Renewable Energy & Hydroelectric Works

8th semester, School of Civil Engineering

Solar energy

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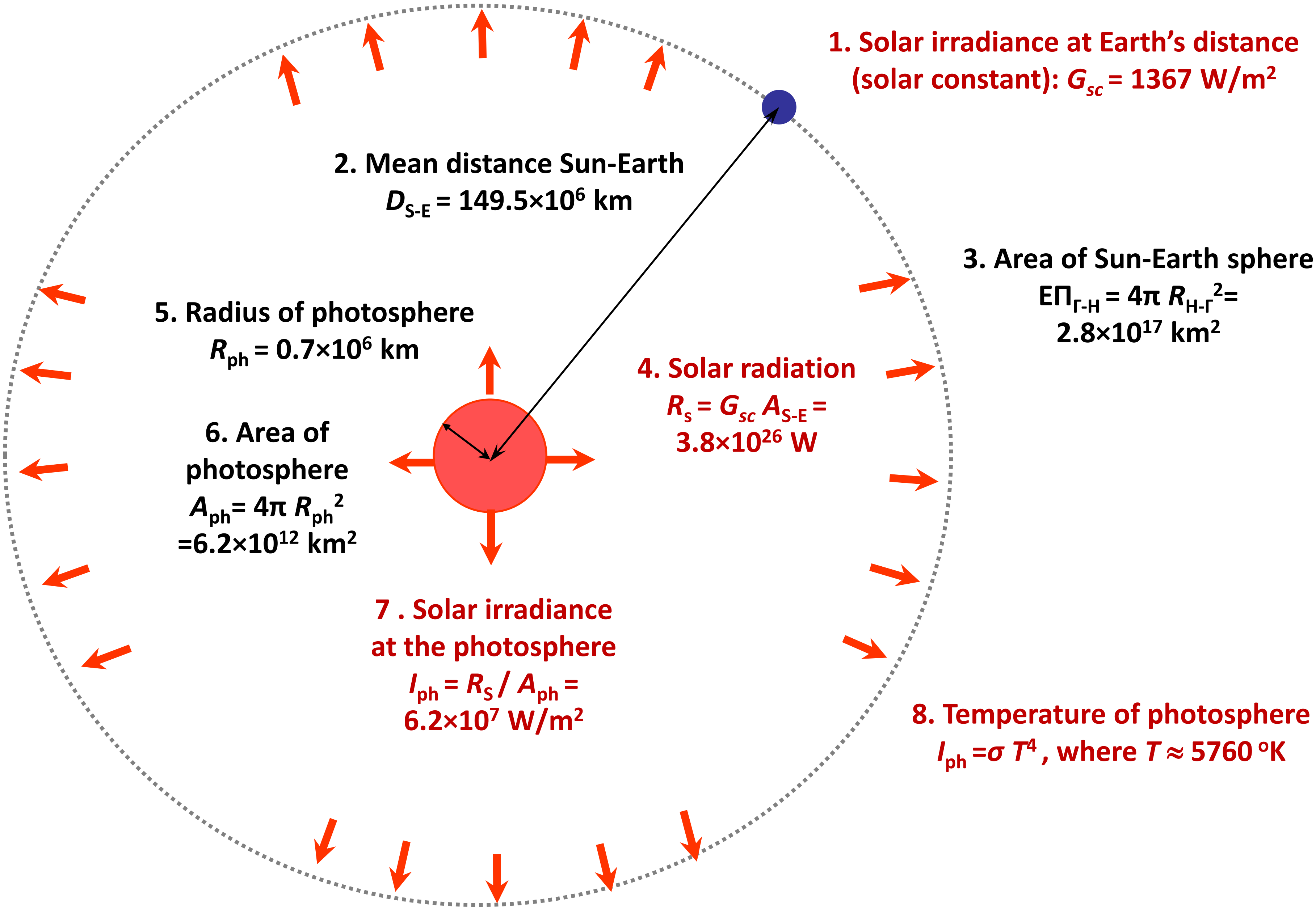
Solar physics: concepts and quantities

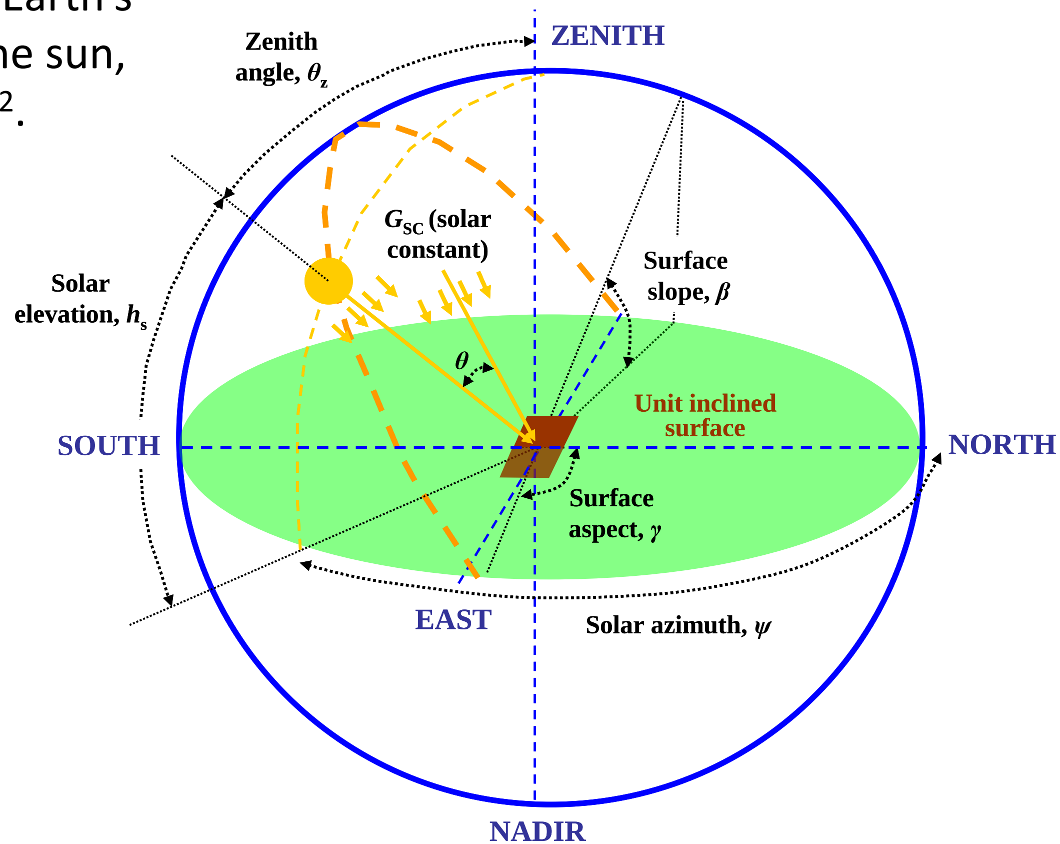


Extraterrestrial radiation: calculations

- The solar radiation received by **the top of the Earth's atmosphere above** a **horizontal surface** is called the **extraterrestrial** (solar) radiation, R_a, which is expressed in W/m^2.
- On **daily basis**, the extraterrestrial radiation is estimated by multiplying the solar constant G_{sc}, the eccentricity coefficient d_r, and the zenith angle ϑ_z, i.e.

$$R_a = G_{sc}\, d_r \cos(\vartheta_z)$$

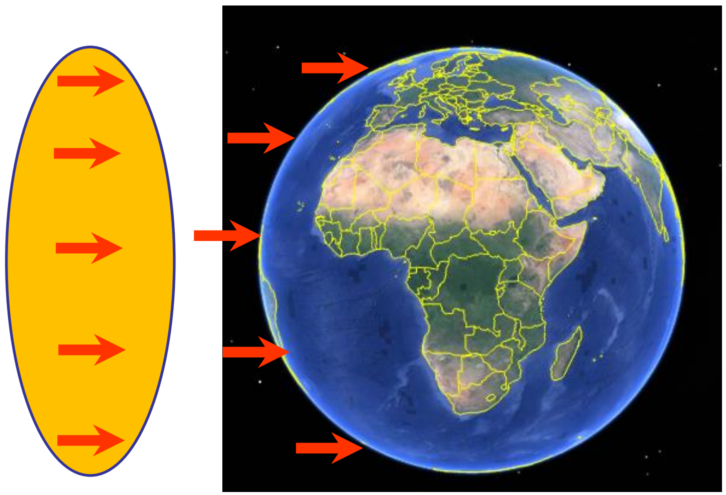
- The **solar constant** denotes the average density of solar radiation outside the Earth's atmosphere at mean distance from the sun, and is approximately G_{sc} = 1367 W/m^2.
- The **eccentricity coefficient** d_r and the **zenith angle** ϑ_z depend on the **solar declination** and the **sunset hour angle**; the former is function of the day of the year, while the latter is also function of the latitude.
- For **hourly or shorter periods**, the solar time angle at the beginning and end of the specific period should be also considered in the calculations.



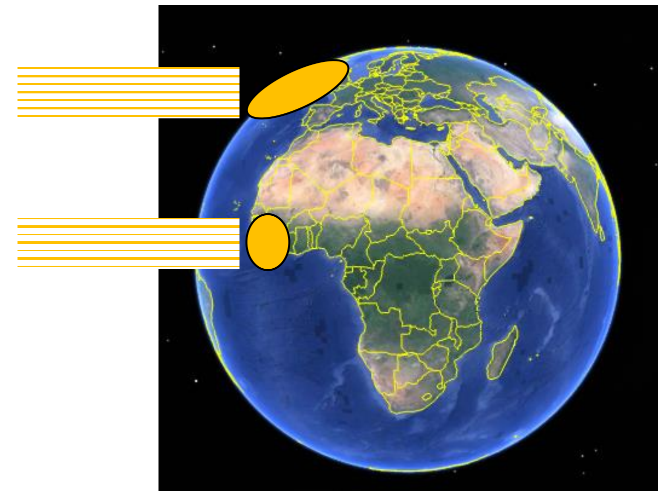
Extraterrestrial radiation: spatial variability

The solar constant (1367 W/m^2) only affects part of the Earth that corresponds to an area of πR^2

Since the total area of Earth is $4\pi R^2$, the average solar irradiance in Earth is equal to 25% of the solar constant

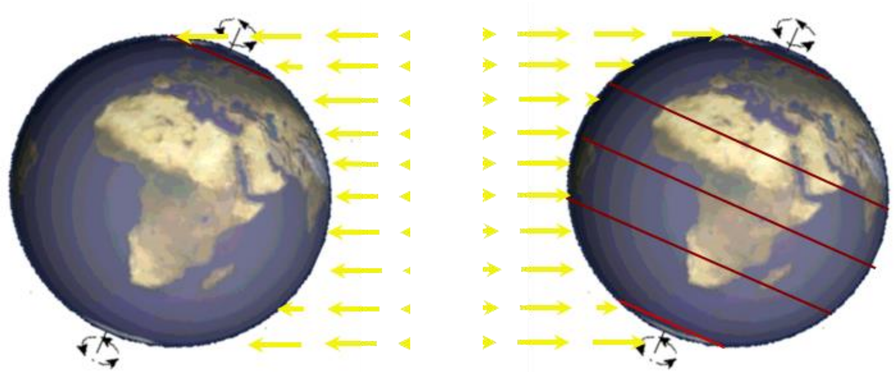


The spatial variation of solar radiation depends on the latitude, as the same irradiance affects areas with different sizes

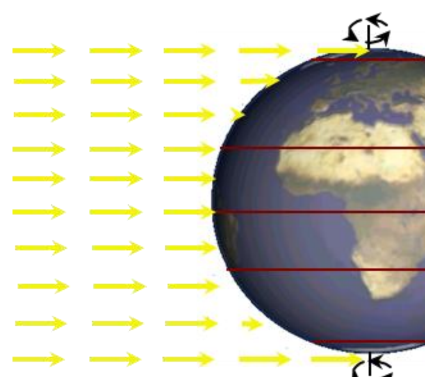


With respect to the equator, the area at 45° latitude is 40% larger, it is double at 60° and it is six times larger at 80°

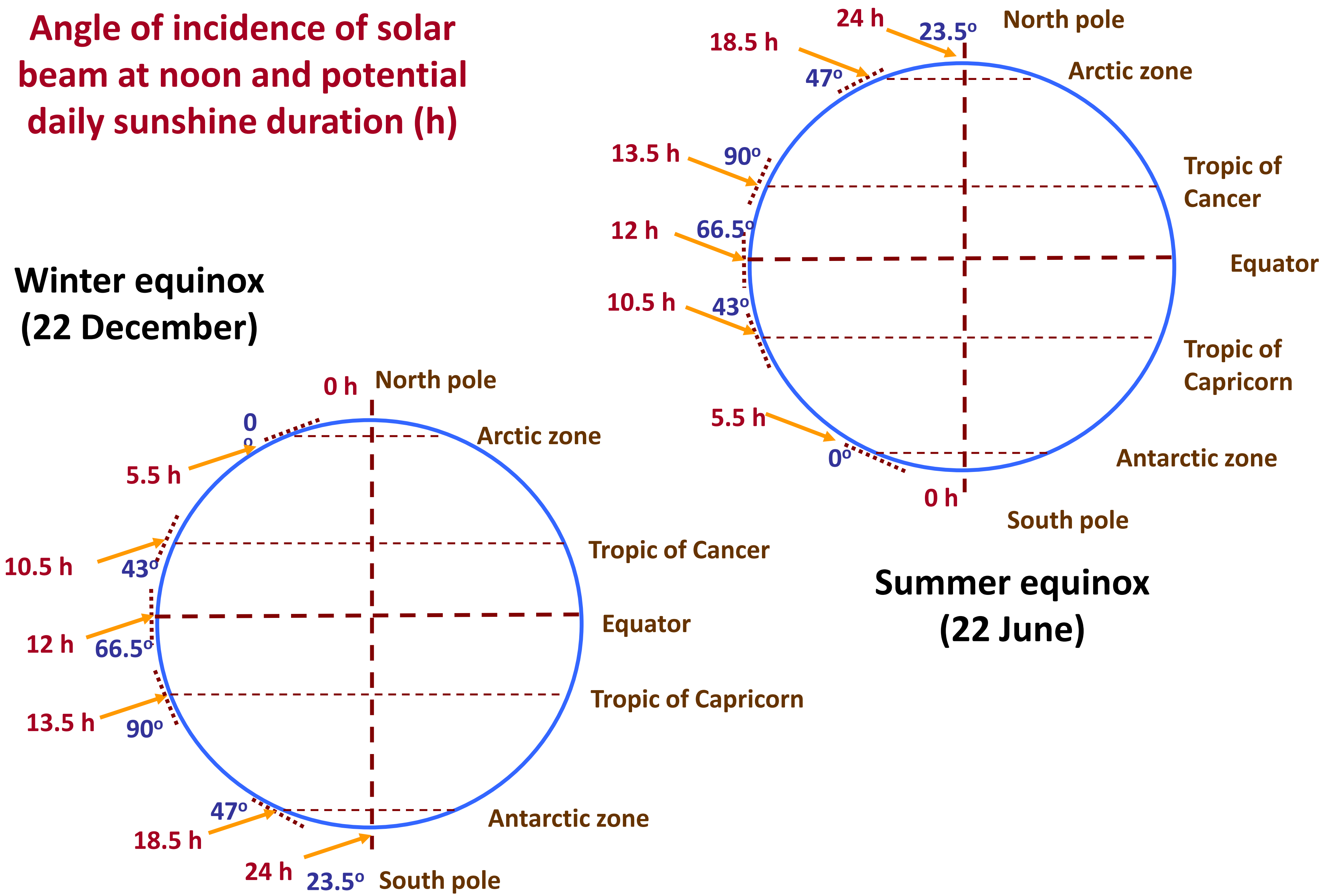
22/6 **Solstices** **22/12**



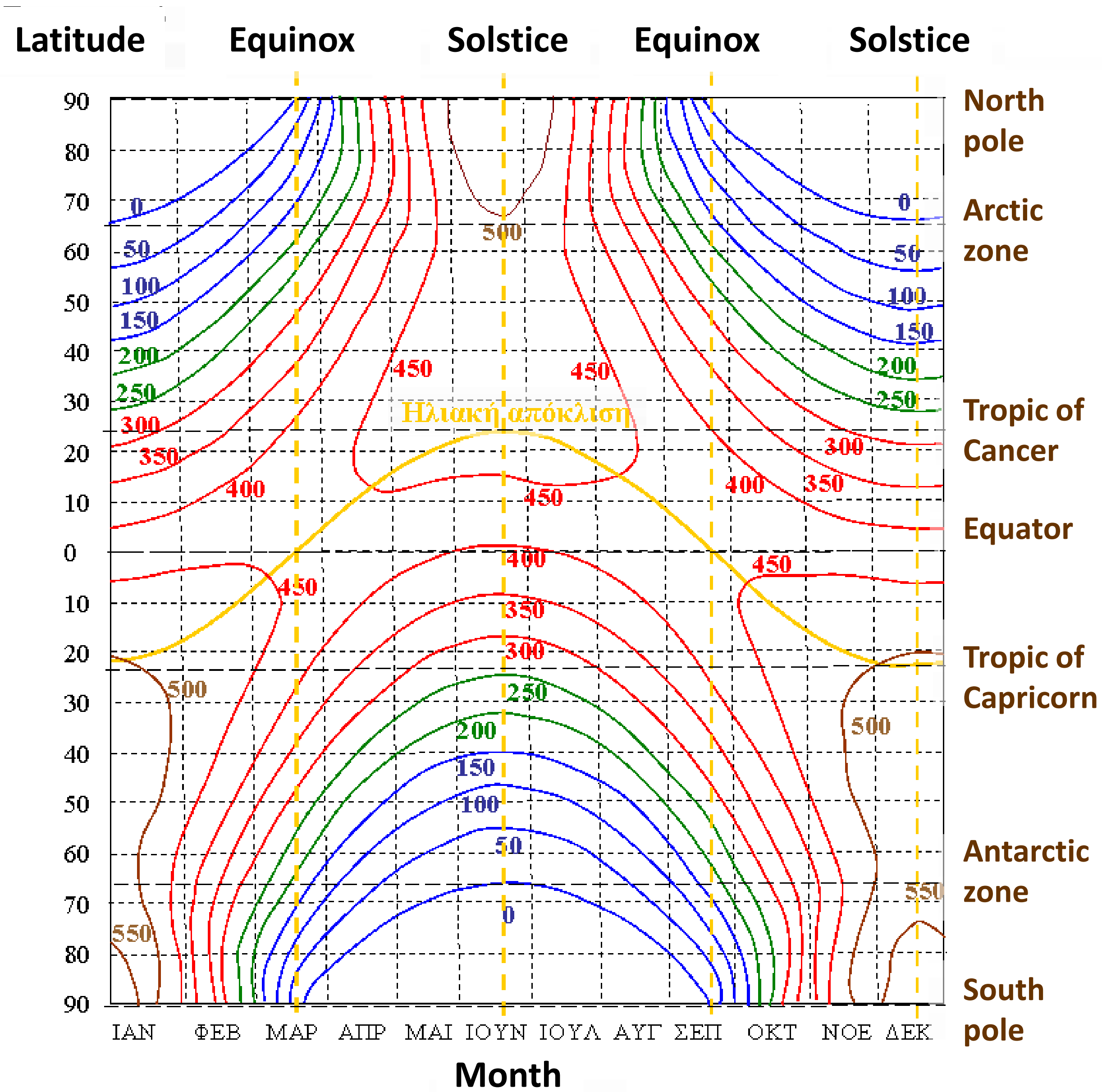
Equinoxes



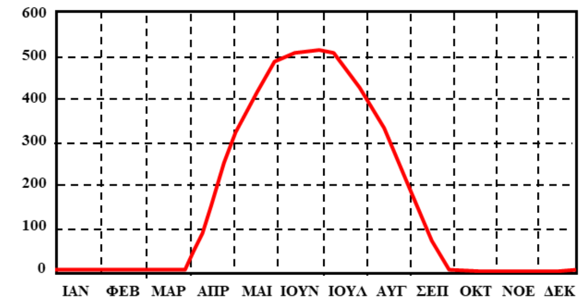
Extraterrestrial radiation: temporal variability



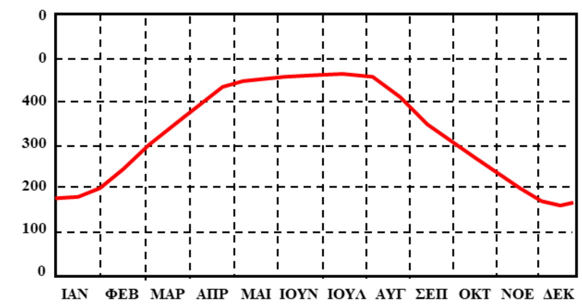
Extraterrestrial radiation: typical values (W/m²)



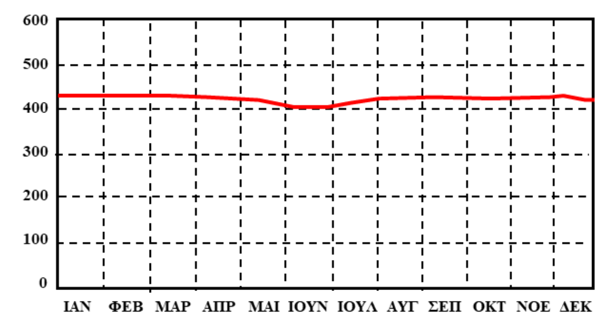
North pole



New York (40° N)



Equator



Source: Christopherson, 2000

Solar/shortwave/global radiation and its components

- As the radiation penetrates the atmosphere, part of it is **scattered**, **reflected** or **absorbed** due to the **transmittance of the atmosphere** in the shortwave bands, which depends on the thickness of the atmosphere, the water vapour content, the concentrations of gases, solid particles, etc.
- The **amount of radiation actually reaching a horizontal plane** is known as **solar or shortwave radiation**, Rs. The term "shortwave" derives from the fact that the sun emits energy by means of electromagnetic waves that are characterized by short wavelengths.
- It is also known as **global radiation**, given that it is the sum of:
  - **direct shortwave radiation** from the sun, also referred to as **beam radiation**, R_b
  - **diffuse sky radiation** from all directions, R_d
- The distribution between direct and diffuse radiation depends on the **atmospheric conditions** (humidity, dust, etc.) and the **solar declination**, which is continuous function of time, although, normally, a unique value is considered for every day of the year.
- Under **clear sky conditions**, the diffuse solar radiation is about 15% or more of the total solar radiation received by a horizontal surface, while on **inclined surfaces facing away from the sun**, the proportion of diffuse to total solar radiation may be much higher.
- On a **cloudy day**, the radiation is scattered in the atmosphere, but even under extremely dense cloud cover (when direct radiation tends to zero), about 25% of the extraterrestrial radiation reaches the earth's surface as diffuse sky radiation.

Solar radiation: measurement & empirical estimations

- The global radiation is measured by **pyranometers**, **radiometers** or **solarimeters**. These instruments contain a sensor installed on a horizontal surface that measures the intensity of the total solar radiation, i.e., **both direct and diffuse radiation from cloudy conditions**.
- In the absence of measurements, solar radiation is estimated through empirical approaches, such as the Angström formula:

$$R_s = R_a\,(a_s + b_s\,n / N)$$

Either provided directly (sunshine values) or in terms of **cloud cover**

where n is the **actual sunshine duration**, N is the **maximum potential daylight hours** (function of **latitude** and **solar declination**), a_s is a regression constant, expressing the fraction of R_a reaching the earth on **overcast days**, when $n = 0$, and $a_s + b_s$ is the fraction of R_a ideally reaching the earth under **clear-sky conditions**, when $n = N$.

- Parameters a_s and b_s depend on the **location**, the **season** and the **state of the atmosphere** and they are related to the distribution of direct and diffuse radiation; if no actual solar radiation data are available for their calibration against local observations, the use of typical values $\boldsymbol{a_s} = \mathbf{0.25}$ **and** $\boldsymbol{b_s} = \mathbf{0.50}$ are recommended.

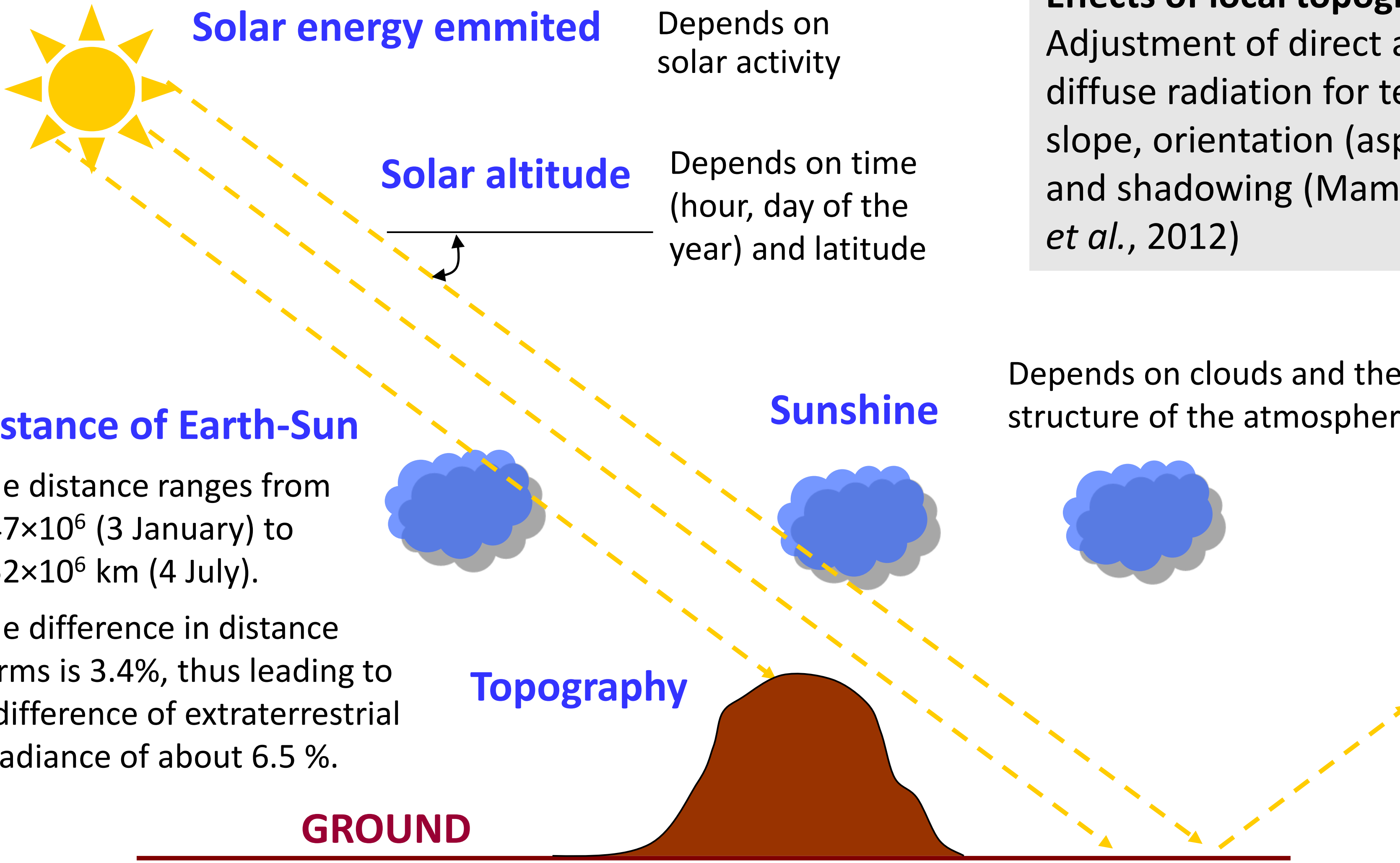
φ (°)	36	38	40	42	44	46
Ιαν	9.8	9.7	9.5	9.3	9.1	8.9
Φεβ	10.6	10.5	10.4	10.3	10.2	10.1
Μαρ	11.7	11.7	11.7	11.7	11.6	11.6
Απρ	12.9	13.0	13.0	13.1	13.2	13.3
Μαϊ	13.9	14.0	14.2	14.4	14.5	14.7
Ιουν	14.4	14.6	14.8	15.0	15.2	15.5

φ (°)	36	38	40	42	44	46
Ιουλ	14.2	14.4	14.5	14.7	14.9	15.2
Αυγ	13.4	13.5	13.6	13.7	13.8	13.9
Σεπ	12.2	12.2	12.3	12.3	12.3	12.3
Οκτ	11.1	11.0	10.9	10.8	10.7	10.7
Νοε	10.1	9.9	9.8	9.6	9.4	9.2
Δεκ	9.6	9.4	9.2	9.0	8.8	8.5

Monthly average potential daylight hours, N, for latitudes φ = 36°-46° at the Northern Hemisphere (Source: Koutsoyiannis & Xanthopoulos, 1997, p. 173)

Factors that influence the ground solar radiation

Effects of local topography: Adjustment of direct and diffuse radiation for terrain slope, orientation (aspect) and shadowing (Mamassis *et al.*, 2012)



Solar energy emmited

Depends on solar activity

Solar altitude

Depends on time (hour, day of the year) and latitude

Distance of Earth-Sun

The distance ranges from 147×10^6 (3 January) to 152×10^6 km (4 July).

The difference in distance terms is 3.4%, thus leading to a difference of extraterrestrial irradiance of about 6.5 %.

Sunshine

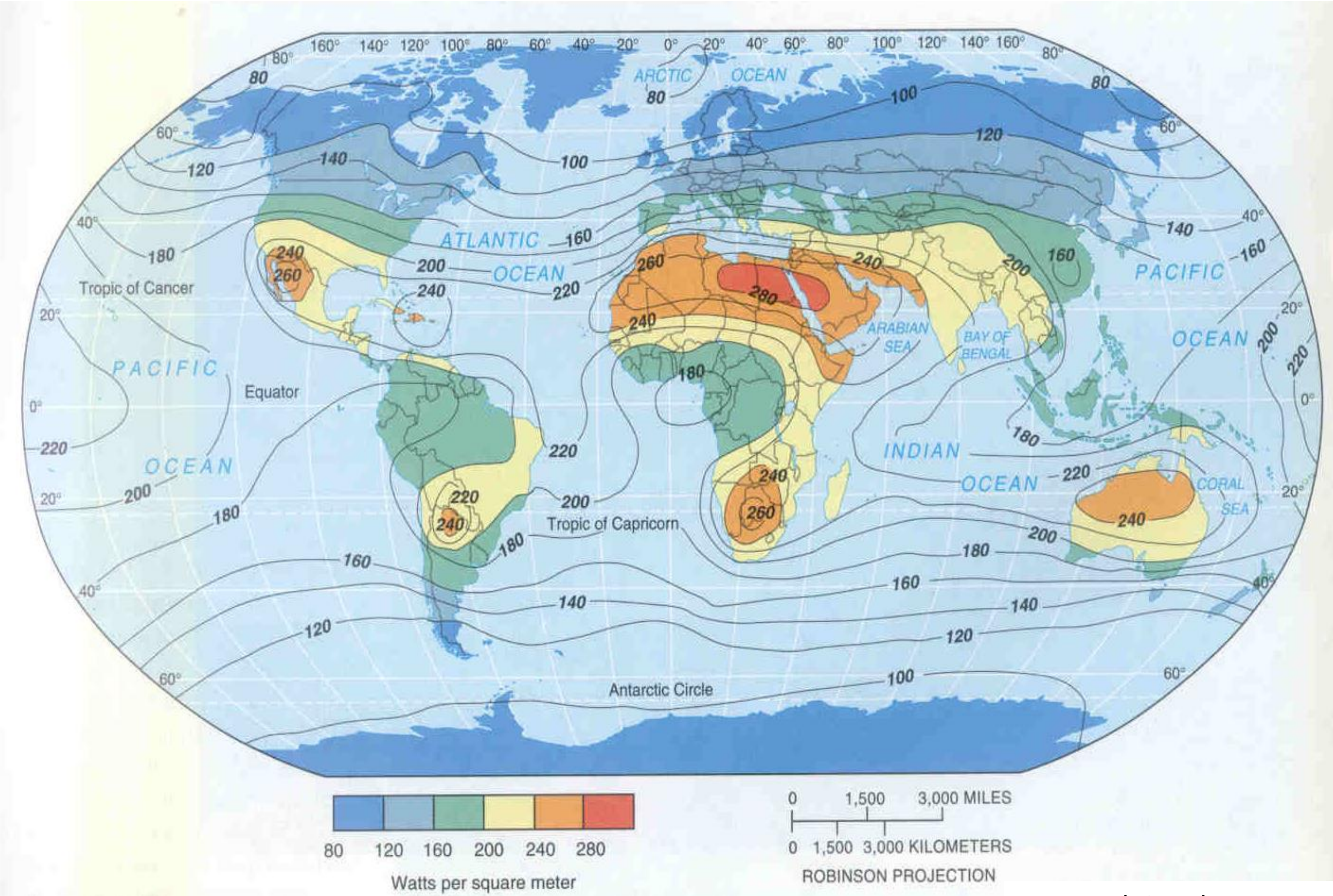
Depends on clouds and the structure of the atmosphere

Topography

Surface albedo

Depends on surface properties. Indicative values: water: 0.06, ground: 0.25, snow: 0.95

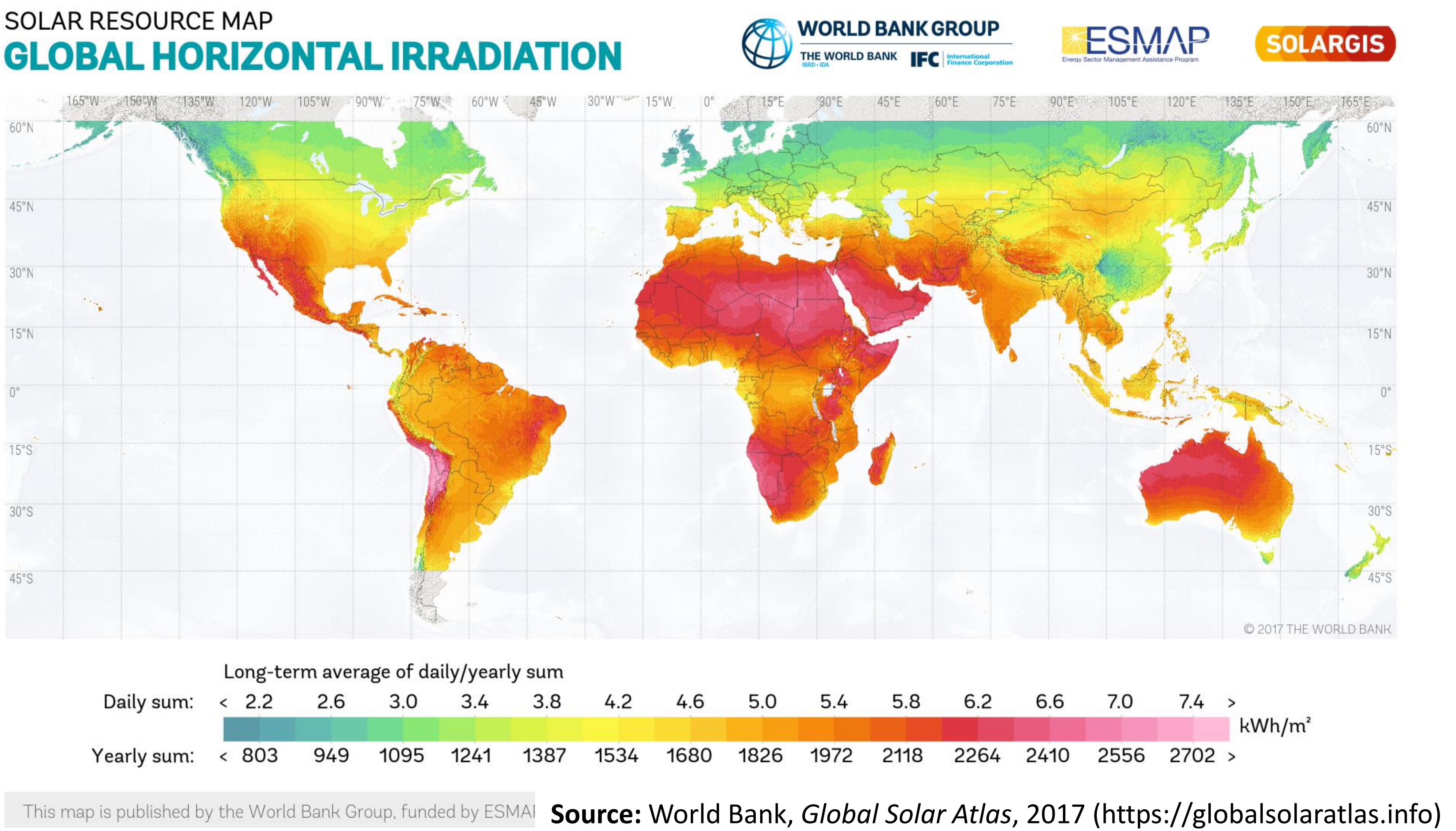
Mean annual solar radiation at ground level (W/m²)



Source: Christopherson, 2000

Global map of horizontal irradiance (kWh/m^2)

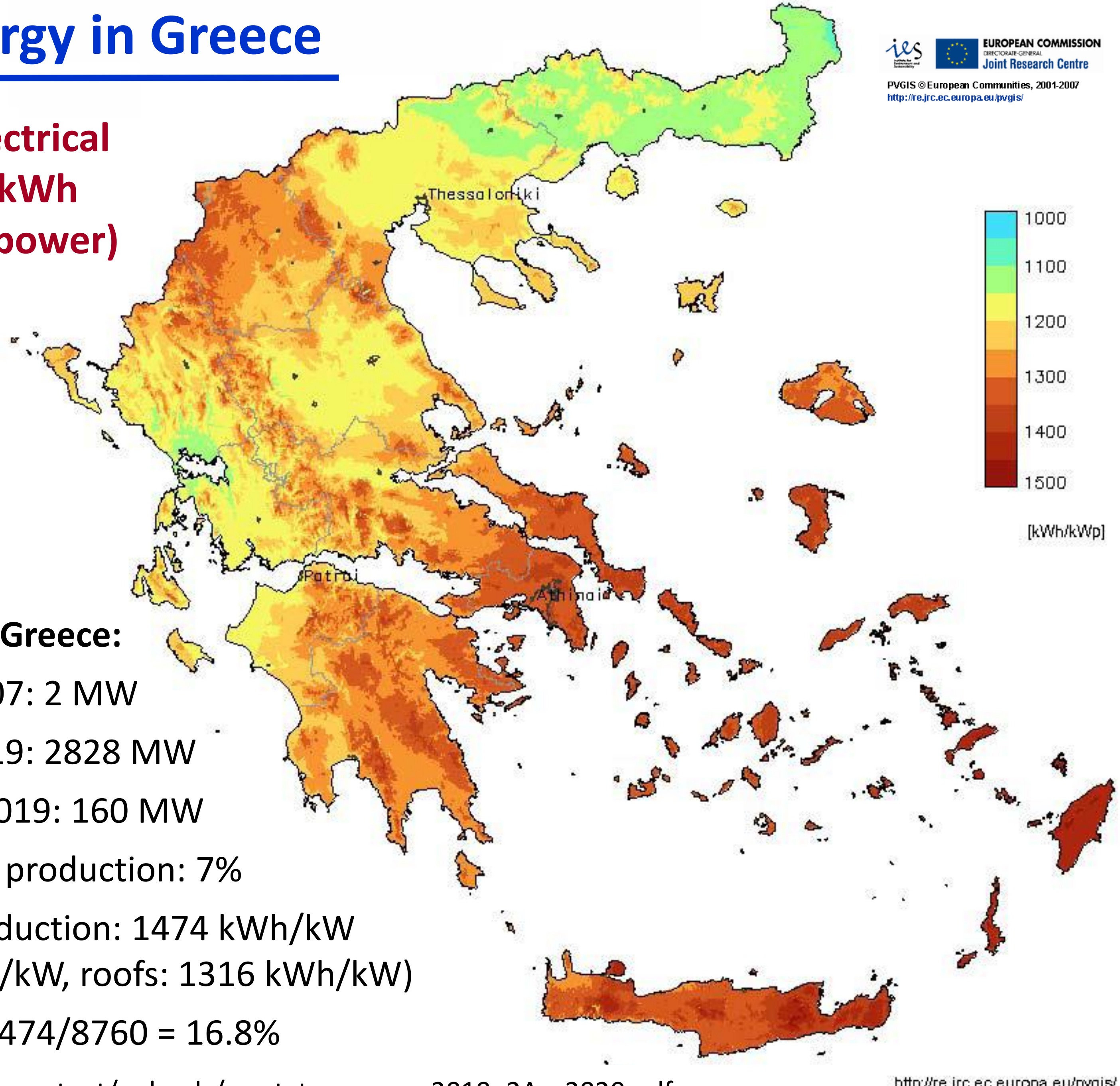
Global Horizontal Irradiance: Total irradiance from the sun on a horizontal surface on Earth, as the sum of **direct irradiance** (after accounting for the solar zenith angle of the sun) and **diffuse horizontal irradiance**.



Source: World Bank, *Global Solar Atlas*, 2017 (https://globalsolaratlas.info)

Solar (PV) energy in Greece

Expected annual electrical energy production (kWh per kW of installed power)



Photovoltaic energy in Greece:

- Total capacity 2007: 2 MW
- Total capacity 2019: 2828 MW
- Added capacity 2019: 160 MW
- Sharing in energy production: 7%
- Mean annual production: 1474 kWh/kW (parks: 1500 kWh/kW, roofs: 1316 kWh/kW)
- Capacity factor: 1474/8760 = 16.8%

Source: https://helapco.gr/wp-content/uploads/pv-stats_greece_2019_2Apr2020.pdf

Photovoltaic cell characteristics

- **Dimensions**: height × width × thickness
- **Nominal power**: Power measured under *Standard Test Conditions* (STC), under light intensity of 1000 W/m^2, with a spectrum similar to sunlight hitting the earth's surface at latitude 35°N in the summer (airmass 1.5), the temperature of the cells being 25 °C.
- **Efficiency**: Portion of energy in the form of sunlight that can be converted via photovoltaics into electricity by the solar cell, equals the nominal power divided by the light power that falls on a given area of a photovoltaic device (area × 1000 W/m^2).
- **Typical range**: 15-20%, most efficient solar panels available today are approximately 23%

Example panel

- Installed power: 280 W
- Dimensions: 1640 × 990 × 46 mm
- The nominal power is achieved at 1000 W/m^2

Calculation of efficiency

- Panel area: 1.64 × 0.99 = 1.624 m^2
- For 1000 W/m^2 of incoming solar radiation each panel receives 1624 W and produces 280 W of electric power
- Efficiency: 280/1624 = 17.2%