Atmospheric Radiation and Visibility

- Atmospheric radiation
- Atmospheric visibility
- Colors of the atmosphere

Radiation
Electromagnetic Energy and Photons

- The electromagnetic energy of radiation is carried by photons.
- The energy of a photon, E_p, depends on its wavelength:

$$\boxed{E_p = h\,\nu = \frac{h\,c}{\lambda}}$$

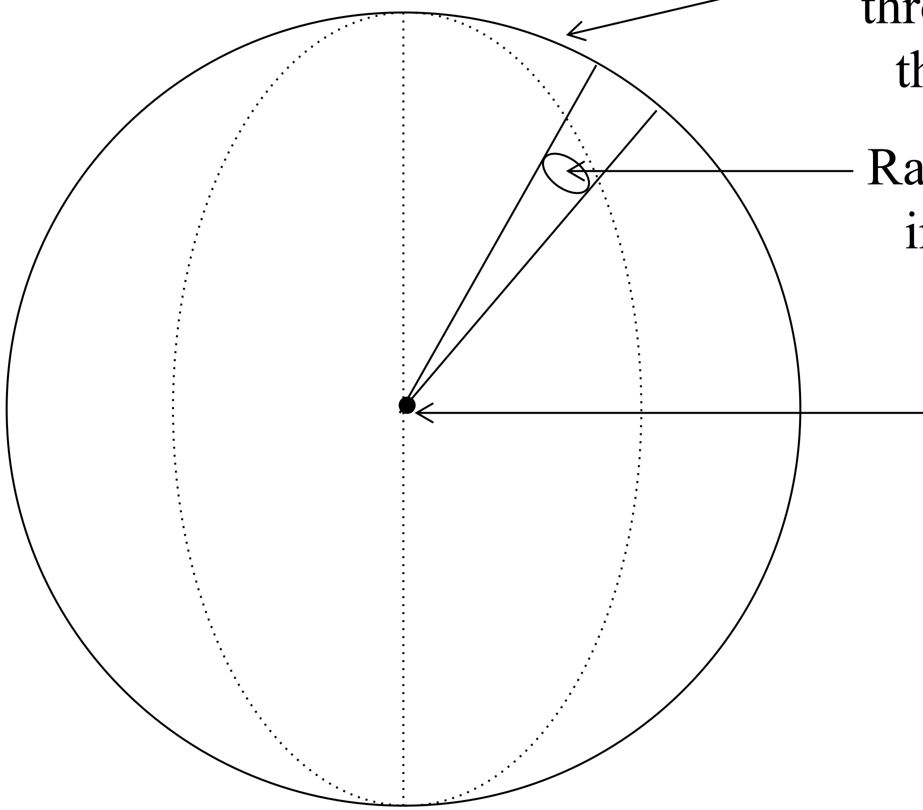
where h is the Planck constant (6.626×10^{-34} J s), ν is the frequency of the photon, c is the speed of light (3×10^{8} m s^{-1}), and λ is the wavelength of the photon.

- Therefore, the ultraviolet radiation has more energy than the infrared radiation:
  - Ultraviolet (UV): < 400 nm
  - Visible: from 400 nm (violet) to 700 nm (red)
  - Infrarouge (IR): > 700 nm

Radiation
Definitions of Radiance and Irradiance

- Energy of radiation (electromagnetic energy): Joule (J)
- Radiative rate (by unit time): J s^{-1} ; W
- Radiance (Intensity; *I*) ; it is the directional radiation flux (3D) : W per steradian (solid angle) per unit surface area; W sr^{-1} m^{-2}
- Irradiance (E_e) ; it is the radiative flux through a surface coming from all directions (2D): W m^{-2}
- Radiance and irradiance may be expressed as a function of the wavelength:
  - Spectral radiance: I_λ (W sr^{-1} m^{-2} nm^{-1})
  - Spectral irradiance: $E_{e,\lambda}$ (W m^{-2} nm^{-1})

Radiation
Definitions of Radiance and Irradiance



Irradiance of the source through the surface of the sphere (W m^{-2})

Radiance of the source in a given direction (W sr^{-1} m^{-2})

Radiative energy rate at the source (W)

Radiation
Temperature and Wavelength

- The spectral radiance of a black body is governed by Planck's law

- The law of Stefan-Boltzmann may be derived from Planck's law; it gives the irradiance, E_e, as a function of temperature:

$$\boxed{E_e = \sigma_{SB}\, T^4}$$

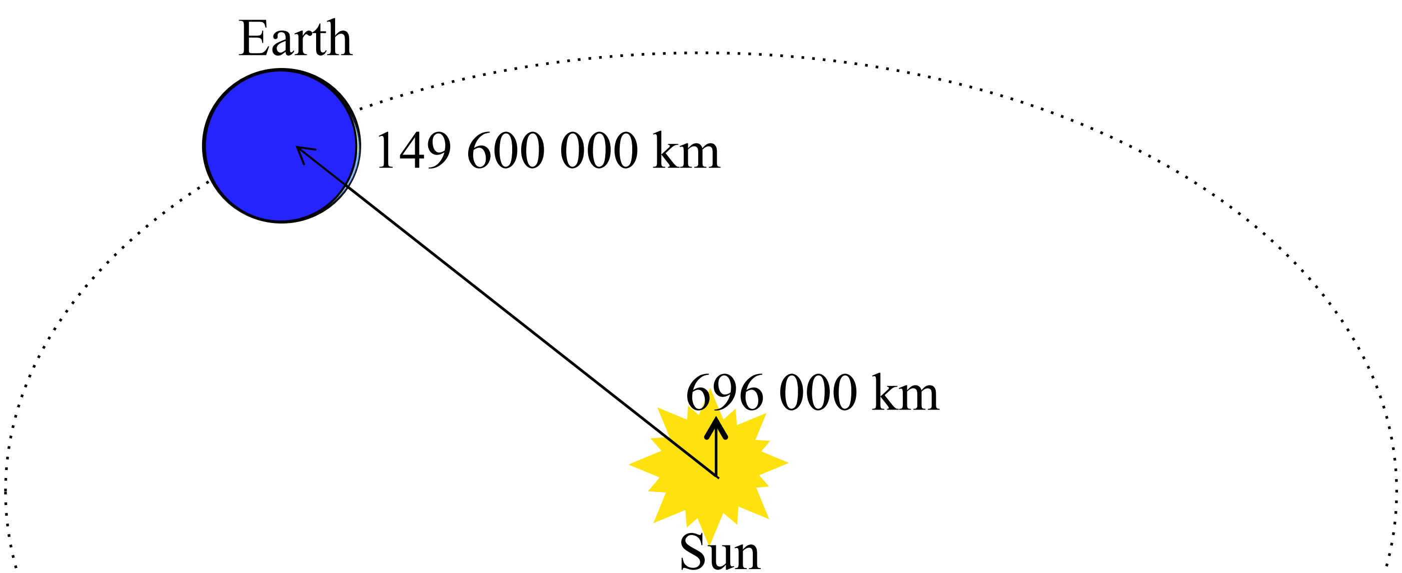
- Wien's law can also be derived from Planck's law; it is the wavelength, λ_{max}, that corresponds to the maximum radiative energy:

$$\boxed{\lambda_{\max} = \frac{h\,c}{\left(5\,k_B\,T\right)} = \frac{2.9 \text{ x } 10^6}{T}}$$

- The Sun's temperature is $T = 5772$ K

Therefore: $E_{e,S} = 6.29 \text{ x } 10^7$ W m^{-2} , $\lambda max_{,S} = 500$ nm (blue-green)

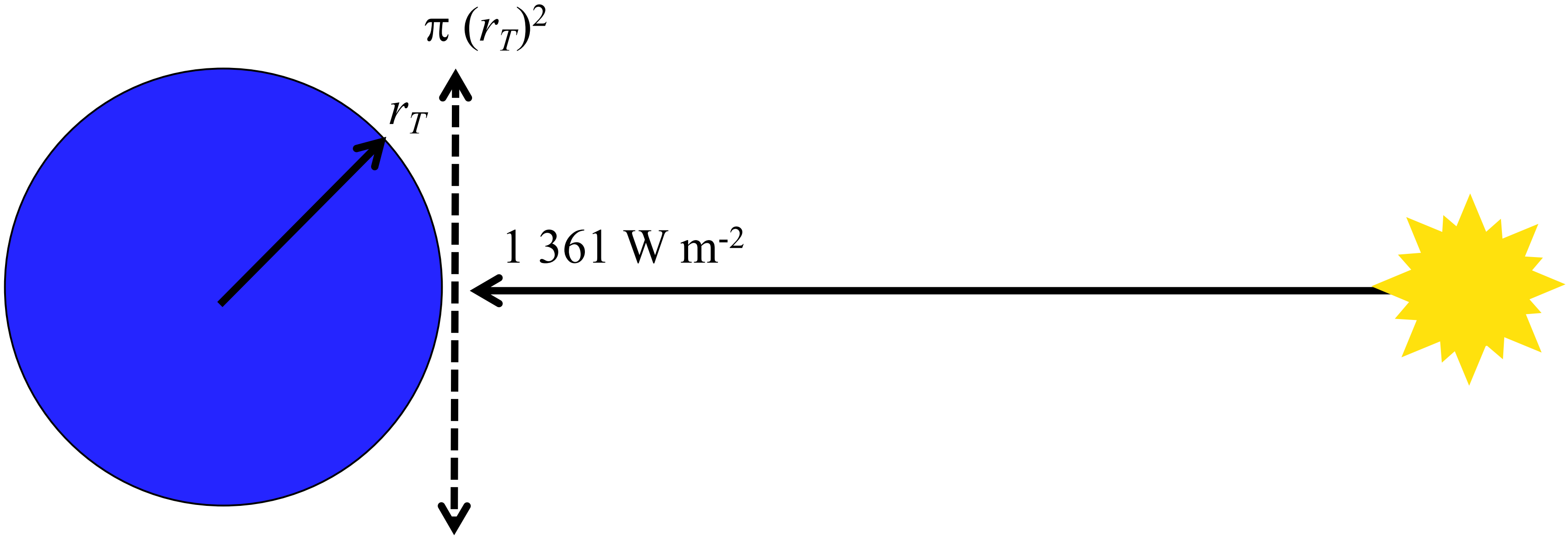
Solar Radiation
Reaching the Earth's Atmosphere



$$E_S = 6{,}29 \text{ x } 10^7 \left(\frac{696}{149\,600} \right)^2 = 1361 \text{ W m}^{-2}$$

E_s is the solar constant

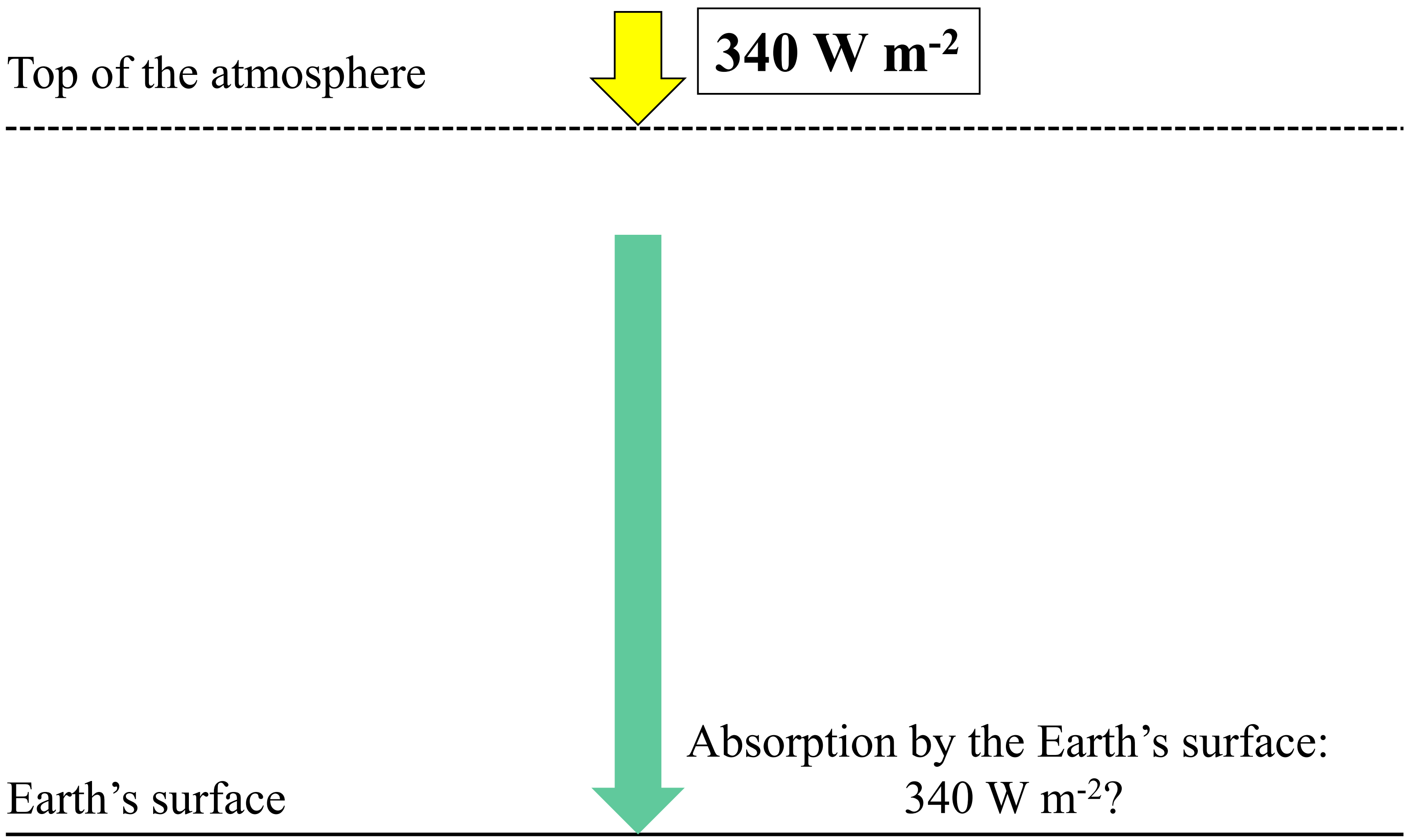
Solar Radiation
Reaching the Earth's Atmosphere



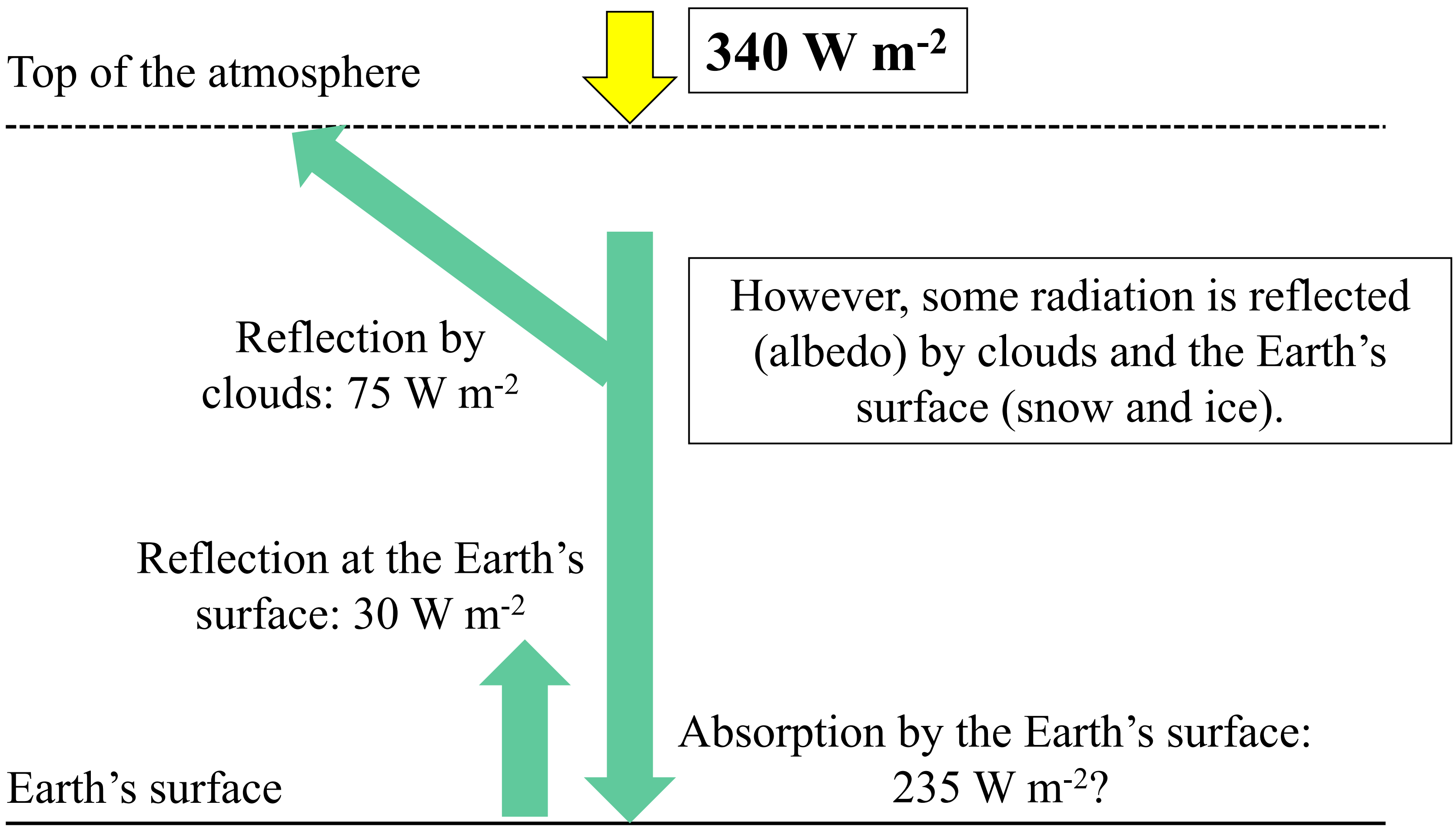
Mean radiative flux ($E_{e,E}$) = 1361 x $\pi\ (r_T)^2$ / (4 $\pi\ (r_T)^2$) = 340 W m^{-2}

It is the mean radiative flux at the top of the atmosphere.

Solar Radiation
Reaching the Earth's Atmosphere



Solar Radiation
Reaching the Earth's Atmosphere



Mean Temperature of the Earth's without the Atmosphere

- According the the law of Stefan-Boltzmann, which relates irradiance and temperature:

$$\boxed{E_e = \sigma_{SB} T^4}$$

- Without any atmosphere, the irradiance reaching the Earth's surface would be 340 W m^{-2}

$$T = \left(\frac{E_{e,E}}{\sigma_{SB}}\right)^{\frac{1}{4}} = \left(\frac{340}{5.67 \text{ x } 10^{-8}}\right)^{\frac{1}{4}} = 278 \text{ K} = +5\ °\text{C}$$

- With clouds and snow/ice (Earth's albedo), but without any absorption of radiation by the atmosphere, the irradiance absorbed by the Earth's surface would be 235 W m^{-2}

$$T = \left(\frac{E_{e,E}}{\sigma_{SB}}\right)^{\frac{1}{4}} = \left(\frac{235}{5.67 \text{ x } 10^{-8}}\right)^{\frac{1}{4}} = 254 \text{ K} = -19\ °\text{C}$$

Interactions between Radiation and Molecules

- No or little interaction: for example, molecular nitrogen (N_2), which absorbs UV radiation at very small wavelengths

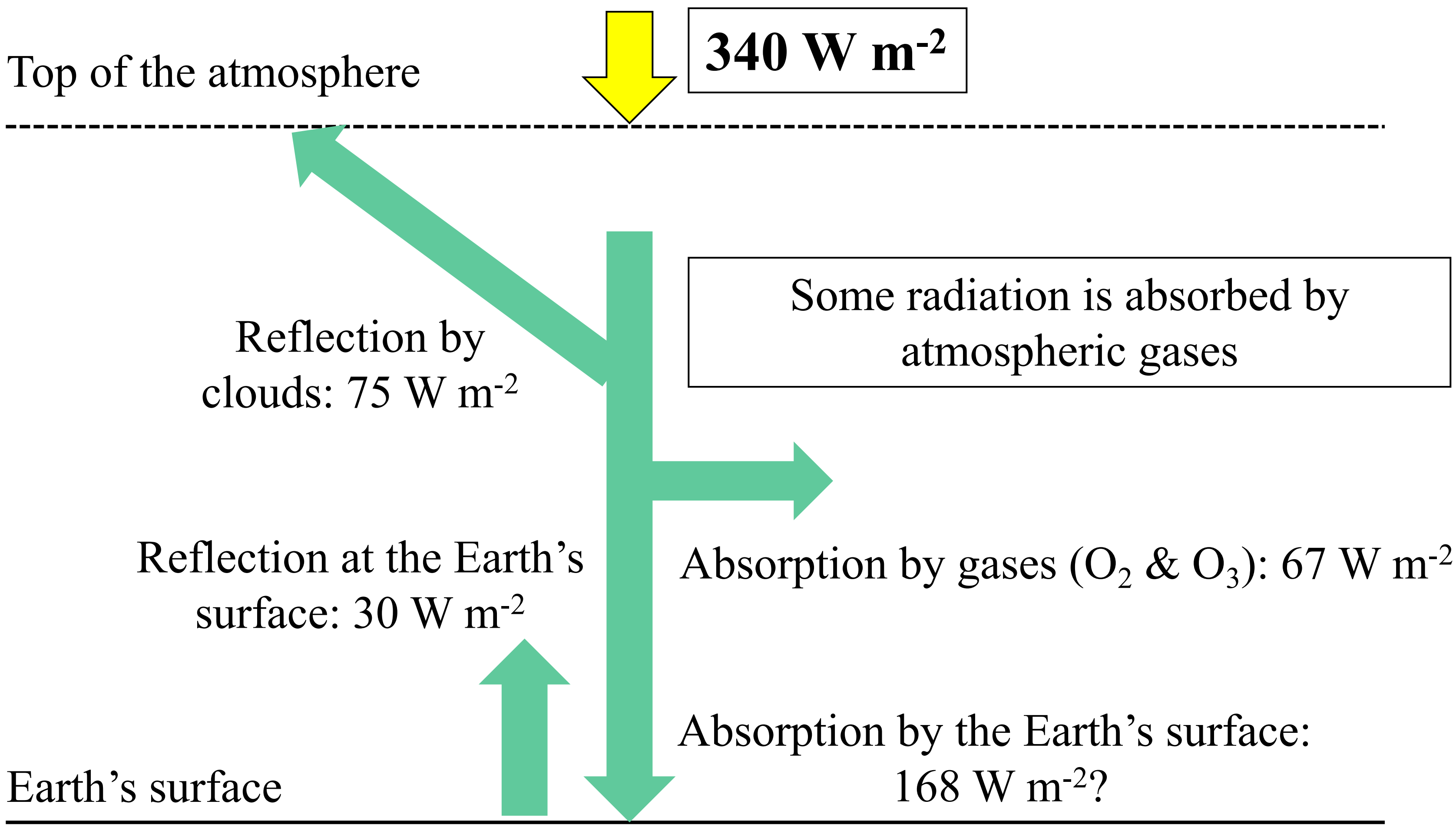
- Absorption of UV and visible radiation:
  - Enough radiative energy to break molecular bonds: O_2, O_3, NO_2, etc.
  - Radiative energy is converted into thermal energy.

$$\begin{array}{c} h\nu \\ \downarrow \\ \text{O-O} \end{array} \Rightarrow 2\ \text{O}$$

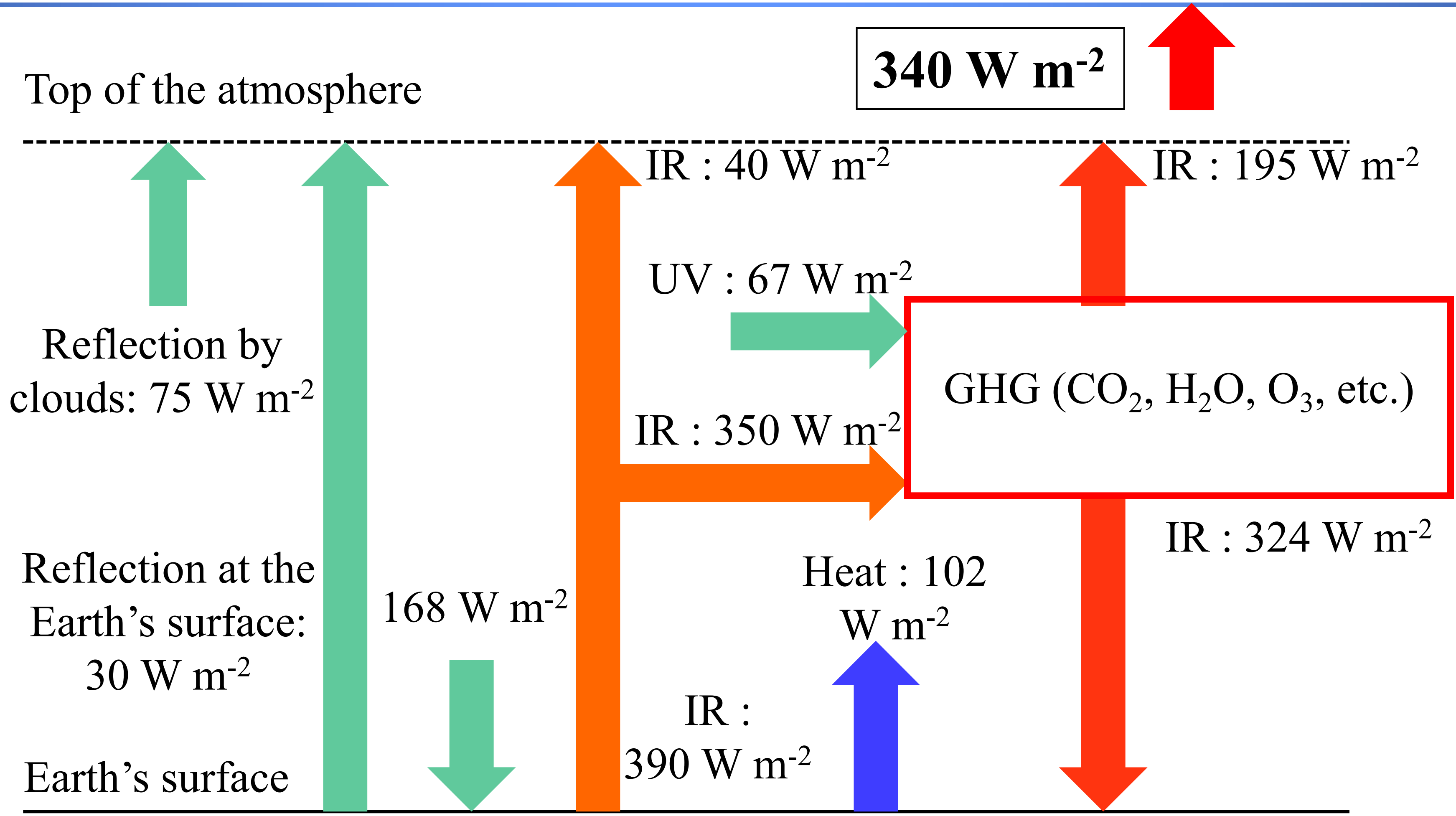
- Absorption of IR radiation:
  - Radiative energy is not sufficient to break the bonds between atoms; instead, the molecule absorbs the energy to reach a higher quantum energy state: CO_2, H_2O, O_3 …
  - Radiative energy is reemitted by the molecule as IR radiation when the molecule comes back to its initial stable energy level.

$$\begin{array}{c} h\nu \\ \downarrow \\ \text{O-C-O} \\ \downarrow \\ h\nu \end{array}$$

Solar Radiation
Reaching the Earth's Atmosphere



Effect of Greenhouse Gases on the Radiative Budget of the Earth



Temperature of the Earth with Greenhouse Gases

•With greenhouse gases (GHG), the irradiance emitted by the Earth is 390 W m^{-2} and the corresponding temperature is:

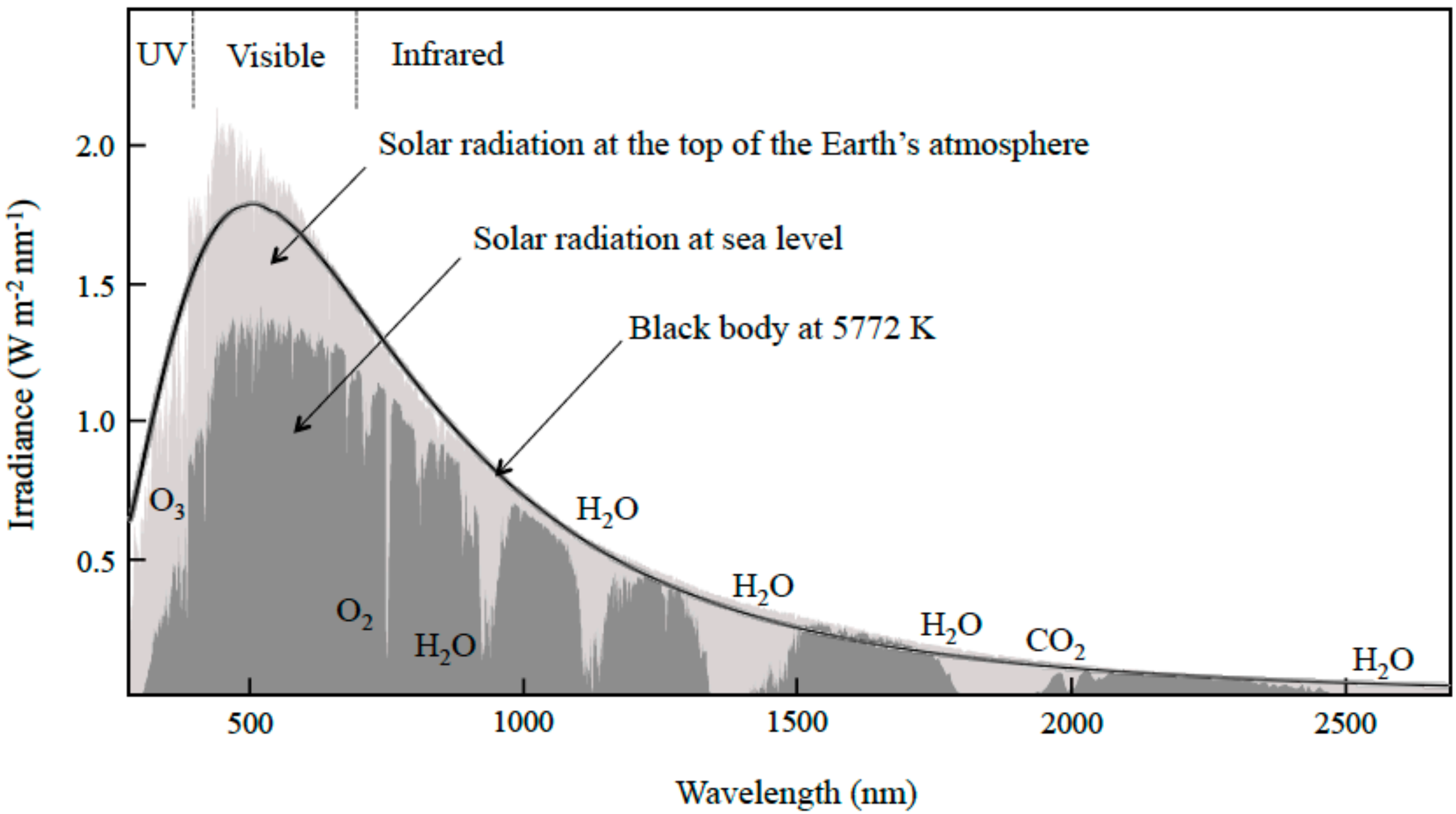
$$\boxed{T = \left(\frac{E_{e,E}}{\sigma_{SB}}\right)^{\frac{1}{4}} = \left(\frac{390}{5.67 \text{ x } 10^{-8}}\right)^{\frac{1}{4}} = 288 \text{ K} = +15\ °\text{C}}$$

•According to Wien's law, the wavelength corresponding to the maximum irradiance is:

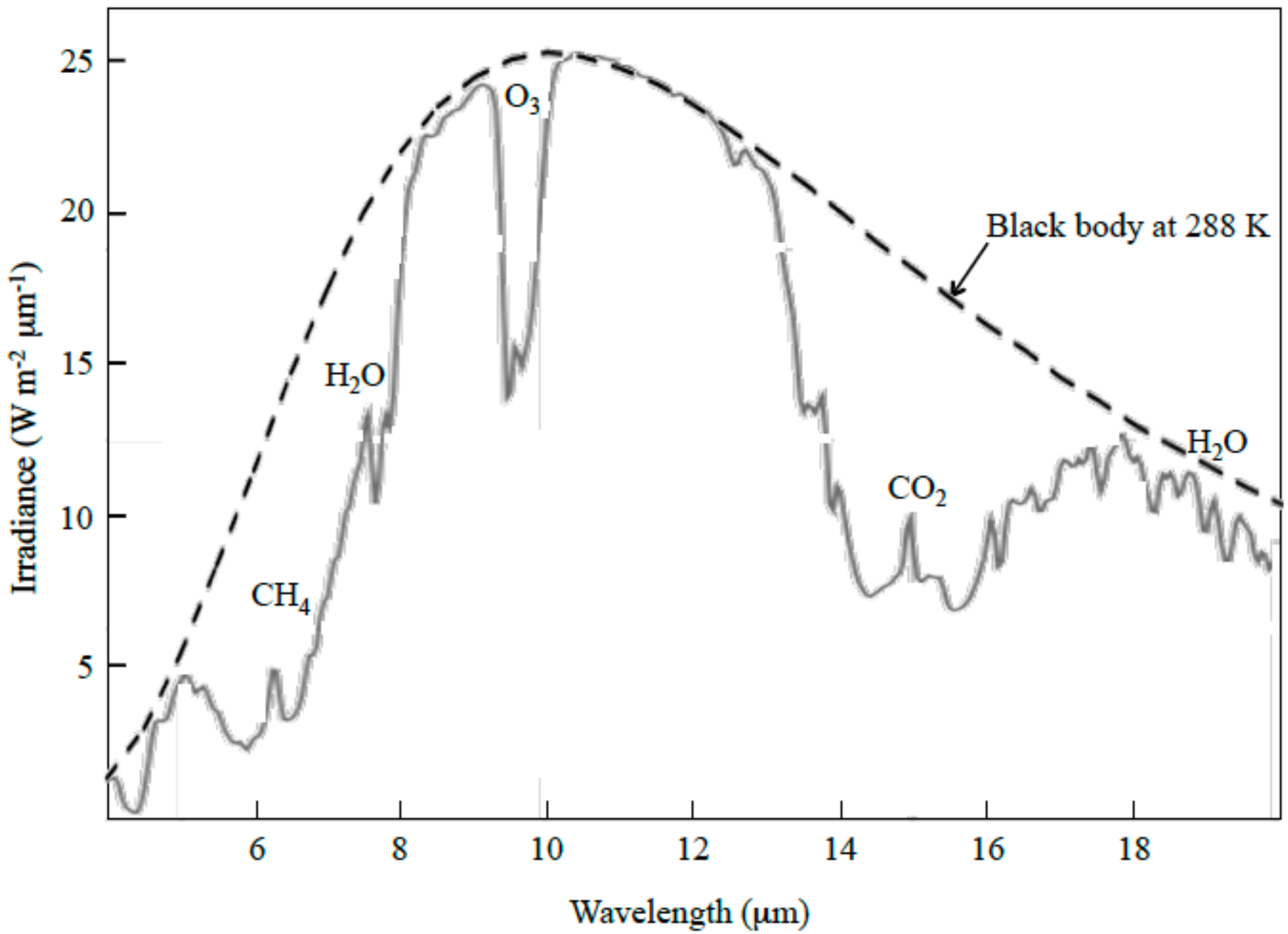
$$\boxed{\lambda_{\max} = \frac{h\ c}{\left(5\ k_B\ T\right)} = \frac{2.9 \text{ x } 10^{6}}{288} = 10\ \mu\text{m}}$$

•Therefore, the Earth emits radiation in the infrared (IR).

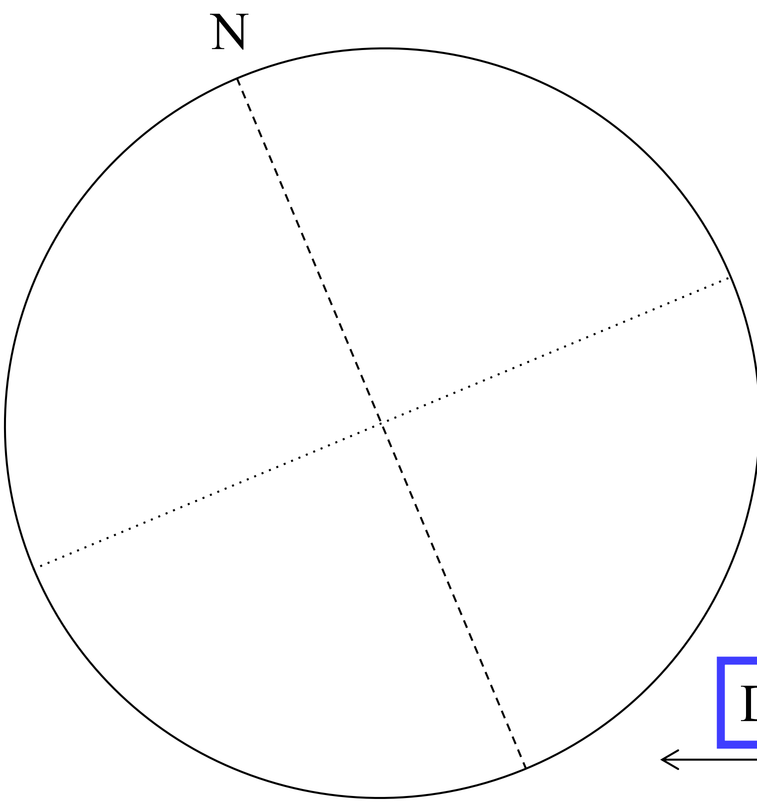
Solar Radiation
Reaching the Earth's Atmosphere



Radiation Emitted by the Earth at an Altitude of 50 km Absorption by Greenhouse Gases



Radiative Energy Budget of the Earth



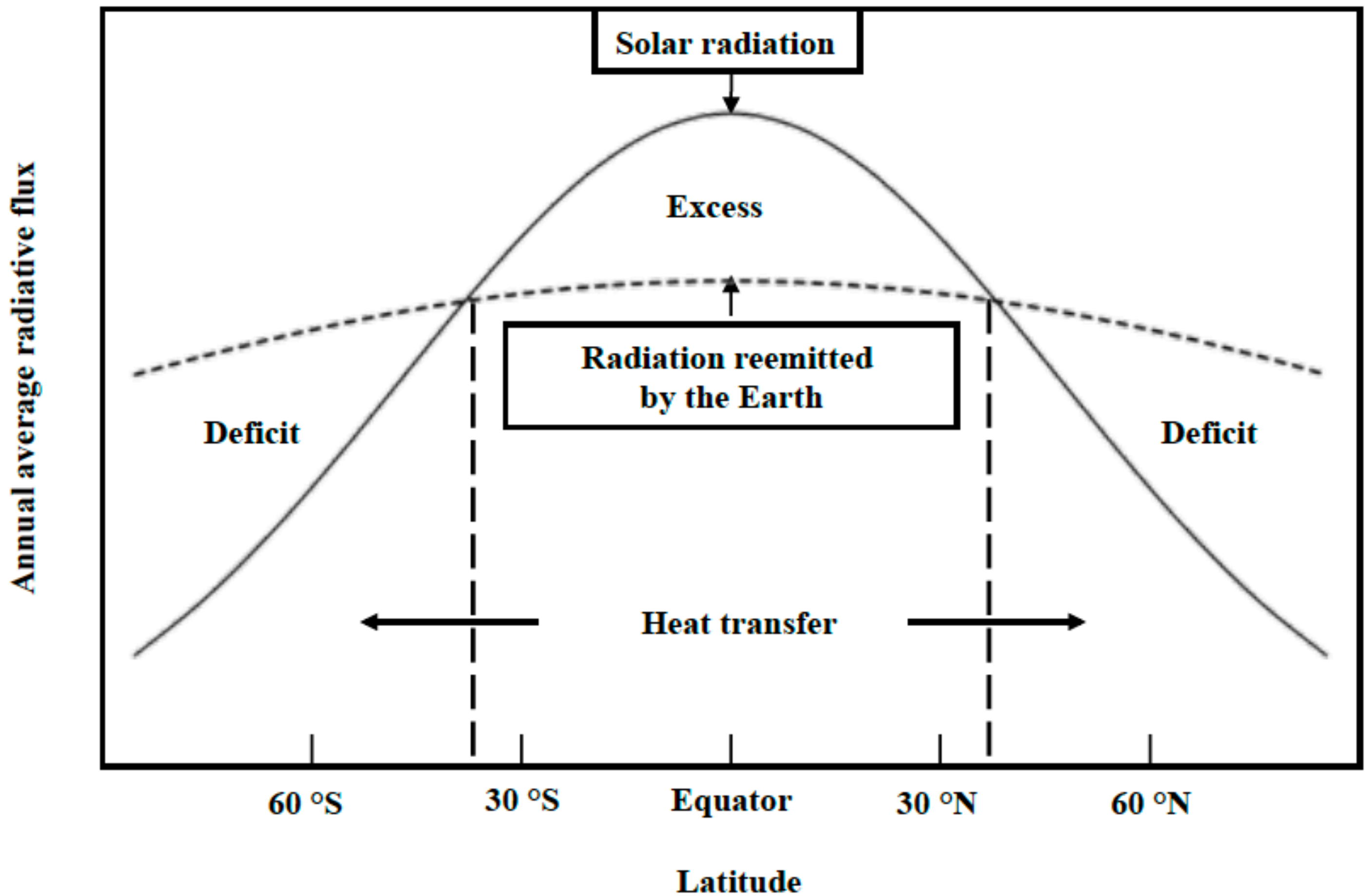
Solar radiation near the solar zenith angle in the tropics
Strong evapotranspiration with associated latent heat

Excess of energy in the tropics

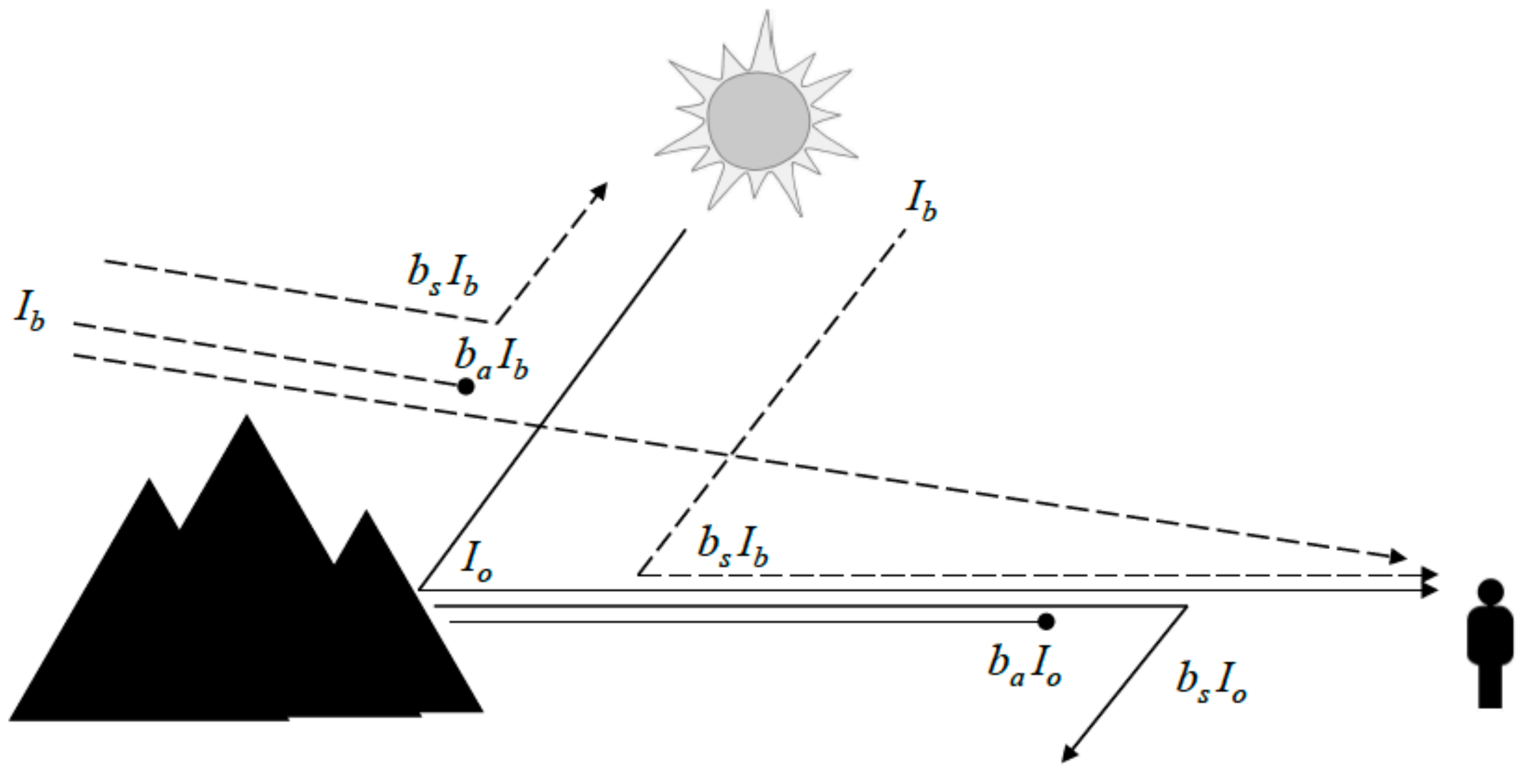
Deficit of energy near the poles

Solar radiation nearly tangential to the Earth's surface
Strong albedo (reflection of atmospheric radiation) in the polar regions

Radiative Energy Budget of the Earth



Atmospheric Visibility



Absorption and Scattering of Visible Radiation

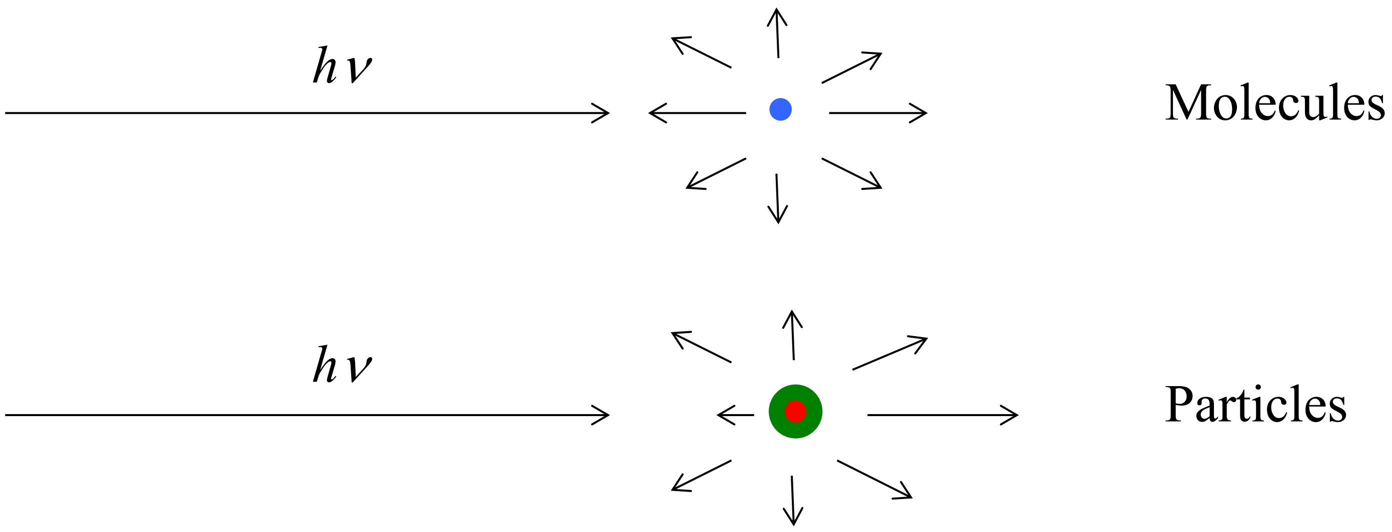
Absorption of visible radiation

$$\xrightarrow{\qquad h\nu \qquad} \bullet \quad T\uparrow \qquad \text{Black carbon}$$

$$\xrightarrow{\qquad h\nu \qquad} \mathrm{NO_2} \longrightarrow \mathrm{NO + O} \qquad \text{Nitrogen dioxide}$$

Absorption and Scattering of Visible Radiation

Scattering of visible radiation



The scattering of radiation by molecules and particles in three dimensions is represented by the phase function $p(\Omega' \rightarrow \Omega)$. It follows the theory of Rayleigh for molecules. It depends on the particle size (Mie scattering).

Absorption of Visibile Radiation

- Absorption of radiation

$$b_a = k_a C$$

where k_a is the absorption efficiency ($m^2\ g^{-1}$), C is the pollutant concentration ($g\ m^{-3}$) and b_a is the absorption coefficient (m^{-1})

- The law of Beer-Lambert gives the change of the radiance, I ($W\ sr^{-1}\ m^{-2}$), as a function of distance due to absorption of radiation:

$$\mathrm{d}I = -b_a\, I\, \mathrm{d}x$$

- Change in radiance along the line of sight:

$$\boxed{I = I_0 \exp\left(-b_a\, x\right)}$$

Scattering of Visible Radiation

- Scattering of radiation

$$b_s = k_s C$$

where k_s is the scattering efficiency ($m^2\ g^{-1}$), C is the pollutant concentration ($g\ m^{-3}$) and b_s is the scattering coefficient (m^{-1})

- Beer-Lambert's law applies to radiative scattering:

$$\boxed{I = I_0 \exp\left(-b_s\, x\right)}$$

Scattering of Visible Radiation

- If there is no pollution, i.e., no particles, only air molecules diffuse atmospheric radiation and the atmosphere is called a Rayleigh atmosphere.

- The Rayleigh scattering coefficient, b_{Ray}, depends strongly on the wavelength:

$$b_{Ray} = function(\lambda^{-4})$$

- Therefore, blue light (λ = 400 nm) is scattered more efficiently than red light (λ = 700 nm): it is the reason why the sky is blue.

- For particles, light scattering is calculated using Mie theory.

Extinction of Visible Radiation

- The extension coefficient, b_e, is defined as the sum of the absorption and scattering coefficients:

$$b_e = b_a + b_s$$

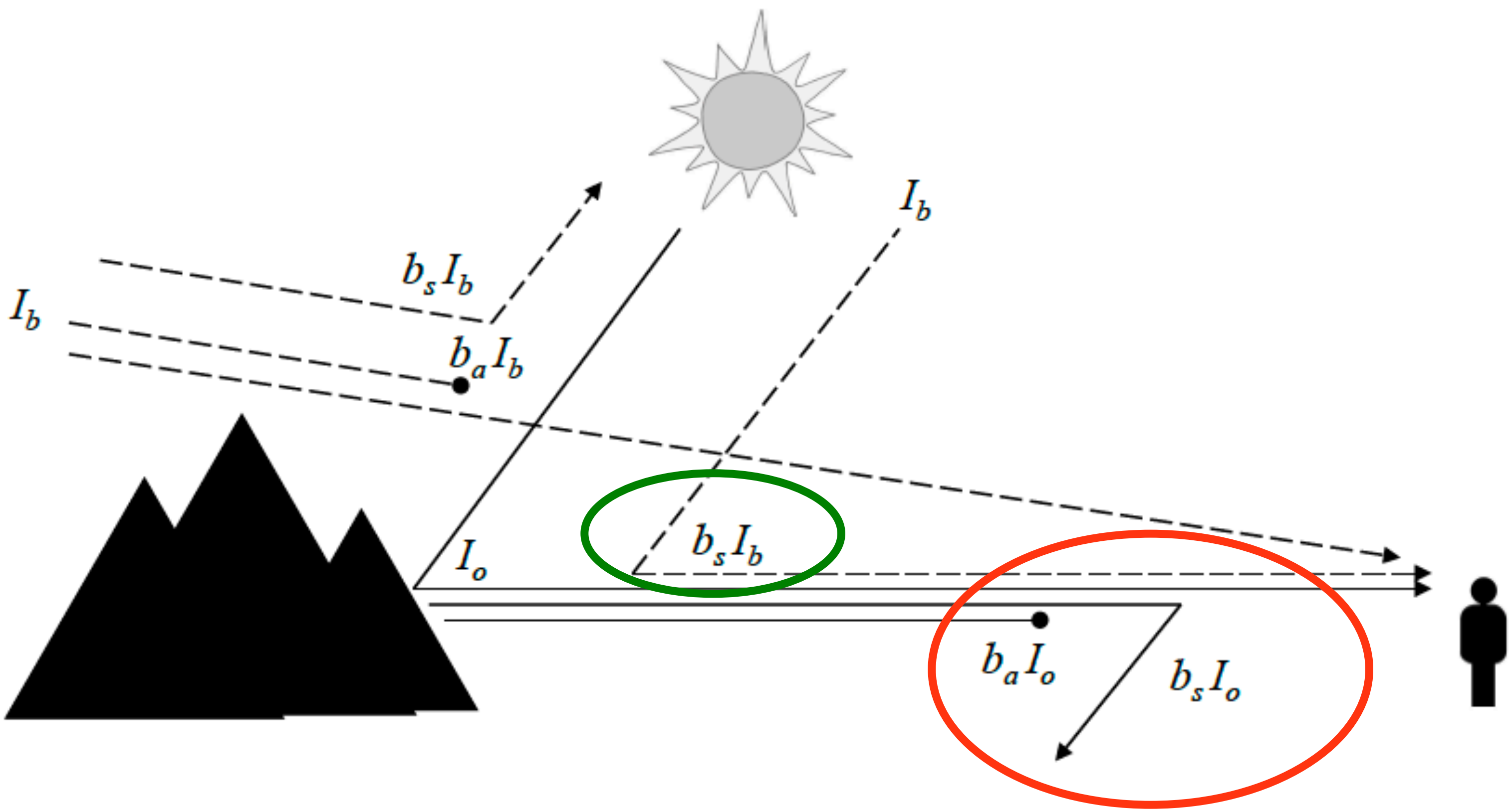
- Beer-Lambert's law applies to the extinction of radiation:

$$\boxed{I = I_0 \exp\left(-b_e\, x\right)}$$

- The optical depth, τ (dimensionless), is defined as follows:

$$\boxed{\tau = \int_0^z b_e(z)\,\mathrm{d}z}$$

Atmospheric Visibility



Radiative Transfer Equation

$$I_{obj}(\Omega, x) = I_{obj}(\Omega, 0)\exp(-\tau_x)$$

$$+\int_0^{\tau_x} \frac{\omega_a(\tau')}{4\pi} \int_{\Omega'=4\pi} I_f(\Omega', \tau')\, p(\Omega' \to \Omega, \tau')\, \mathrm{d}\Omega' \exp(-\tau')\mathrm{d}\tau'$$

Radiative Transfer Equation

Radiance reaching the observer (i.e., atmospheric visibility)

Intrinsic radiance (at the object)

$$I_o(\Omega, x) = I_o(\Omega, 0)\exp(-\tau_x)$$

$$+\int_0^{\tau_x} \frac{\omega_a(\tau')}{4\pi} \int_{\Omega'=4\pi} I_b(\Omega', \tau')\, p(\Omega' \rightarrow \Omega, \tau')\, \mathrm{d}\Omega' \exp(-\tau')\mathrm{d}\tau'$$

Background radiance of the atmosphere

Radiative Transfer Equation

Phase function (spatial distribution of scattering)

$$I_o(\Omega, x) = I_o(\Omega, 0)\exp(-\tau_x)$$

$$+\int_0^{\tau_x} \frac{\omega_a(\tau')}{4\pi} \int_{\Omega'=4\pi} I_b(\Omega', \tau')\, p(\Omega' \rightarrow \Omega, \tau')\, \mathrm{d}\Omega' \exp(-\tau')\mathrm{d}\tau'$$

Single scattering albedo (ratio of scattering and extinction)

Angle between incoming radiation and the line-of-sight

Optical depth

Radiative Transfer Equation

Radiance reaching the observer

$$I_o(\Omega, x) = I_o(\Omega, 0)\exp(-\tau_x)$$

Radiance from the object

$$+\underbrace{\boxed{\int_0^{\tau_x} \frac{\omega_a(\tau')}{4\pi} \int_{\Omega'=4\pi} I_b(\Omega', \tau')\, p(\Omega' \rightarrow \Omega, \tau')\, \mathrm{d}\Omega' \exp(-\tau')\, \mathrm{d}\tau'}}_{\text{Radiance added by the background atmosphere}}$$

Contrast and Visibility

- Contrast is defined as the relative difference between the radiances of the observed object and the background (i.e., the atmosphere).

$$\boxed{Co = \frac{\left(I_b - I_o\right)}{I_b}}$$

- An object is considered to be discernable if $Co \geq 2\ \%$

- Contrast follows Beer-Lambert's law for scattering:

$$\boxed{Co = Co_0 \exp\left(-b_s\, x\right)}$$

- However, it does not for absorption (although one generally makes the approximation that it does).

Contrast and Visibility

- The Koschmieder relationship gives the visual range for a scattering atmosphere (*Co* = 2 %).

$$0.02 = \exp\left(-b_s VR\right)$$

- Therefore:

$$\boxed{VR = \frac{-\ln(0.02)}{b_s} = \frac{3.9}{b_s}}$$

- There are several assumptions associated with this relationship.

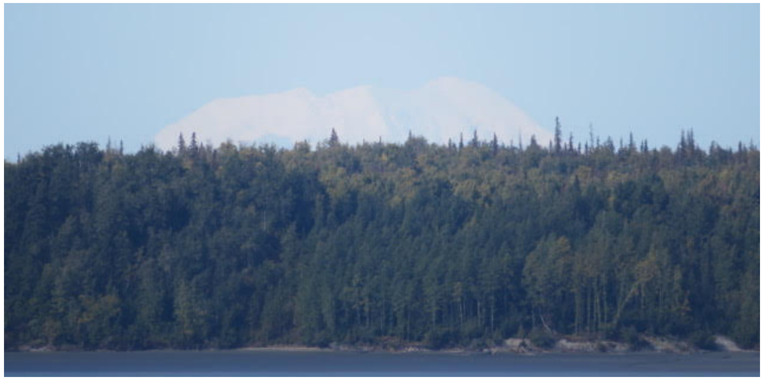
- This equation is also used for absorption and, therefore, extinction (b_s is replaced by b_{ext}), but this is no longer an exact solution.

Contrast and Visibility

View of Denali, highest mountain in North America (6,190 m),
at different distances

Assumption of Rayleigh scattering: visual range of about 300 km

View from Denali National Park at 40 km
60 % of the intrinsic contrast



View from Anchorage at 210 km
8 % of the intrinsic contrast

Contrast and Visibility

- Several empirical formulas are available to calculate the visual range as a function of the concentrations of atmospheric particles. For example, the formula from the National Park Service (NPS), is widely used.

$$
\begin{aligned}
b_e = {} & 3\ \mathrm{f(humidity)}\ ([\mathrm{sulfate}] + [\mathrm{nitrate}]) \\
& + 4\ [\mathrm{organic\ matter}] + 10\ [\mathrm{black\ carbon}] \\
& + [\mathrm{inorganic\ dust}] + 1{,}7\ \mathrm{f(humidity)}\ [\mathrm{sea\ salt}] \\
& + 0{,}6\ [\mathrm{coarse\ particles}] + 10
\end{aligned}
$$

Rayleigh scattering

- b_e is in Mm^{-1} and is calculated at 550 nm. Particle concentrations are in $\mu g\ m^{-3}$.

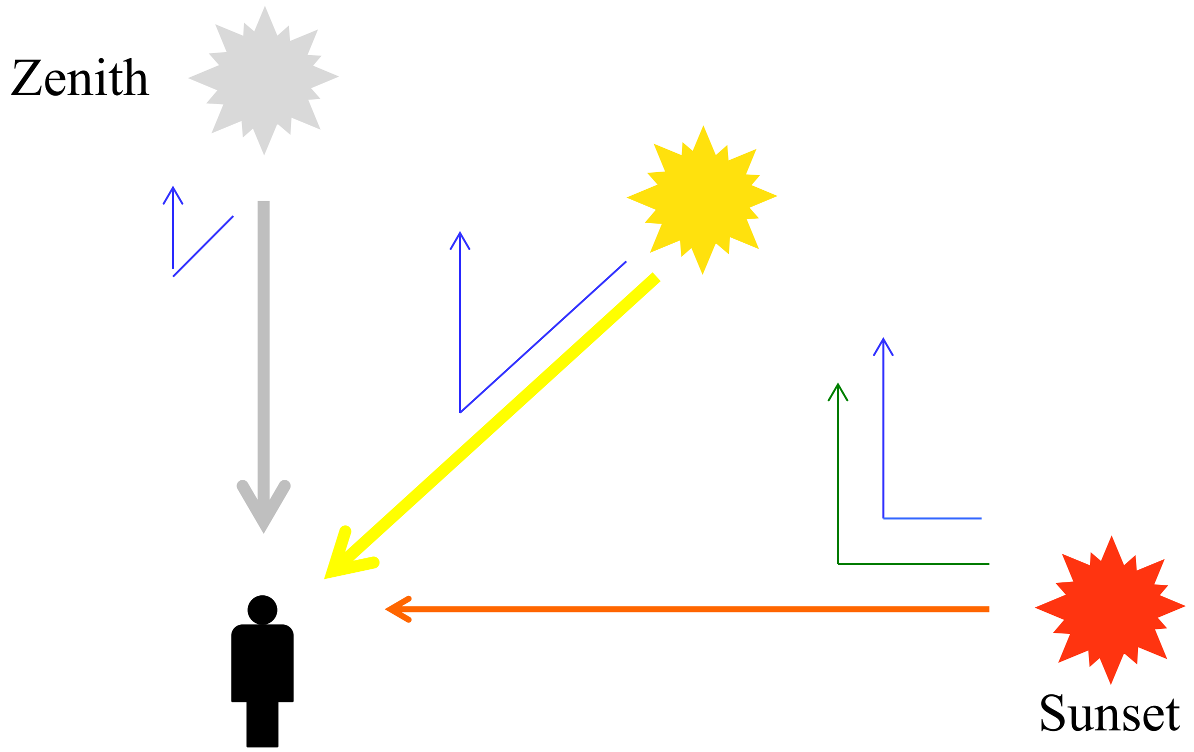
- The dependence of hygroscopic particles (i.e., those that may absorb water) on relative humidity may vary from 1 to 10.

Colors of the Atmospheric Environment

- The visible light spectrum ranges from violet (400 nm) to red (700 nm).
- The human eye perceives best at 550 nm (green).
- If all wavelengths are present, the radiation appears white.

Colors of the Sun

- The Sun emits mostly in the visible range with a maximum at 500 nm (blue-green).



Colors of the Sky

- A pristine sky (i.e., without any pollution) is blue because of Rayleigh light scattering by molecules.
- In the presence of atmospheric particles, scattering does not depend much on wavelength and the scattered light appears white/gray

Rayleigh scattering

Particle scattering

Colors of Air Pollution

- Ultrafine particles (< 100 nm) behave similarly to molecules (< 1 nm) and scatter preferentially blue light.
- Above pristine forests, where the formation of ultrafine particles (≈10 nm) may occur due to biogenic emissions, the atmosphere may appear bluish.

Blue Mountains, New South Wales, Australia

Colors of Air Pollution

- A stack plume may appear
  - brown-orange if there is a large amount of NO_2 (which absorbs blue light and, therefore, lets yellow to red wavelengths through)
  - gray if there are a lot of fine and/or coarse particles (which scatter light in all wavelengths)

Colors of Air Pollution

- Soot particles absorb light, because they contain black carbon. Therefore, those particles appear black.