

Solar photometry basics

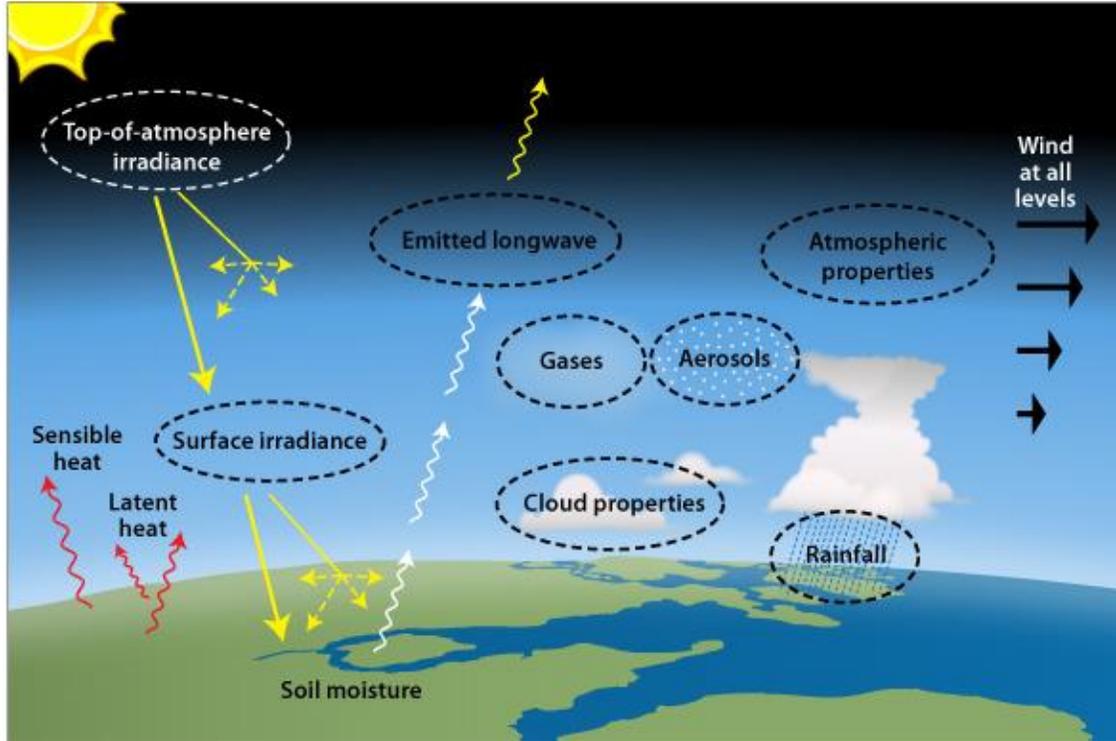


Stelios Kazadzis, PMOD World Radiation Center

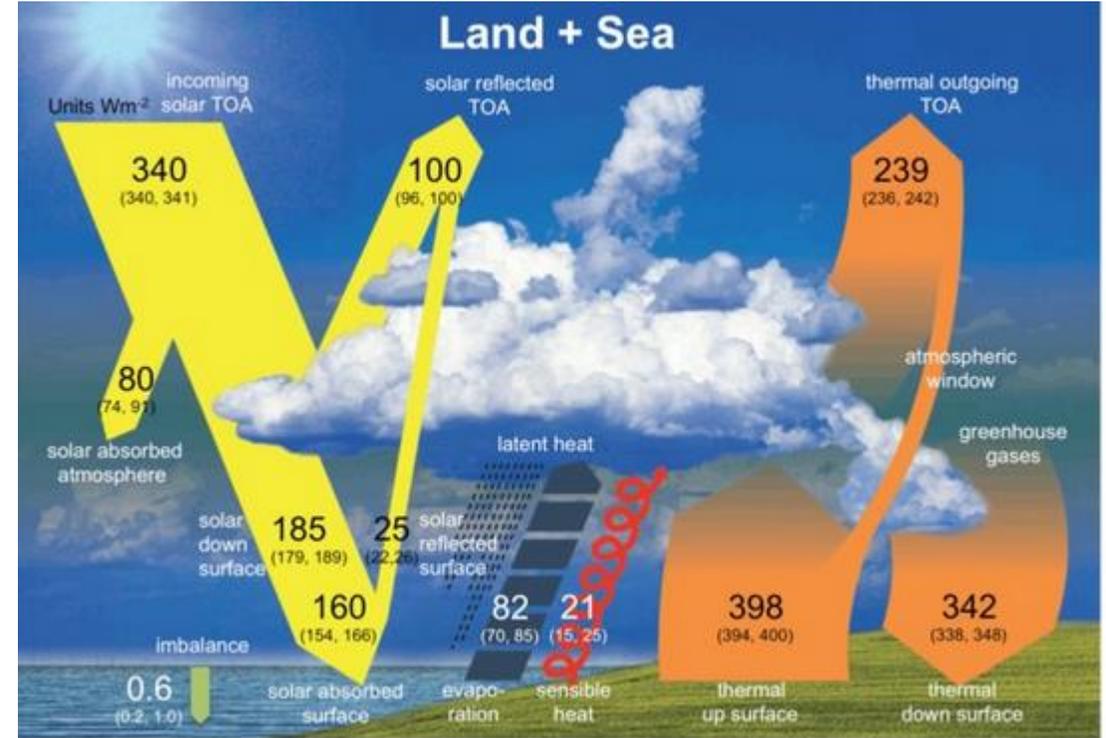
Atarri Workshop: “Aerosol microphysical properties and solar radiation” and Training “GRASP model use”

6–7 March 2025, Limassol, Cyprus

Remote Sensing and radiation and the Atmosphere



Using atmospheric “windows” and absorption ranges
To detect the amount of an atmospheric parameter.
Isolating other effects.



Use the derived atmospheric parameters to explain
the Earth – Atmosphere system (im)balance

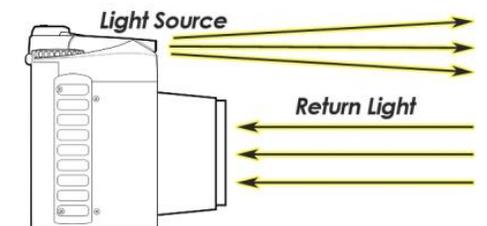
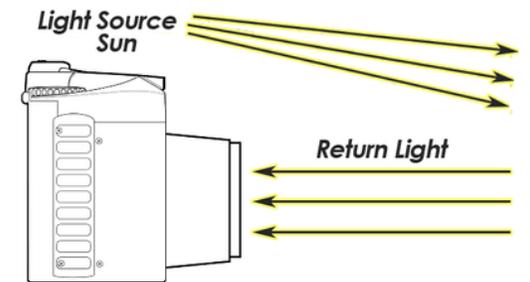
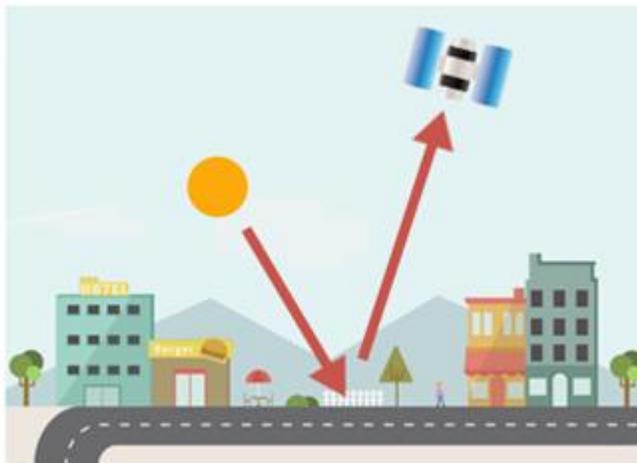
Radiation sources

Active versus Passive remote sensing

Remote sensing uses the attenuation of radiation as it passes through the atmosphere to determine a particular property of the atmosphere.

➤ Passive remote sensing uses a natural light source
Sun, (Moon, Stars)

➤ Active remote sensing uses an artificial light source
Laser, Microwaves...



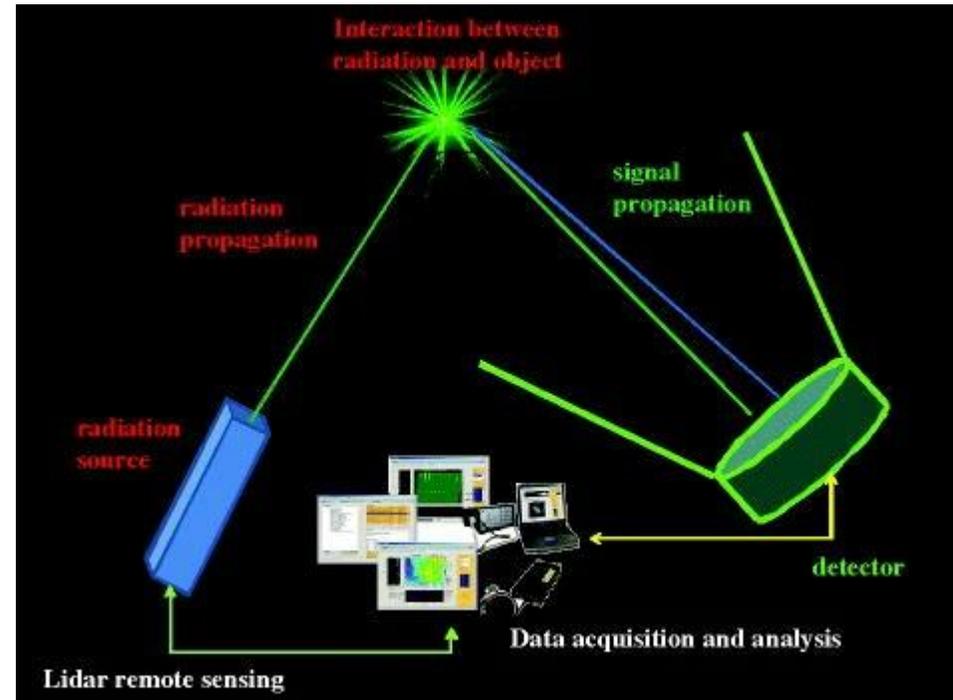
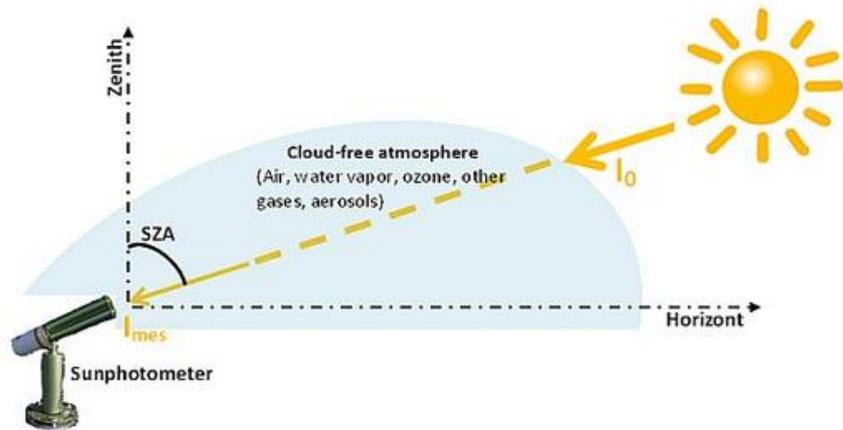
Radiation sources

Active versus Passive remote sensing



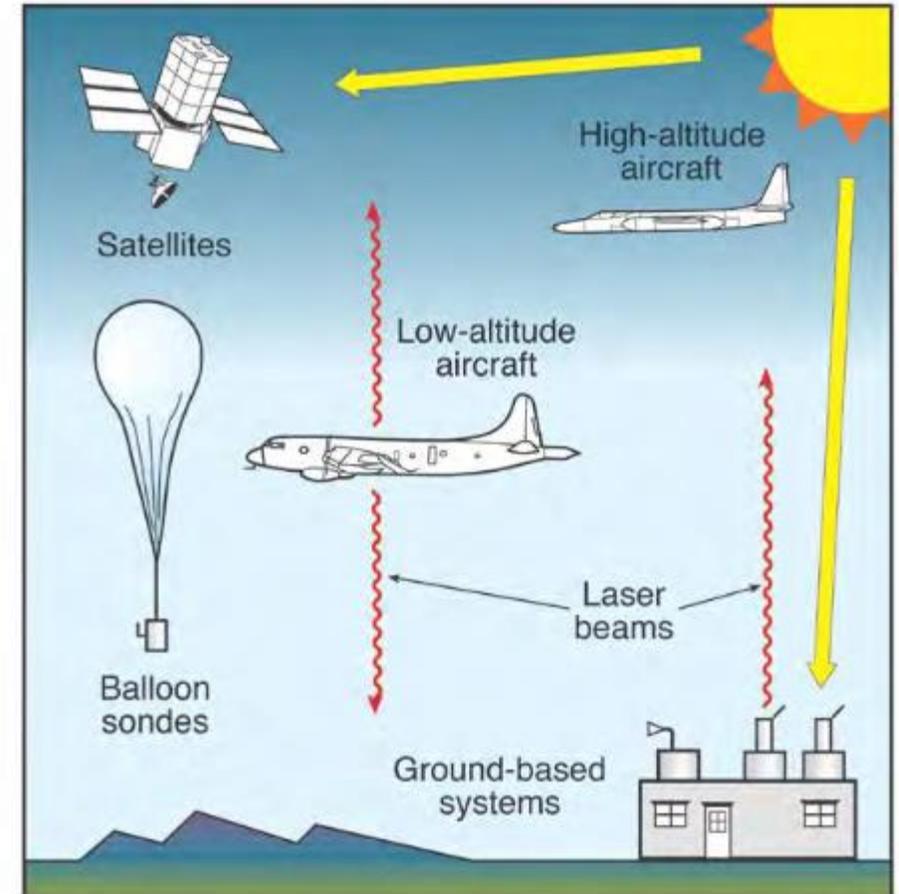
Radiation sources

Active versus Passive remote sensing



RS Platforms

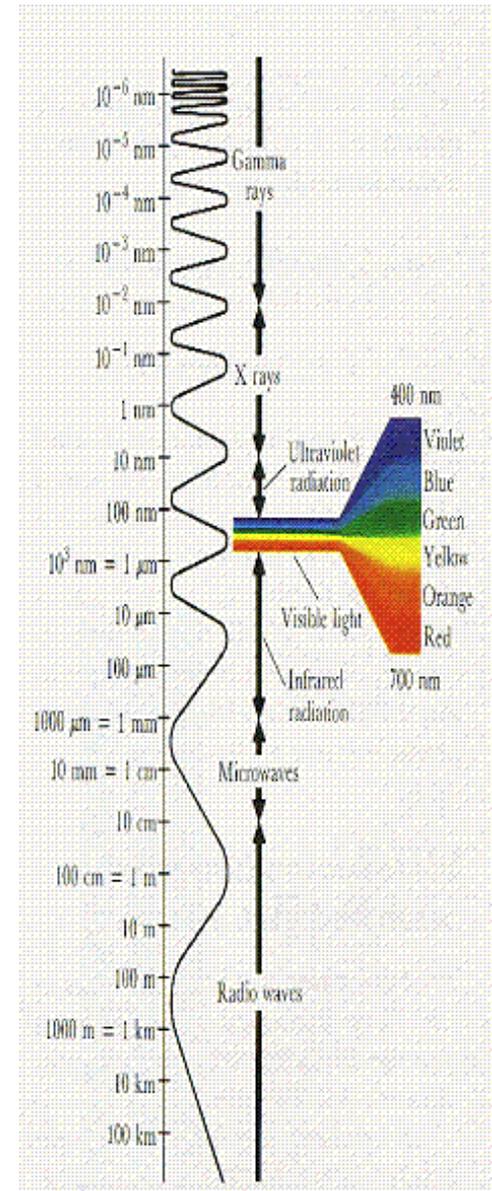
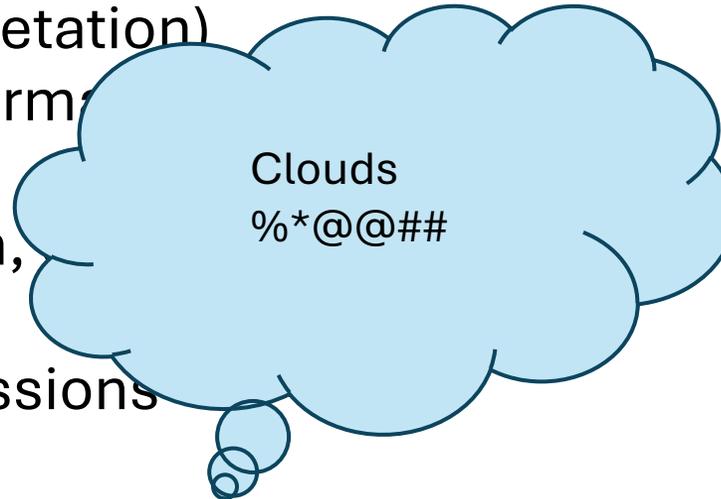
- ground-based measurements
 - continuous, high accuracy, easy accessibility
 - local measurement
- air-borne measurements (up to 15 km)
 - fast moving, long distance
 - expensive, sporadic
- sonde / balloon measurements (up to 30 km)
 - high altitude
 - logistically difficult, often expensive
- rocket measurements (up to 80 km)
 - very high altitude
 - expensive, sporadic
- Space Shuttle / Space Station measurements
 - global coverage, limited time coverage, good accessibility
- satellite measurements
 - global coverage
 - poor accessibility, expensive



Ground, aircraft, balloon, rocket, satellite

Wavelength Range in RS

- **UV:** absorption + profile information aerosols
Aerosol and molecular scattering
- **vis:** surface information (vegetation)
absorptions aerosol information
- **IR:** temperature information,
water / ice distinction
many absorptions / emissions
+ profile information
- **MW:** no problems with clouds
ice / water contrast
surfaces
some emissions + profile information



Wavelength Range in RS

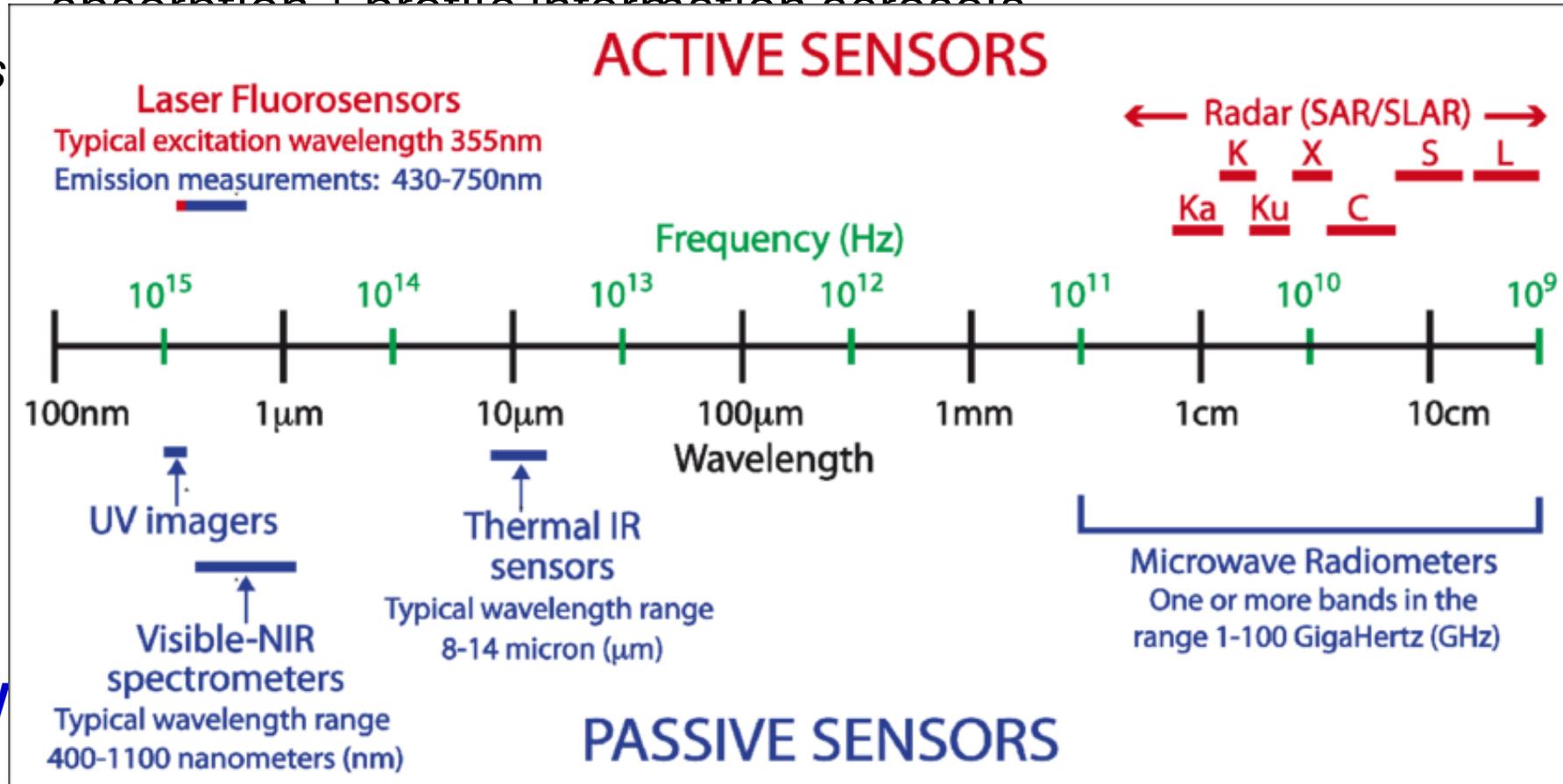
- **UV:** observation + profile information

Aeros

- **vis:**

- **IR:**

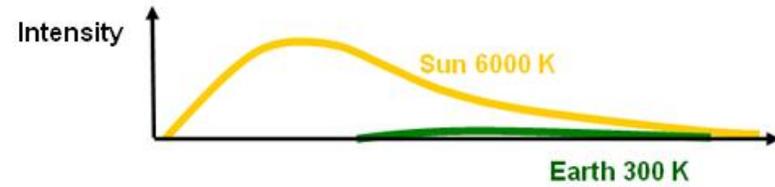
- **MW**



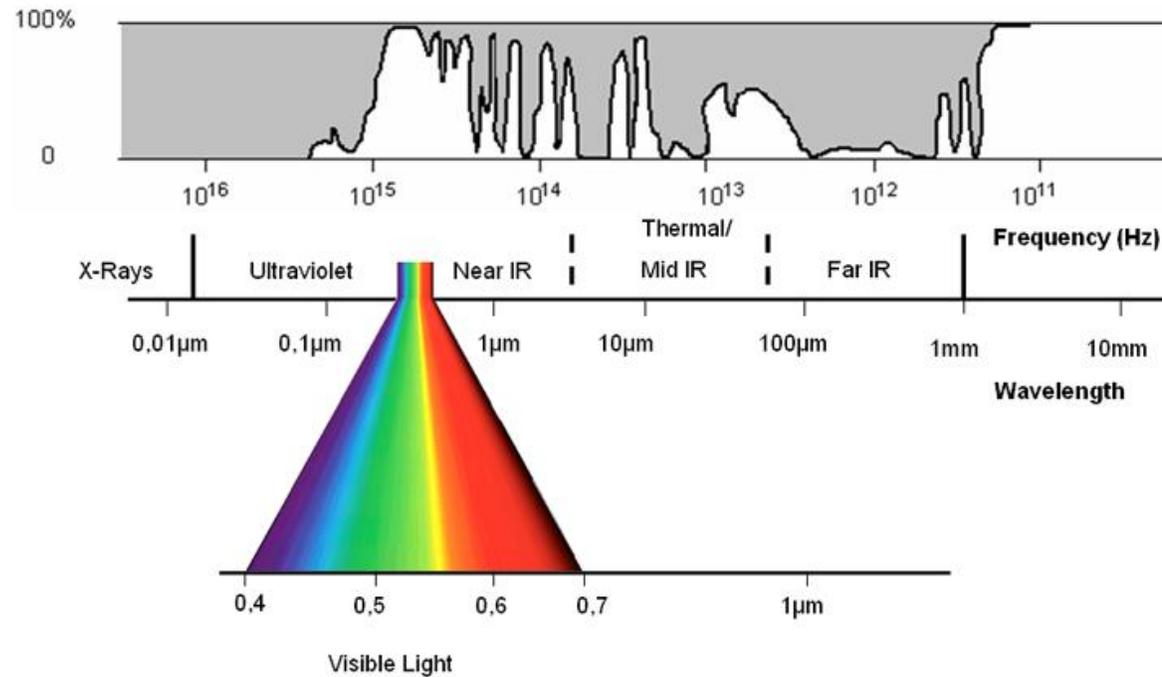
surfaces

some emissions + profile information

Atmospheric transmission

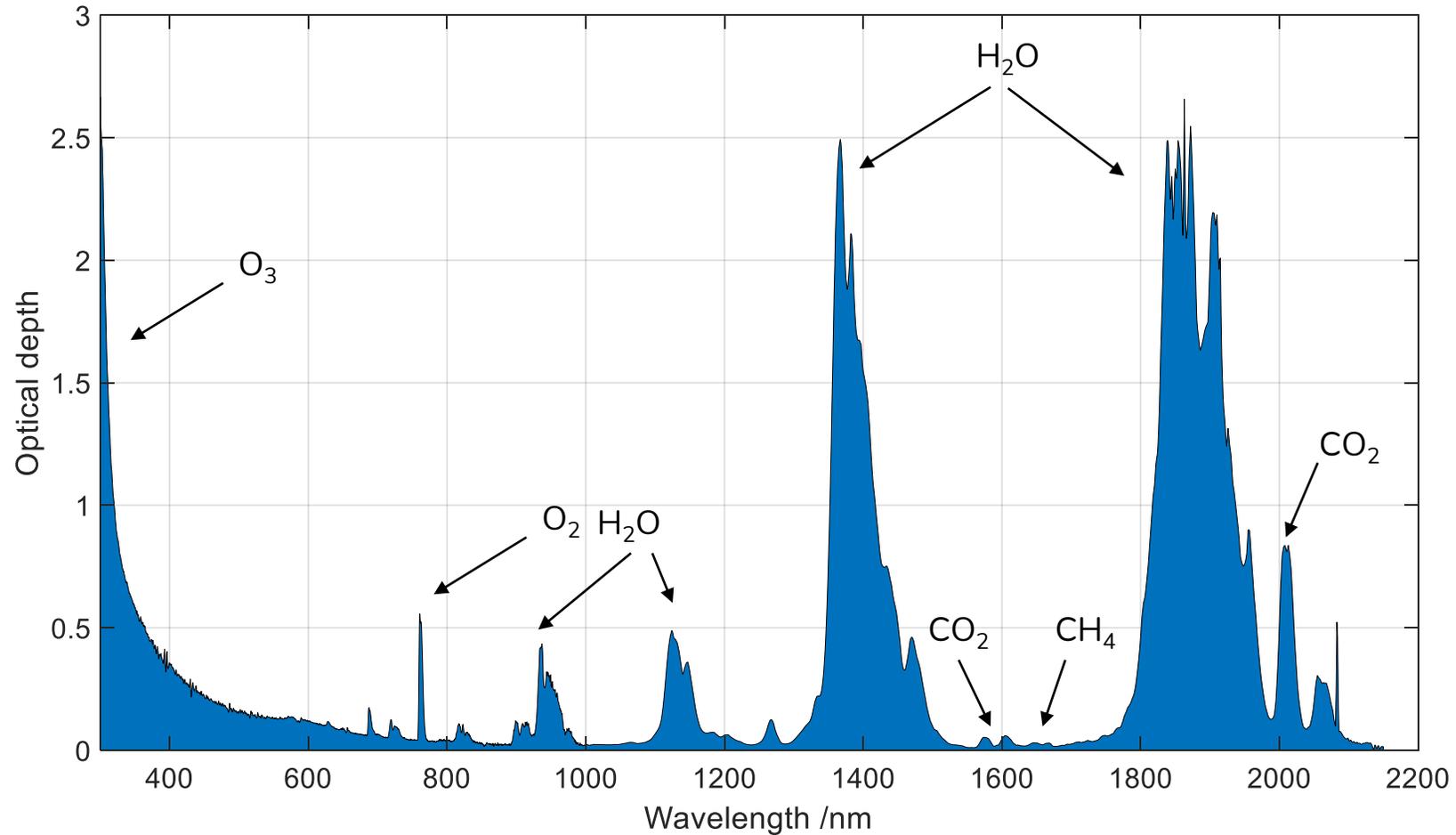


Atmospheric Transmittance



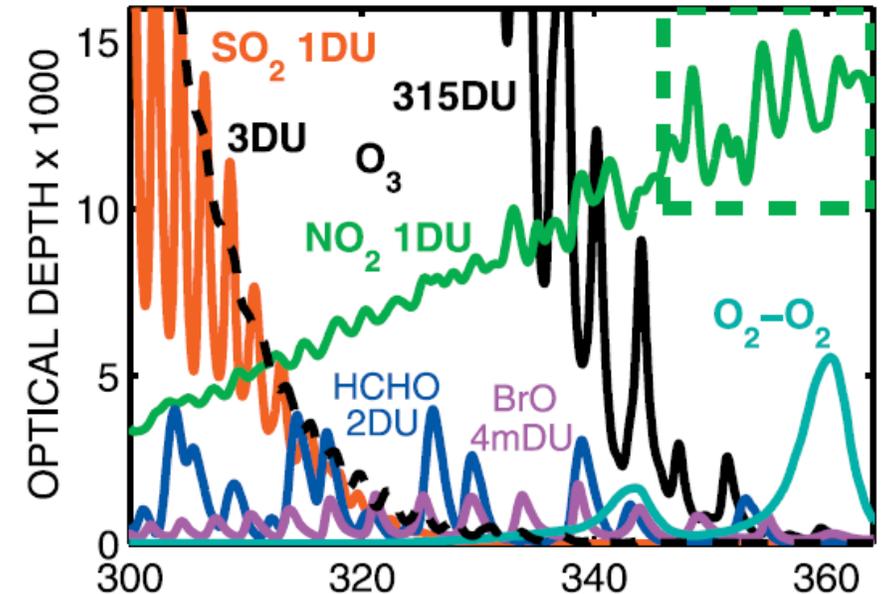
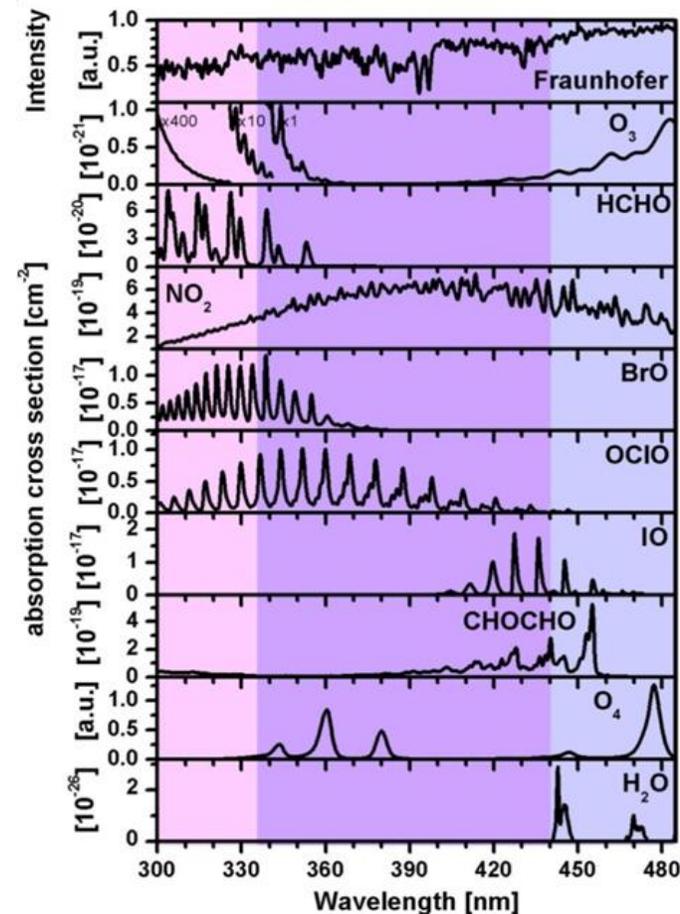
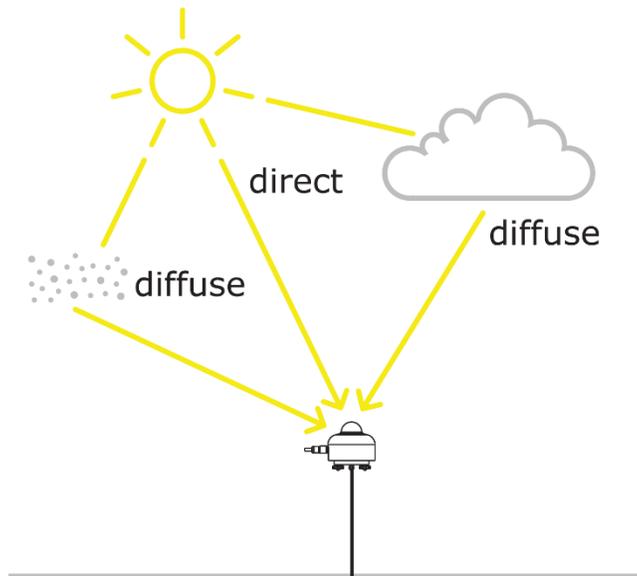
From: <https://seos-project.eu/remotesensing/remotesensing-c01-p04.html>

Spectral atmospheric absorption



Which Quantities are Measured?

- absolute intensities in dedicated wavelength intervals
- intensities relative to the intensity of a reference source
- ratios of intensities at different wavelengths
- variations of intensities
- degree of polarisation



Radiance

The radiance is the fundamental radiation quantity from which all other quantities can be derived:

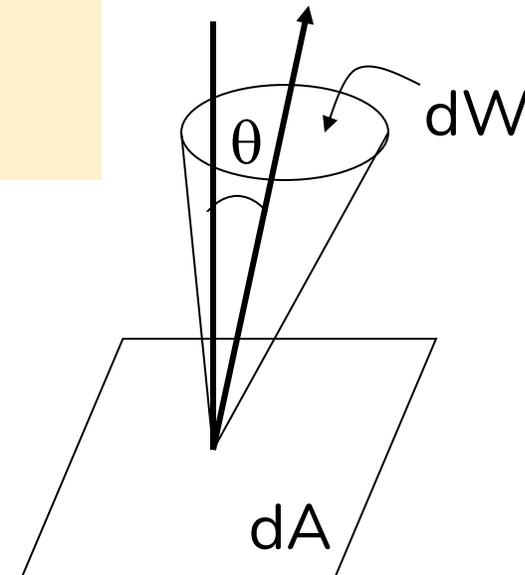
$$L = \frac{d^3\Theta}{dA d\lambda d\Omega} \quad \leftarrow \text{radiant flux}$$

Spectral radiance is defined as the energy flowing through unit area in unit solid angle in unit time in unit spectral interval

$$\text{units: } \text{W} \cdot \text{m}^{-2} \cdot \text{nm}^{-1} \cdot \text{sr}^{-1}$$

When the solid angle is tilted by θ relative to the normal direction of the area, the radiance L is projected on the area by $\cos \theta$:

$$L = \frac{d^3\Theta}{dA d\lambda d\Omega} \cos \theta$$



Irradiance

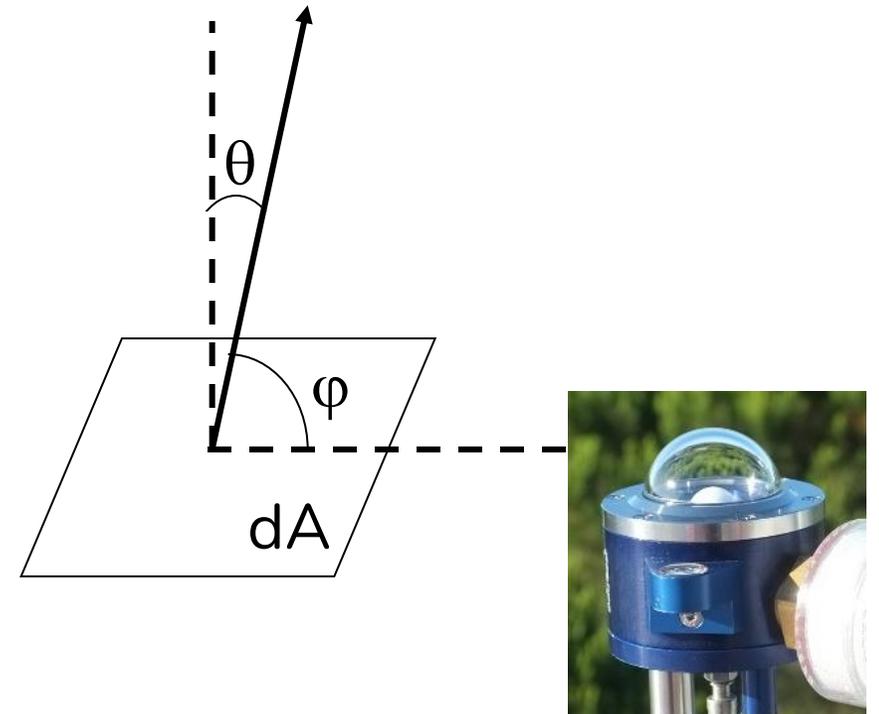
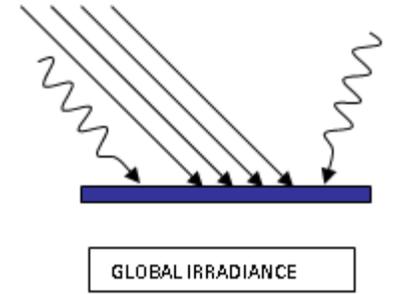
The spectral irradiance is defined as the energy flowing through unit area in unit time and unit spectral interval :

units: $W \cdot m^{-2} \cdot nm^{-1}$

$$E = \int_0^{2\pi} \int_0^{\pi/2} L(\theta, \phi) \cos \theta \underbrace{\sin \theta d\theta d\phi}_{d\Omega}$$

If the radiance L is isotropic, then the irradiance E is

$$\begin{aligned} E &= L 2\pi \int_0^{\pi/2} \cos \theta \sin \theta d\theta = L 2\pi \frac{1}{2} \sin^2 \theta \Big|_0^{\pi/2} \\ &= \pi L \end{aligned}$$



Actinic Flux

The spectral actinic flux is defined as the energy flowing through a unit sphere in unit time and unit spectral interval :

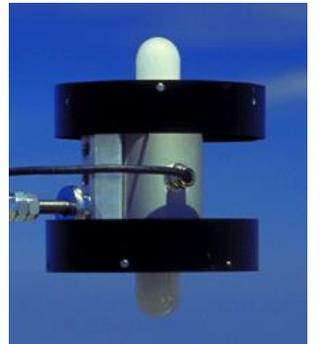
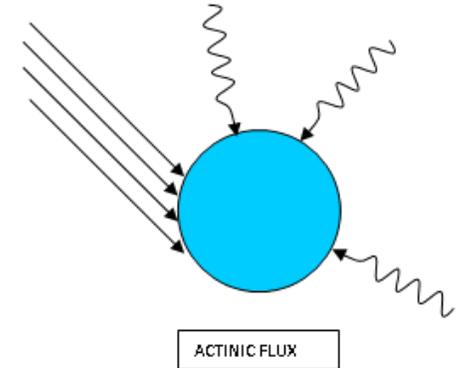
units: $W \cdot m^{-2} \cdot nm^{-1}$

$$F = \int_0^{2\pi} \int_0^{\pi} L(\theta, \phi) \overbrace{\sin \theta d\theta d\phi}^{d\Omega}$$

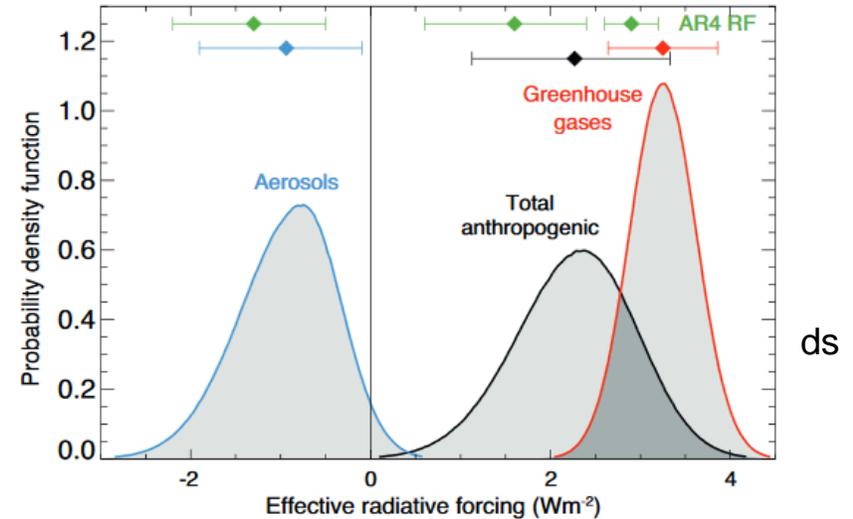
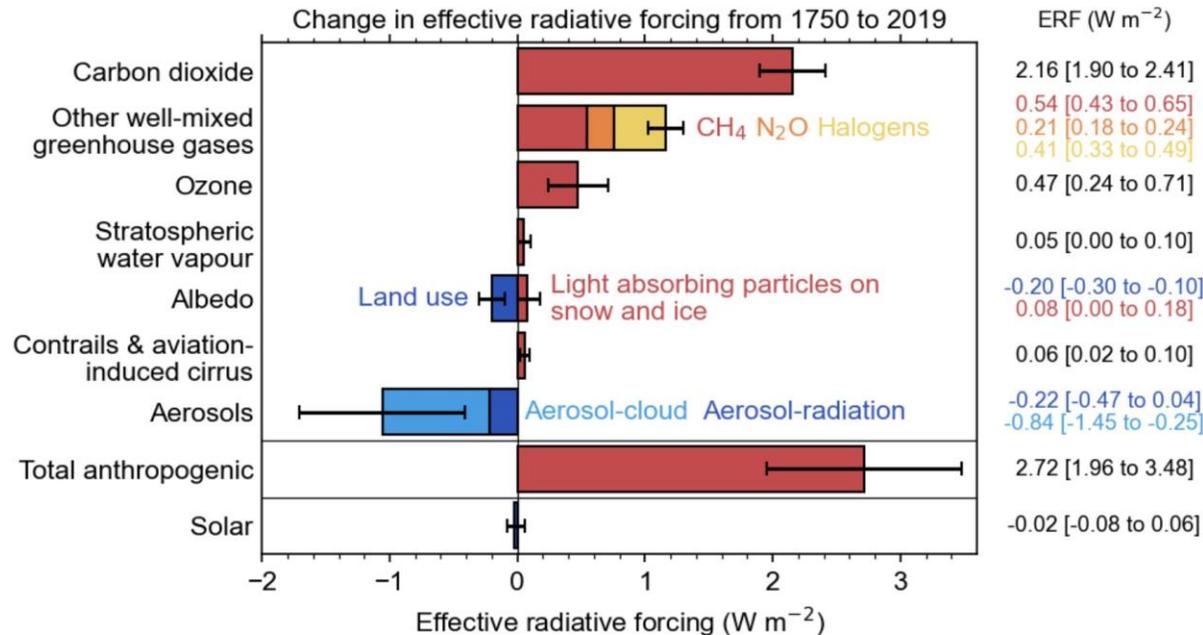
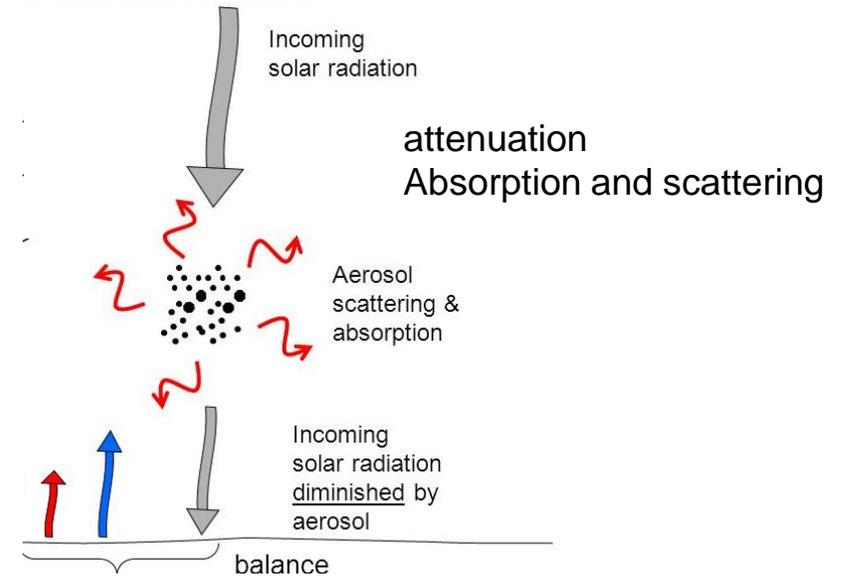
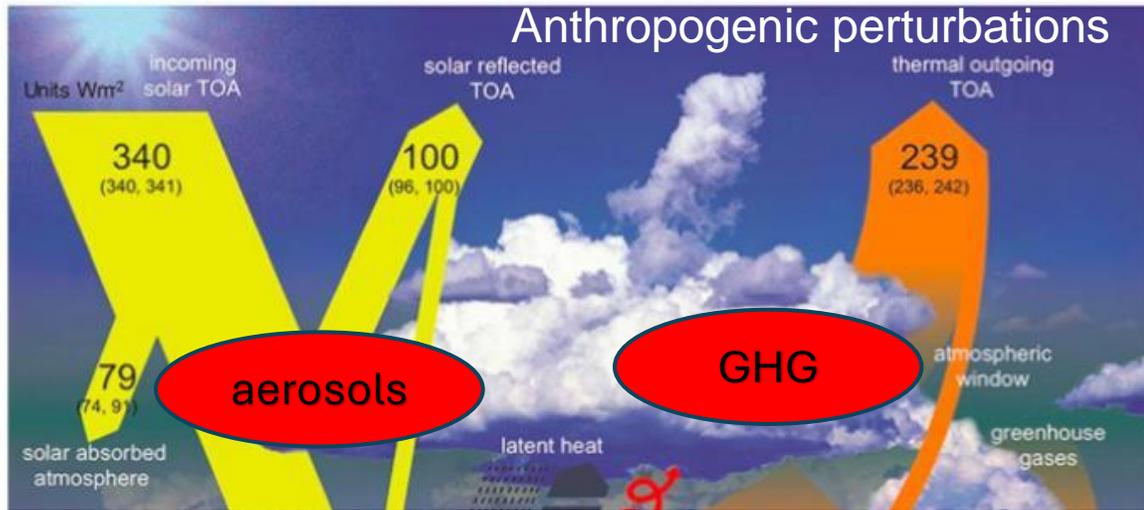
If the radiance L is isotropic, then the Actinic Flux F is

$$F = 4\pi L$$

The Actinic flux is used to determine photolysis frequencies and is usually expressed in photons per cm^{-2} per second



Motivation: Aerosols and Climate

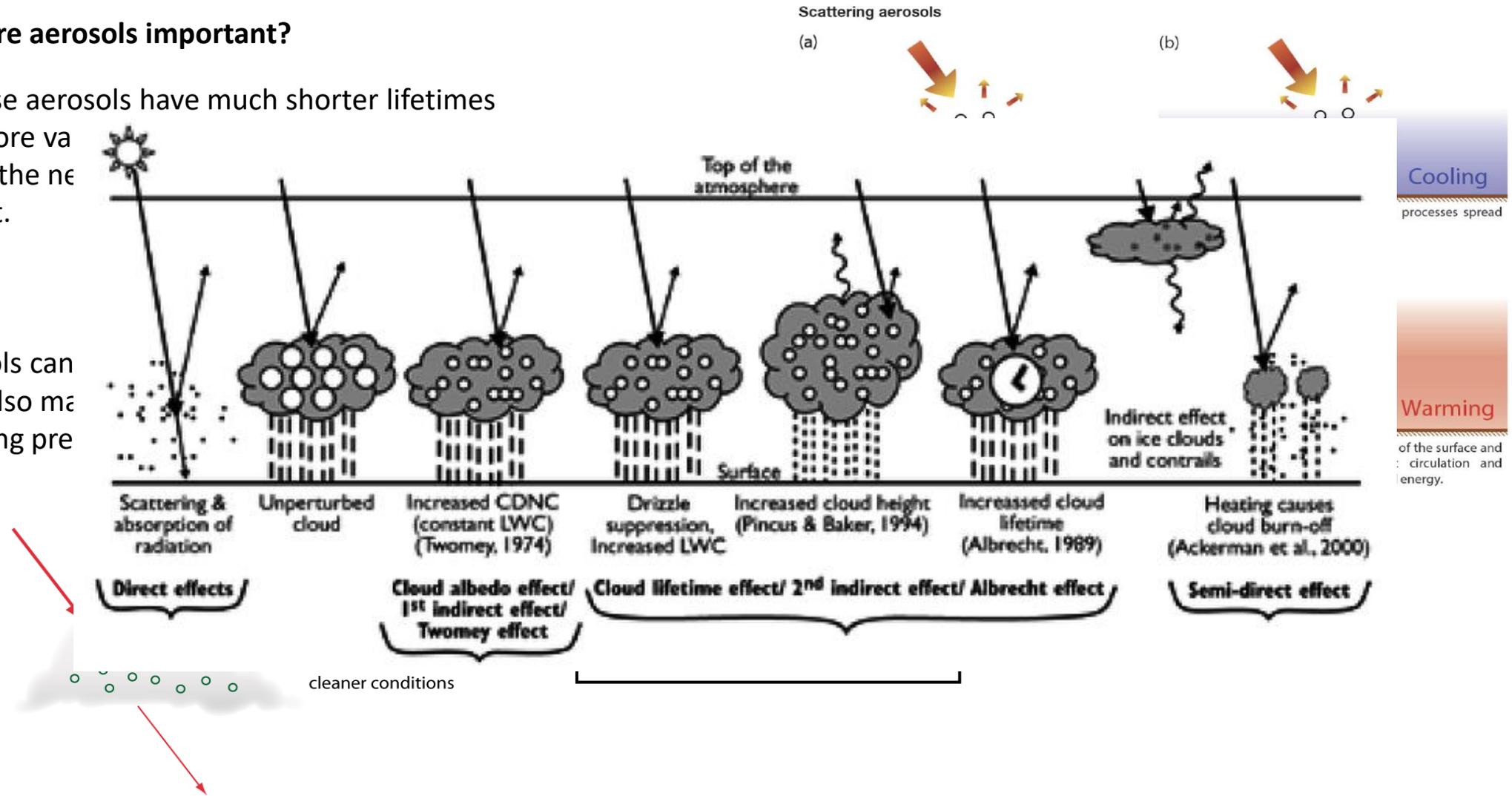


Aerosols – Radiative forcing

Why are aerosols important?

Because aerosols have much shorter lifetimes and more varied properties than greenhouse gases, the net radiative forcing is difficult to predict.

Aerosols can directly affect the Earth's energy balance. They also indirectly affect the climate by influencing cloud properties and processes.



First indirect effect: cloud-albedo effect

Source: IPCC, Fifth Assessment Report, 2013

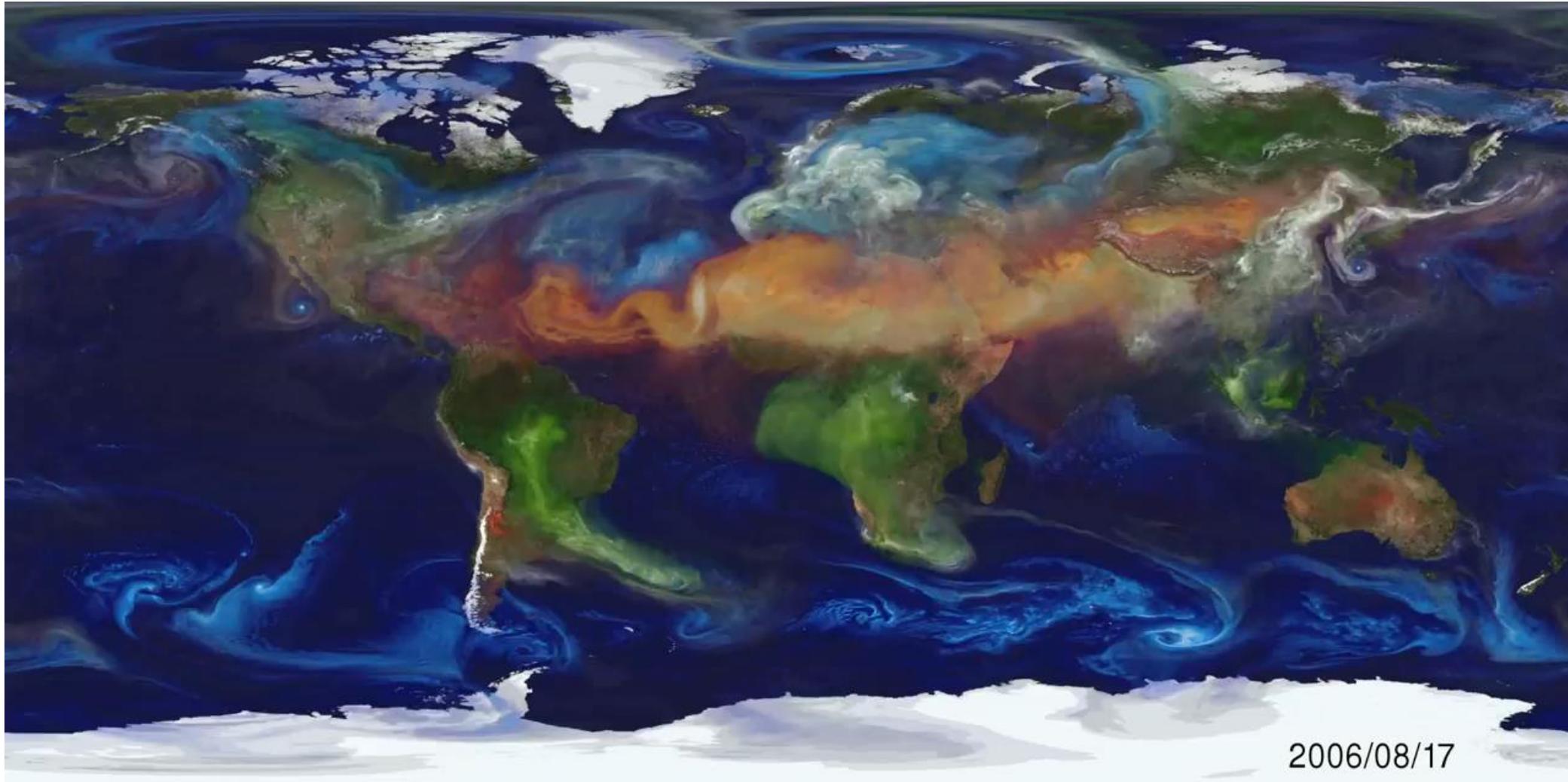
Aerosols

Dust

Smoke

anthropogenic

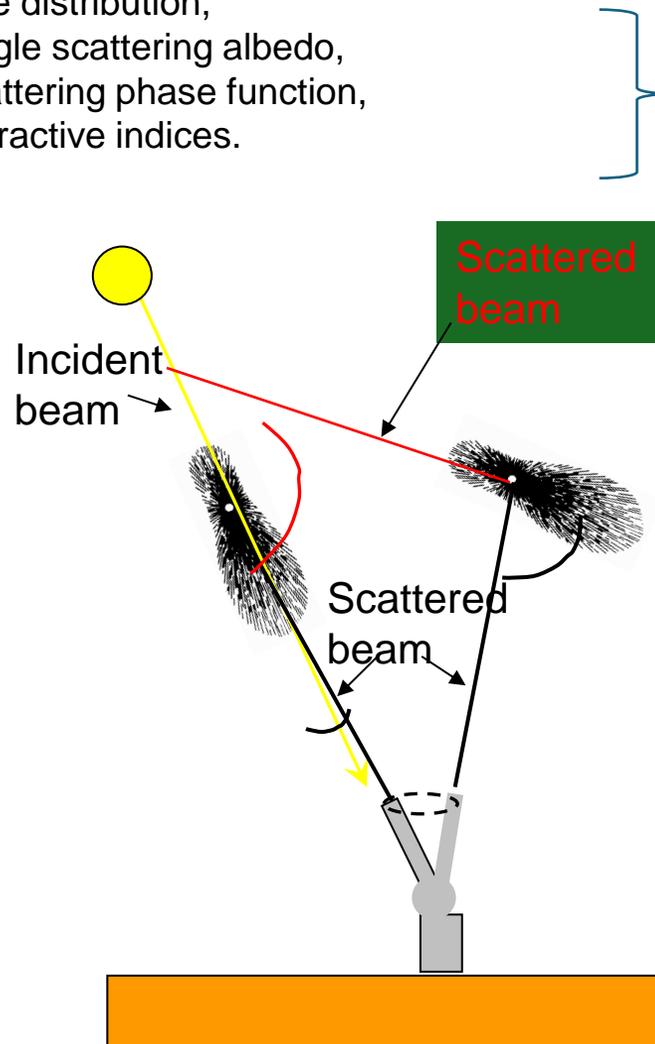
Sea salt



Sun-photometers: Retrieval of aerosol optical properties

Aerosol products:

- Aerosol optical depth retrieved from direct solar/lunar irradiance
- Size distribution,
- Single scattering albedo,
- Scattering phase function,
- Refractive indices.



solar radiance

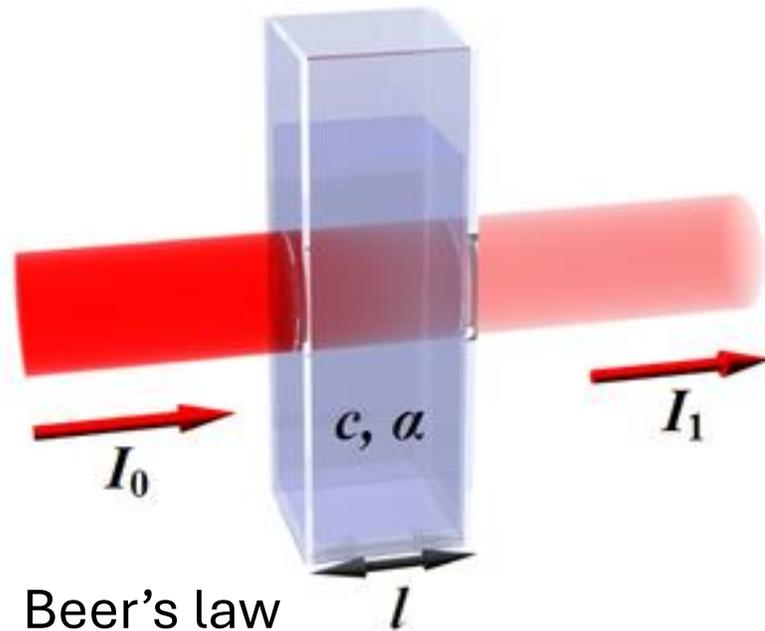
Aerosol optical depth (AOD) is obtained from transmission measurements of the atmosphere:

Other aerosol properties are obtained from inversion modelling combining direct and scattered solar irradiance.

What columnar aerosol properties are retrieved / used for studying their radiative effects ?

Aerosol Optical Depth (AOD) ~ aerosol amount

$$I = I_0 * e^{-m\tau}$$

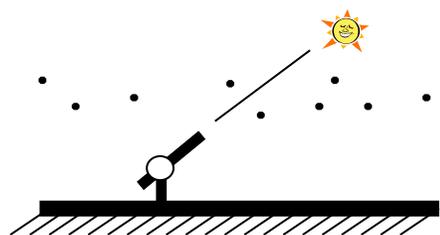
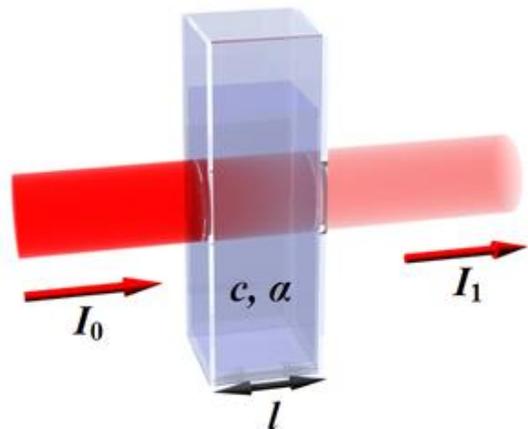


I = measurement
 I_0 = TOA / calibration
 τ = total extinction

$$\tau_{(wl)} = \tau_{O_3} + \tau_{aer} + \tau_{Ray} + \tau_{cl} + \tau_{gas}$$

Aerosols

Aerosol Optical Depth (AOD) ~ aerosol amount in the atmospheric column Beer-Lambert law



Signal
Volts (λ)



Calibration
Post processing (Atm. inputs)



AOD (λ)
unitless

$$I_{\lambda} = I_{\lambda}^0 * e^{-\tau_{\lambda} m}$$

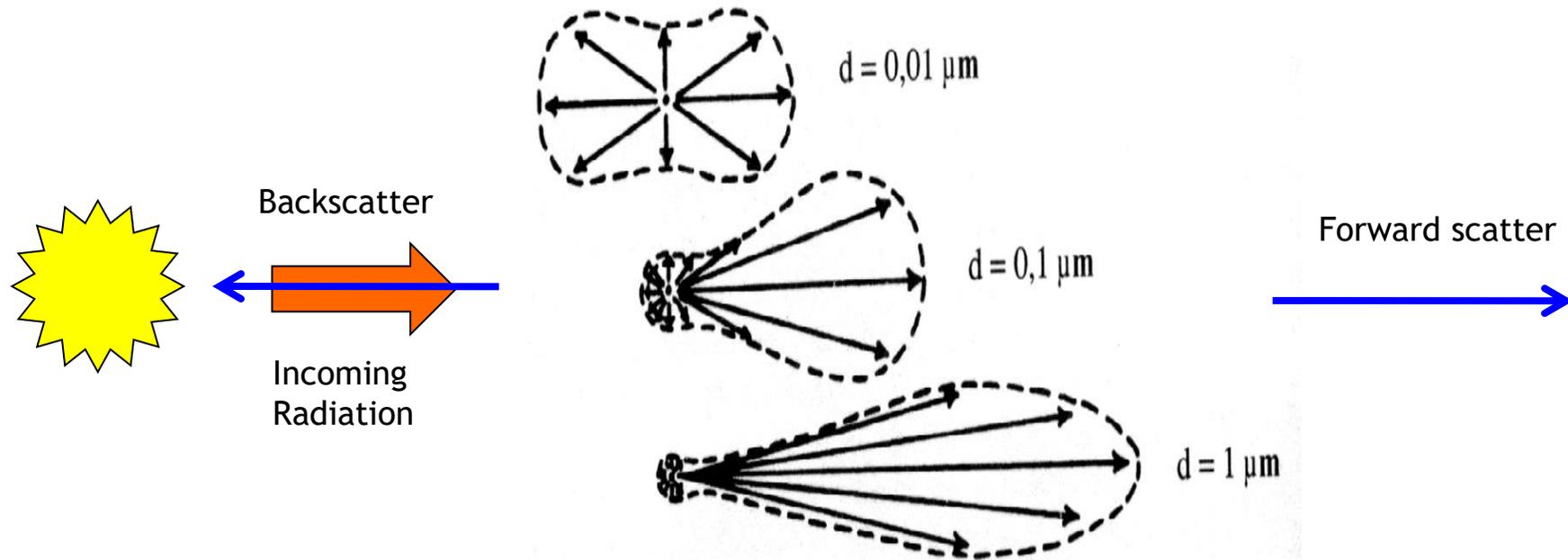
$$T(\lambda) = \frac{\ln I_0/I}{m} = \sum_i \tau_{att(i)} m_{att(i)} / m$$

$$\tau_{\lambda} = \tau_{O_3} + \tau_{aer} + \tau_{Ray} + \tau_{clouds} + \tau_{NO_2}$$

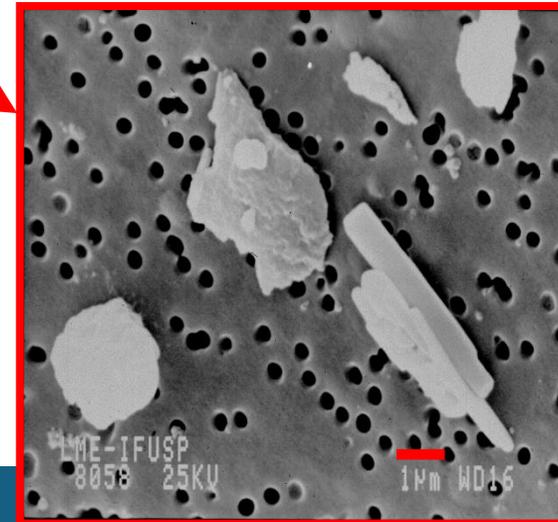
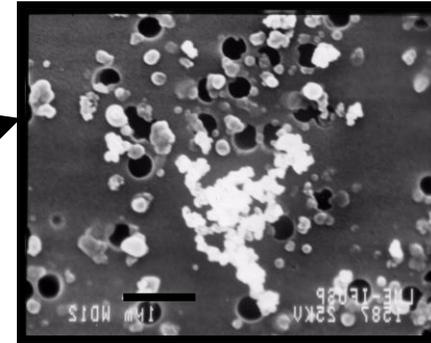
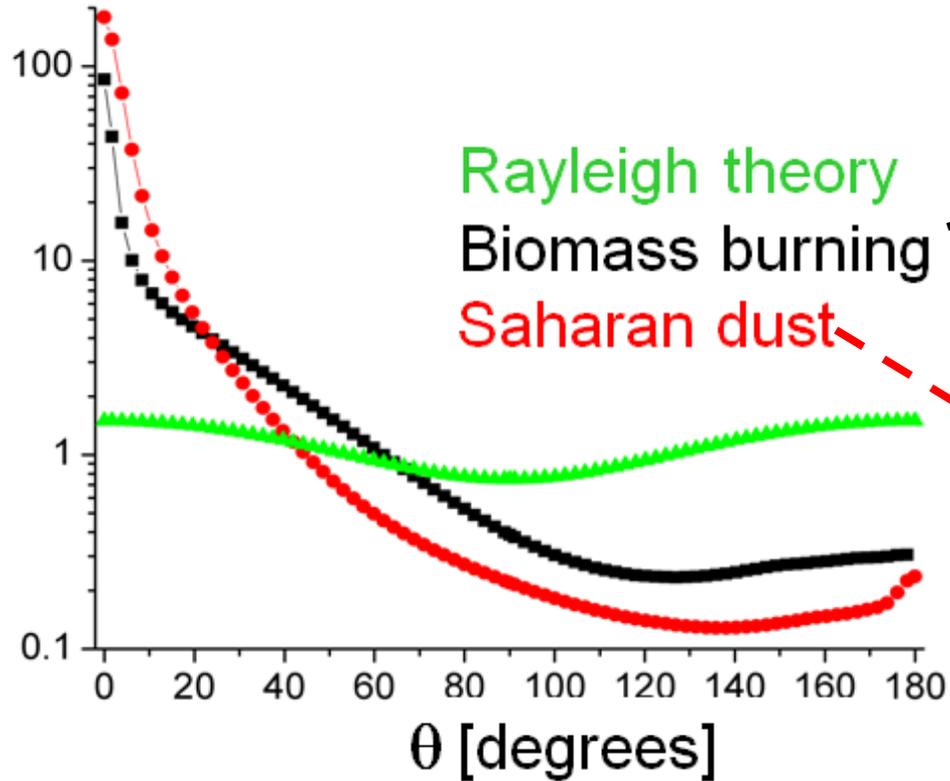
Optical Properties

Scattering Phase Function

The directional light scattering due to the aerosol particles



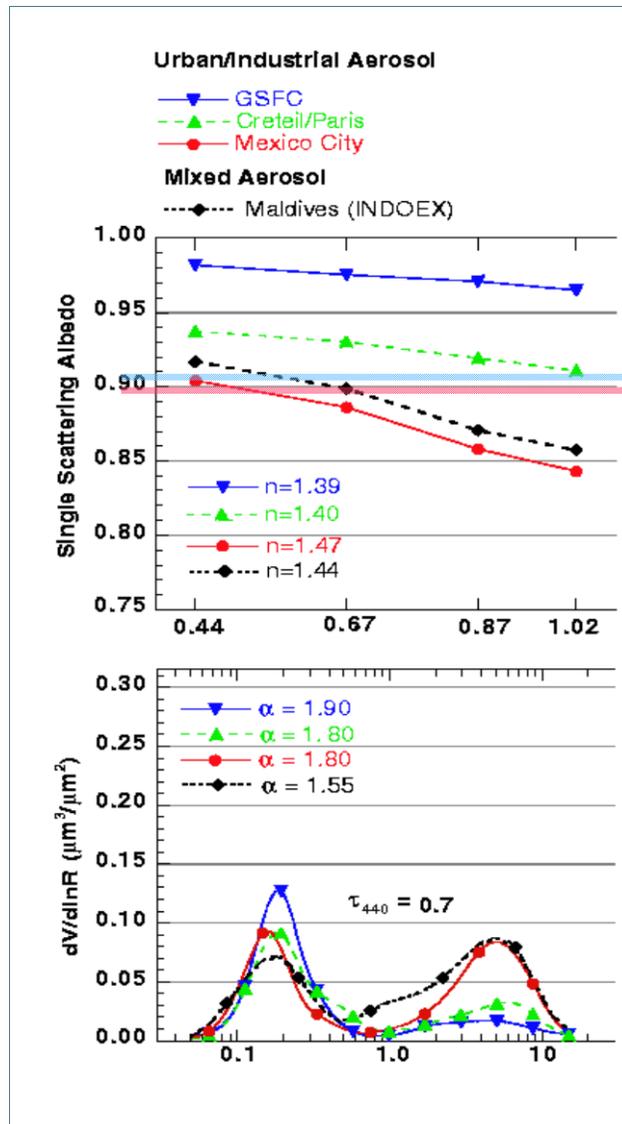
Typical aerosols and their properties



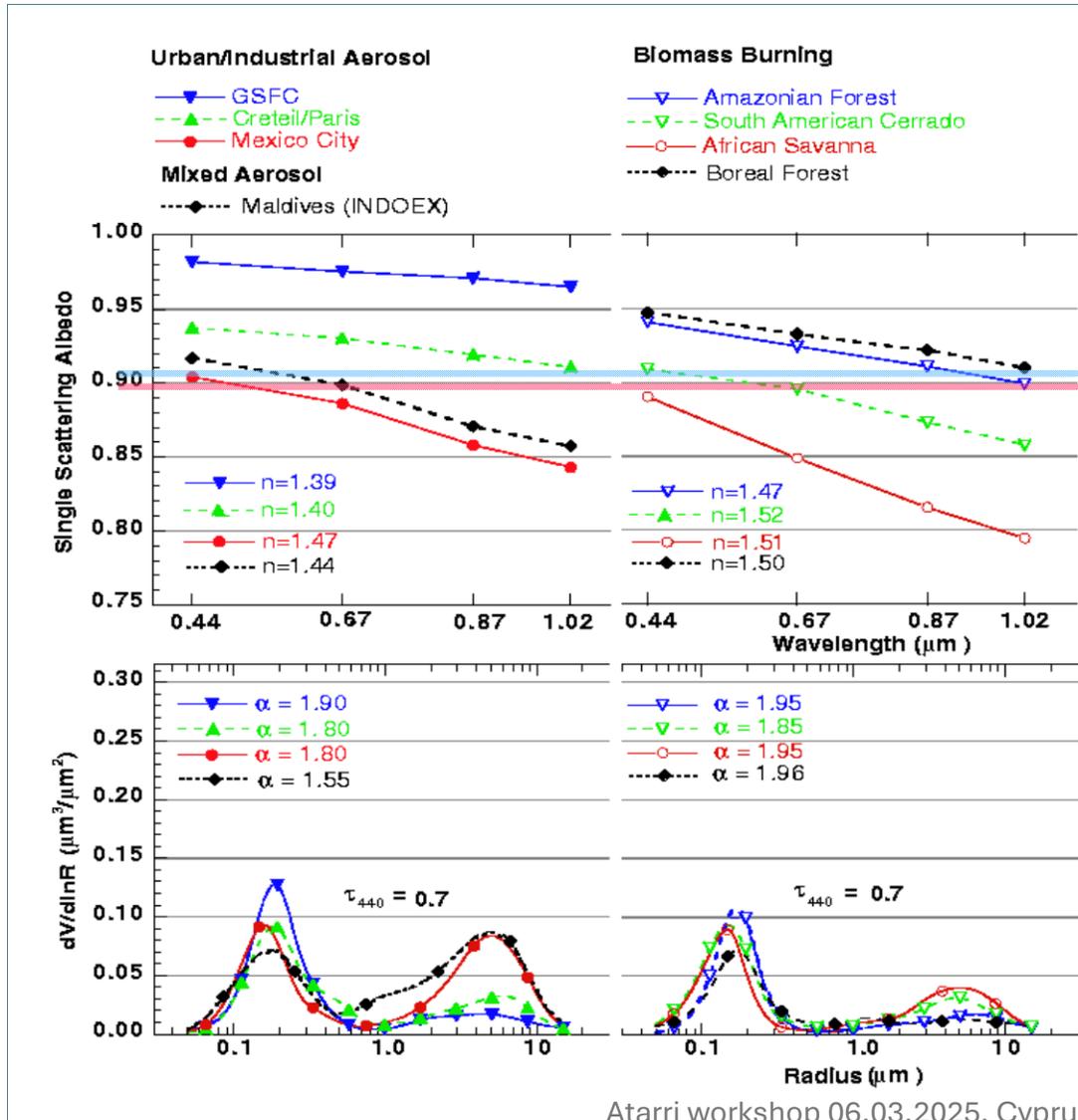
The phase function:

- relative angular distribution of scattered light
- heavily depends on the size and shape of aerosol particles

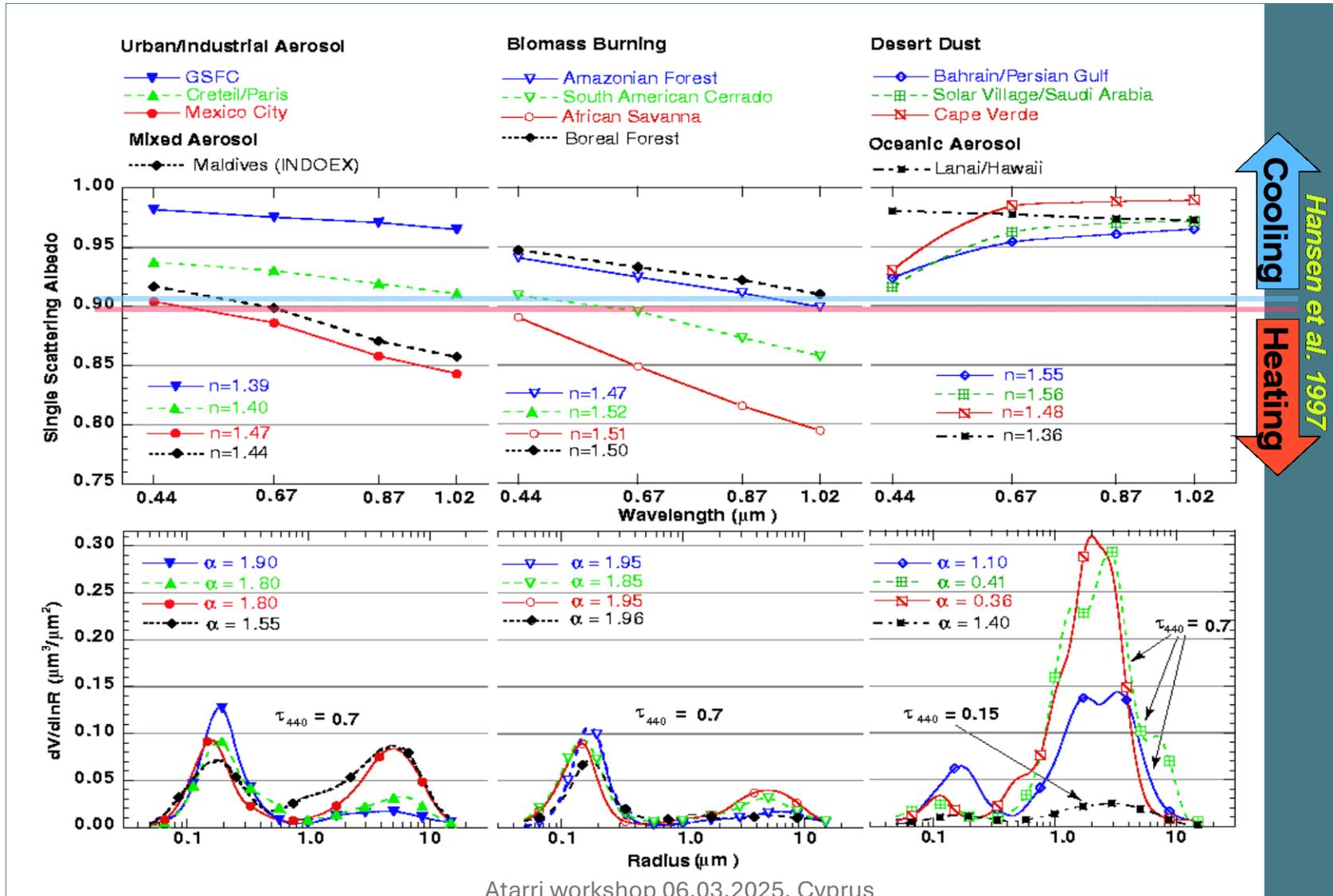
Example of aerosol types



Example of aerosol types



Example of aerosol types



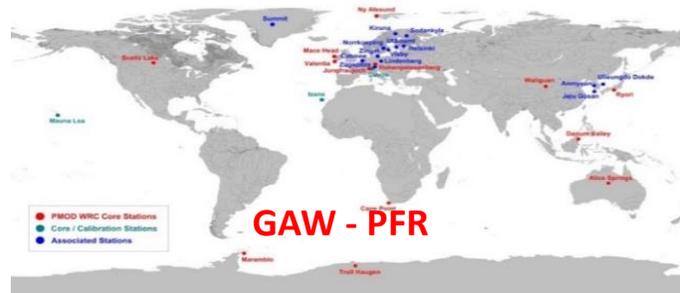
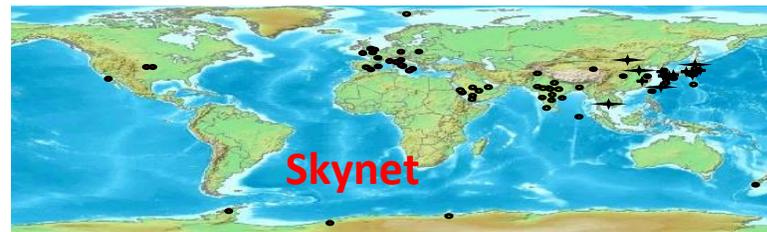
WMO - Homogenization of established techniques and existing tools

World aerosol optical depth research and calibration center

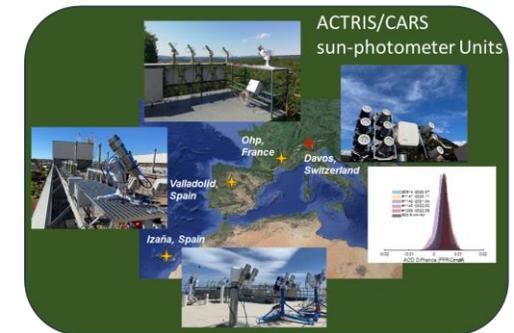
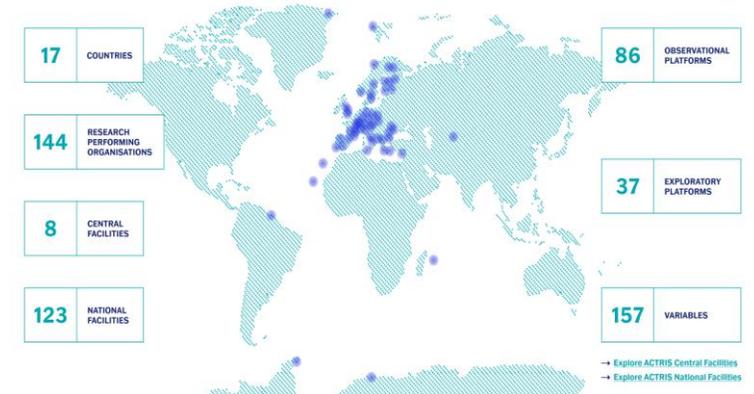
**Precision Filter Radiometer (PFR)
Sun-photometer
WMO reference**



Filter Radiometer Comparisons (2000-2021)



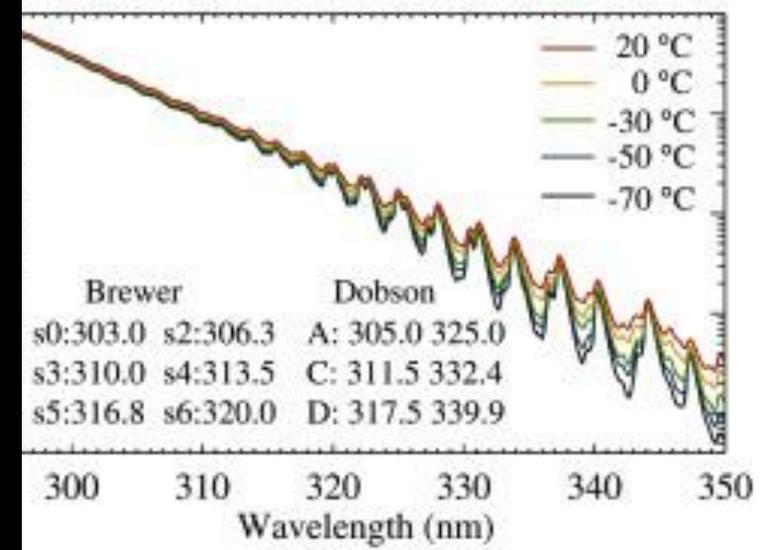
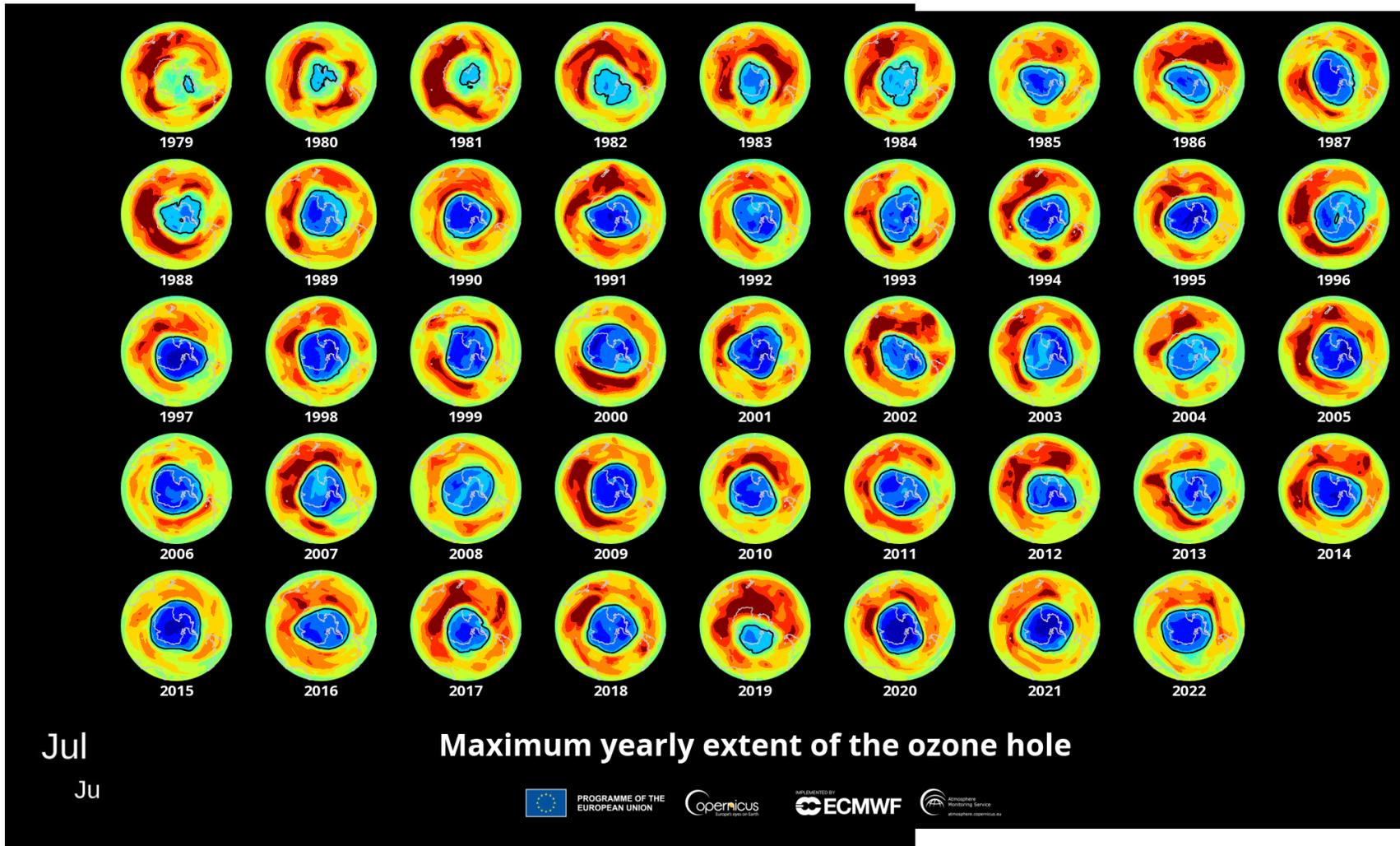
ACTRIS European RI



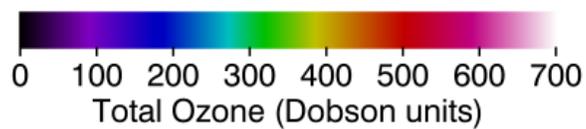
Atarri workshop 06.03.2025, Cyprus

World aerosol Optical depth Research and calibration Center vs global networks

Total Column Ozone



Differential absorption



Total column ozone retrieval

Total column ozone can be retrieved from solar radiation measurements based on the knowledge of the ozone absorption coefficient.

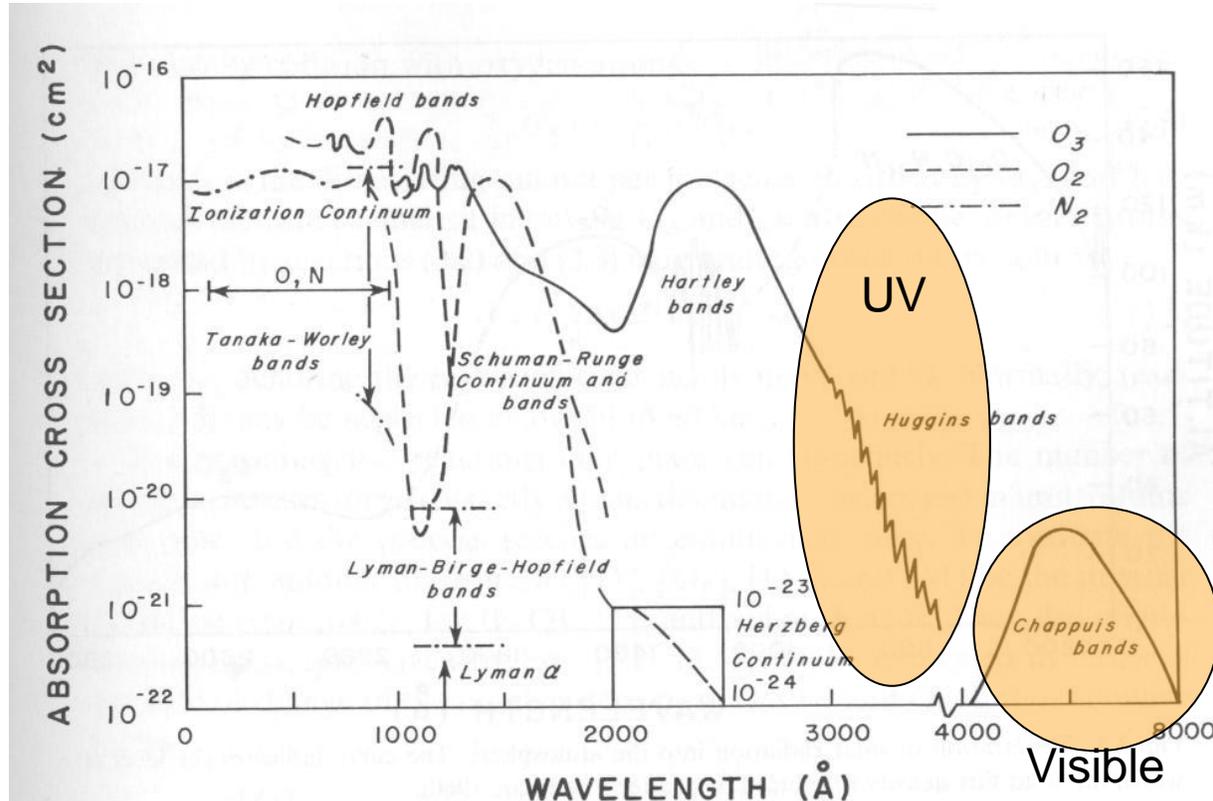


Fig. 3.2 Absorption cross sections σ (in units of cm^2) of ozone, molecular oxygen, and molecular nitrogen in the ultraviolet spectral region. Absorption regions for atomic nitrogen and oxygen are also shown.

Total column ozone retrieval

“The double ratio method”

$$\log I_\lambda = \log I_\lambda^0 - \tau_\lambda^R m_R - \tau_\lambda^{O_3} m_{O_3} - \tau_{(\lambda)}^{abs} m_{abs}$$

known

unknown

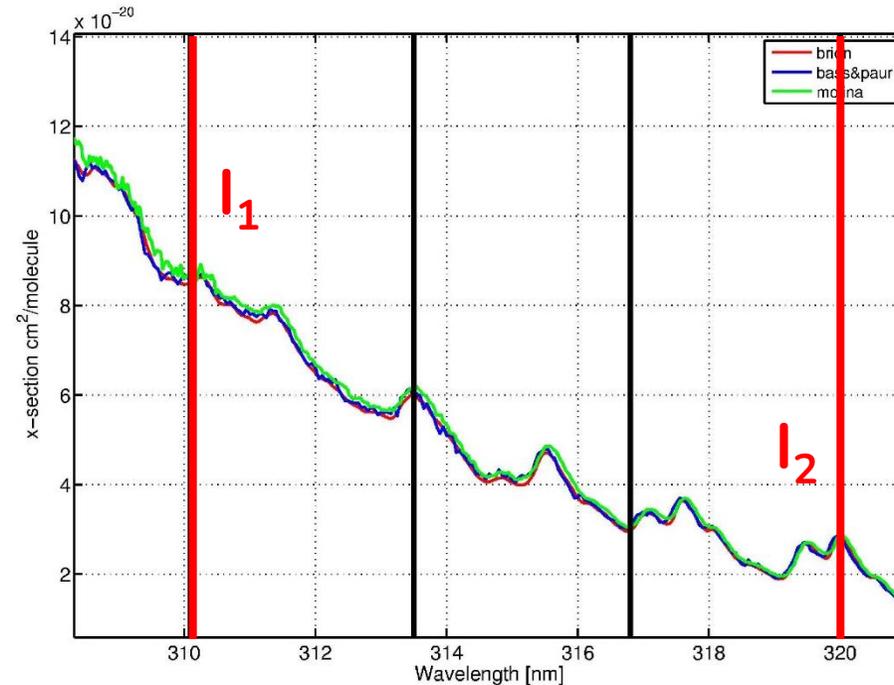
We use their different spectral absorption features: ozone has a very distinct spectral absorption in the UV.

Simplest approach:

1) Take a measurement strongly absorbed by ozone and one measurement weakly absorbed by ozone and take the ratio.

$$R = \log\left(\frac{I_1}{I_2}\right) = \log(I_1) - \log(I_2)$$

This should take care of $\tau_{(\lambda)}^{abs}$



Total column ozone retrieval

“The double ratio method”

Obtaining F_0 – Langley-plot

The langley-plot uses the Beer-Lambert law

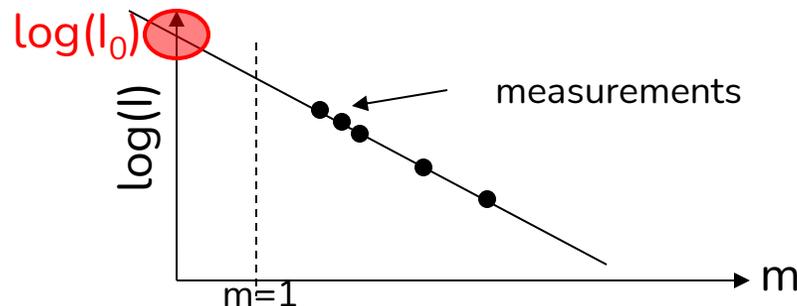
$$I_\lambda = I_\lambda^0 e^{-\tau_\lambda m}$$

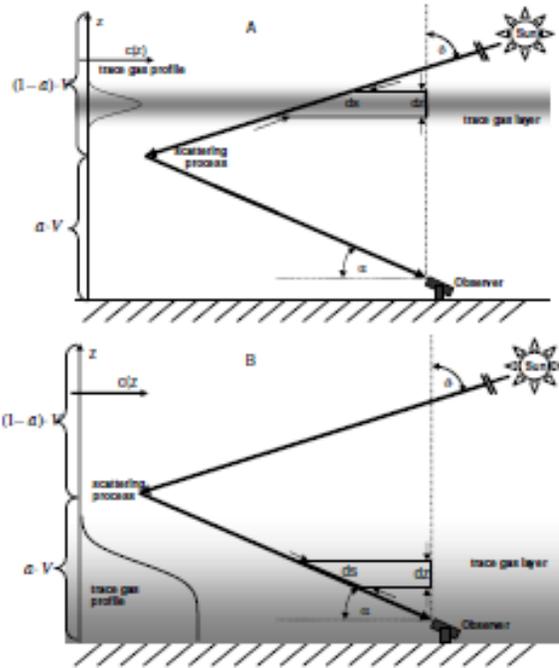


under the assumption that the atmosphere is constant, i.e. the total optical depth τ is constant. The Beer-Lambert law can be rewritten as,

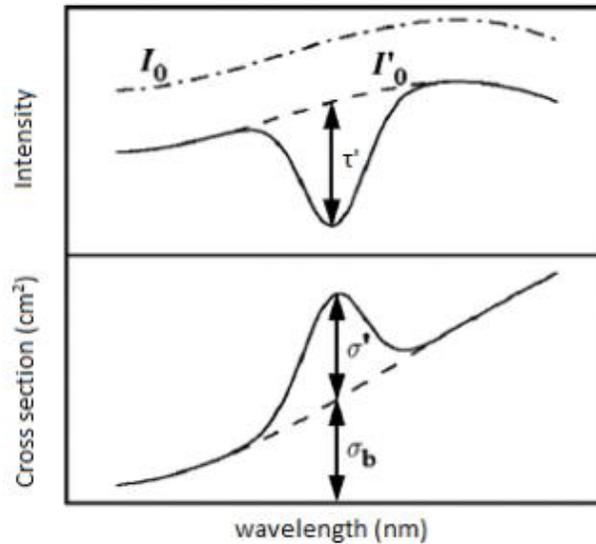
$$\log I_\lambda = \log I_\lambda^0 - \tau_\lambda m$$

This is now a linear equation which varies with the airmass m . At airmass 0 one obtains the extraterrestrial constant.



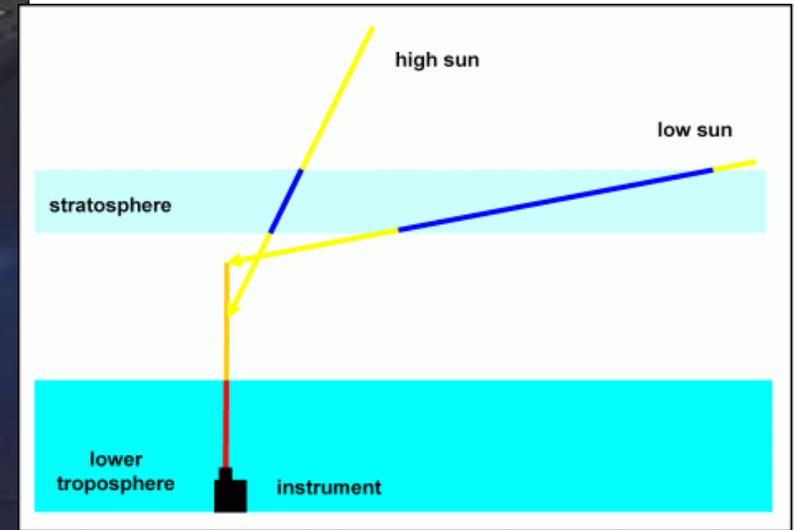
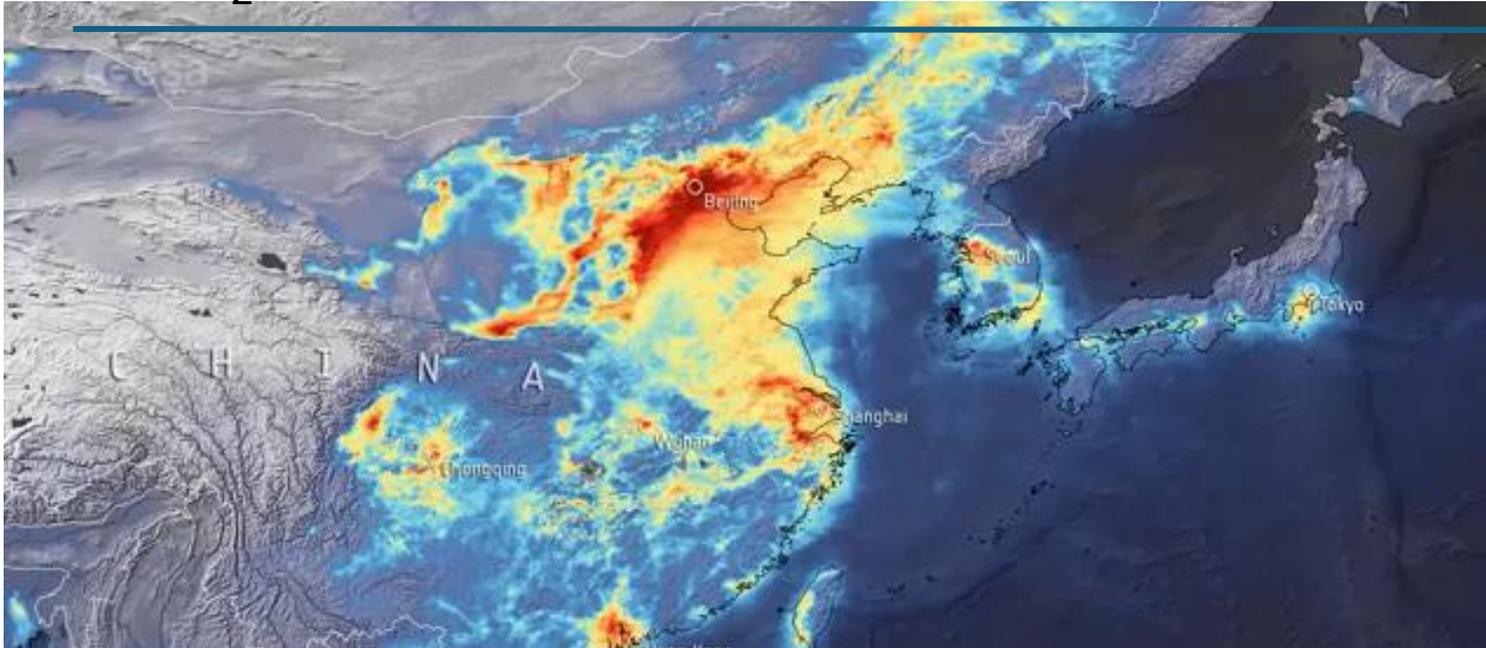


Differential Optical Absorption Spectroscopy (DOAS) technique

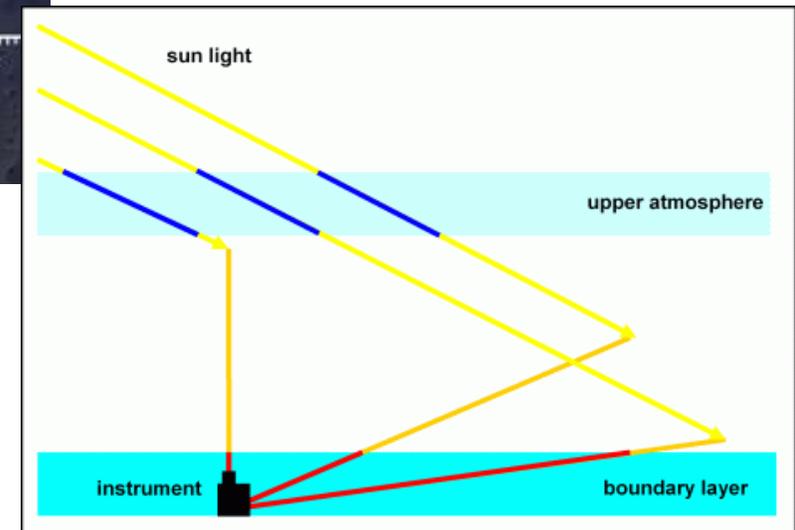
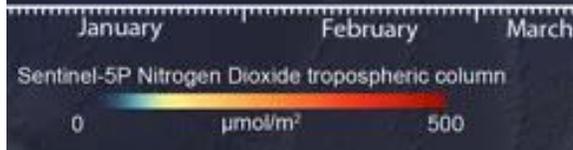
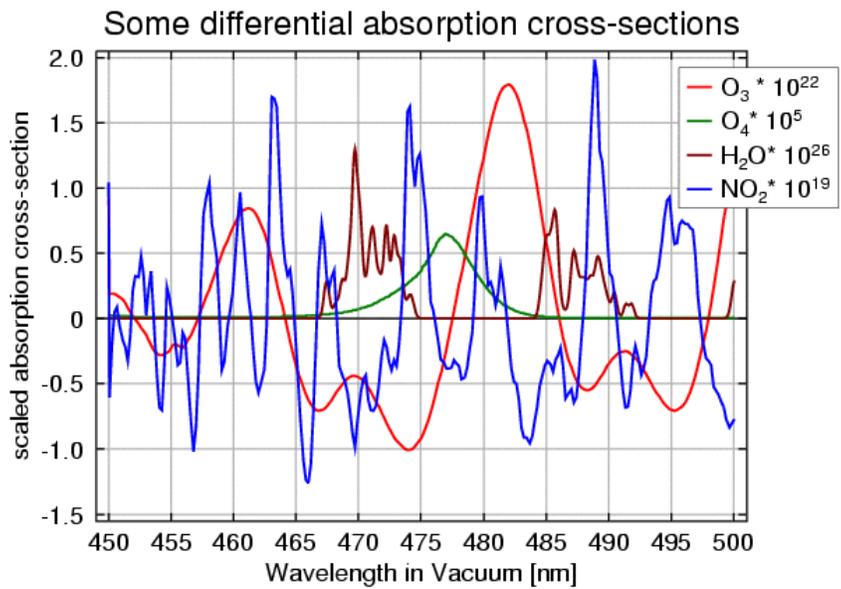


NO₂ - Gases

Differential Optical Absorption Spectroscopy (DOAS)



“looking” at the zenith

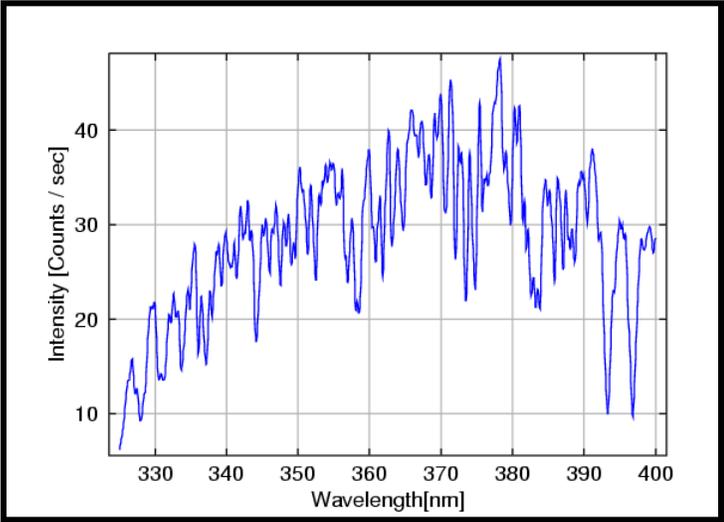


“looking” towards the Horizon

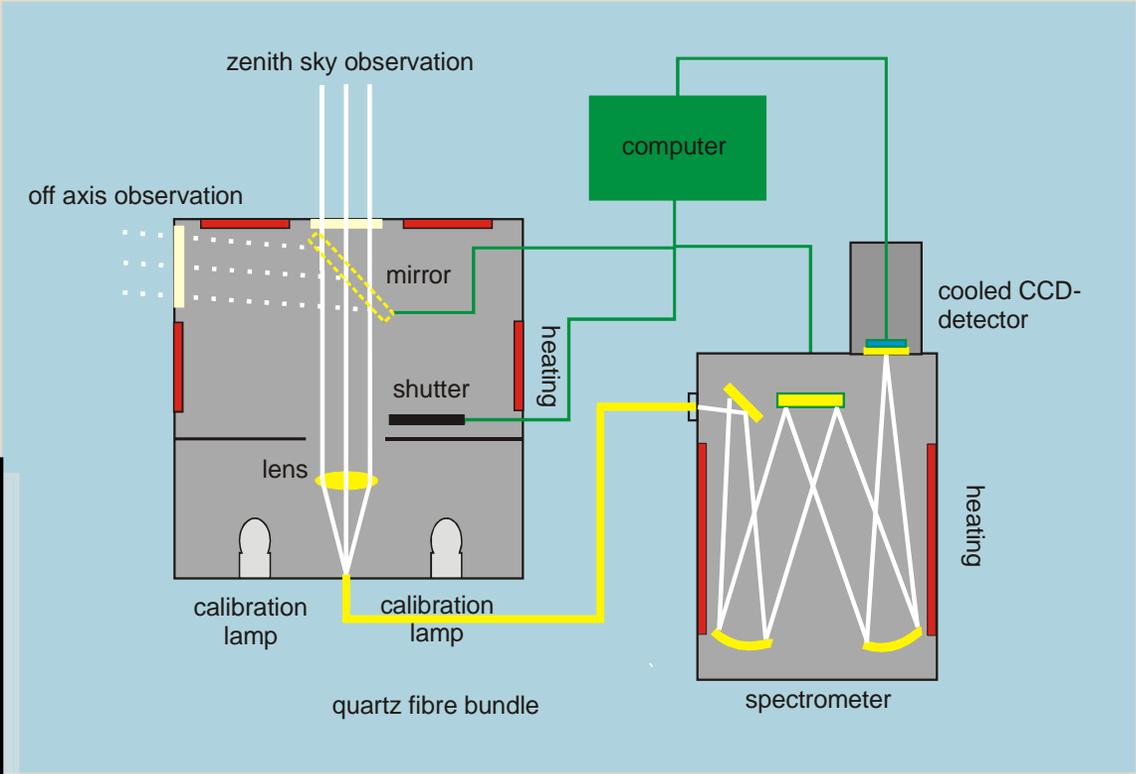
The MAXDOAS instrument

MAXDOAS = Multi Axis Differential Optical Absorption Spectroscopy

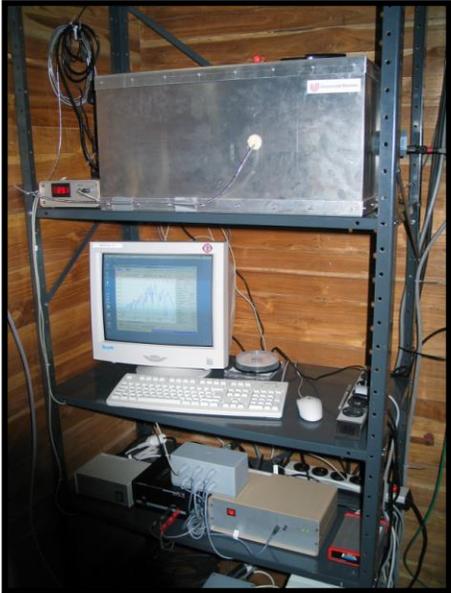
Measured Spectrum



Telescope



Spectrometer



Airmass factors – Slant column densities

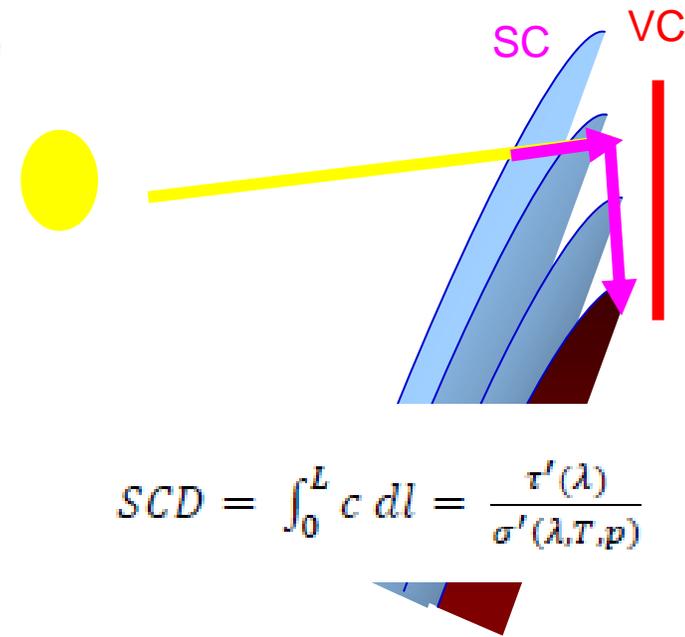
The primary quantity retrieved by applying the DOAS analysis is the Slant Column Density (SCD), which is defined as the integrated trace gas concentration c along the light path L , and is given in the units of molecules/cm²:

The airmass factor (AMF) is the ratio of the measured slant column (SC) to the vertical column (VC) in the atmosphere:

$$AMF = \frac{SC(\lambda, \Theta, \dots)}{VC}$$

The AMF depends on a variety of parameters such as

- wavelength
- geometry
- vertical distribution of the species
- clouds
- aerosol loading
- surface albedo



$$SCD = \int_0^L c \, dl = \frac{\tau'(\lambda)}{\sigma'(\lambda, T, p)}$$

The basic idea is that the sensitivity of the measurement depends on many parameters but if they are known, signal and column are proportional

DOAS equation I

The intensity measured at the instrument is the extraterrestrial intensity weakened by absorption, Rayleigh scattering and Mie scattering along the light path:

$$I(\lambda, \Theta) = a(\lambda, \Theta) I_0(\lambda) \exp\left\{-\int \left(\sum_{j=1}^J \sigma_j(\lambda) \rho_j(s) + \sigma_{Mie}(\lambda) \rho_{Mie}(s) + \sigma_{Ray}(\lambda) \rho_{Ray}(s)\right) ds\right\}$$

Annotations:

- scattering efficiency (points to $a(\lambda, \Theta)$)
- unattenuated intensity (points to $I_0(\lambda)$)
- integral over light path (points to the integral symbol \int)
- absorption by all trace gases j (points to the sum $\sum_{j=1}^J$)
- extinction by Mie scattering (points to $\sigma_{Mie}(\lambda) \rho_{Mie}(s)$)
- extinction by Rayleigh scattering (points to $\sigma_{Ray}(\lambda) \rho_{Ray}(s)$)
- exponential from Lambert Beer's law (points to the entire exponential term)

DOAS equation IV

Finally, the logarithm is taken and the scattering efficiency included in the polynomial. The result is a linear equation between the optical depth, a polynomial and the slant columns of the absorbers. by solving it at many wavelengths (least squares approximation), the slant columns of several absorbers can be determined simultaneously.

intensity with absorption (the measurement result)

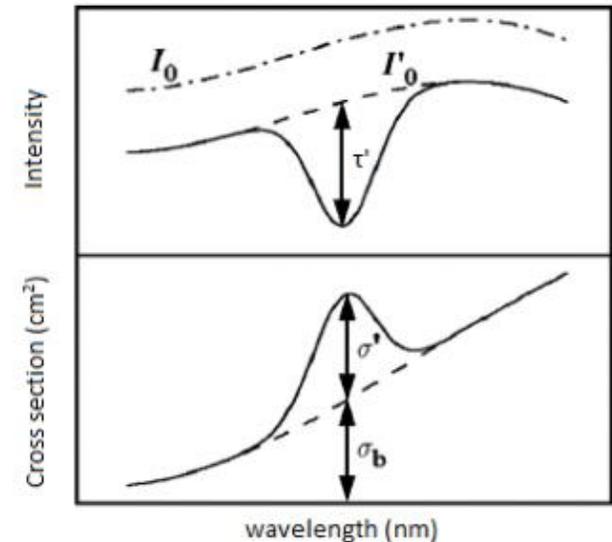
intensity without or with less absorption (reference measurement)

$$\ln(I(\lambda, \Theta) / I_0(\lambda)) = - \sum_{j=1}^J \sigma'_j(\lambda) SC_j + \sum_p b_p^* \lambda^p$$

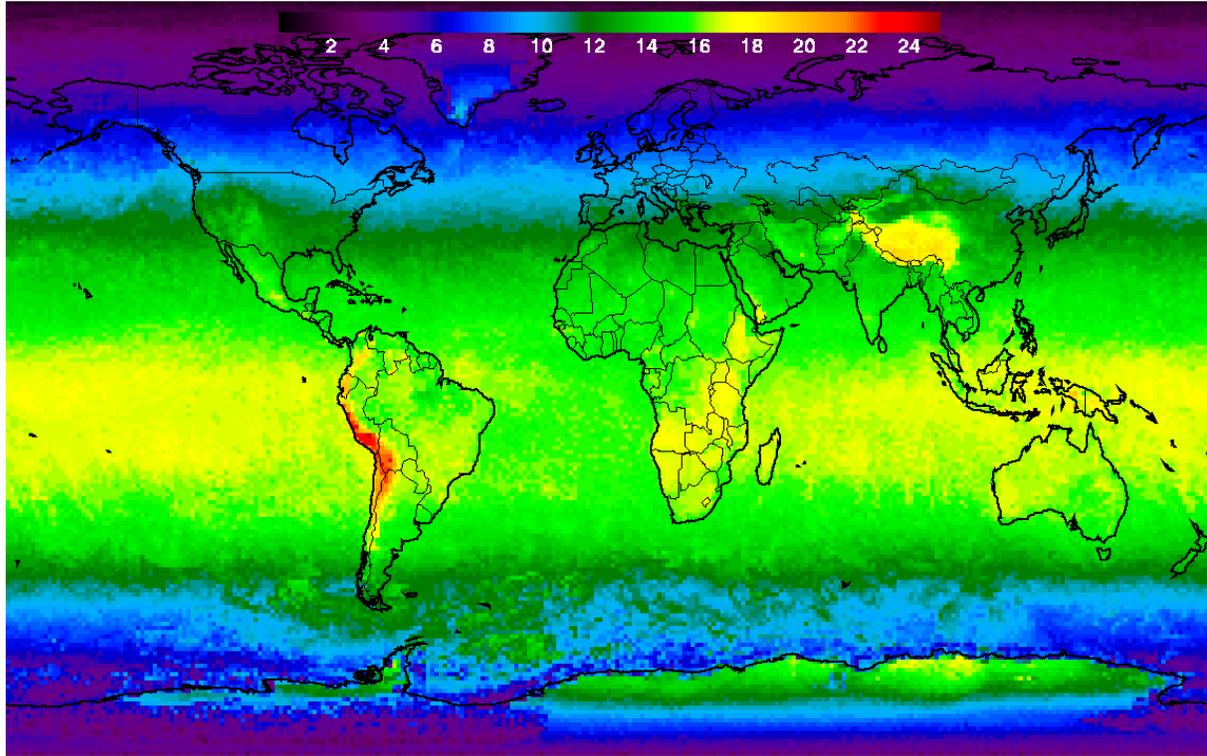
absorption cross-sections (measured in the lab)

slant columns SC_j are fitted

polynomial (b_p^* are fitted)

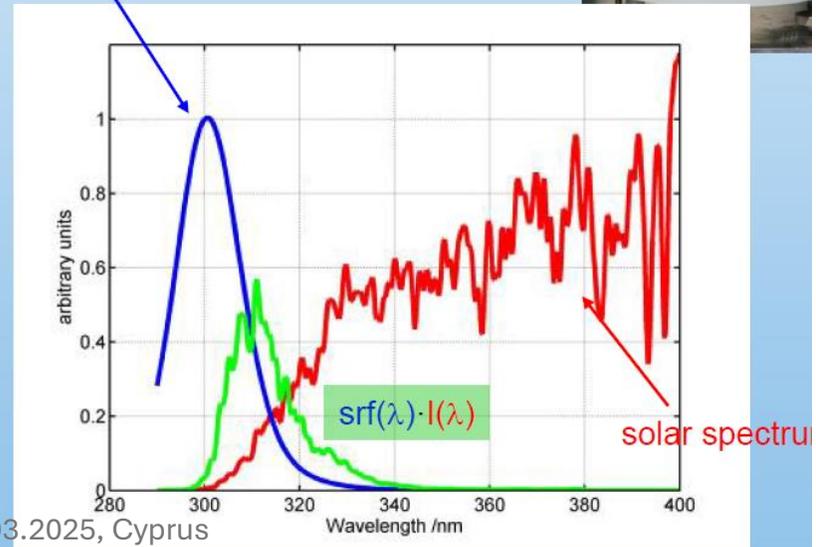


Solar radiation - UV

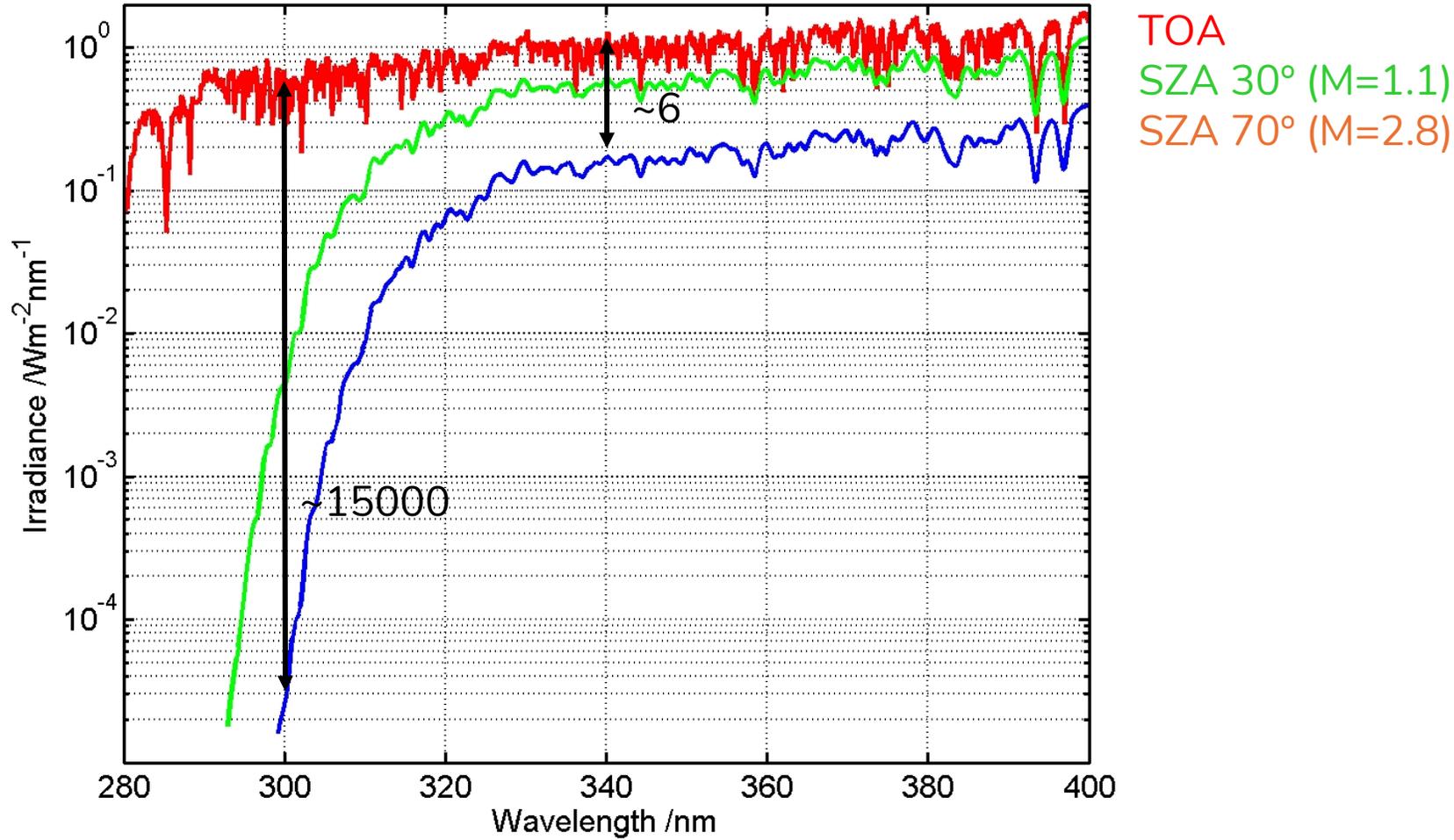


Direct measurement in volts
Spectral and absolute calibration

spectral response (srf)



Solar UV radiation from space to ground



Human health effects of UV Radiation

Positive

Converts cholesterol to Vitamin D which protects against:

- bone disease
- rickets
- rheumated arthritis

Vitamin D deficiency is linked to:

- increased mortality rate
- Various forms of internal cancer
- Hypertension
- stroke
- multiple sclerosis
- diabetes
- Cardiovascular disease
- Mental illness
- autoimmune diseases

Negative

Acute

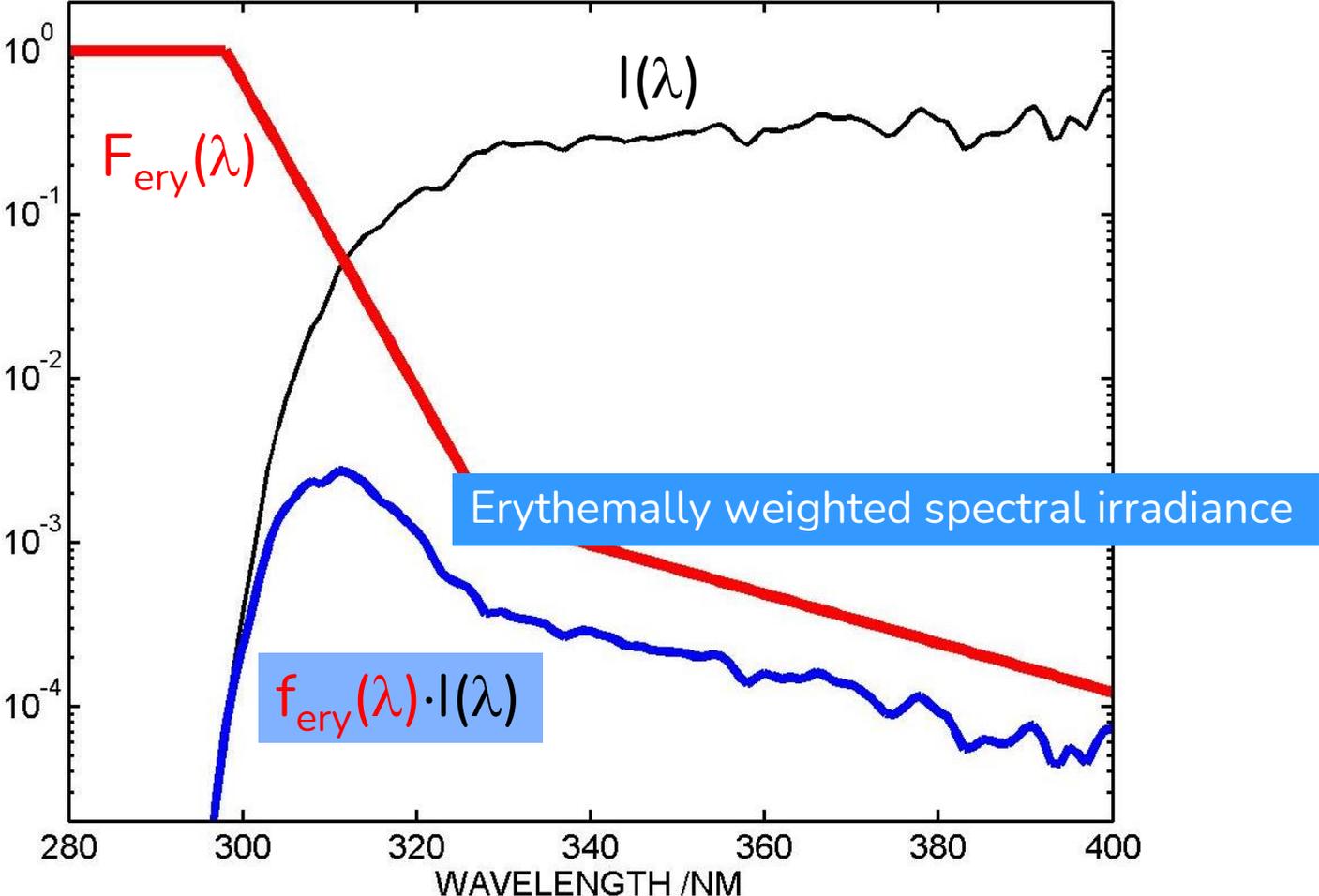
- Erythema (sun burn)
- Photokeratitis and Photoconjunctivitis
- Decreased immune response

Chronic

- Melanoma (Skin cancer)
- Skin aging
- Cataracts

UV radiation is recognized as a human carcinogen by the WHO and National Institutes of Health

Erythema action spectrum



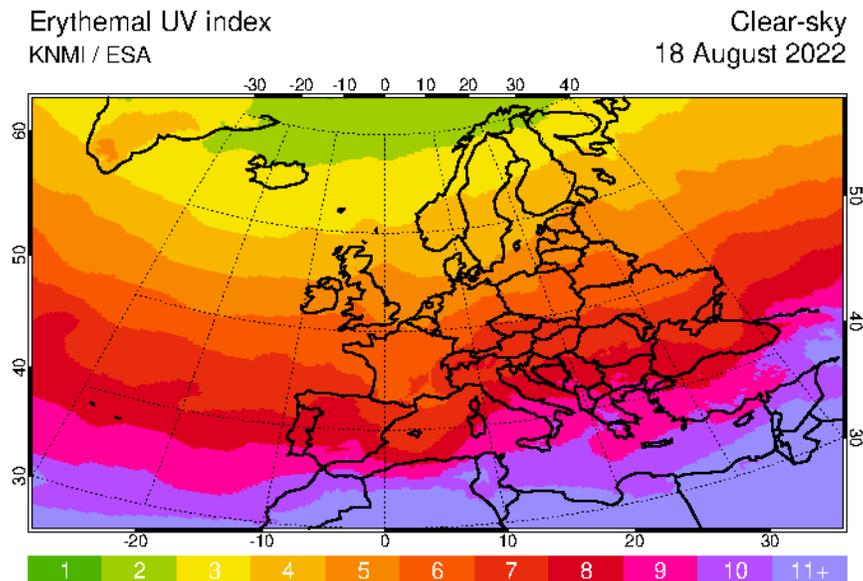
UV Index

The UV Index is the preferred method endorsed by the World Meteorological Organisation (WMO) to disseminate information of UV exposure to the public.

The UV Index is an open ended number obtained by multiplying the erythemally effective irradiance in W/m^2 by $40 \text{ W}^{-1}\text{m}^2$.

Example: $E_{\text{ery}} = 0.29 \text{ W}/\text{m}^2$ \rightarrow 12 UV Index

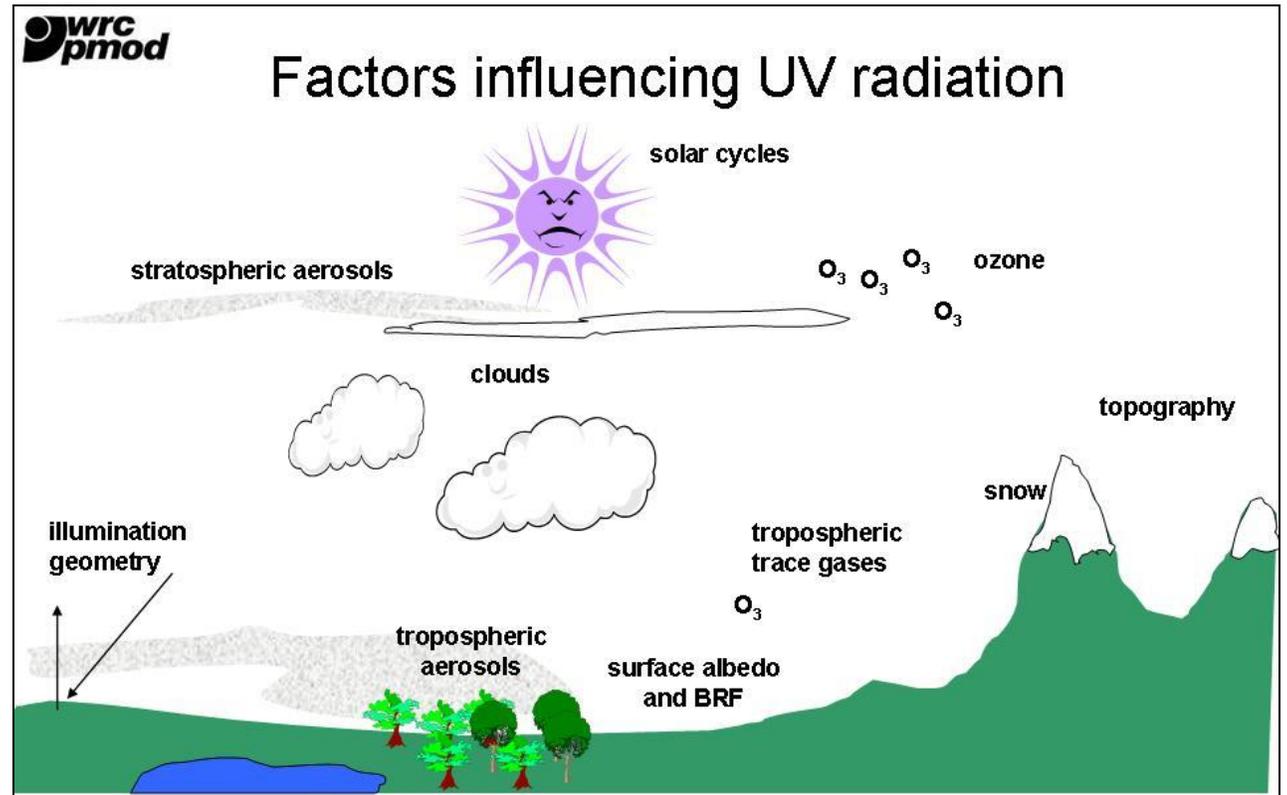
Factor empirically chosen to provide a UV Index between 0 – 10 in middle latitudes (standard situation).



<https://www.temis.nl/uvradiation/UVindex.php>

Investigating the variability of solar UV Radiation

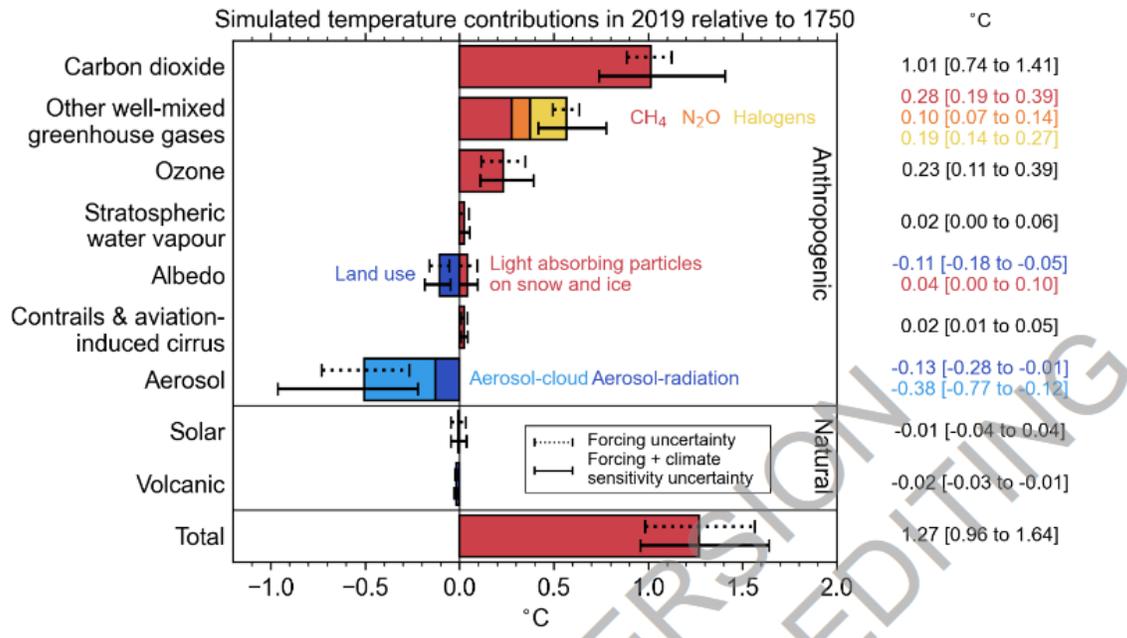
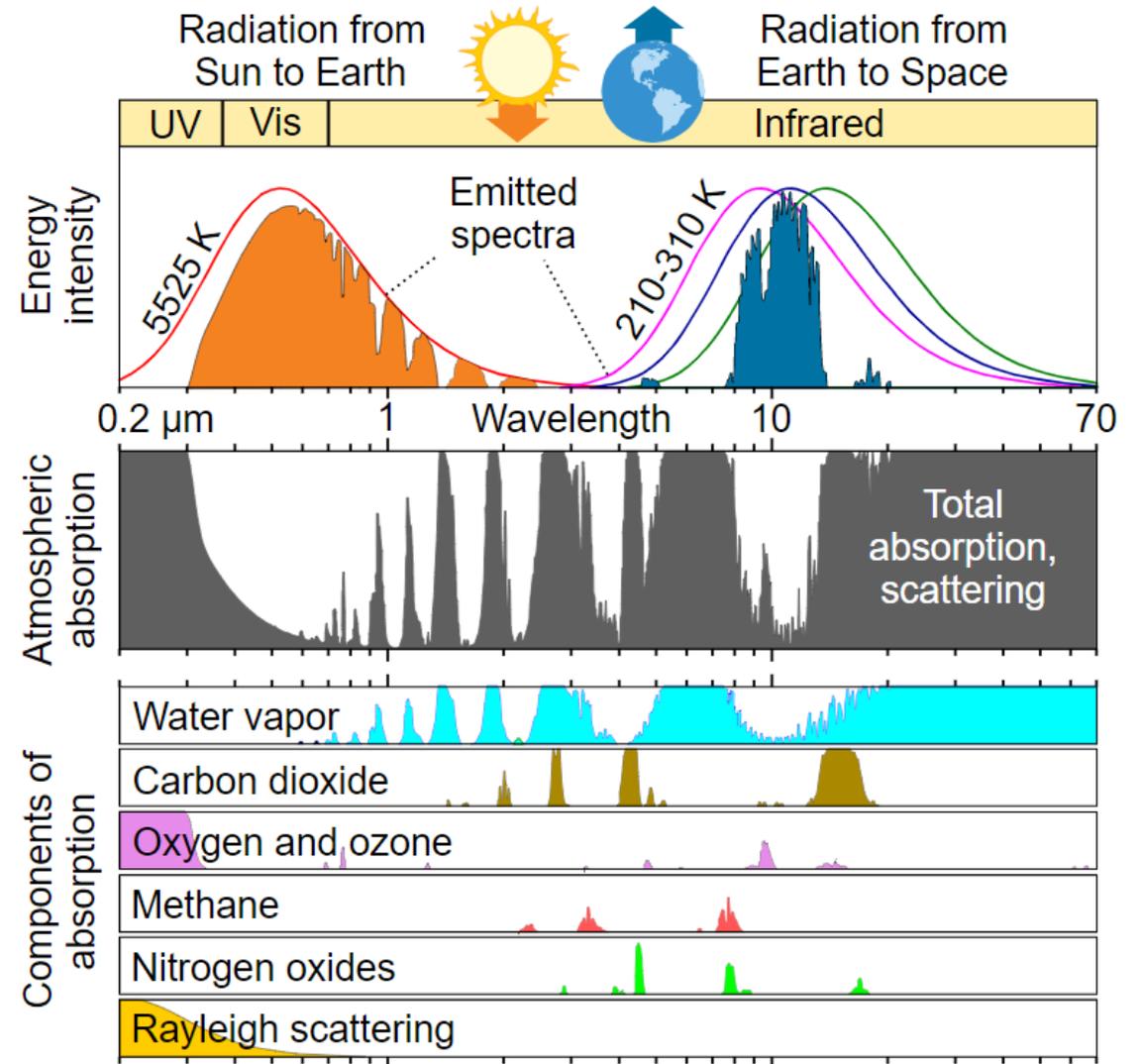
- Sun-Earth Distance
- Extra-terrestrial radiation (Top of the atmosphere)
- Variability due to the atmosphere:
 - Atmospheric composition
 - Ozone
 - Sulphure dioxide
 - Aerosols
 - Clouds
 - Molecules
- Solar Zenith Angle
- Ground reflection
- Ground topography



Greenhouse gases (GHGs)

- The green house effect:**

Some atmospheric trace gases absorb more strongly in the LW part of the spectrum (terrestrial) than the SW part (incoming solar)



<https://gml.noaa.gov/ccgg/about.html>

Spectroscopic Techniques in Remote Sensing

Tropospheric Remote sensing using **Back-scattered Solar radiation: UV/VIS/SW IR Absorption Spectroscopy** (e.g. SCIAMACHI)

- Spectral range: 0.3-2.4 μm
- Technique: measuring the spectral absorption structure of trace gases using spectrometers
- Mode: normal passive, but active techniques have the potential for the determination of trace gases profiles
- Advantage: high sensitivity which allows for the SW IR the precise determination of total column amount of important greenhouse gases such as CO_2 and CH_4 , with relative errors typically below 1%.

Remote Sensing using **thermal infrared: IR Spectroscopy** (e.g. IASI)

- Spectral range: 3.5-30 μm (is characterized by thermal emission from the Earth's atmosphere and the ground - TIR)
- Technique: using TIR emerging from the atmosphere (correlation radiometers, spectrometers, interferometers) for the measurements of atmospheric parameters
- Modern IR spectrometers are based on FT techniques (able to measure CO_2 , etc)
- Advantage: that **passive** operation is not restricted to daylight, more molecules than solar, vertical information for nadir

Infrared Instruments

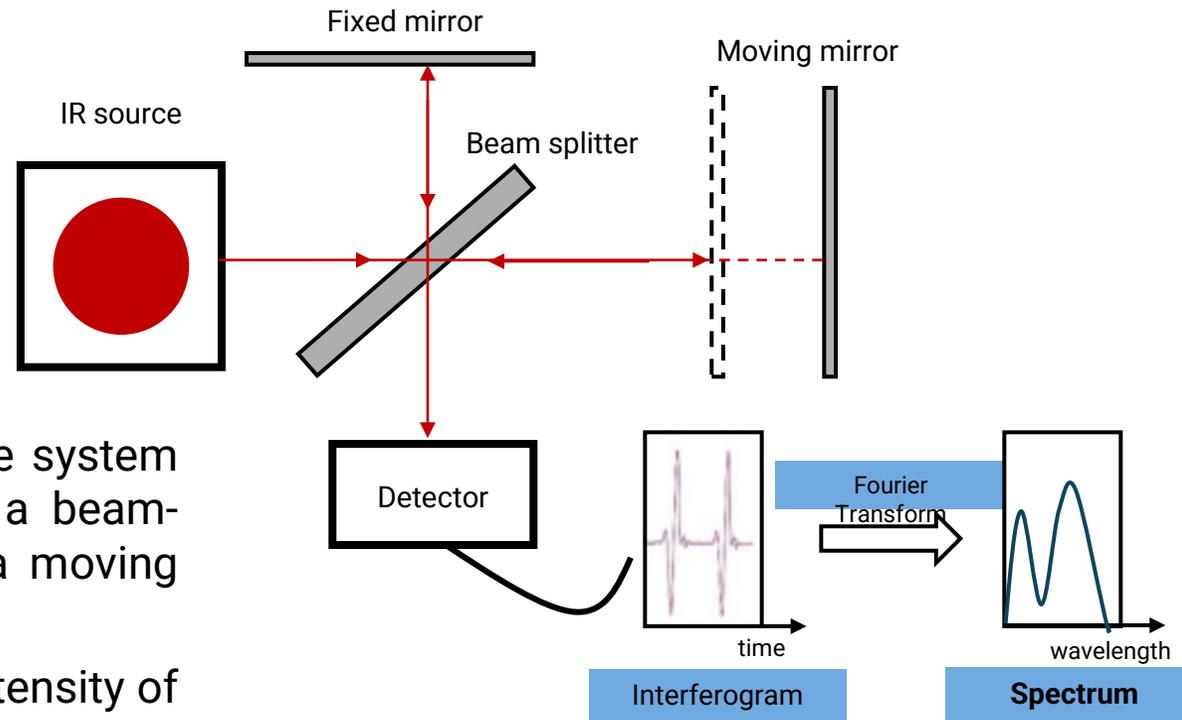
1) Cell correlation radiometry

2) Grating spectrometry

3) Fourier Transform Spectroscopy (FTS)

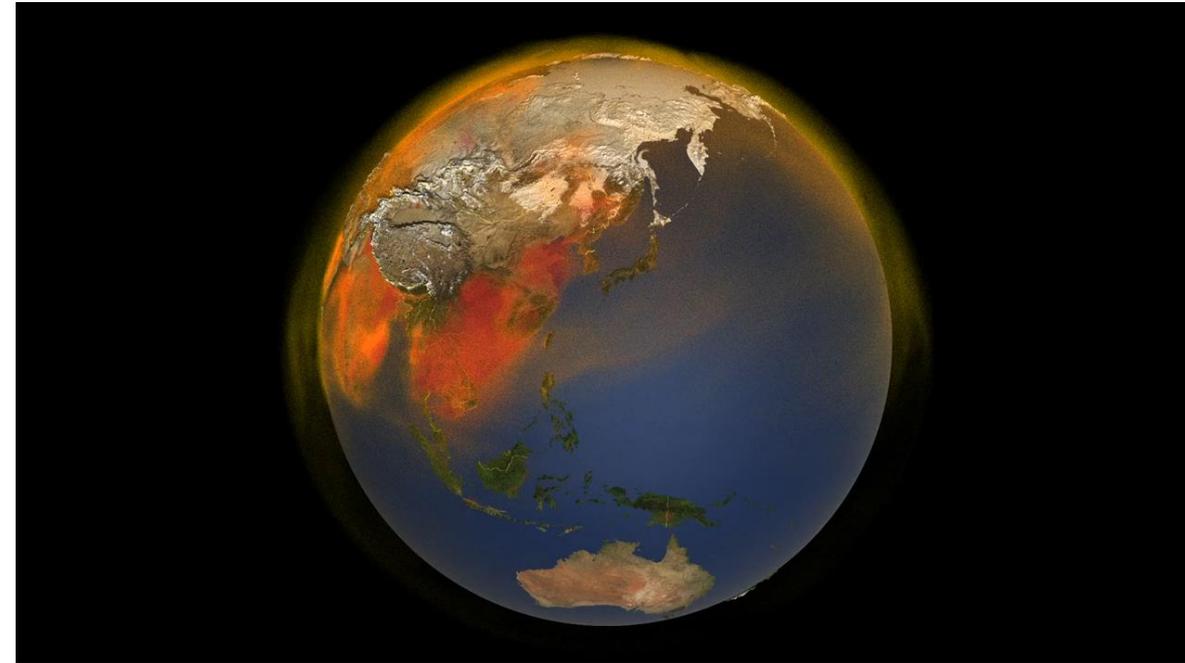
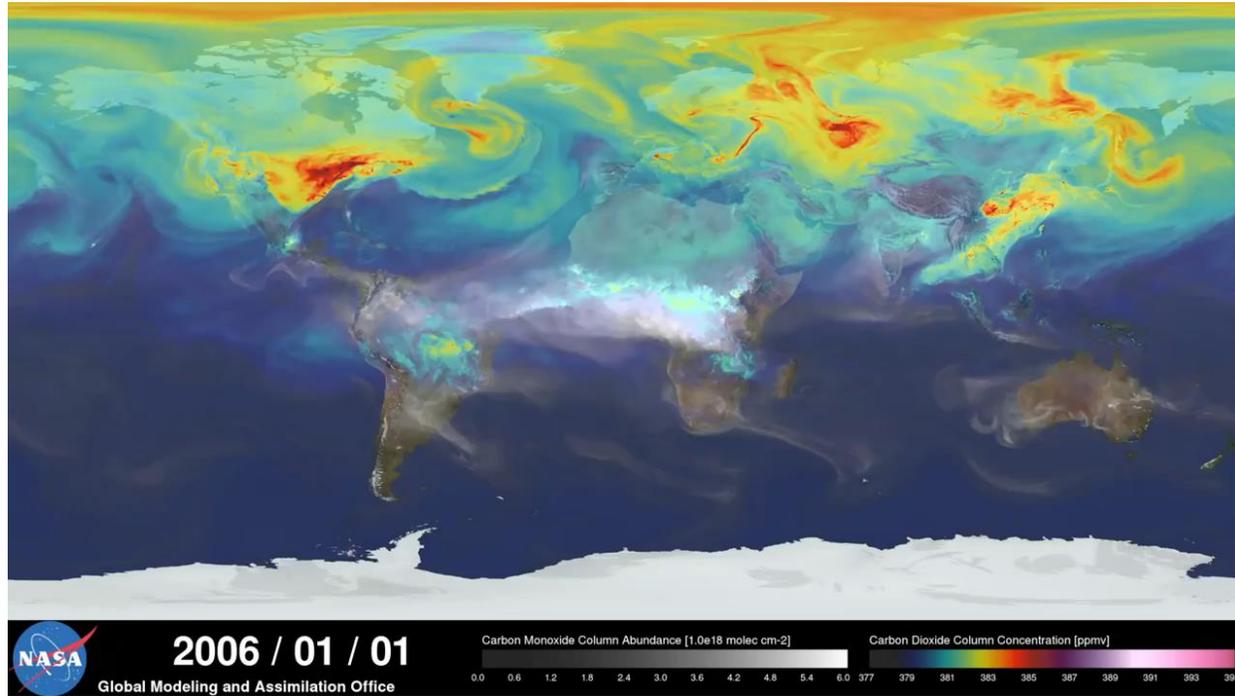
collecting infrared spectra using a Michelson-type interferometer

- Thermal infrared radiation emitted from the Earth-Atmosphere system is **split into two beams** by a half-transparent mirror called a beam-splitter, one is reflected from a fixed mirror and one from a moving mirror, which introduces a time delay, or optical path difference
- The two beams are then allowed to **interfere**, and the overall intensity of the light is measured at different time delay settings.
- By making measurements of the signal at many discrete positions of the moving mirror (the so-called “**interferograms**”), the source spectrum can finally be reconstructed using the inverse Fourier transform.
- In order to avoid oscillations around spectral lines that are due to the finite length of the interferograms, the latter are usually multiplied by a numerical function that decreases to zero at maximum delay;



Fourier Transform Spectroscopy (FTS)

Remote Sensing of Green house gases



<https://www.youtube.com/watch?v=GpLbd2fe3h4>

<https://www.youtube.com/watch?v=x1SgmFa0r04>

Thank you



Radiation sources

Active versus Passive remote sensing

Passive sensors can only be used to detect energy when the naturally occurring energy is available.

For all reflected energy, this can only take place during the time when the sun is illuminating the Earth.

Energy that is naturally emitted (such as thermal infrared) can be detected day or night, as long as the amount of energy is large enough to be recorded.



Radiation sources

Active versus Passive remote sensing

Active sensors, on the other hand, provide their own energy source for illumination.

The sensor emits radiation which is directed toward the target to be investigated.

The radiation reflected from that target is detected and measured by the sensor.

Active sensors can be used for examining wavelengths that are not sufficiently provided by the sun, such as microwaves, or to better control the way a target is illuminated. However, active systems require the generation of a fairly large amount of energy to adequately illuminate targets.

