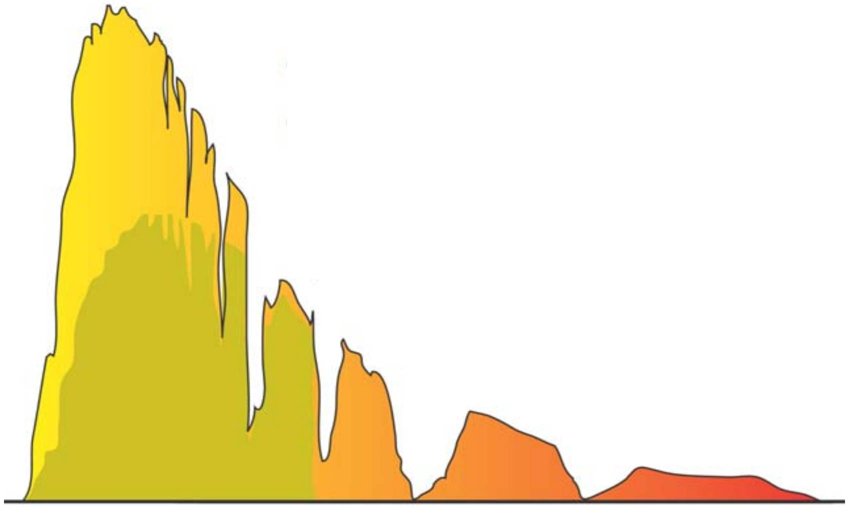
SOLAR ENERGY METEOROLOGY

An Introductory Lecture

by Detlev Heinemann

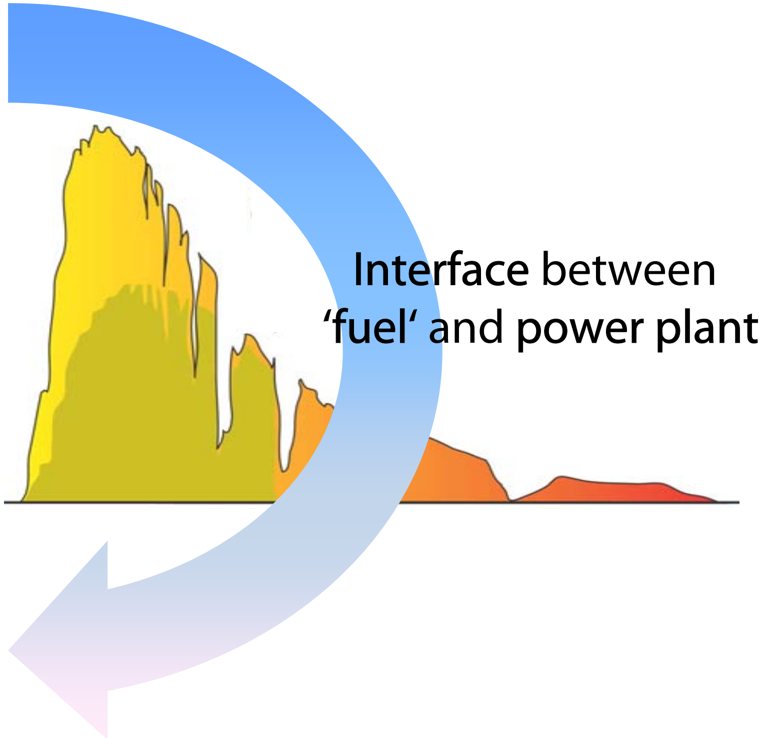


International PV Summer School 2006, Oldenburg, 28 August 2006

SOLAR ENERGY METEOROLOGY

What‘s (Solar) Energy Meteorology for ?

SOLAR ENERGY METEOROLOGY



Interface between
‘fuel‘ and power plant

ENERGY METEOROLOGY

Precise information on various aspects of the new ‘fuels‘ wind and solar are key elements for an efficient use of these technologies

⇨ Characterization of performance of wind and solar energy systems under influence of fluctuating energy fluxes

✸ Interface fuel - power plant ✸

⇨ Providing specific data sets and methods for analysis, planning and operation (spatial/temporal statistics, ..)

⇨ **Job of Energy Meteorology**

WE NEED TO ...

- characterize the relevant atmospheric energy fluxes in various spatial and temporal scales
- model their influence on the performance of energy systems

⇨ highly interdisciplinary approach

Overview of this Lecture

- Scientific Basis: Radiation Laws, Extinction Processes and Radiative Transfer
- Solar Climatology
- Solar Irradiance Modeling

Emission of Radiation

All matter with T > 0 K shows a lot of changes of energetic levels mainly due to molecular activities

Reminder: moving charge carriers, electric dipole, ..

→ Emission of electromagnetic radiation

Questions:

- How can this emission be described?
- Which are the relevant parameters?

→ Radiation laws

Kirchhoff‘s Law

Assumption: A body emits radiation **E_λ [$Wm^{-2} sr^{-1} \mu m^{-1}$]** in a certain direction (from its unit area and per wavelength interval) and absorbs radiation from the same direction in relative amounts α_λ.

- Experiments showed: E_λ **/** $\alpha_\lambda = f(\lambda,T)$
- Emissions only occur for wavelengths for which absorption occurs
- For complete absorption ($\alpha_\lambda = 1$) it is: $E_\lambda = E_{max} = f(\lambda,T)$
- A body showing this behavior ($\alpha_\lambda=1$, $E_\lambda=E_{max}$) is called a **blackbody**

Question: Explicit form of $f(\lambda,T)$

Radiation Laws

$$L(\lambda,T)\,d\lambda = \frac{2\,h\,c^2}{\lambda^5}\left(\exp\left(\frac{h\,c}{\lambda\,k\,T}\right)-1\right)^{-1} d\lambda$$

Planck‘s law

integration

$$M = \sigma\,T^4$$

Stefan-Boltzmann (Stefan‘s) law

differentiation

$$T\,\lambda_{max} = \text{const} = 2898\ (\mu\text{m K})$$

Wien‘s law

$L(\lambda,T)$	spectral radiance	(W$m^{-2}sr^{-1}\mu m^{-1}$)
$M(T)$	specific emittance of a blackbody	(Wm^{-2})
λ	wavelenght of radiation	(μm)
T	absolute temperature	(K)

k	Boltzmann-Konstante	$1.381 \cdot 10\text{-}23$ (JK^{-1})
h	Planck-Konstante	$6.626 \cdot 10\text{-}34$ (Js)
c	velocity of light in vacuum	$2.9979 \cdot 108$ (ms^{-1})
σ	Stefan-Boltzmann constant	$5.67 \cdot 10\text{-}8$ (W$m^{-2}K^{-4}$)

RADIATION LAWS

Planck‘s Law

$$u_\nu(T)d\nu = \frac{8\pi h}{c^3}\frac{\nu^3}{e^{h\nu/kT}-1}d\nu$$

Spectral photon energy density, i.e. per volume element

$$L_\nu(T)d\nu = \frac{2h}{c^2}\frac{\nu^3}{e^{h\nu/kT}-1}d\nu$$

Spectral radiance
per frequency interval

$$L_\lambda(T)d\lambda = \frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda kT}-1}d\lambda$$

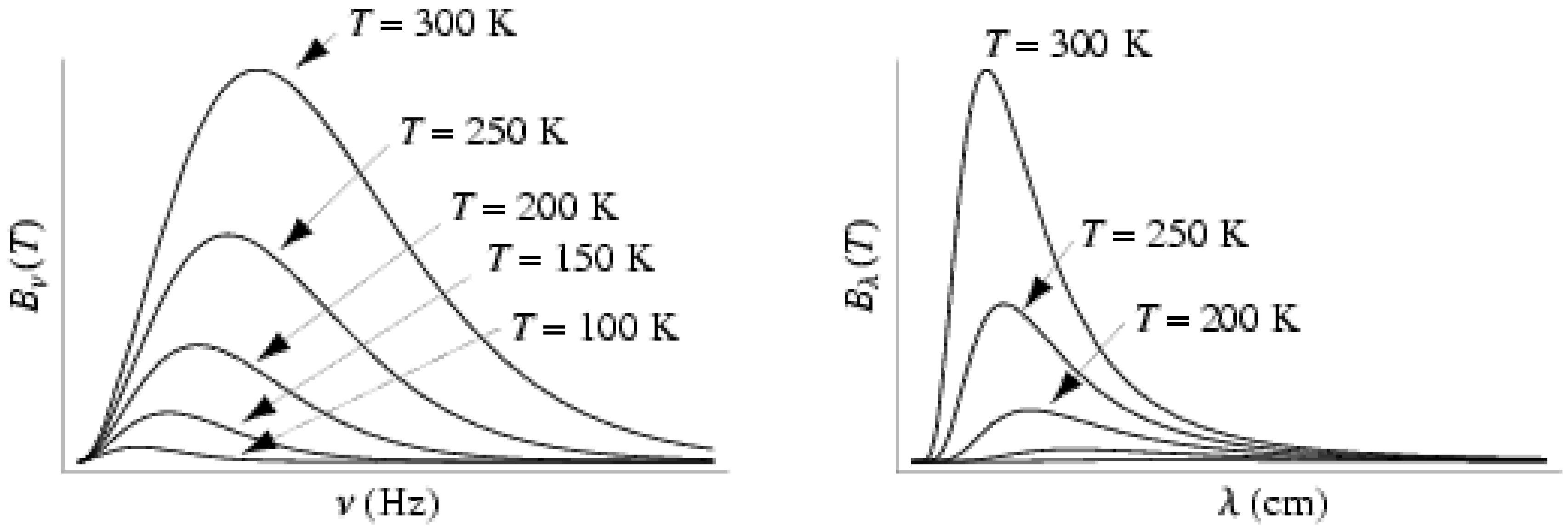
Spectral radiance
per wavelength interval

$$M_\lambda(T) = \pi L_\lambda(T)$$

Spectral radiant flux density
per wavelength interval

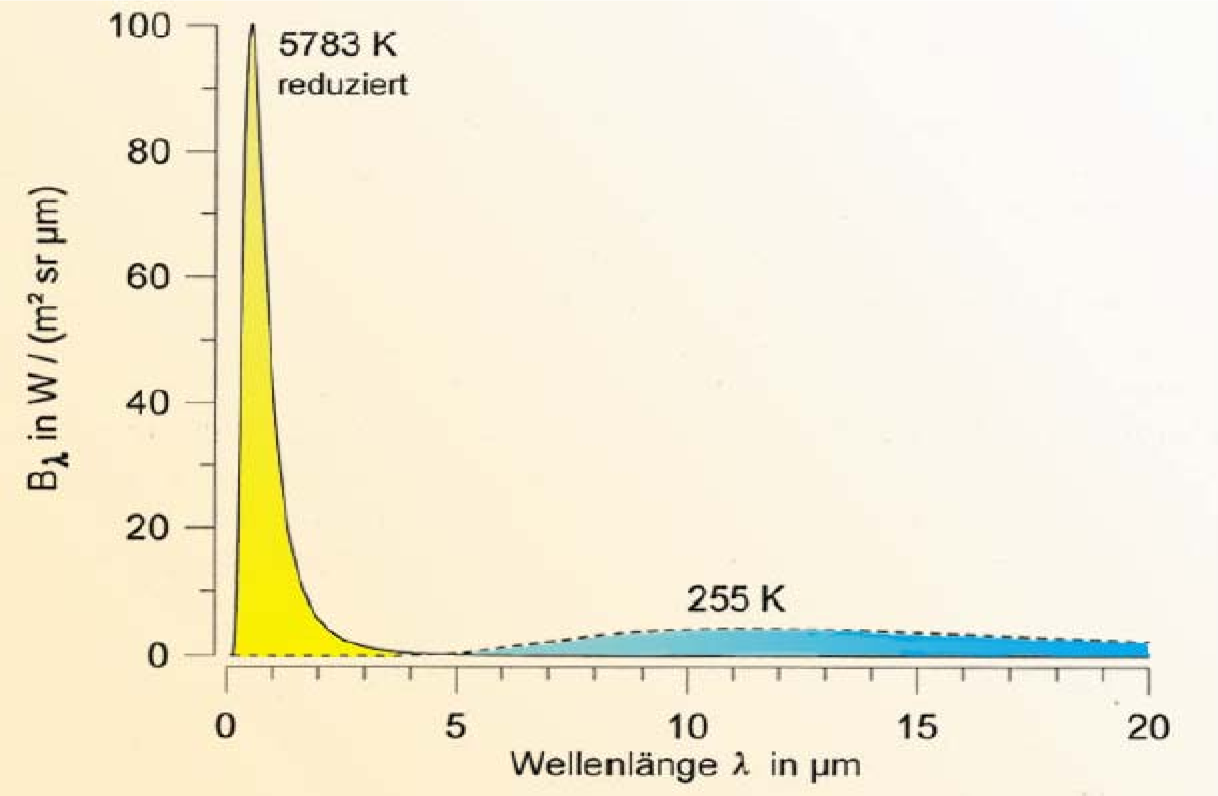
RADIATION LAWS

Planck‘s Law



Intensity radiated by a blackbody as a function of frequency (left) or wavelength (right)

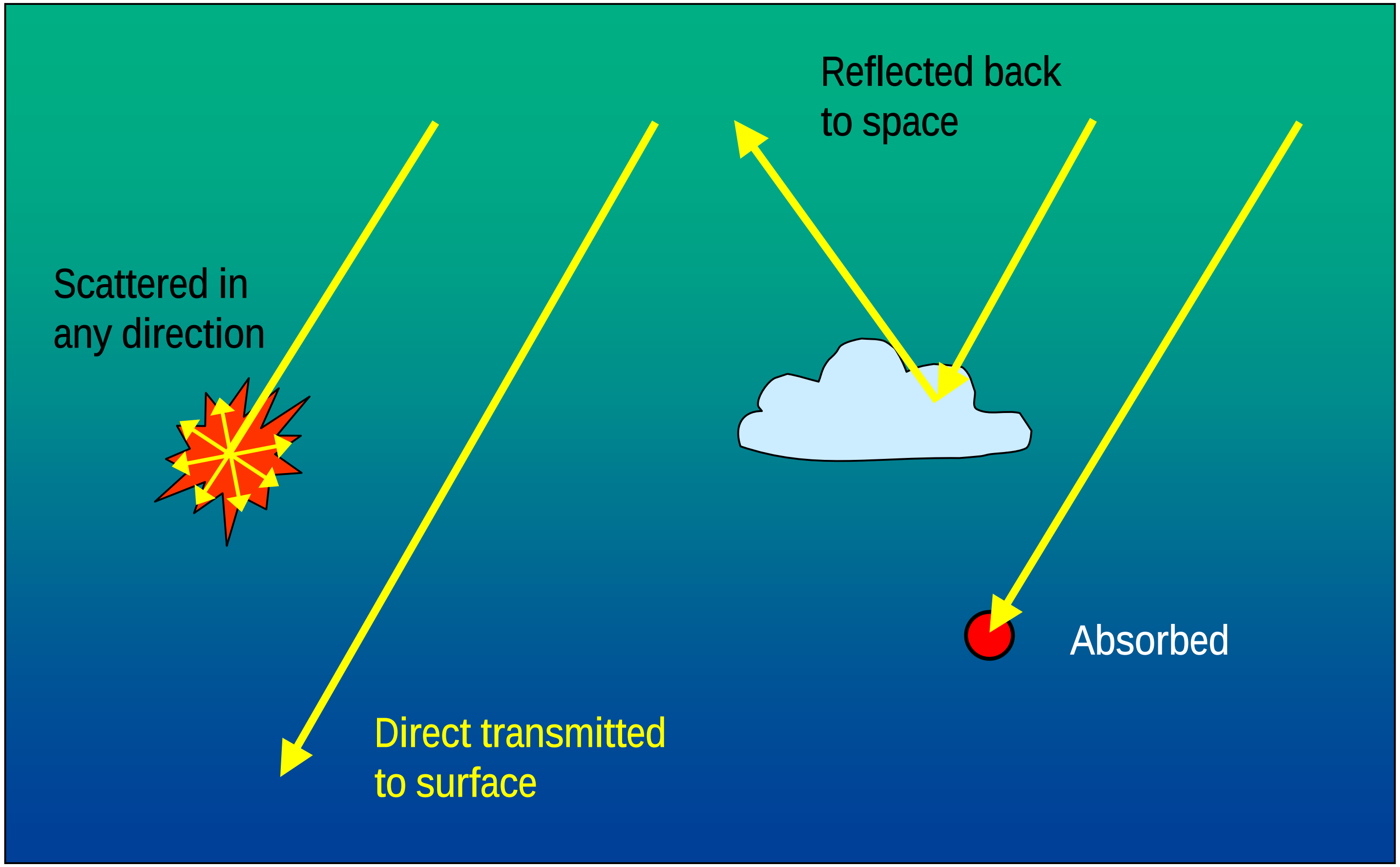
Solar and Terrestrial Spectrum



Source: Vogt

ATMOSPHERIC EXTINCTION

Atmospheric Extinction Processes



ATMOSPHERIC EXTINCTION

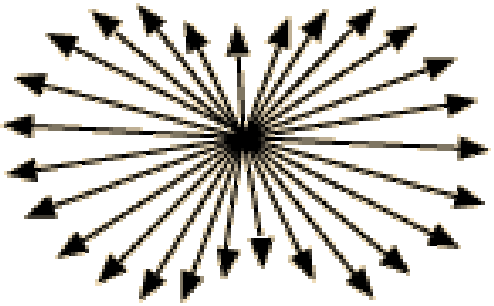
Atmospheric Scattering

Rayleigh scattering	Mie scattering
particle size $<<$ wavelength	particle size $\geq$ wavelength
$\sim \lambda^{-4}$	$\sim \lambda^{-1.3}$
directionality: $(1 + \cos^2 \alpha)$	directionality: very strong foreward scattering
	large variability by non-uniform particles (aerosols!)

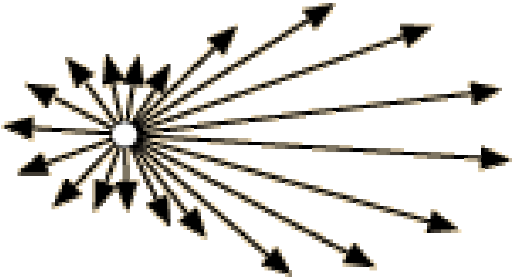
ATMOSPHERIC EXTINCTION

Atmospheric Scattering

Rayleigh scattering



Mie scattering

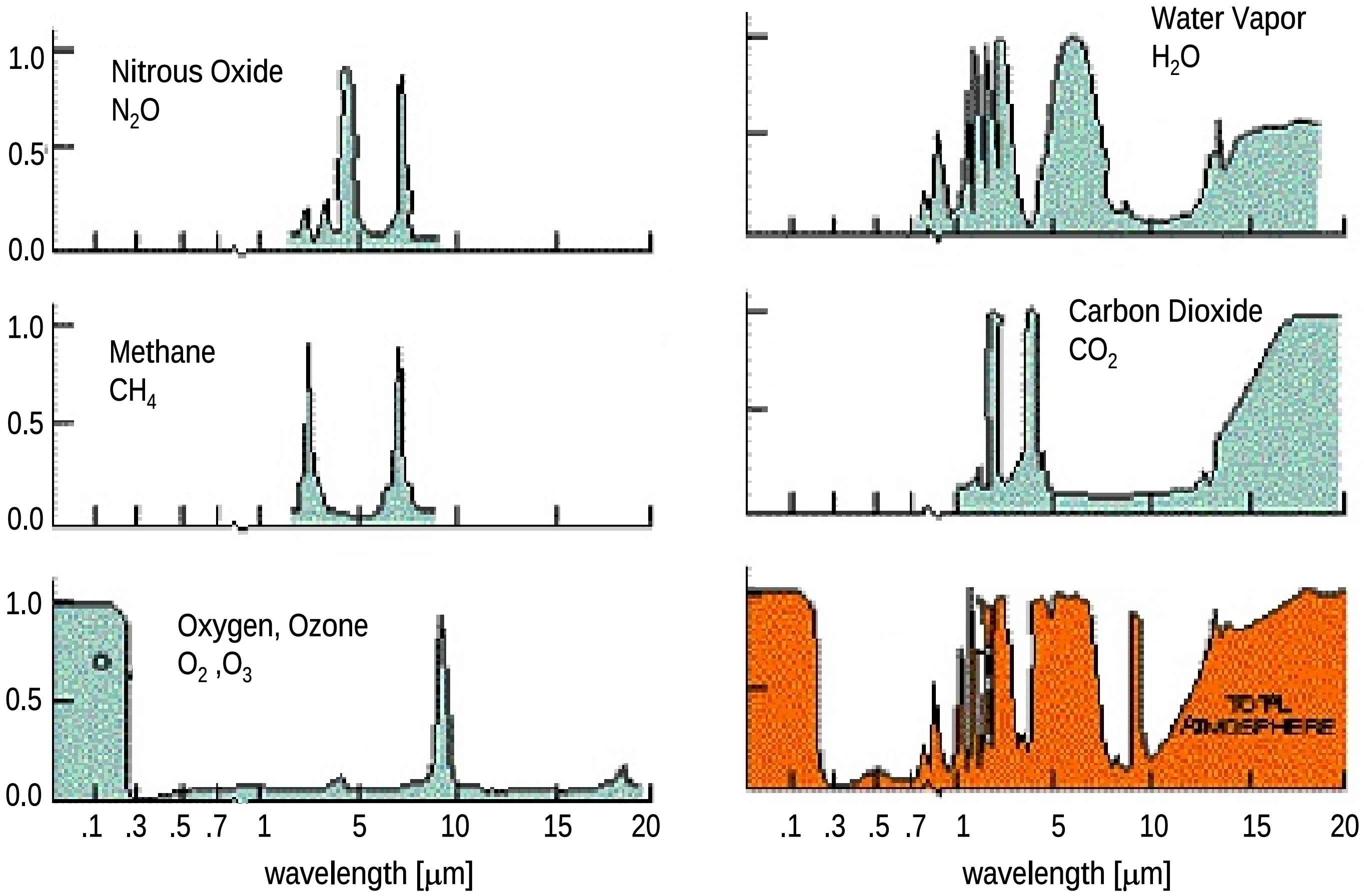


Mie Scattering,
larger particles

→ Direction of incident light

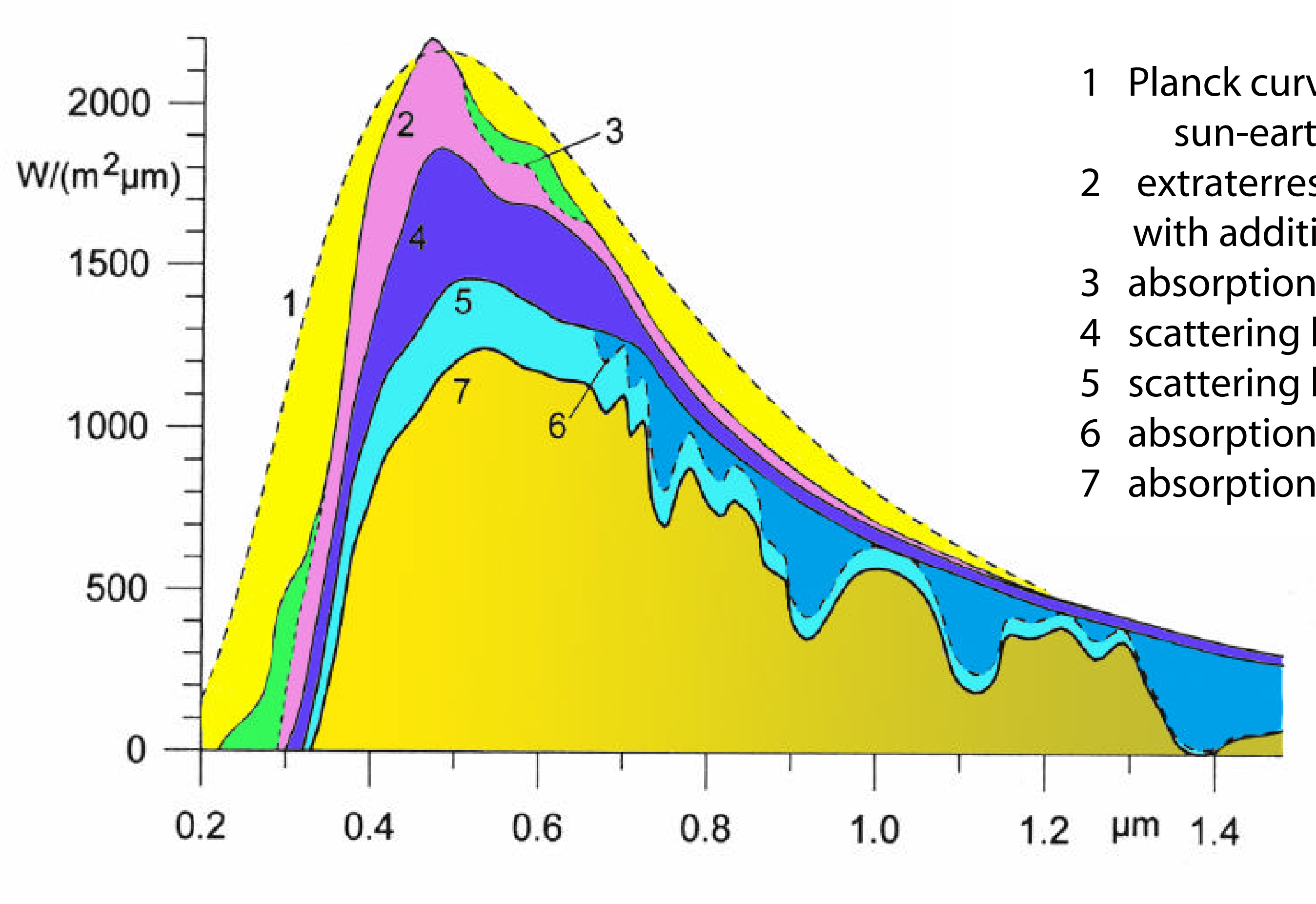
ATMOSPHERIC EXTINCTION

Selective Absortion in the Atmosphere



ATMOSPHERIC EXTINCTION

Spectral Solar Radiant Flux Density



1 Planck curve T=5780 K at mean
sun-earth distance

2 extraterrestrial solar spectrum
with additional

3 absorption by 0_3

4 scattering by 0_2 und N

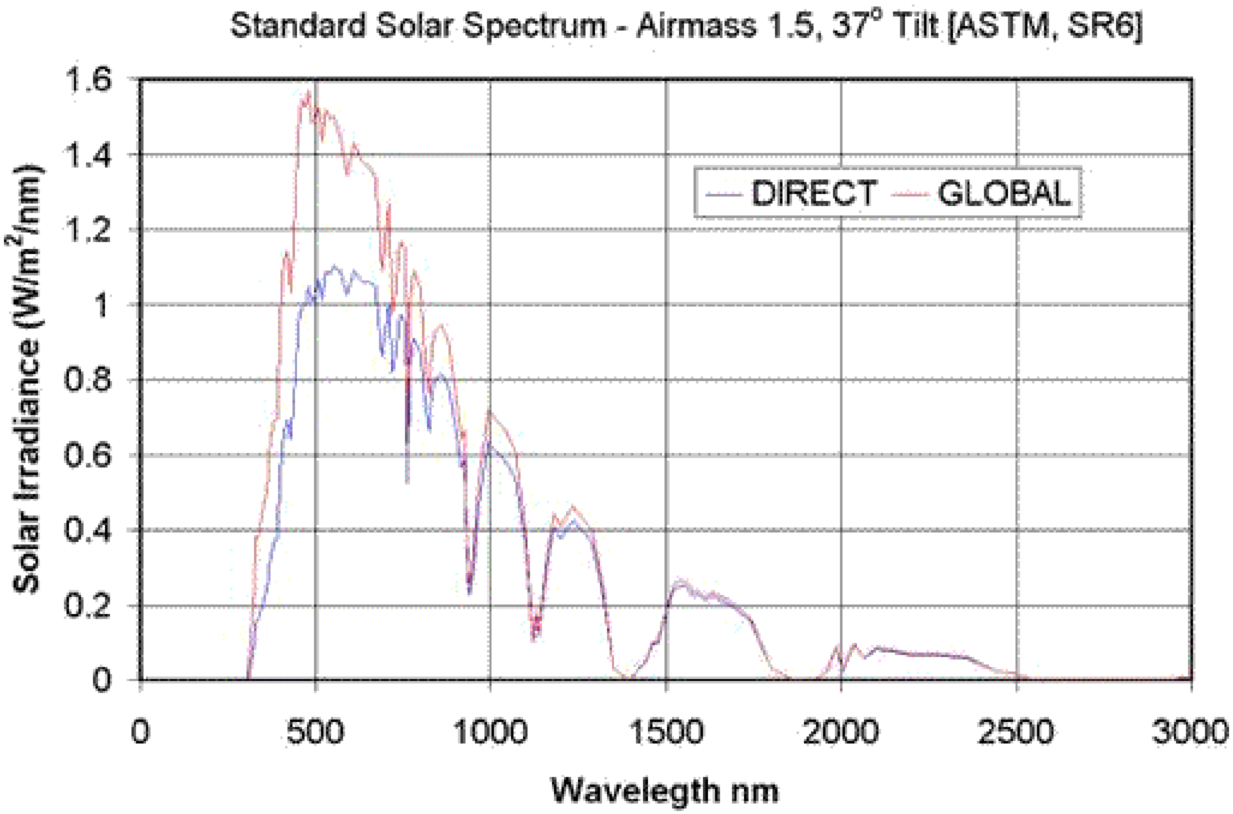
5 scattering by aerosols

6 absorption by H_2O vapor

7 absorption by aerosols

Source: Vogt

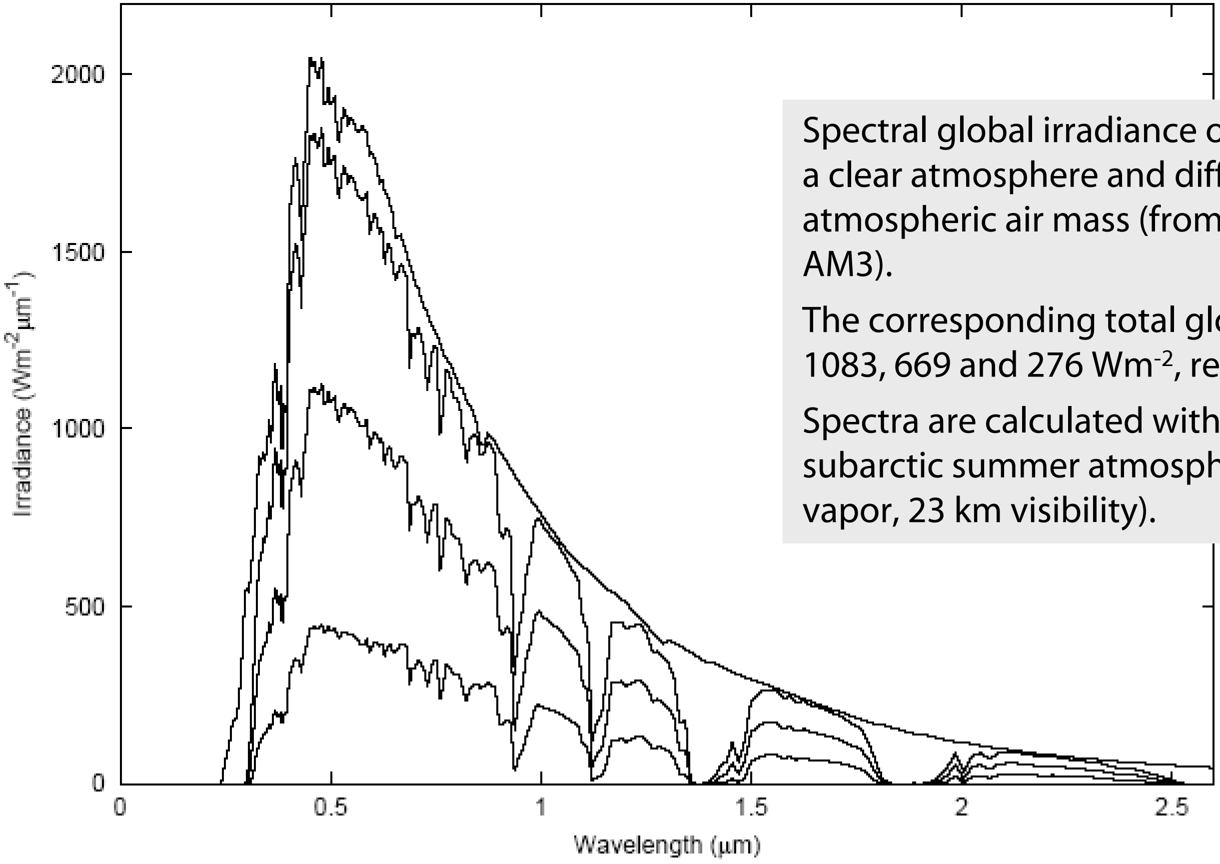
Standard Solar Spectrum



AM 1.5, 37° tilt

ASTM Standards
(E-891) and (E-892)

Spectral Irradiance depending on Air Mass



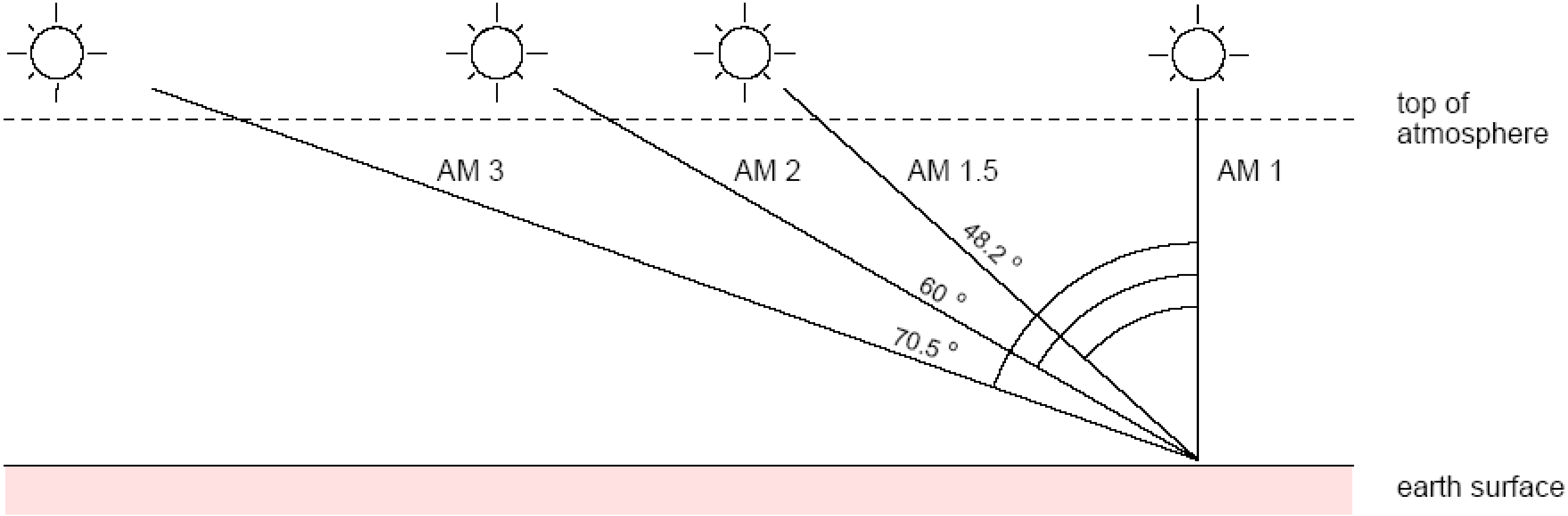
Spectral global irradiance on a horizontal surface for a clear atmosphere and different values of the atmospheric air mass (from top: AM0, AM1, AM1.5, AM3).

The corresponding total global irradiances are 1367, 1083, 669 and 276 Wm^{-2}, respectively.

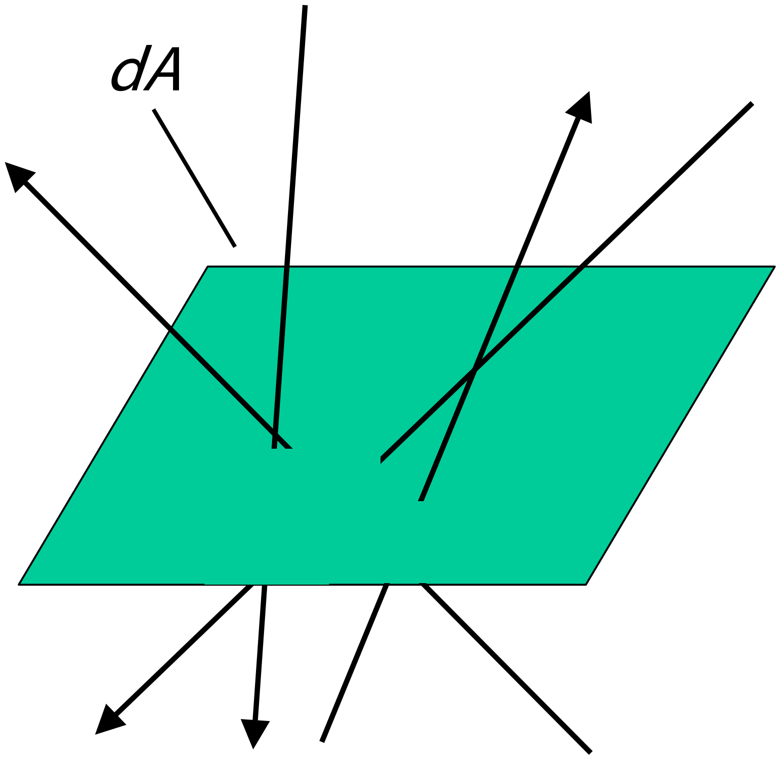
Spectra are calculated with SBDART using a subarctic summer atmosphere (1.42 gm^{-3} water vapor, 23 km visibility).

ATMOSPHERIC EXTINCTION

Air Mass



Definition: Radiant flux density



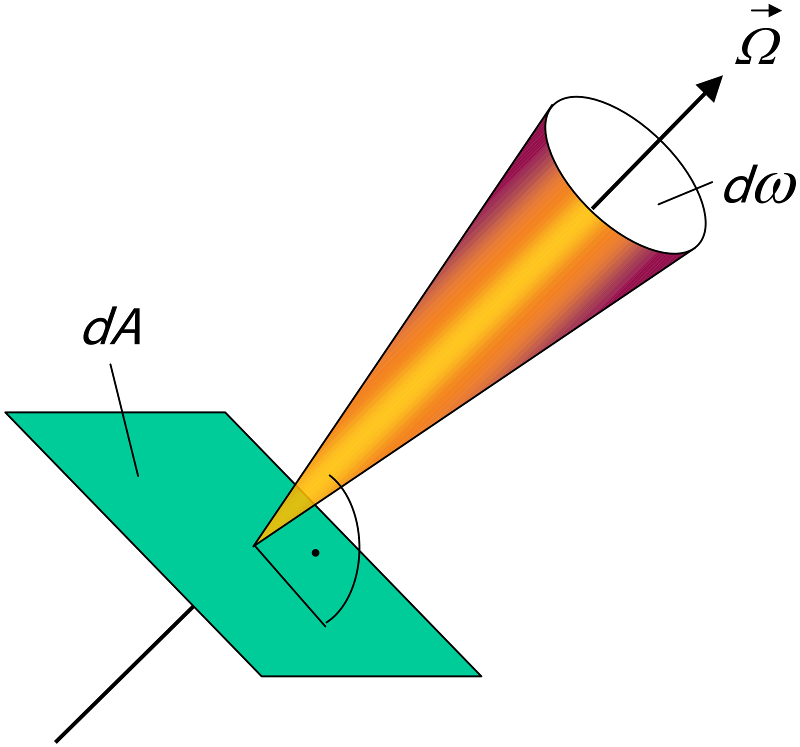
Energy flux density F

defines the radiant energy dQ passing through an area dA in the time interval t, $t+dt$:

$$d^2Q = F\,dA\,dt$$

Units of F are Wm^{-2}.

Definition: Radiance



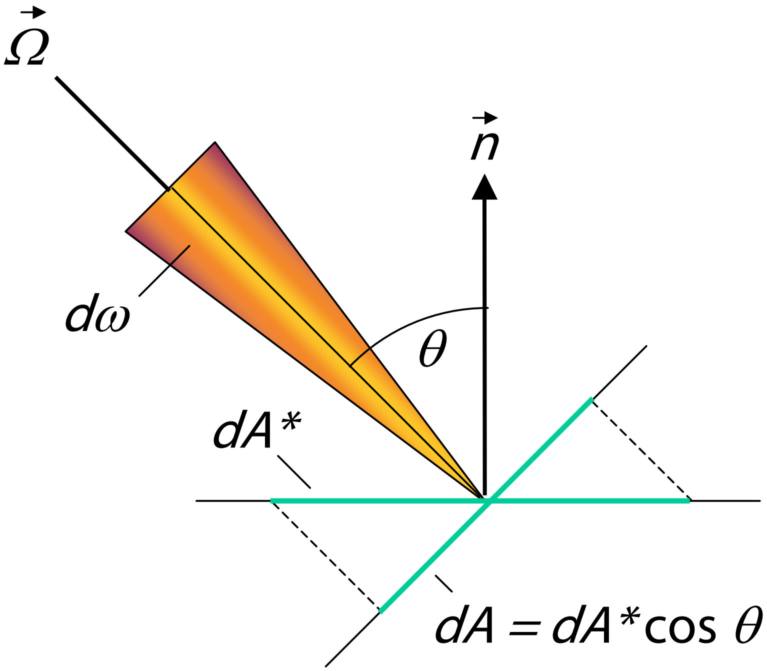
Radiance L

defines the radiant energy flux $d\Phi = dQ/dt$ passing through an area dA perpendicular to the direction Ω into by the solid angle $d\omega$:

$$d^3Q = L\,dA\,dt\,d\omega$$

Units of L are $\mathrm{Wm^{-2}sr^{-1}}$.

Relation between Radiance and Radiant Flux Density



According to the cosine law, the radiance crossing a surface *dA**, whose normal *n* makes an angle θ with the beam axis Ω, is:

$$L^* = \cos\theta\, L$$

and the radiant flux density calculates to

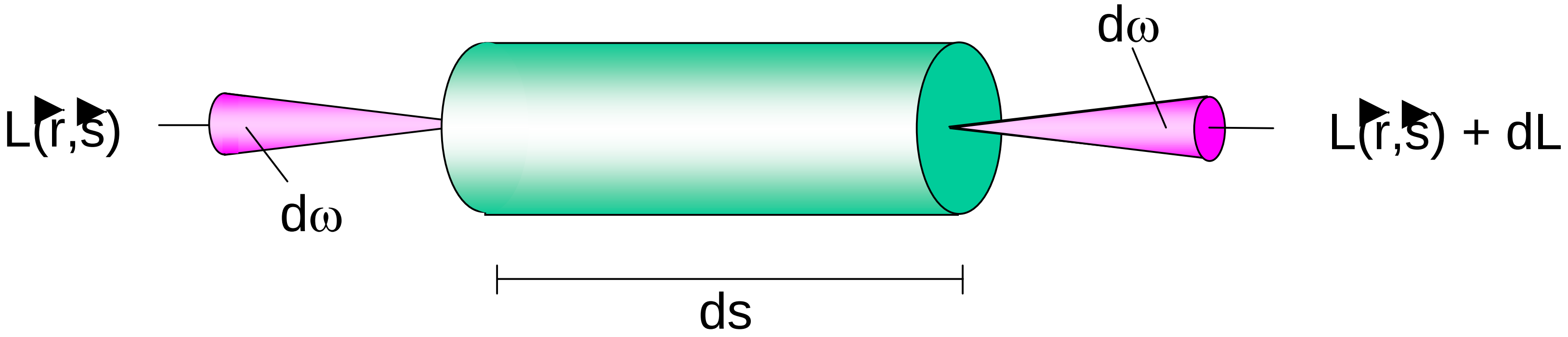
$$F = \iint_{4\pi} L \cos\theta \, d\omega$$

Macroscopic description of energy transfer by radiation

- parameterization of elementary processes:
  absorption, scattering, emission by equally distributed gases,
  ozone, water vapor, aerosols, clouds
- characterization of the radiation field by mean quantities

- *radiance* completely describes radiation field (location, direction)
- all energetically essential quantities can be derived from here!

ATMOSPHERIC RADIATIVE TRANSFER



$$\frac{dL_\lambda(\vec{r},\vec{s})}{ds} = -\sigma_{e\lambda}(\vec{r})\left[L_\lambda(\vec{r},\vec{s}) - J_\lambda(\vec{r})\right]$$

$$J_{\lambda,sc}(\vec{r},\vec{s}) = \frac{\sigma_{sc}}{\sigma_e}\frac{1}{4\pi}\int_{4\pi} P_\lambda(\vec{r},\vec{s},\vec{s}')L_\lambda(\vec{r},\vec{s}')d\omega'$$

ATMOSPHERIC RADIATIVE TRANSFER

Large numerical efforts necessary (Integro DE)

➔ approximations:

plan-parallel atmosphere (horizontally homogeneity)

good approximation, because mostly it is: d/dz << d/dx, d/dy

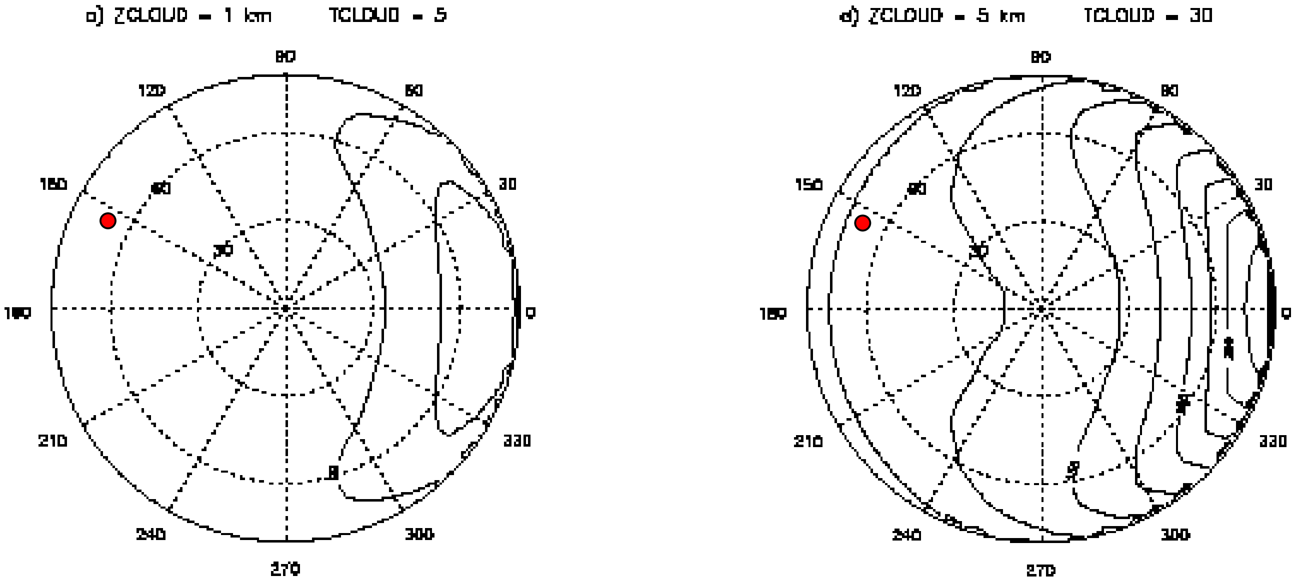
But: finite clouds, heterogeneous surface, low solar altitude

necessary:

- extinction coefficient for all interactive processes
- wavelength dependency of absorption
- phase functions for scattering processes
- validity of approximations

ATMOSPHERIC RADIATIVE TRANSFER

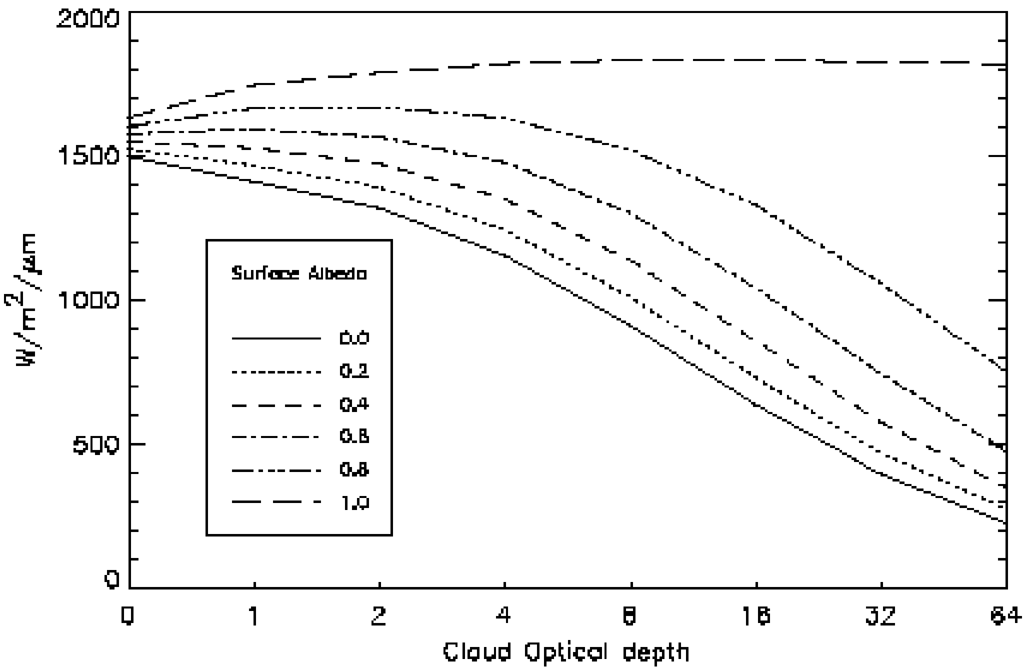
Example 1:



Directional distribution of reflected solar irradiance at top of atmosphere for low thin (left) and high thick clouds (right)

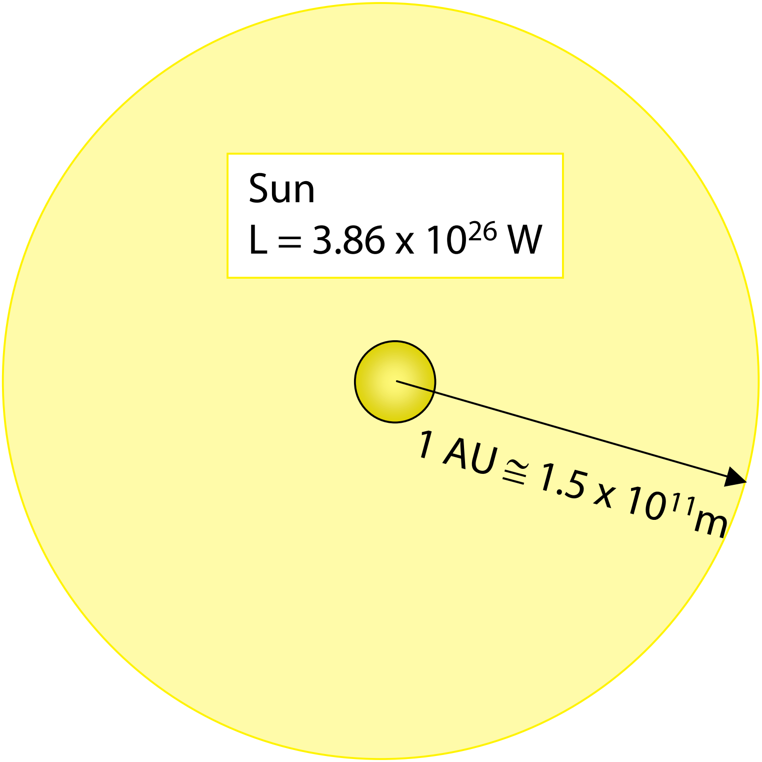
ATMOSPHERIC RADIATIVE TRANSFER

Example 2:



Monochromatic solar surface irradiance ($\mu = 550$ nm, $\theta_z = 30°$)

Solar Constant



Area of a sphere = $4\pi r^2$

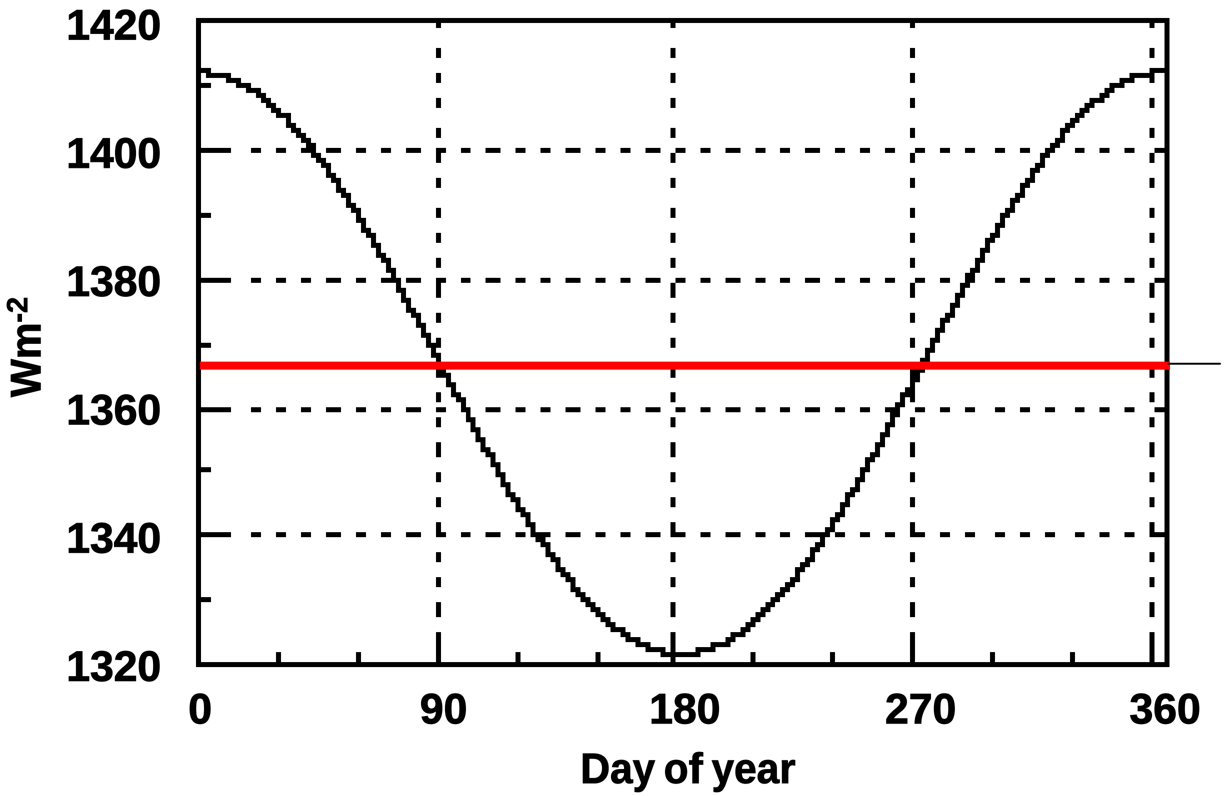
Conservation of energy requires that the total energy flux coming out of the sun must also pass through a sphere at 1 AU.

The energy flux density at 1 AU is

$$\frac{L}{4\pi r^2} = 1367\ \mathrm{Wm^{-2}}.$$

This is the **Solar Constant**.

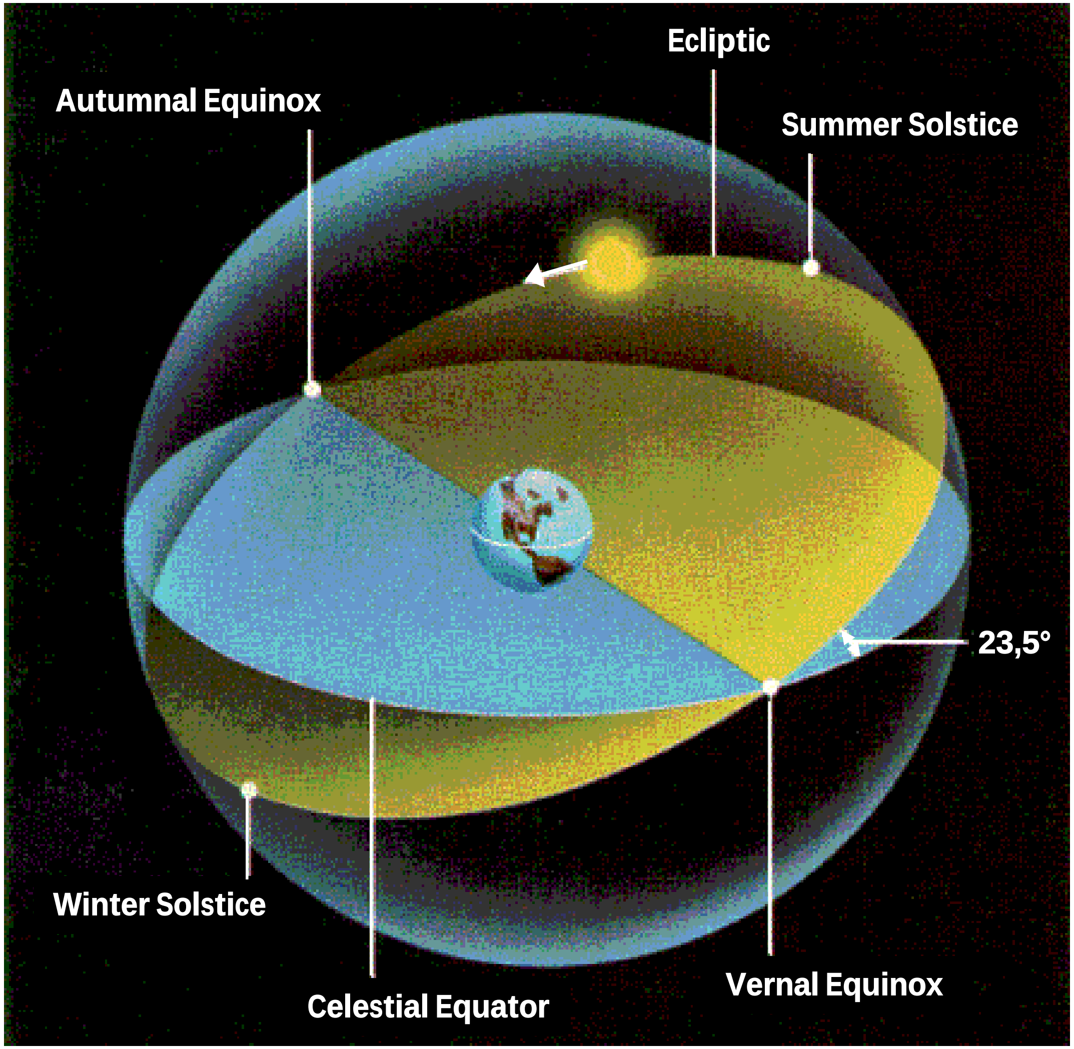
Extraterrestrial Radiation



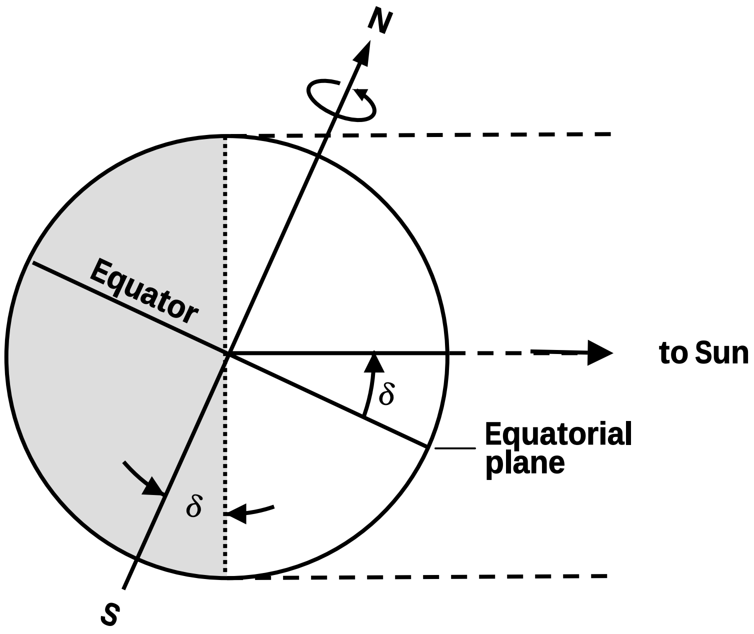
Solar constant = 1367 Wm^{-2}

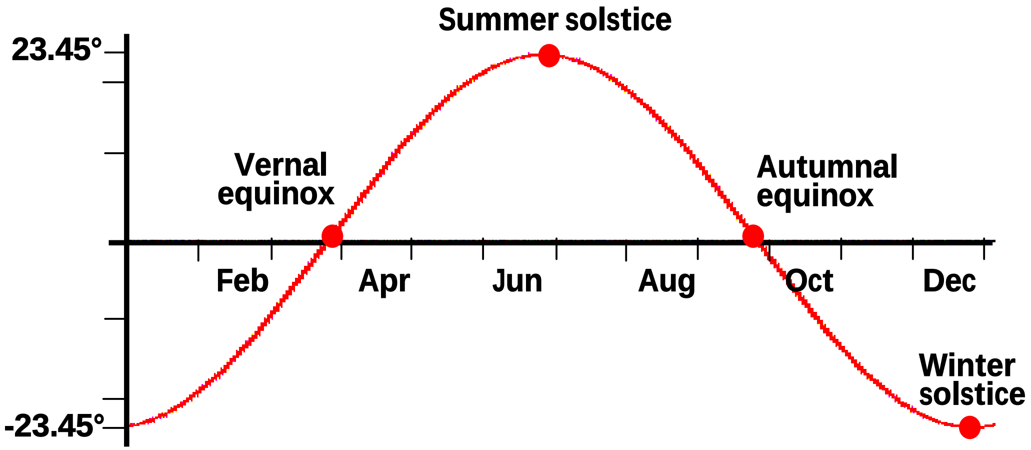
THE SOLAR RESOURCE

Ecliptic



Solar Declination





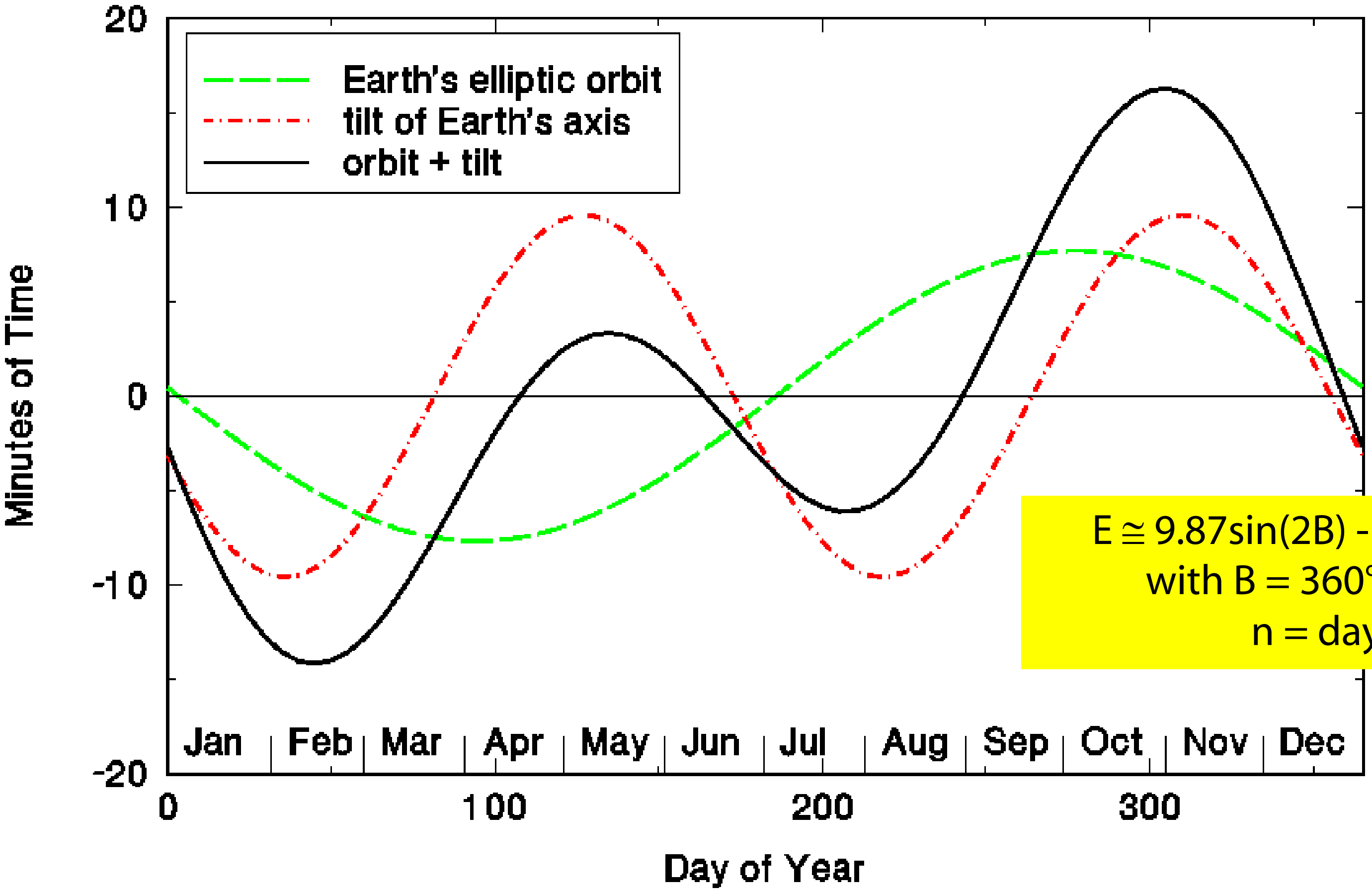
Declination angle $\delta = 23.45°$

Variation of the declination angle:

$\delta \cong 23.45 * \sin [360 / 365 * (284 + n)]$

with n = day of the year

Equation of Time

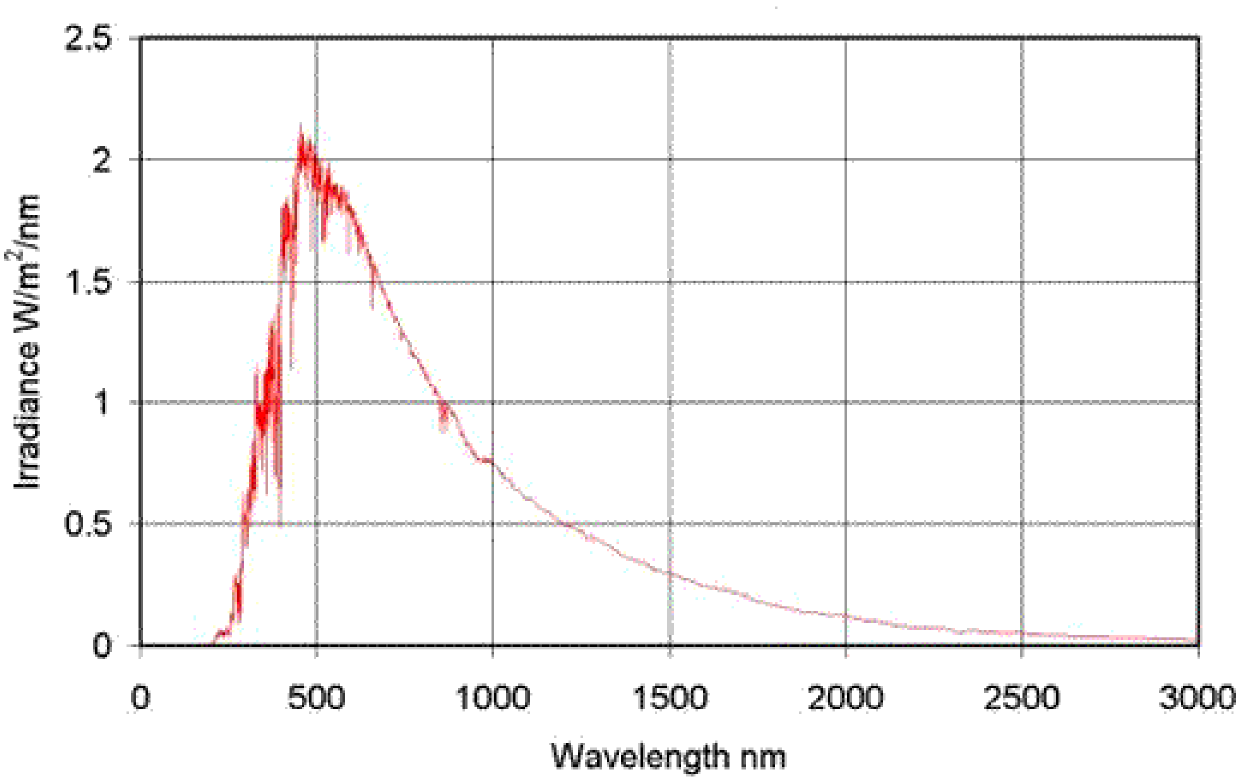


$$E \cong 9.87\sin(2B) - 7.53\cos(B) - 1.5\sin(B)$$

with $B = 360° (n - 81) / 364$ and

n = day of the year

Extraterrestrial Solar Spectrum



Source: C. Wehrli,1985

Extraterrestrial Solar Irradiance
Solar Spectral Irradiance at Sea Level

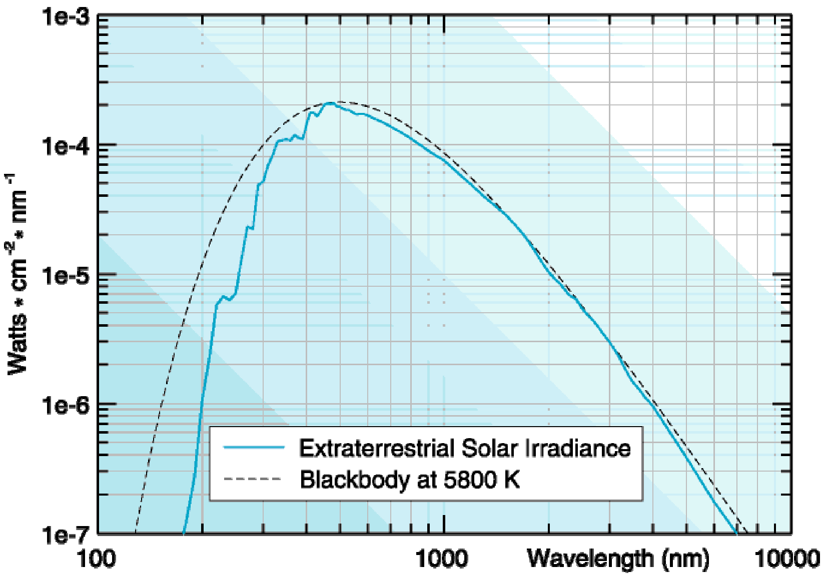


Fig. 5.7 Extraterrestrial solar irradiance compared to a blackbody.

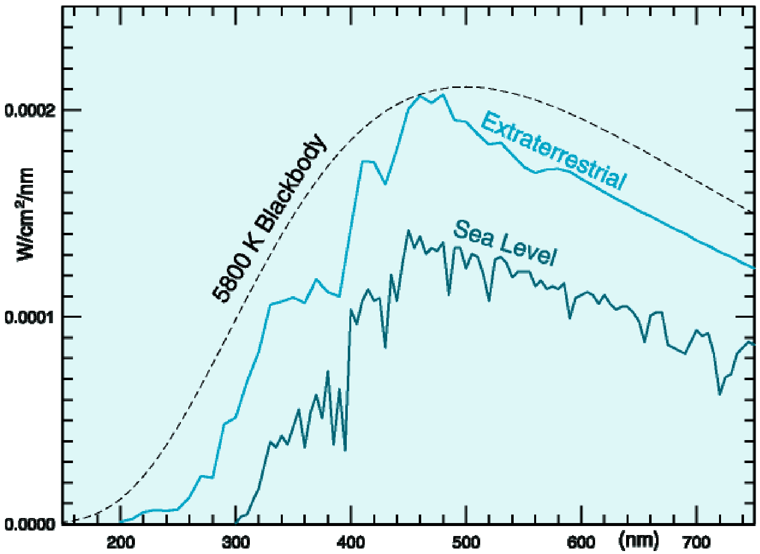
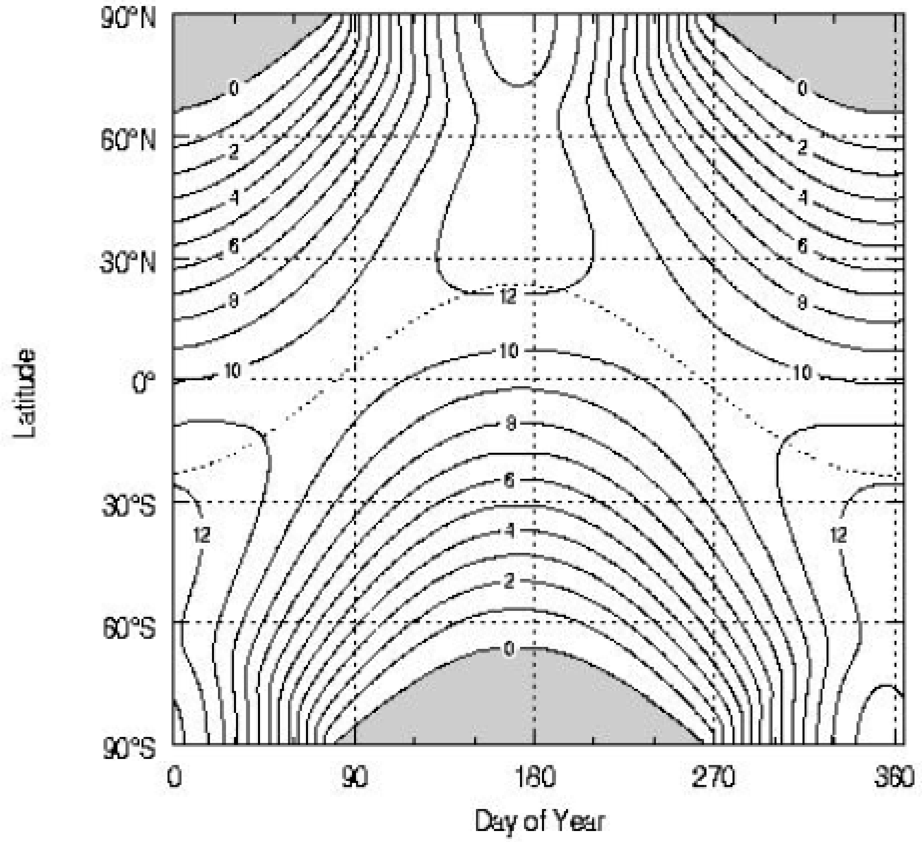


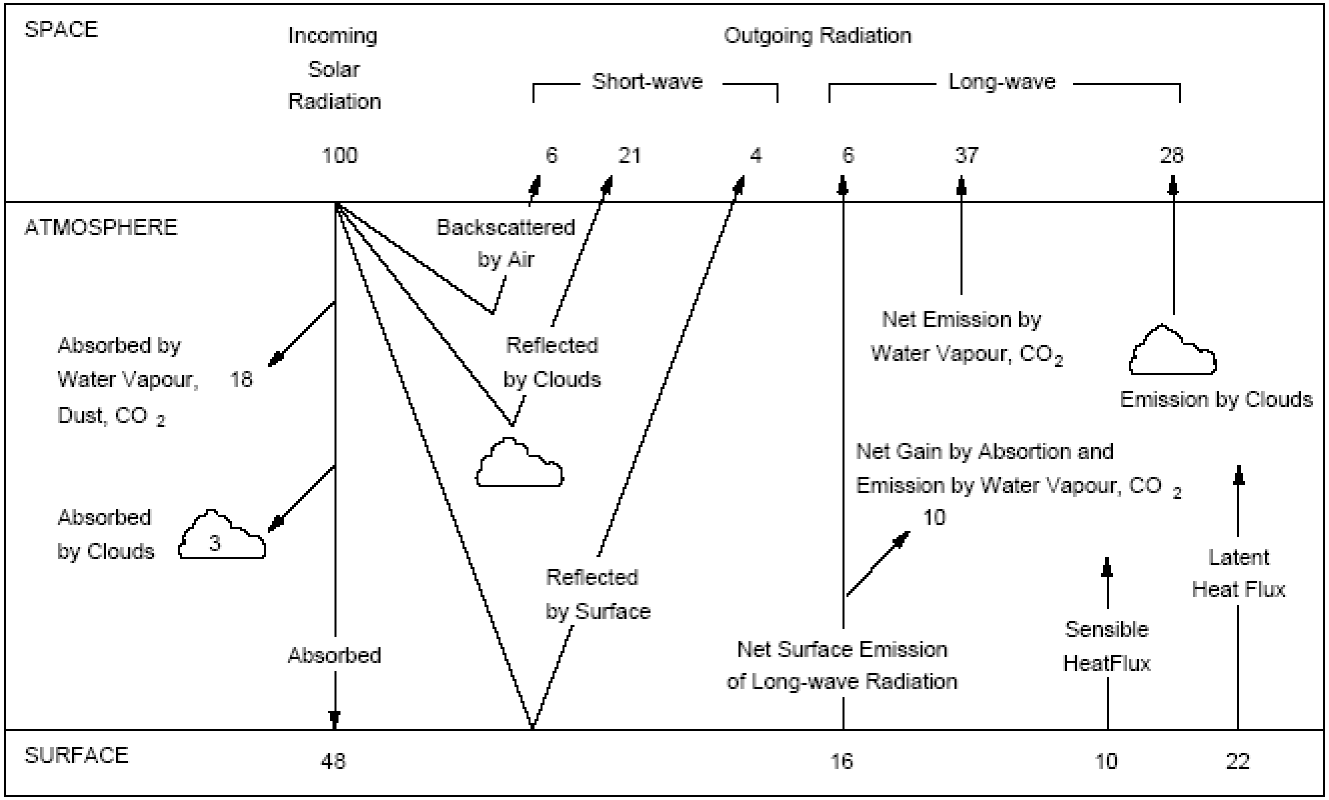
Fig. 5.8 Solar irradiance at sea level.

Average Daily Extraterrestrial Radiation on a Horizontal Surface



in kWh m^{-2} d^{-1}

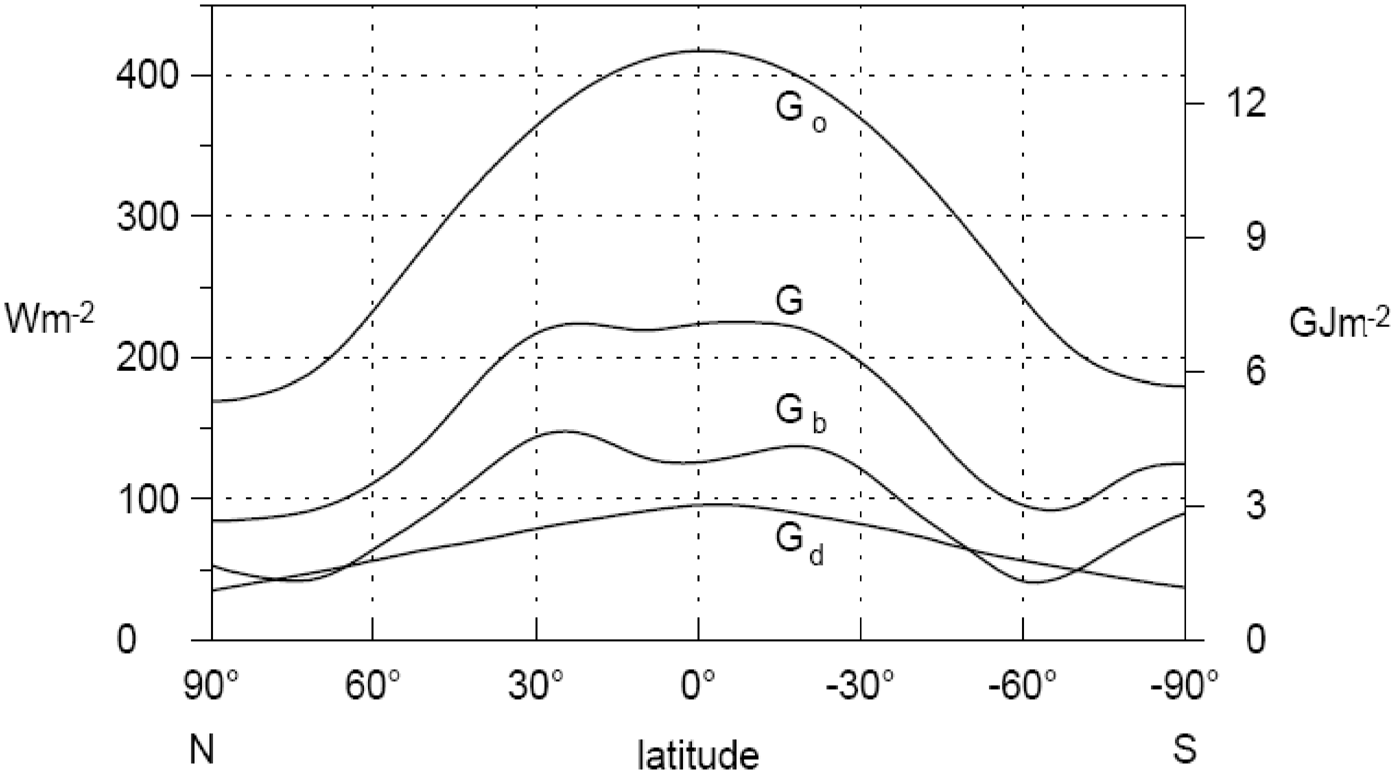
Global Mean Radiative Energy Budget



Numbers are given in percent of the mean solar input.

100 % = 342 Wm^{-2}

Mean Meridional Radiation Profiles



extraterrestrial radiation G_o

global radiation G

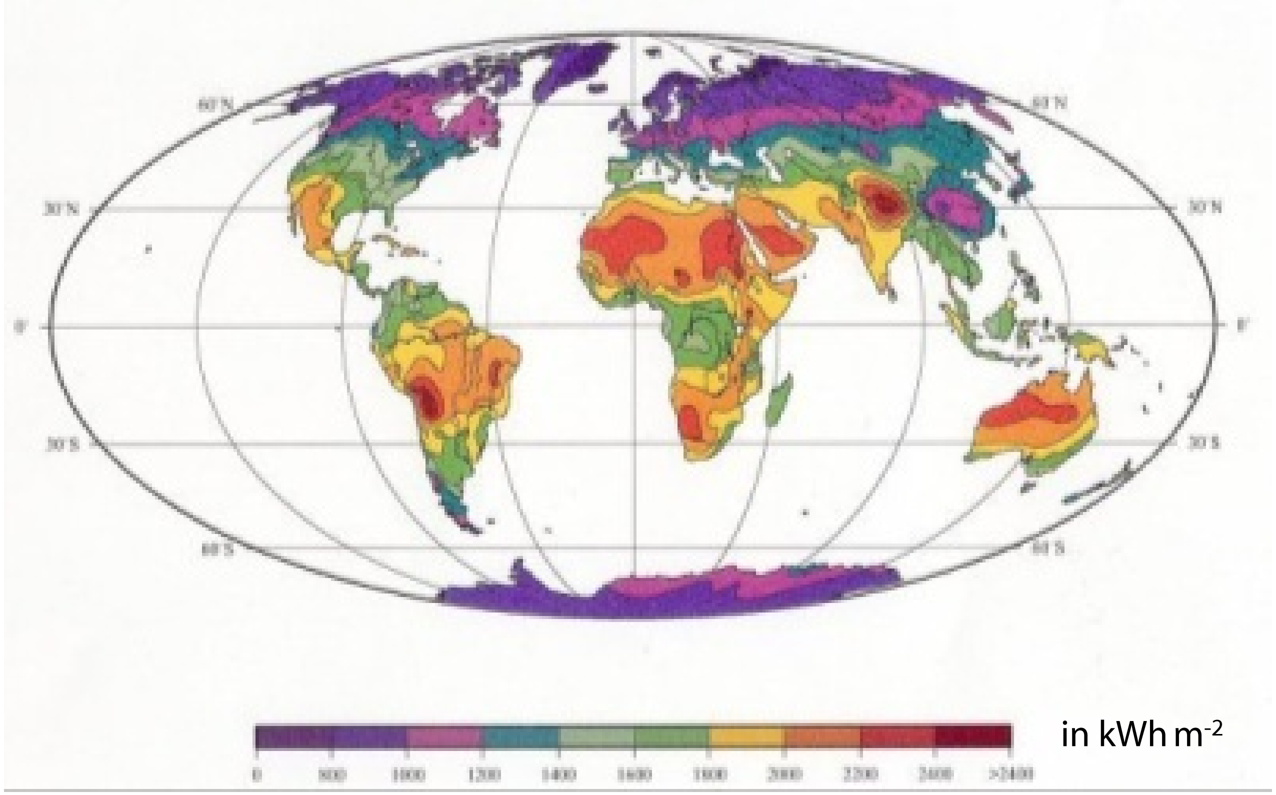
direct radiation G_b

diffuse radiation G_d

on a horizontal surface.

The scales are average irradiance (left, in Wm^{-2}) and annual solar radiation (right, in GJm^{-2}).

Global Average Annual Solar Radiation

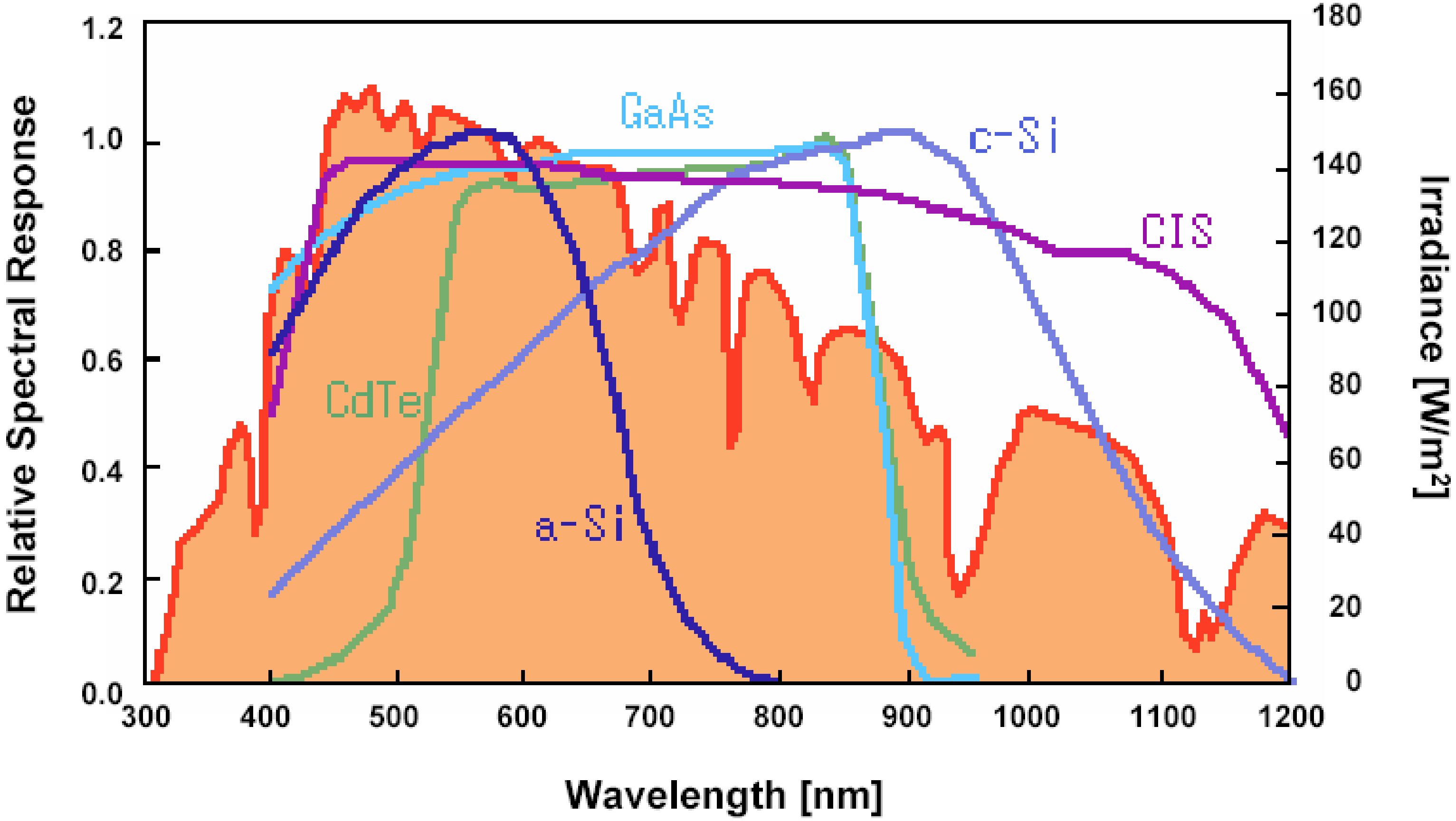


in kWh m^{-2}

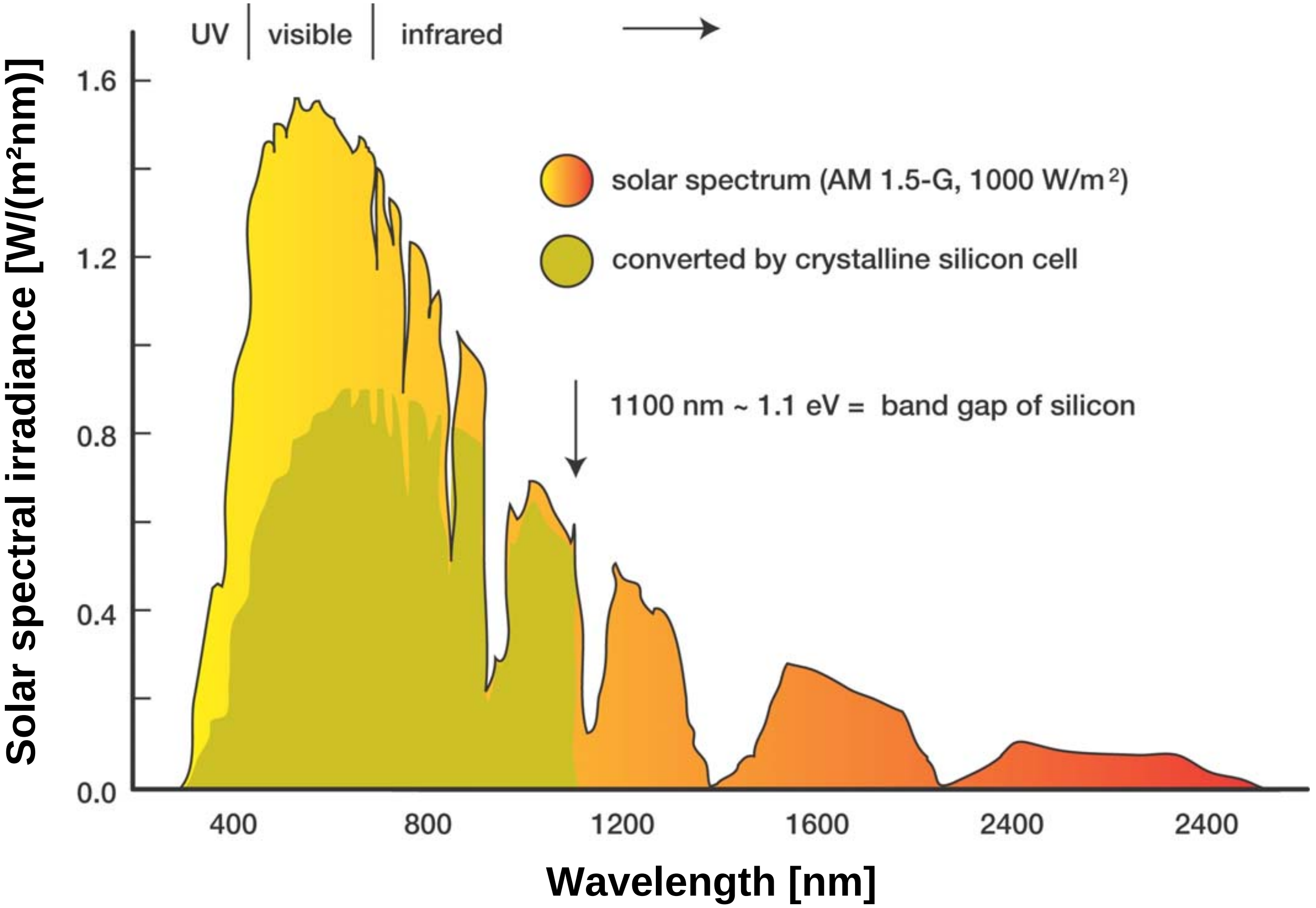
Source: German Weather Service DWD

SPECTRAL RESPONSE

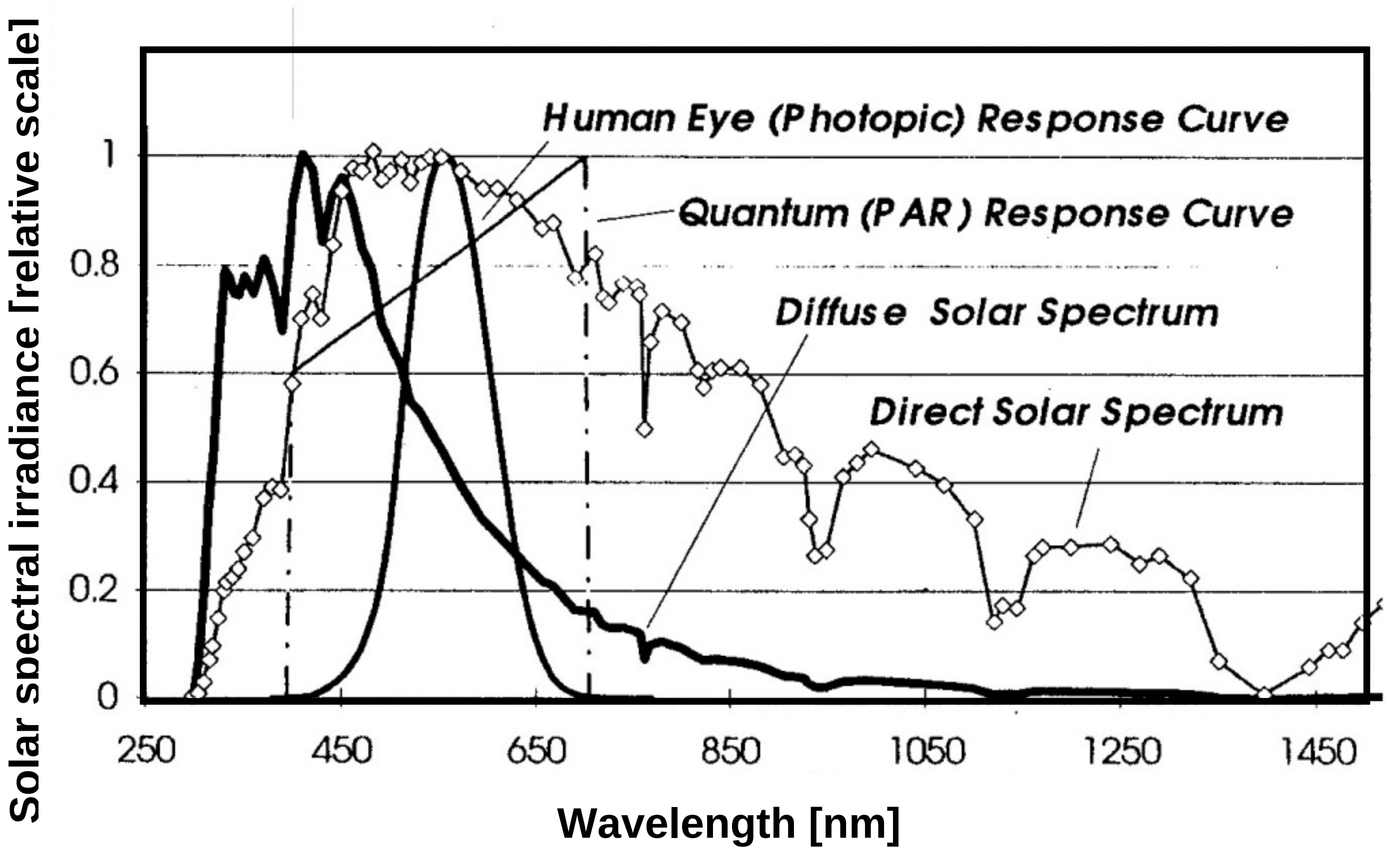
Spectral Response of Solar Cells



Spectral Irradiance and Solar Cell Response

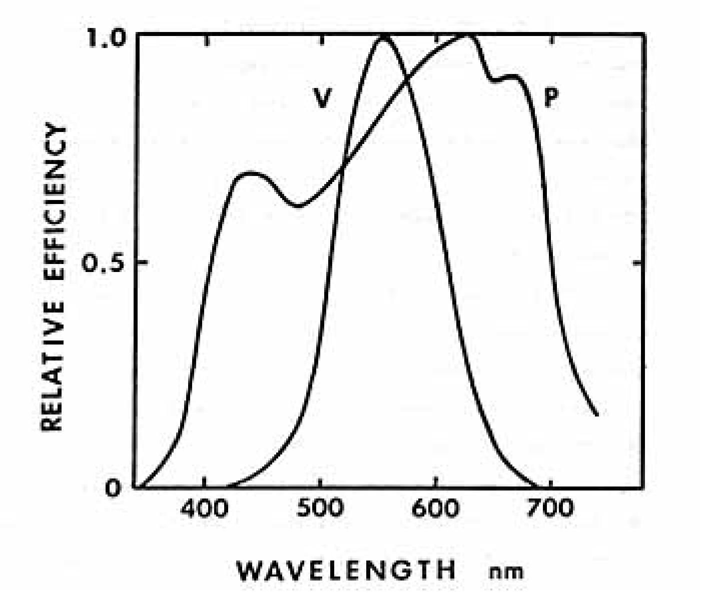


Spectral Response: Daylighting, Photosynthesis



Source: Perez et al.

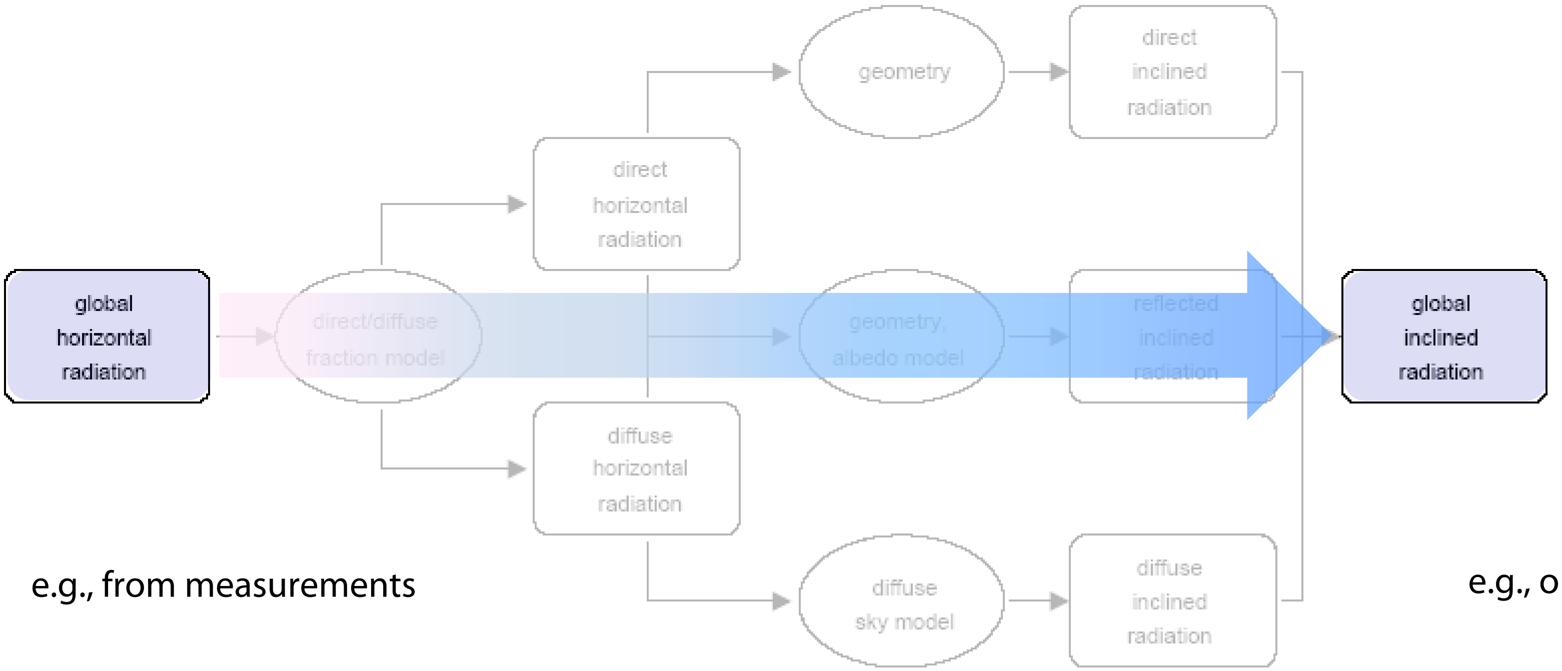
Spectral Response: Daylighting, Photosynthesis



V: Relative luminous efficiency of equal incident radiant fluxes as a function of wavelength, for the C. I. E. Standard Photometric Observer (C.I.E., 1970)

P: relative photosynthetic efficiency of equal absorbed quantum fluxes, as a function of wavelength, for an average green leaf (McCree, 1972)

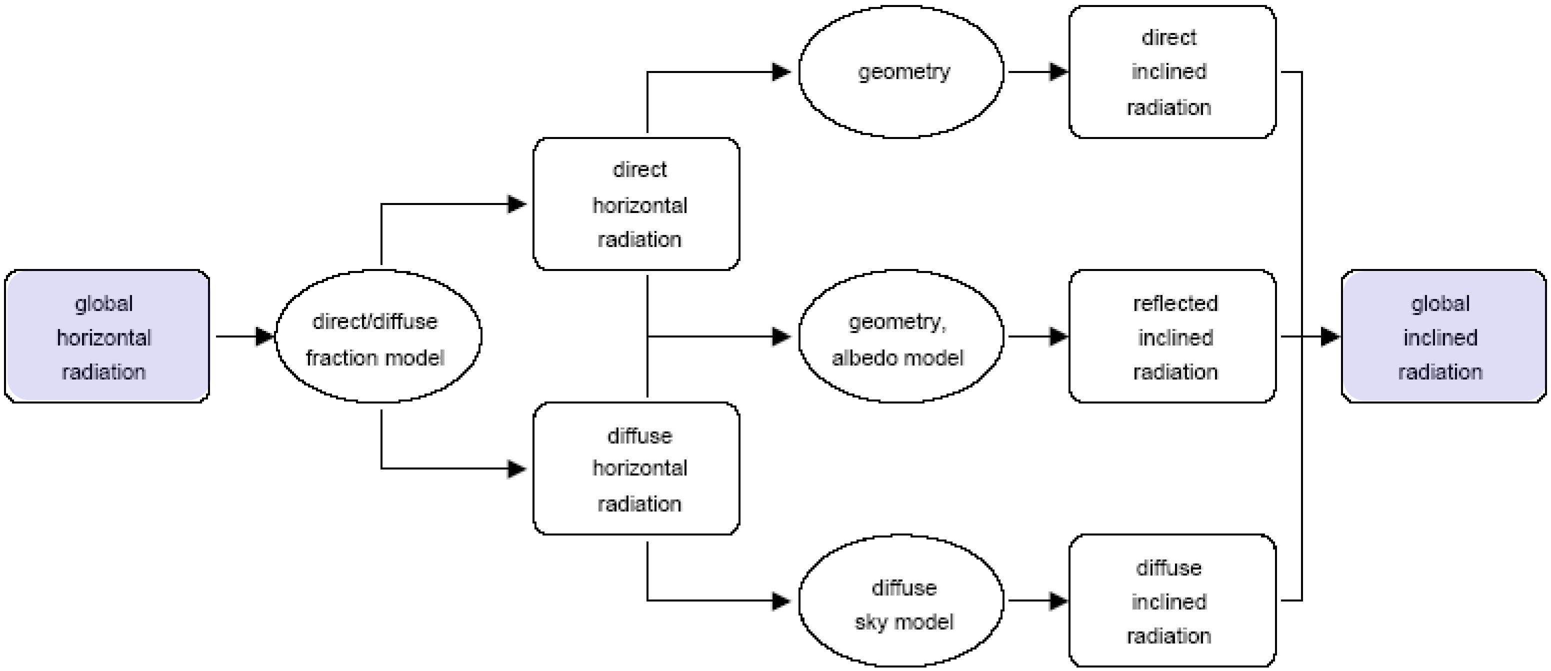
Conversion to Arbitrarily Oriented Surfaces



e.g., from measurements

e.g., on PV array

Conversion to Arbitrarily Oriented Surfaces



global horizontal radiation

direct/diffuse fraction model

direct horizontal radiation

diffuse horizontal radiation

geometry

geometry, albedo model

diffuse sky model

direct inclined radiation

reflected inclined radiation

diffuse inclined radiation

global inclined radiation

Diffuse Fraction Models

- Calculation of tilted radiation needs diffuse fraction
- but: depends heavily on empirical tuning
- available for various time scales
- nonlinear!
- mainly related with: clearness index (global irradiance), solar elevation, turbidity, hour-to-hour-variability, surface albedo
- important: proper probability distribution of diffuse fraction

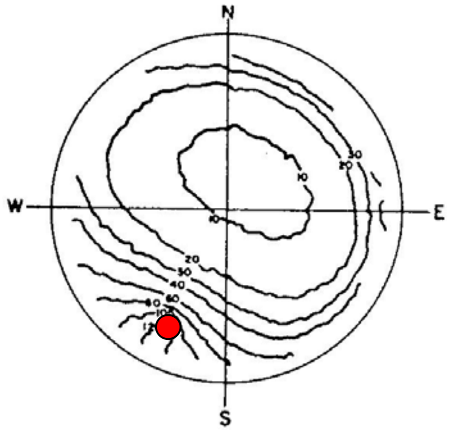
The mystery of Solar Geometry: angle of incidence θ

$$\begin{aligned}\cos\theta = {} & \sin\delta\,\sin\phi\,\cos s - \sin\delta\,\cos\theta\,\sin s\,\cos\gamma \\ & + \cos\delta\,\cos\phi\,\cos s\,\cos\omega + \cos\delta\,\sin\phi\,\sin s\,\cos\gamma\,\cos\omega \\ & + \cos\delta\,\sin s\,\sin\gamma\,\sin\omega\end{aligned}$$

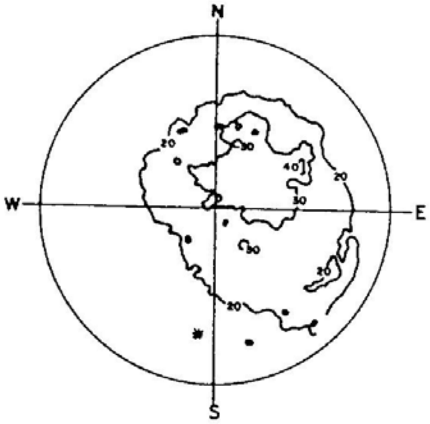
with:
latitude ϕ
solar declination δ
hour angle ω
slope s
surface azimuth γ

Diffuse Irradiance Modeling

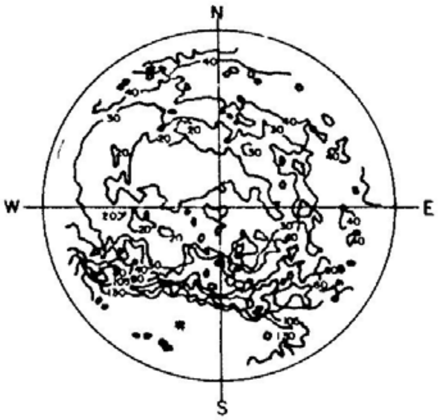
Problem: Directionality of diffuse radiation



Clear sky



Cloudy sky



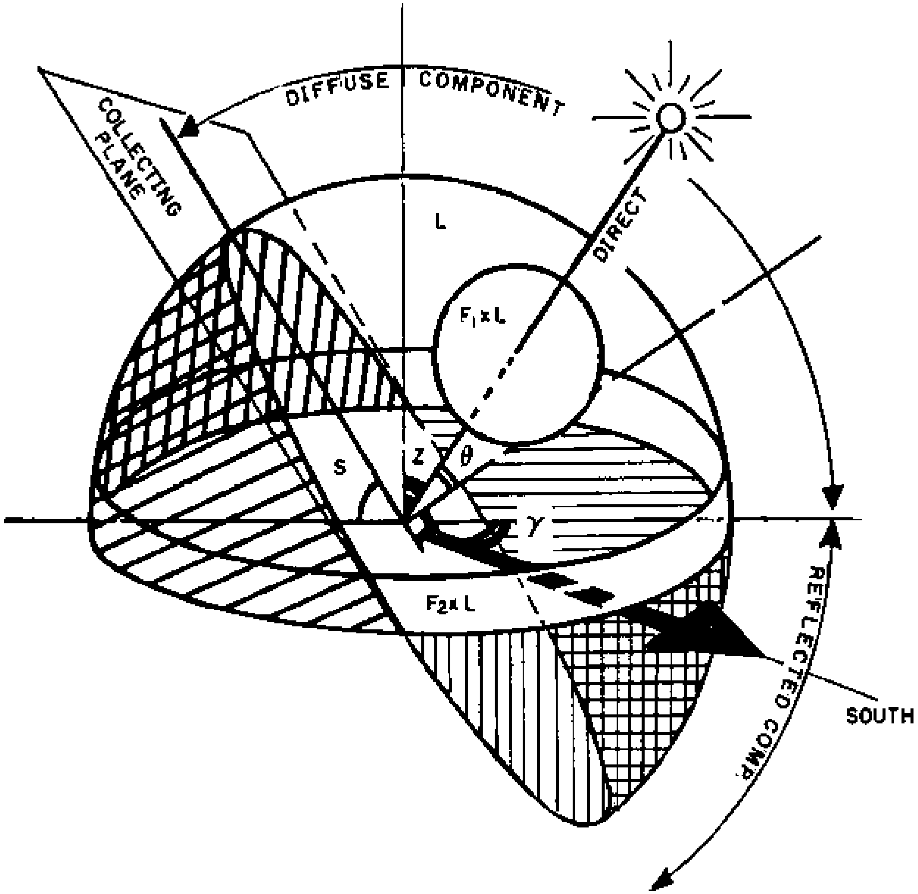
Intermediate sky
(broken cloudiness)

Isotropic approximation only acceptable – if at all – for cloudy skies!

Diffuse Irradiance Modeling

- Part of transposing radiation from available horizontal components
- strongly depends on number and quality of input data
- ground reflected radiation important for tilt > 45°
- simplest approach: isotropic model (Liu/Jordan) – o.k. for low quality input and/or longer averages
- accounting for circumsolar diffuse component next step to increase accuracy
- horizon brightening effect, if both radiation components are available

Example: Perez Diffuse Irradiance Model



Representation of the three radiation components seen by a tilted plane (direct, diffuse and reflected) and representation of the sky dome used in the Perez algorithm.

Sky radiance is respectively equal to L, F_1L, and F_2L for the main, the circumsolar, and the horizon zone.

Highly empirical approach!

SOLAR IRRADIANCE MODELING

Modeling of Clear Sky Irradiance

Simple broadband clear sky model for direct and diffuse irradiance (Bird)

Basic equations:

$$I_{dir} = I_o (\cos \theta)\ (0.9662)\ \tau_{Rayl}\tau_{O3}\tau_{MolAbs}\tau_{H2O}\tau_{Aer}$$

$$I_{atm\_sc} = I_o (\cos \theta)\ (0.79)\ \tau_{O3}\tau_{H2O}\tau_{MolAbs}\tau_{H2O}\tau_{AerAbs} \\ [0.5\ (1-\tau_{Rayl}) + B_a\ (1-\tau_{AerSc})]\ /\ 1 - m + (m)^{1.02}$$

$$I_g = (I_{dir} + I_{atm\_sc})\ /\ (1-r_g r_s)$$

with I_o: extraterrestrial irradiance, τ: atmospheric transmittances

Modeling of Clear Sky Irradiance

Model input:

Solar constant, zenith angle, surface pressure, surface albedo, precipitable water content, total ozone column, turbidity, aerosol foreward scattering ratio

RESEARCH TOPICS

- Remote sensing of surface solar irradiance
- Satellite-based surveillance of PV systems
- Solar irradiance forecasting
- Spatial and temporal variability of the solar resource

SUMMARY

- Use of renewable energies adds new challenge for meteorology (methods, data)
- integrated, interdisciplinary approach necessary (various sources, various systems)
- detailed knowledge of ‘fuel‘ is key to integration of RE technologies (information as energy source, high economic benefits)
- both, applied and fundamental research is necessary

ENERGY METEOROLOGY

INSTITUTE OF PHYSICS
ENERGY METEOROLOGY

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Energy Meteorology is a major research field within the Department of Energy and Semiconductor Research EHF of the Institute of Physics. It is a new disclipline at the interface between renewable energy research (mainly solar and wind) and atmospheric physics.

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