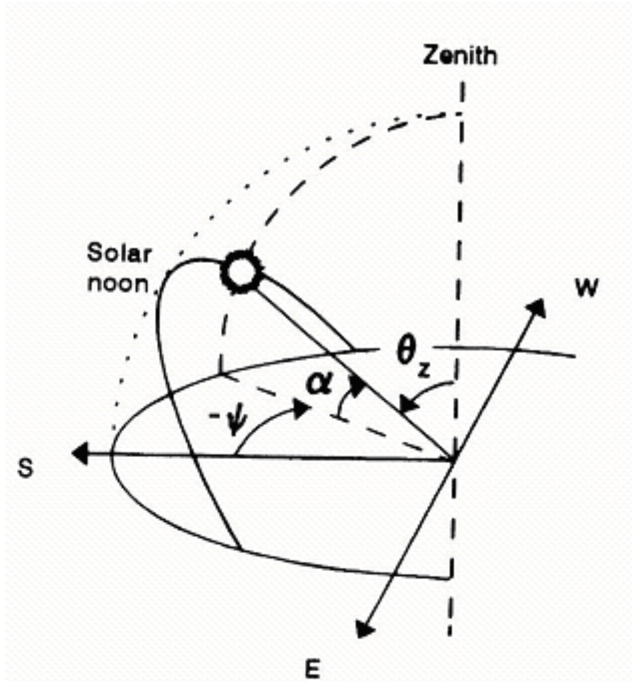
$$\cos\psi \equiv \frac{(\sin\alpha\sin\phi - \sin\delta)}{\cos\alpha\cos\phi} \qquad (6)$$

These equations can be used to determine the sunrise and sunset hour angle ω_s,

$$\omega_s \equiv \cos^{-1}(-\tan\phi\tan\delta) \qquad (7)$$

where ω_s is negative for sunrise and positive for sunset

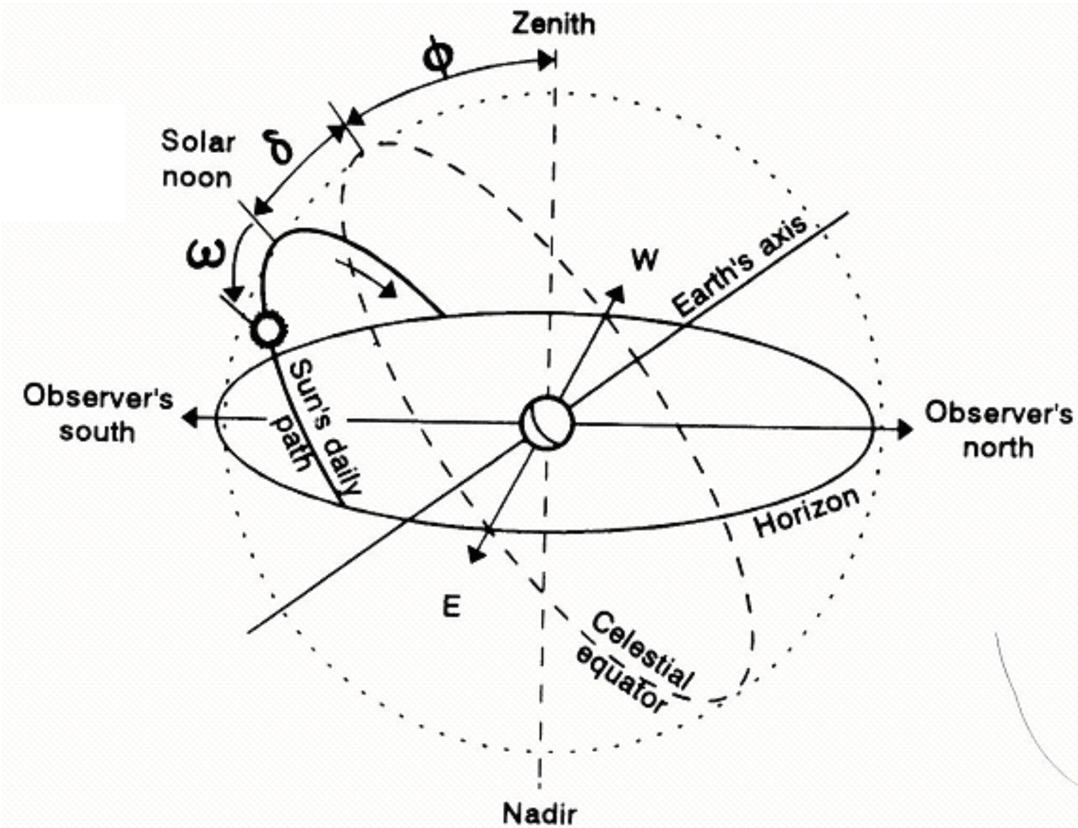
To convert ω_s into hours from solar noon multiply by ±24/360



Extraterrestrial Irradiation Dependence

Solar extraterrestrial radiation falling on a horizontal area at the top of the atmosphere can be calculated from

$$H_o \equiv I_o\left(\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta\right) \qquad (8)$$



Example problem

Example Solution

For 10 A.M. on the 21st Nov (day 325) at a latitude 40ºN

(a) Find the sun's altitude, sunset angle and the length of the solar day

First find the hour angle at -2 hours from solar noon

$$\omega \equiv -2 \times \frac{360}{24} \equiv -30^{o}$$

Then calculate the solar declination angle

$$\delta \equiv 23.45^{\circ} \sin\left[\left(\frac{325-80}{370}\right) \times 360\right] \equiv -20^{\circ}$$

Example Solution

For 10 A.M. on the 21st Nov (day 325) at a latitude 40ºN

(a) Find the sun's altitude, sunset angle and the length of the solar day

The solar altitude can now be found using

$$\sin\alpha \equiv \sin\delta\sin\phi + \cos\delta\cos\phi\cos\omega$$

Substituting values gives

$$\sin\alpha \equiv \sin(-20^\circ)\sin(40^\circ) + \cos(-20^\circ)\cos(40^\circ)\cos(-30^\circ) \equiv 0.404$$

Therefore the altitude α = 23.8º

Example Solution

For 10 A.M. on the 21st Nov (day 325) at a latitude 40ºN

(a) Find the sun's altitude, sunset angle and the length of the solar day

The solar altitude can now be found using

$$\sin\alpha \equiv \sin\delta \sin\phi + \cos\delta \cos\phi \cos\omega$$

Substituting values gives

$$\sin\alpha \equiv \sin(-20°)\sin(40°) + \cos(-20°)\cos(40°)\cos(-30°) \equiv 0.404$$

Therefore the altitude α = 23.8º and the sunset angle is

$$\omega_s \equiv \cos^{-1}\left(-\tan(40°)\tan(-20°)\right) \equiv 72.22°$$

Example Solution

For 10 A.M. on the 21st Nov (day 325) at a latitude 40ºN

(a) Find the sun's altitude, sunset angle and the length of the solar day

The length of the solar day can now be found by converting the sunset angle into hours from solar noon using

$$\omega_s \equiv \frac{\pm 24}{360} \times \omega_s \equiv \pm 4.81 \text{ hr}$$

So the length of the solar day is 2 x 4.81 = 9.62 hr

(b) Now find the extraterrestrial irradiance falling on the horizontal area outside the atmosphere at 10 A.M.

Example Solution

For 10 A.M. on the 21st Nov (day 325) at a latitude 40ºN

We have shown that the solar declination δ is -20º and the hour angle ω is -30º

(b) Now find the extraterrestrial irradiance falling on the horizontal area outside the atmosphere at 10 A.M.

First find the value of solar constant on day 325 from

$$I_o \equiv I_{SC}\left[1+0.033\text{Cos}\left(\frac{360 d_n}{370}\right)\right]$$

Using a value of 1370 Wm^{-2} for I_{sc} we have

$$I_o \equiv 1370\left[1+0.033\text{Cos}\left(\frac{360\times 325}{370}\right)\right] \equiv 1392 \text{ Wm}^{-2}$$

Example Solution

For 10 A.M. on the 21st Nov (day 325) at a latitude 40ºN

We have shown that the solar declination δ is -20º and the hour angle ω is -30º

(b) Now find the extraterrestrial irradiance falling on the horizontal area outside the atmosphere at 10 A.M.

We now find the radiation flux on the horizontal surface from

$$H_o \equiv I_o\left(\cos\phi\cos\delta\cos\omega+\sin\phi\sin\delta\right)$$

Therefore

$$H_o \equiv 1392\left(\cos\left(40°\right)\cos\left(-20°\right)\cos\left(-30°\right)+\sin\left(40°\right)\sin\left(-20°\right)\right)\equiv 562\ \mathrm{Wm}^{-2}$$

Variation in Extraterrestrial Radiation

The total daily extraterrestrial radiation intercepted by a horizontal area can be determined by integration of the above equation over the solar day to give

$$H_{\mathrm{ot}} \equiv \frac{I_{o(\text{daily sum})}}{\pi}\left[\cos\varphi\cos\delta\sin\omega_s + \left(\frac{2\pi\omega_s}{360}\right)\sin\varphi\sin\delta\right] \qquad (9)$$

where $I_{o(dailysum)}$ is the total direct normal extraterrestrial radiation for the day where

$$I_{o(\text{daily sum})} \equiv 24 \times I_o\left(\mathrm{W.hr.m^{-2}}\right) \equiv 24 \times 0.0036 \times I_o\left(\mathrm{MJ.m^{-2}}\right)$$

Example Solution

Now we can calculate the total extraterrestrial radiation received on the 21st Nov (day 325) at a latitude 40ºN

We have shown that the solar declination δ is -20º and a value of I_o of 1392Wm^{-2}

Firstly

$$I_{o(\text{daily sum})} \equiv 24 \times 0.0036 \times 1392 \equiv 120\left(\text{MJm}^{-2}\right)$$

Then we can calculate daily total radiation

$$H_{ot} \equiv \frac{120}{\pi}\left[\cos(40°)\cos(-20°)\sin(72.22°) + \left(\frac{2\pi 72.22°}{360}\right)\sin(40°)\sin(-20°)\right]$$

So

$$H_{ot} \equiv 15.60\left(\text{MJm}^{-2}\right)$$

Monthly Typical Days Average Radiation Data

More common to calculate monthly average data and use in conjunction with local meteorological weather records

Using the day of the month representing the average solar declination we can predict mean daily radiation levels available

So far we have considered only extraterrestrial radiation available so need to account for effect of atmosphere to predict irradiance at sea level

Date	Day Number (non-leap year)
17 Jan	17
15 Feb	46
17 Mar	76
15 Apr	105
15 May	135
11 Jun	162
18 Jul	199
17 Aug	229
15 Sep	258
15 Oct	288
14 Nov	318
12 Dec	346

Estimation of solar irradiance at Earth's surface

Introduction to Solar Energy

How much solar radiation reaches Earth's surface?

When solar radiation enters the atmosphere part is removed by scattering and absorption by air molecules, clouds and aerosols

Radiation reaching the surface directly is called direct or beam radiation, B

Scattered radiation that reaches the ground is called diffuse radiation, D

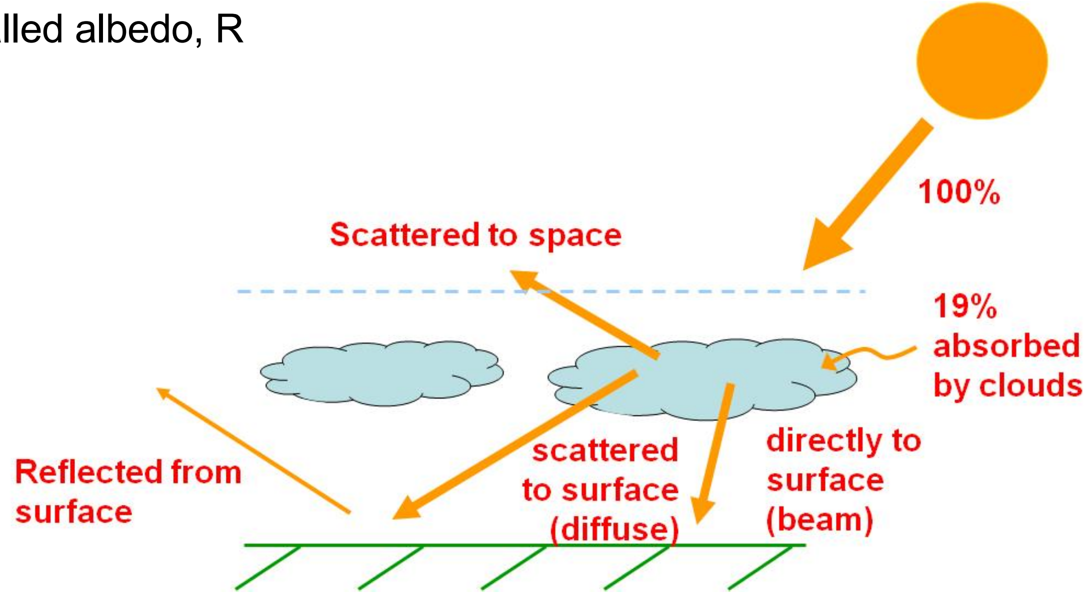
Reflected radiation reaching a collector is called albedo, R

The total radiation received is called the global radiation, G

∴Global, G = B + R + D

Global level is extremely variable due to regular daily and yearly apparent motion of sun but also due to irregular variations due to climatic conditions (cloud cover) and atmospheric composition

Therefore, performance prediction for solar thermal and photovoltaic systems rely on the input of measured data close to site of interest



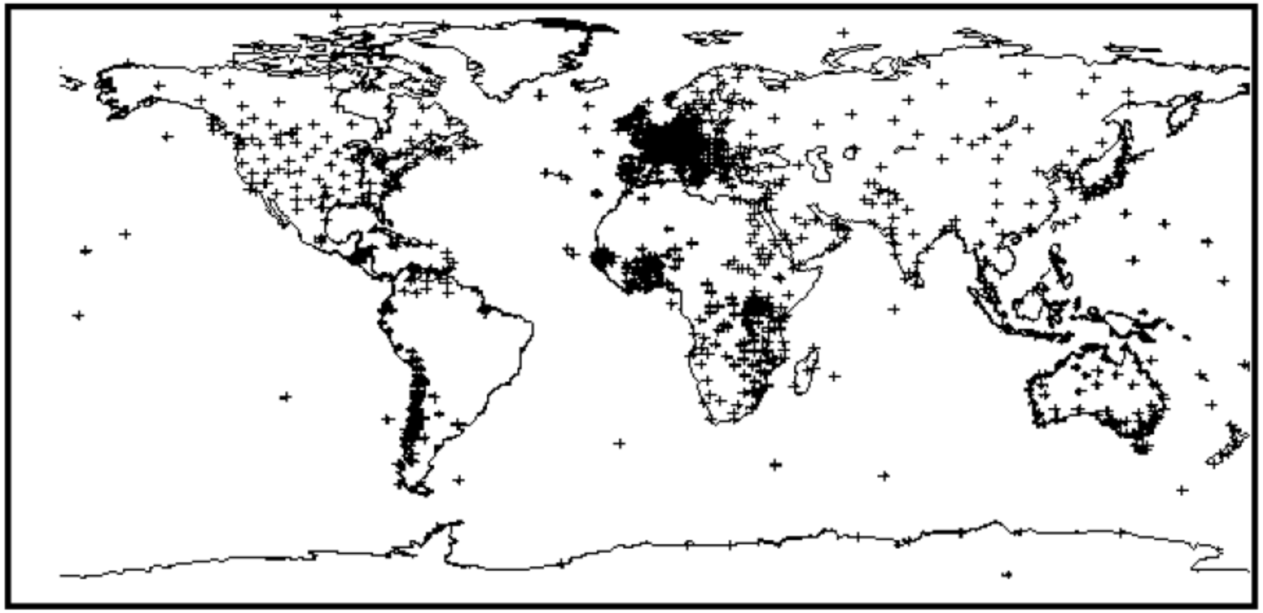
Effect of atmosphere on incoming solar irradiation

Introduction to Solar Energy

History of Solar Irradiance Data

- Solar radiation at ground level is a necessary input for performance modelling and sizing in PV and solar thermal systems
- Solar global irradiance measurements have been available from ground measurement stations since the mid 20^{th} century
- According to the World Meteorological Organisation (WMO) there were ~750 monitoring sites worldwide in 2002

- Very uneven distribution
- Very little oceanic data
- Are the data available close to site of interest?

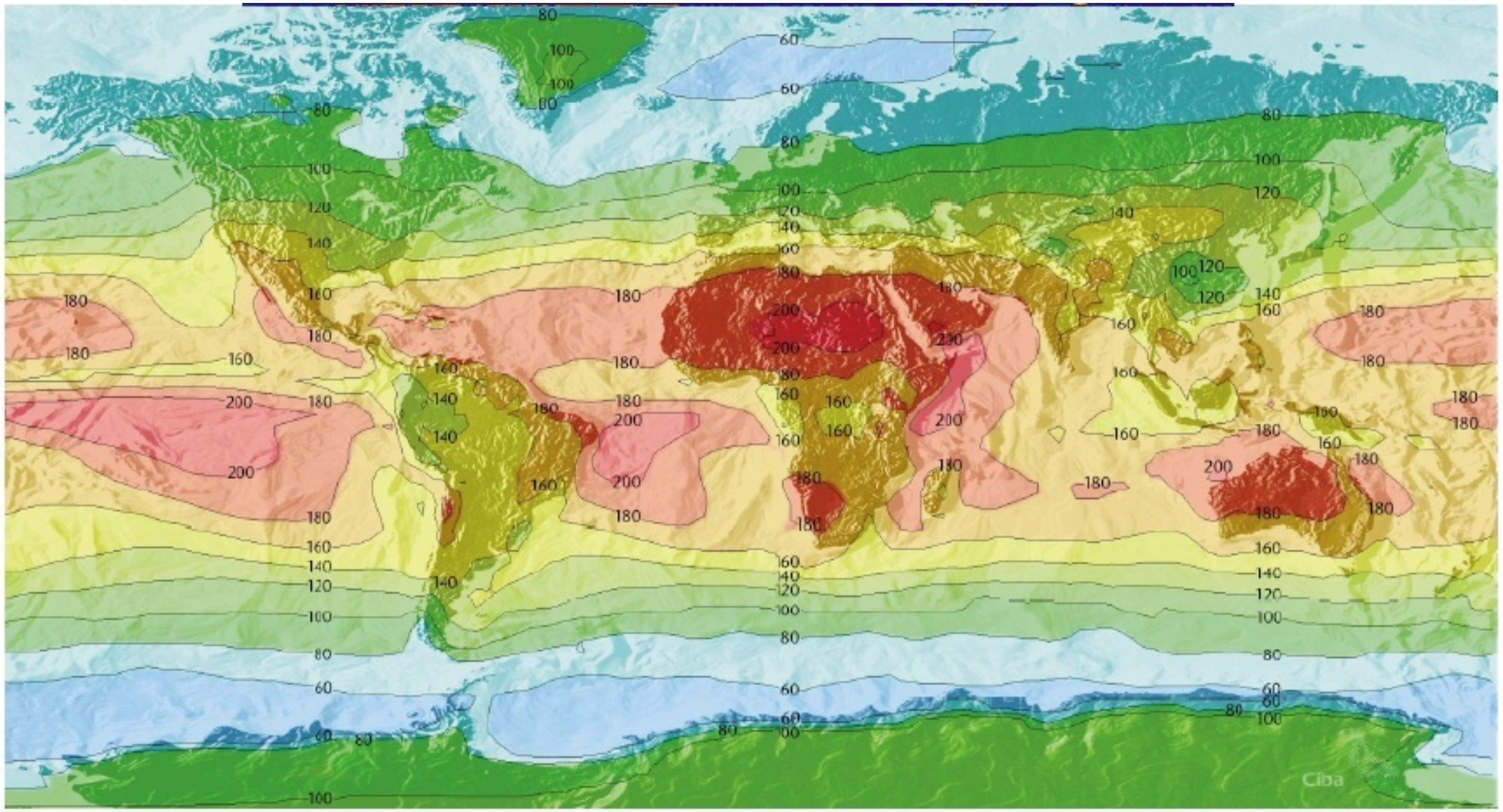


Solar global irradiance measurement stations (Source: WRDC/WMO)

Introduction to Solar Energy

History of Solar Irradiance Data – Satellite derived data

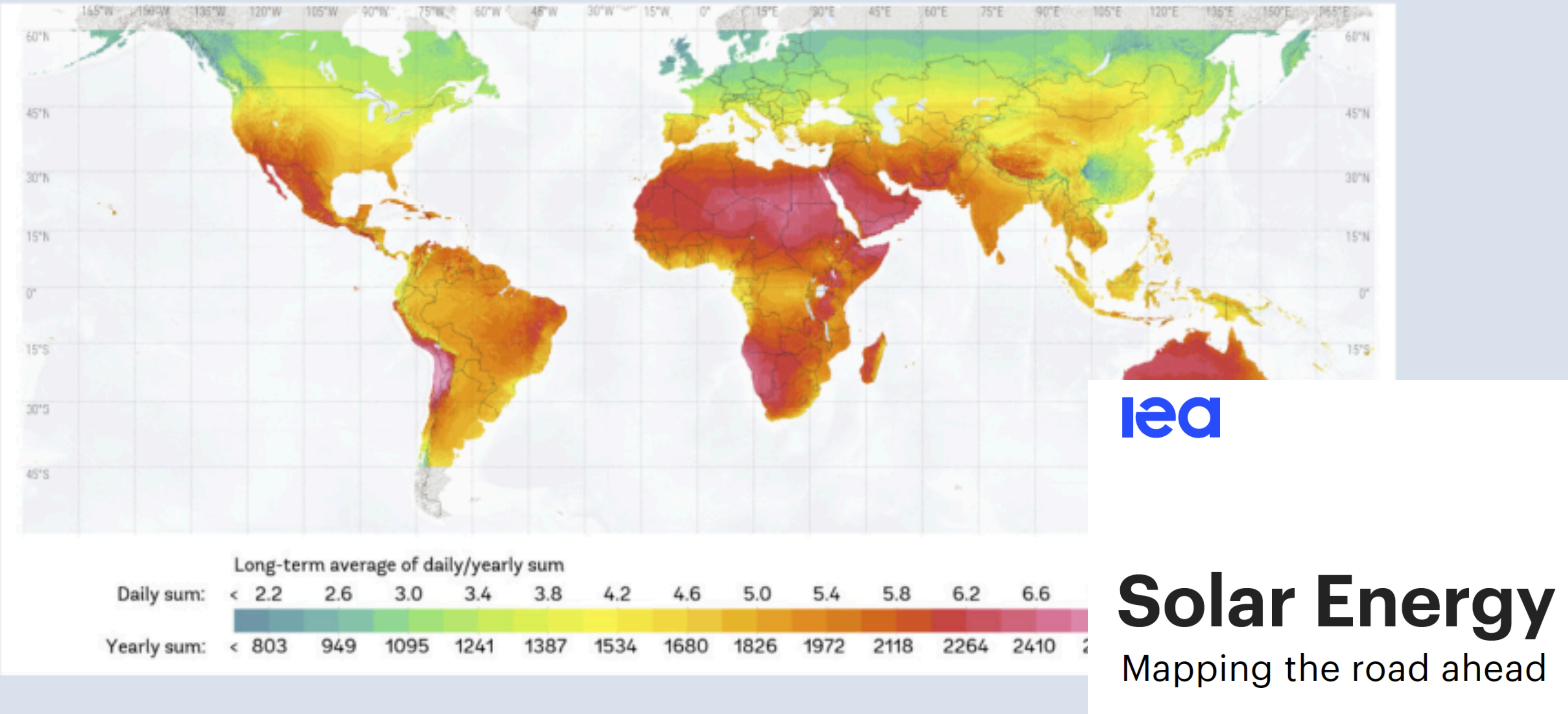
- For last 20 years there have been a large number of Earth observation satellites yielding surface irradiance data over broad areas
- Today, global irradiance levels are available over large geographic regions



Example worldwide average irradiance data from NASA Surface Radiation Budget (SRB) Project
Note: units are kLangley – need to multiply by 1.33 to convert to W/m^2

Solar energy – mapping the road ahead 2019

Global horizontal irradiance

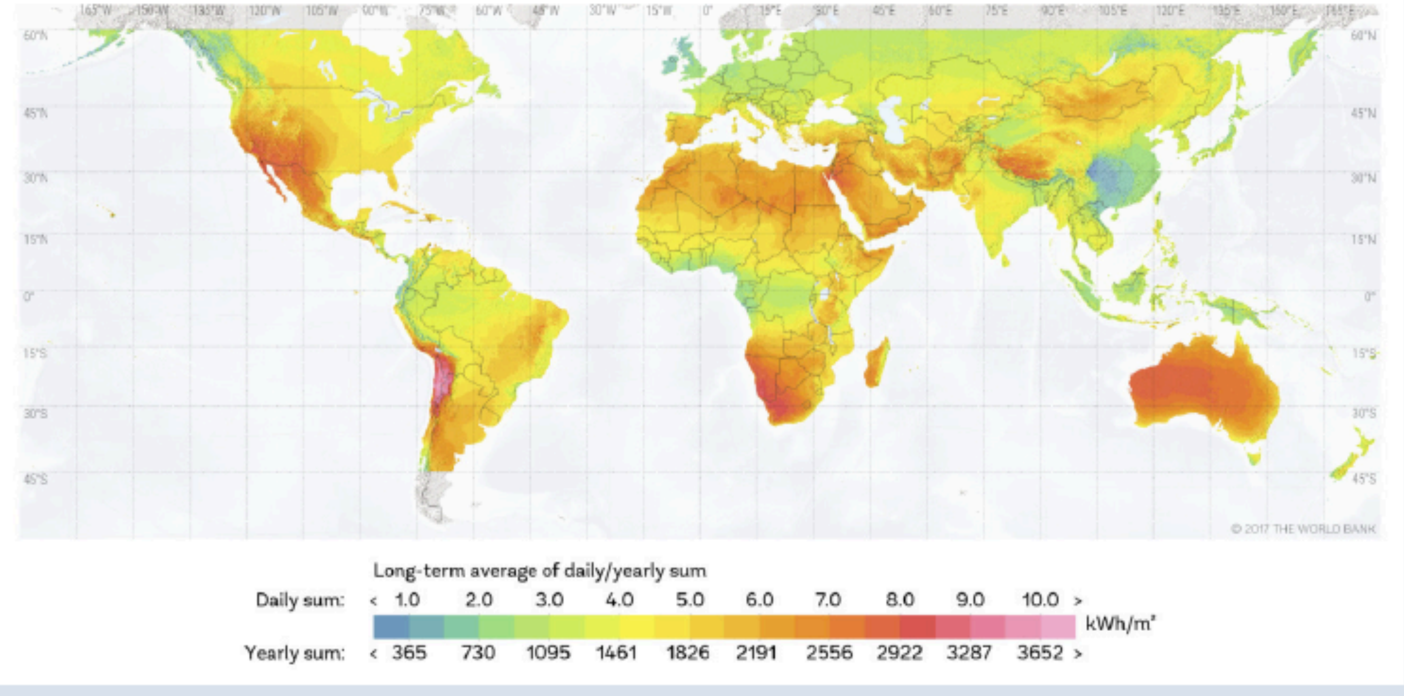


This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.
Source: World Bank Group, ESMAP and Solargis (2019), *Global Solar Atlas*, http://globalsolaratlas.info.

Solar energy – mapping the road ahead 2019

Global horizontal irradiance (GHI) measures the density of solar resources available per horizontal surface area, including both direct and diffuse radiations. Other measures of resource availability also need to be considered, depending on the technology to be deployed. For concentrating solar technologies for power or industrial heat particularly, the relevant metric is direct normal irradiance (DNI).

Direct normal irradiance



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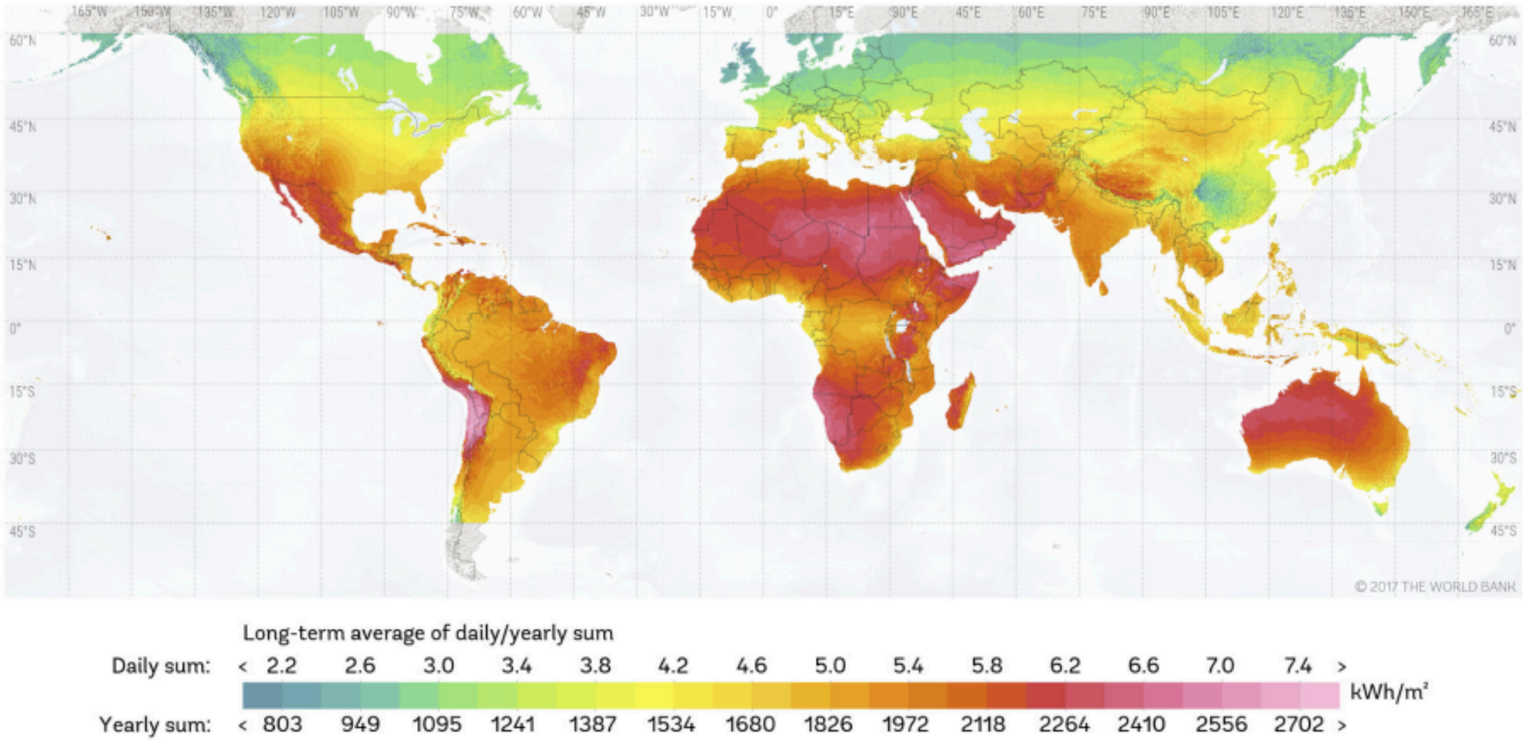
Source: World Bank Group, ESMAP and Solargis, *Global Solar Atlas*, http://globalsolaratlas.info.

Solar energy – mapping the road ahead 2019

Figure 9. Global horizontal irradiation



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Source: World Bank Group, ESMAP and Solargis (2019), *Global Solar Atlas*, http://globalsolaratlas.info.

Vast regions with rising energy needs receive immense amounts of solar irradiation, but opportunities to use solar energy are increasing even for regions with less solar resources.

Radiation at the Earth's Surface

Measured average global radiation levels received over each month allows calculation of the *clearness index* K_T, which is given by the ratio of the daily extraterrestrial radiation to the global radiation received at the site

$$K_T \equiv \frac{G}{H_o} \qquad (10)$$

K_T describes the average attenuation of the solar radiation by the atmosphere at a given site over the month

The diffuse radiation component, D, can be calculated using the simple formula due to Page (1961) where

$$\frac{D}{G} \equiv 1 - 1.13 K_T \qquad (11)$$

Hence the beam or direct radiation is then obtained from

$$B \equiv G - D \qquad (12)$$

Radiation on Inclined Surfaces

At latitudes above 23.45º in the winter months the sun is never directly overhead leading to the need for inclined collector surfaces to increase the amount of radiation collected

Once the global radiation received by a horizontal surface is known the beam, diffuse and reflected components intercepted by a collector inclined at angle β to the horizontal can be calculated as follows

The beam irradiation on a south-facing collector is given by

$$B(\beta) \equiv B \frac{\cos(\phi-\beta)\cos\delta\sin\omega_o + \left(\frac{2\pi\omega_o}{360}\right)\sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\sin\omega_s + \left(\frac{2\pi\omega_s}{360}\right)\sin\phi\sin\delta} \qquad (13)$$

where,

$$\omega_o \equiv \min\{\omega_s, \omega_s^{'}\} \quad \text{and} \quad \omega_s^{'} \equiv \cos^{-1}\{-\tan(\phi-\beta)\tan\delta\}$$

$\omega_s^{'}$ is the sunrise angle about a plane inclined at angle β to the horizontal

Radiation on Inclined Surfaces

The diffuse radiation on the inclined surface is given by

$$D(\beta) \equiv \frac{1}{2}(1+\cos\beta)D \qquad (14)$$

The albedo radiation on the inclined surface is generally small and given by

$$R(\beta) \equiv \frac{1}{2}(1-\cos\beta)\rho G \qquad (15)$$

where ρ is the ground reflectivity

The total global irradiation G(β) on an inclined surface is the sum of all three contributions

$$G(\beta) \equiv B(\beta) + D(\beta) + R(\beta) \qquad (16)$$

Example problem

Example Solution

For December (use day 346) at a latitude 40ºN

First calculate the solar declination δ from

$$\delta \equiv 23.45^\circ \sin\left[\left(\frac{346-80}{370}\right)\times 360\right] \equiv -23^\circ$$

Now find the sunset angle

$$\omega_s \equiv \cos^{-1}\left(-\tan\left(40^\circ\right)\tan\left(-23^\circ\right)\right) \equiv 69.1^\circ$$

Now calculate I_o using a value of 1370Wm^{-2} for I_{sc} giving

$$I_o \equiv 1370\left[1 + 0.033 Cos\left(\frac{360\times 346}{370}\right)\right] \equiv 1401 \text{ Wm}^{-2}$$

Example Solution

Now we can calculate the total extraterrestrial daily radiation

$$H_{ot} \equiv \frac{I_{o(dailysum)}}{\pi}\left[\cos\phi\cos\delta\sin\omega_s + \left(\frac{2\pi\omega_s}{360}\right)\sin\phi\sin\delta\right]$$

therefore

$$H_{ot} \equiv \frac{24\times 0.0036\times 1401}{\pi}\left[\cos(40°)\cos(-23°)\sin(69.1°)+\left(\frac{2\pi 69.1°}{360}\right)\sin(40°)\sin(-23°)\right] \equiv 13.7\ \mathrm{MJ.m^{-2}}$$

With a K_T value of 0.55 the total global radiation reaching the Earth's surface over an average day can be calculated

$$G \equiv K_T \times H_{ot} \equiv 0.55\times 13.7 \equiv 7.54\ \mathrm{MJ.m^{-2}}$$

The diffuse and beam components are given by

$$D \equiv (1-1.13K_T)G \equiv 2.85\ \mathrm{MJ.m^{-2}} \qquad B \equiv G - D \equiv 4.69\ \mathrm{MJ.m^{-2}}$$

Example Solution

To calculate the daily beam radiation on the inclined panel we need to determine ω_o where

$$\omega_o \equiv \min\left\{\omega_s, \omega_s'\right\} \qquad \textbf{and} \qquad \omega_s' \equiv \cos^{-1}\left\{-\tan(\phi-\beta)\tan\delta\right\}$$

We have already found ω_s to be 69.1º but need to evaluate ω_s'

$$\omega_s' \equiv \cos^{-1}\left\{-\tan(40°-30°)\tan -23°\right\} \equiv 85.7°$$

therefore

$$\omega_o \equiv 69.1°$$

The beam component collected by the surface inclined at 30º is

$$B(\beta) \equiv B\,\frac{\cos(40°-30°)\cos-23°\sin 69.1° + \left(\dfrac{2\pi 69.1°}{360}\right)\sin(40°-30°)\sin-23°}{\cos 40°\cos-23°\sin 69.1° + \left(\dfrac{2\pi 69.1°}{360}\right)\sin 40°\sin-23°} \equiv 10.08\ \mathrm{MJ.m^{-2}}$$

Example Solution

Now the diffuse component can be found

$$D(30) \equiv \frac{1}{2}(1+\cos 30)\times 2.85 \equiv 2.66\ \mathrm{MJ.m^{-2}}$$

And the reflected component from

$$R(30) \equiv \frac{1}{2}(1-\cos 30)\times 0.2\times 7.54 \equiv 0.1\ \mathrm{MJ.m^{-2}}$$

Therefore total global radiation collected by the surface inclined at 30º is

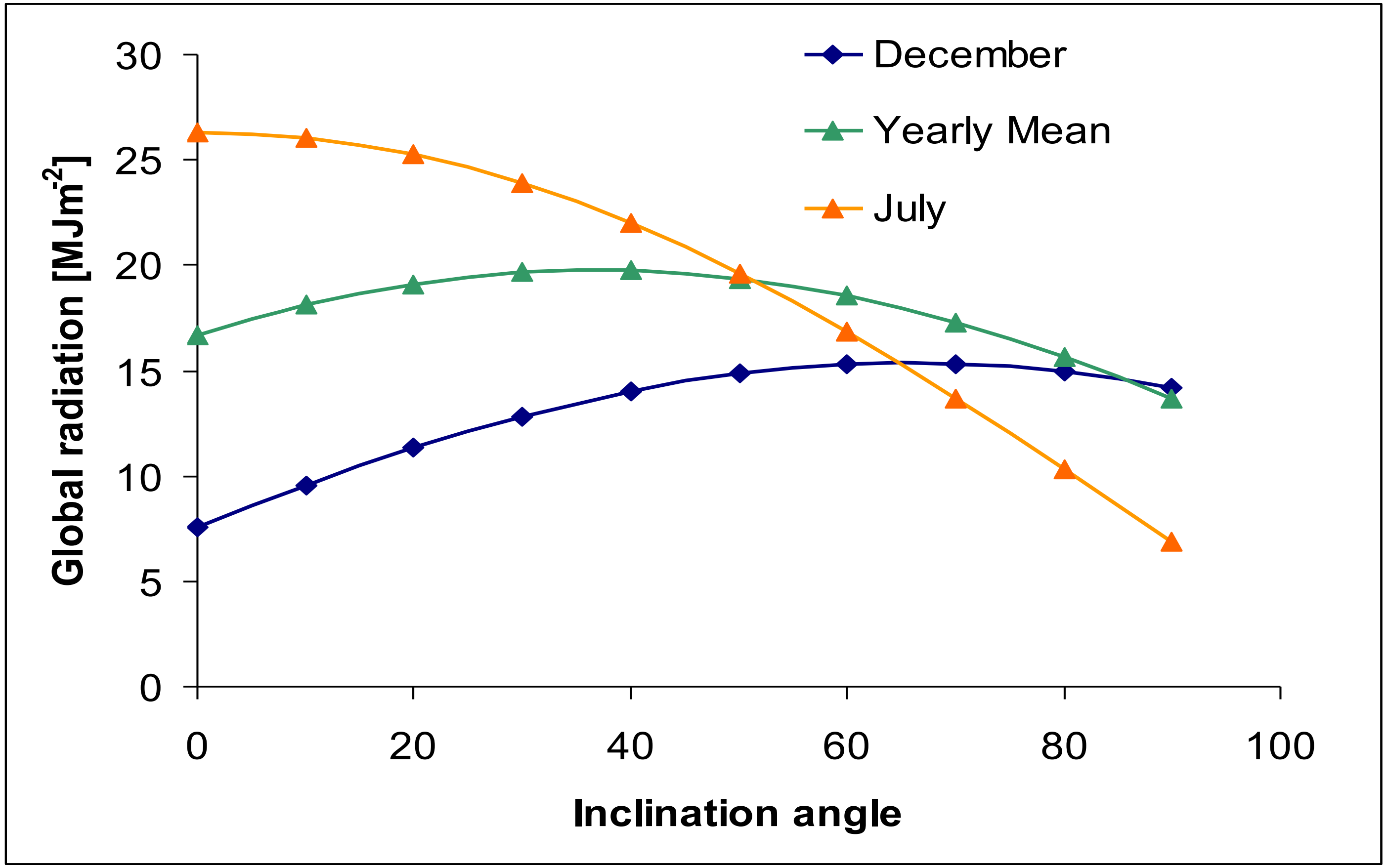
$$G(30) \equiv B(30)+D(30)+R(30) \equiv 12.84\ \mathrm{MJ.m^{-2}}$$

For the inclination angle of 60º the global radiation is

$$G(60) \equiv B(60)+D(60)+R(60) \equiv 15.28\ \mathrm{MJ.m^{-2}}$$

Example Solution

This can be done for each month and the optimum inclination angle can be predicted for site
In this case an angle of 40º gives the highest yearly average of 19.74 MJm^{-2} each day



Summary

- Extraterrestrial solar radiation stable and predictable
- Earth's atmosphere absorb and reflects incoming radiation
- Great variability in solar radiation levels reaching Earth's surface due to these effects – unpredictable!
- Extraterrestrial solar radiation can be estimated
- Combined with Weather Station data close to site of interest (clearness index) available solar irradiance can be estimated
- Very important quantity for solar PV & solar thermal installation design and sizing