Environmental Science. Physics and Applications

Chapter 2. Physics of the atmosphere

2. Basic physics of the atmosphere

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2.1 Basic physics of the atmosphere

Light waves

In this chapter we will discuss the electromagnetic spectrum and some basics about waves. Waves as acoustic waves, light waves, radar waves, infrasound waves, all can be classified by wavelength, frequency and speed. If we focus on electromagnetic waves traveling through space and oscillate with frequency f at the speed of light, *c*. The wavelength λ, the speed of light and the oscillating frequency *f* are related by

$$c = f\lambda$$

The speed of light in vacuum is approximately 3.0×10^8 m/s. When the electromagnetic wave travels through another medium, the speed is reduced to *v*, and we define the refractive index as

$$n = \frac{c}{v}$$

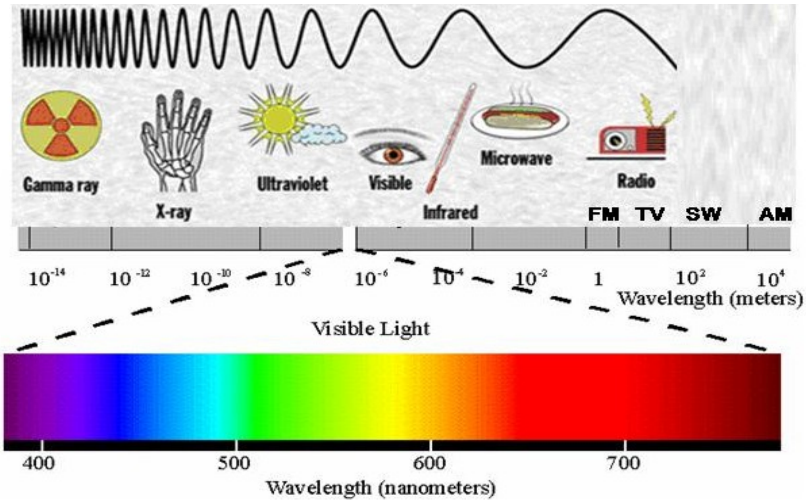
We can also define it as the change in wavelength by the expression below:

$$n = \frac{\lambda}{\lambda_{medium}}$$

The refractive index of air is *n = 1.00033* meaning that for instance a wavelength of 600 nm in vacuum will be 600/1.00033 nm = 599.8 nm in air. The difference is 0.2 nm in this wavelength region, but the difference also depends on the wavelength region. When doing accurate measurements of wavelength in studying atoms and molecules, this small difference has to be taken into account. Nowadays measurements can be made at resolutions around $1:10^8$ where this "small" difference is really quite large.

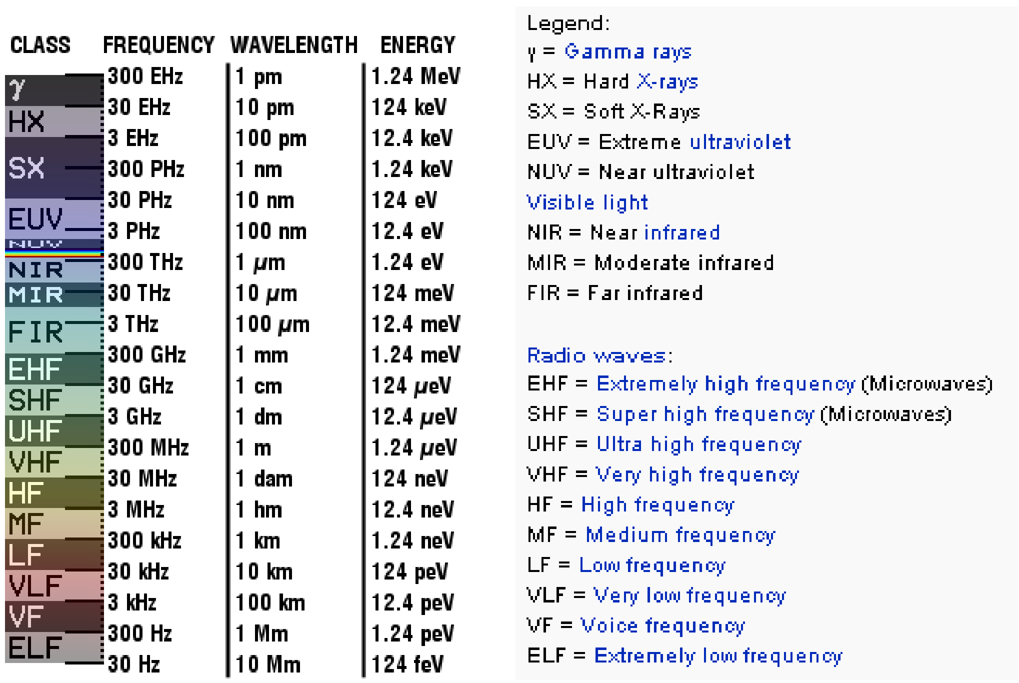
The Electromagnetic spectrum

Let us now study the electromagnetic spectrum that covers a wide range from radio waves around 1 km to gamma and X-rays in the nm and Å wavelength region:



The electromagnetic spectrum including the visible region

We can split the electromagnetic spectrum into different bands, for instance the UHF-band, lies between 3 GHz and 300 MHz, or in wavelength 1 dm < λ < 1 m:



CLASS
γ
HX
SX
EUV
NUV
NIR
MIR
FIR
EHF
SHF
UHF
VHF
HF
MF
LF
VLF
VF
ELF

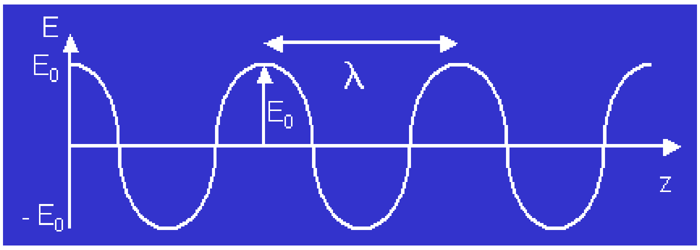
FREQUENCY	WAVELENGTH	ENERGY
300 EHz	1 pm	1.24 MeV
30 EHz	10 pm	124 keV
3 EHz	100 pm	12.4 keV
300 PHz	1 nm	1.24 keV
30 PHz	10 nm	124 eV
3 PHz	100 nm	12.4 eV
300 THz	1 μm	1.24 eV
30 THz	10 μm	124 meV
3 THz	100 μm	12.4 meV
300 GHz	1 mm	1.24 meV
30 GHz	1 cm	124 μeV
3 GHz	1 dm	12.4 μeV
300 MHz	1 m	1.24 μeV
30 MHz	1 dam	124 neV
3 MHz	1 hm	12.4 neV
300 kHz	1 km	1.24 neV
30 kHz	10 km	124 peV
3 kHz	100 km	12.4 peV
300 Hz	1 Mm	1.24 peV
30 Hz	10 Mm	124 feV

Legend:
γ = Gamma rays
HX = Hard X-rays
SX = Soft X-Rays
EUV = Extreme ultraviolet
NUV = Near ultraviolet
Visible light
NIR = Near infrared
MIR = Moderate infrared
FIR = Far infrared

Radio waves:
EHF = Extremely high frequency (Microwaves)
SHF = Super high frequency (Microwaves)
UHF = Ultra high frequency
VHF = Very high frequency
HF = High frequency
MF = Medium frequency
LF = Low frequency
VLF = Very low frequency
VF = Voice frequency
ELF = Extremely low frequency

Frequency classification of the E-M spectrum

The spectrum can be classified by wavelength, by frequency or by energy as can be seen in the table above. Often one uses the energy scale in electron volts, eV, related to the SI-system by 1 eV = 1.6×10^{-19} J.



The electric field can be described mathematically as a wave with an oscillating frequency, *f*, moving in the positive *z*-direction:

$$E(x,y,z,t) = E_0 \cos[\omega t - kz]$$

Here, the angular velocity is $\omega = 2\pi f$ and the wave number is given by $k = \frac{2\pi}{\lambda}$.

Comment: The spectroscopic wave number $\sigma = \frac{1}{\lambda}$ in the unit cm^{-1} can be regarded as proportional to the energy of a photon, where $E = hf = \frac{hc}{\lambda}$

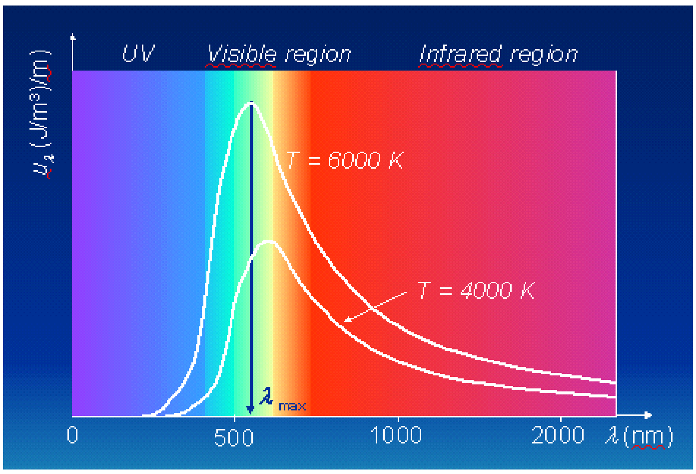
So, light can be regarded as an electromagnetic wave with energy, *E*, wavelength λ and frequency *f*. According to Planck we can describe light as a flux of particles, photons, with energy $E = hf$, where h = Planck's constant = 6,626 10^{-34} Js, $f = c/\lambda$ and where *c* is the speed of light. The photons have momentum *p* and energy $E = pc$.

2.2 The Planck Radiation law - Wien's law

When looking at so called black-body radiation and the emitted radiation from the heated object, Planck found that the emitted radiation energy per second I_λ between the wavelengths λ and λ + dλ, is given by

$$I_\lambda = \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}$$

This curve can be plotted for different temperatures as below:



The Sun has a surface temperature around 5800 K and has its wavelength maximum at 500 nm. Wien analysed this curve and derived an expression for the temperature, *T (K)* and the wavelength λ_{max} where the curve has its maximum.

If you take the derivative of the Planck expression you will get the maximum of the function:

$$\frac{du(\lambda)}{d\lambda} = 0$$

The wavelength when the maximum occurs we can call λ_{max}. After taking the derivative we obtain:

$$\lambda_{\max} = \frac{hc}{4.965k}\frac{1}{T}$$ or with inserting of the values of the constants:

$$\lambda_{\max} = 2898 \times 10^{3}\frac{1}{T} \text{ nm}$$ is the wavelength in nm if the temperature is given in Kelvin.

This formula is called the *Wien's displacement law*, which shows how the wavelength maximum is displaced with temperature *T*.
If we integrate the curve over all frequencies at a certain temperature *T* we obtain the *Stefan-Boltzmann law* that gives the total emitted energy (*e*) per second and over area unit:

$$e = \sigma T^{4}$$

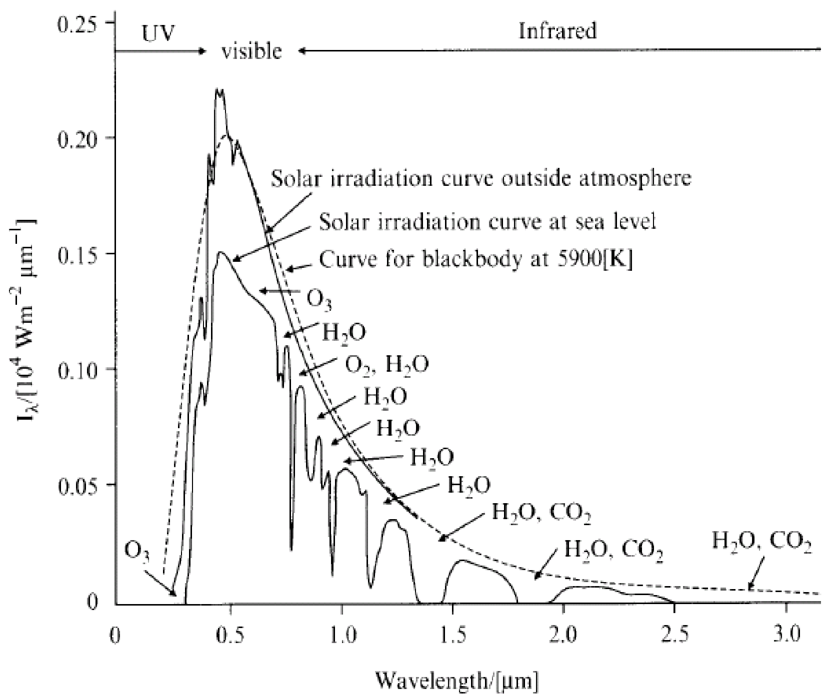
$\sigma = 5.67 \times 10^{-8}$ W/(m^2 K^4)

Example
If you double the temperature of a blackbody, how much more energy is radiated?
Solution
According to the Stefan-Boltzmann law the energy is proportional against T^4. If $T' = 2T$ we obtain the total radiated energy becomes 2^4 times greater, that is 16 times greater.

Example
If you study the solar spectrum from the Earth, you find that the intensity maximum is found around 500 nm. Calculate the Sun's surface temperature if you regard the Sun as a blackbody radiator.
Solution
Wien's law gives: $T = (2898 \times 10^3/500)$ K = 5800 K

2.3 Atmospheric absorption of sunlight

When the radiation from the Sun reaches the surface of the Earth, several parts of the spectrum have been absorbed due to molecules and atoms of the atmosphere, both the solar atmosphere and the Earth's atmosphere. For instance ozone (O_3) of the stratosphere shows absorption at 300 nm, 550 nm and at 10 micrometers. One of the most dominating molecules regarding strong absorption is water vapour as can easily be seen in the spectrum. H_2O also disturbs regions where radio communications is vital. The vibrational absorption bands of water has a very special feature called Fano-shape, where one side of the absorption band is steep and the other looks more soft.



One sees directly the strong absorption due to water vapour, H_2O, in many regions of the spectrum. If we look in a much wider spectral region we also finds other interesting features. For instance the dip at 0.4 μm is due to atmospheric calcium, and actually consists of several Ca absorption lines. However, if we look at the solar curve above the atmosphere, the dips are already there, indicating absorption due to calcium in the solar atmosphere (One of the so called Fraunhofer lines).

2.4 The constituents of the atmosphere

This picture was taken in 1992 from the Space Shuttle Atlantis, showing how thin the atmosphere is compared to the radius of the Earth. The blue light is Rayleigh scattered sunlight, while the red shows to be emitted radiation having its origin in a large volcanic eruption in 1991.

The atmosphere consists mainly of permanent gases as nitrogen (78.08%), oxygen (20.9%) and argon (0.95%). The concentrations of these gases are changing extremely slowly, of the order of millions of years. The gases that are more important are the variable gases, mainly water vapour (variable concentration, up to 3%), carbon dioxide (350 ppm) and ozone (0.020 ppm). If we discuss the change in concentration, ozone and carbon dioxide have both yearly and long term variations, while the CFC:s (3 ppb) stratospheric concentrations peaked in the late nineties and then started to decrease slowly. The lifetimes of stratospheric CFC:s are in the order of 50-200 years.

Why do we have an atmosphere?

Here we will try to explain why there exists an atmosphere and why the atmospheric molecules and atoms do not leave the Earth. Every system, man, rockets, particles, atoms or molecules have to have a certain velocity to be able to overcome the gravitational attraction force due to the large mass of the Earth. This velocity is called the *escape velocity*.

Let us try to determine the escape velocity for gases of interest:

The gravitational force: $F = G\dfrac{mM}{R^2}$

where the gravitational constant $G = 6.67 \times 10^{-11}\ \mathrm{Nm^2/kg^2}$

We can calculate the gravitational potential by applying the work (dW) done by the force F when moving a particle with mass m a distance of dr: $dW = Fdr$.

By integrating from the surface of the Earth with radius R to a distant point we get the potential of for instance a molecule with mass m at the surface of the Earth with mass M:

$$V_G = -\int_R^\infty Fdr = -\int_R^\infty G\frac{mM}{r^2}dr = -\left[GmM\frac{1}{r}\right]_R^\infty = -G\frac{mM}{R}$$

The radius of the Earth is $R = 6.37 \times 10^6$ m and its mass $M = 6.0 \times 10^{24}$ kg.

We can use the Energy conservation law to determine the escape velocity v_{esc}:

$$\frac{1}{2}mv_{esc}^2 - G\frac{mM}{R} = 0 \Rightarrow \quad v_{esc} = \sqrt{\frac{2GM}{R}} = \sqrt{\frac{2 \times 6.67 \times 10^{-11} \times 6.0 \times 10^6}{6.37 \times 10^6}}\ \mathrm{m/s} \approx 11\,\mathrm{km/s}$$

The escape velocity for any system trying to leave the Earth has to reach at least 11 km/s. Observe that this value is strictly speaking only valid for objects starting from the earth surface. However, the atmosphere is quite thin compared to the radius of the earth, and essentially the same escape velocity turns out to apply even for the upper layers of the atmosphere.

The next question is if the atoms and molecules of the atmosphere come close to this velocity.

We can apply the Kinetic gas theory to try to evaluate this. A gas molecule at temperature T (absolute temperature of the Kelvin scale) has a mean kinetic energy E_k:

$$E_K = \frac{3}{2}kT = \frac{1}{2}mv^2 \Rightarrow \quad v_{RMS} = \sqrt{\frac{3kT}{m}}$$, where $k = 1.38 \times 10^{-23}$ J/K

It can be shown that the mean velocity v_m is related to v_{RMS} through the equation:

$$v_m = \sqrt{\frac{8}{3\pi}}v_{RMS}$$

Let us calculate v_{RMS} and v_m of atmospheric atoms and molecules if the temperature is 20^oC = 293K:

Gas	v_{RMS}	v_m
Hydrogen H_2	1912 m/s	1761 m/s
Helium He	1352 m/s	1245 m/s
Neon Ne	605 m/s	557 m/s
Argon Ar	427 m/s	394 m/s
Methane CH_4	676 m/s	623 m/s
Water H_2O	637 m/s	587 m/s
Oxygen O_2	478 m/s	440 m/s
Nitrogen N_2	511 m/s	471 m/s
Carbon dioxide CO_2	408 m/s	375 m/s

All these velocities are far from the escape velocity of 11 km/s, why only H_2 and He have non-negligible probabilities of leaving the gravitational field of the Earth. The probabilities can be calculated through integration of the Maxwell-Boltzmann probability distribution function:

$$f(v) = \sqrt{\frac{2}{\pi}\left(\frac{m}{kT}\right)^3} v^2 e^{-\frac{mv^2}{2kT}}$$

For Jupiter ($M = 2x10^{27}$ kg, $R = 7x10^7$ m) we can calculate the escape velocity as above, obtaining about 60 km/s. Comparing this value with a corresponding mean velocity of H_2 at 100 K (about 1 km/s), it is possible to understand why Jupiter continues to be rich in hydrogen.

2.5 Ozone in the atmosphere

Ozone (O_3) is formed in the stratosphere through the splitting of ordinary oxygen molecules (O_2) by ultraviolet radiation from the sun. The liberated oxygen atoms (O) react, through the mediation of some arbitrary molecule (M), with molecular oxygen in the following way:

$O_2 + hf$ (UV-photons) $\rightarrow$ O + O

$2\,[\ O + O_2 + M \rightarrow O_3 + M\ ]$

$3\,O_2 \rightarrow 2\,O_3$

However, these formulas do not describe the actual reactions in detail, since we then have to know in which atomic and molecular quantum states the atoms or molecules are. Much effort has been done to investigate these reactions in laboratories as well by theory. For more details about atomic and molecular physics look for instance at this Internet-book in Modern Physics:

http://kurslab.physics.kth.se/~berg/Modern Physics.html

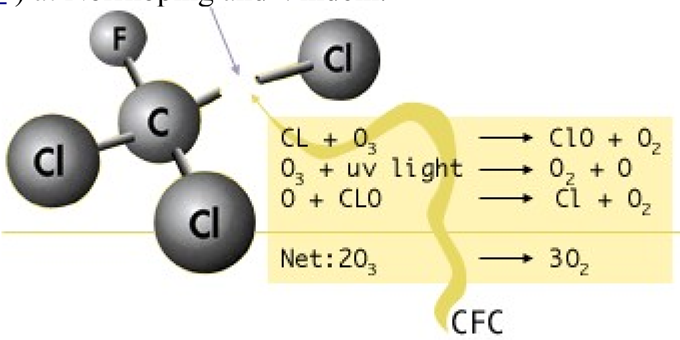
Ozone in small amounts
If all atmospheric ozone were compressed to the pressure at the earth's surface, the layer would be only 3 mm thick.
Even though ozone occurs in such small quantities it plays a fundamental role for life on earth.

Ozone and the Dobson unit
The atmosphere surrounding the earth contains small quantities of ozone, most of which is in the ozone layer in the stratosphere, 10-50 km above the earth's surface.
Stratospheric ozone, together with molecular oxygen, absorbs most of the ultraviolet radiation from the sun. This prevents the radiation from reaching the earth's surface where it can damage plants, animals and humans.
The Dobson unit is the most basic measure used in ozone research, named after G.M.B. Dobson, who investigated atmospheric ozone (~1920 - 1960). He also designed the 'Dobson Spectrometer' - the standard instrument used to measure ozone from the ground. The Dobson spectrometer measures the intensity of solar UV radiation at four different wavelengths, two of which are absorbed by ozone and two of which are not.

1 Dobson Unit (DU) is defined to be 0.01 mm thickness at Standard temperature and Pressure, stp; the ozone layer over Scandinavia is around 350 DU.

The ozone content in the lower layer of air (the troposphere, 0-10 km) has increased through the release of gaseous nitrogen oxides and hydrocarbons from vehicles, industrial plants and other sources. Ozone here can damage crops and people's health and also contribute to raising the temperature at the surface - the "greenhouse effect".

In Sweden, the measurement of stratospheric total ozone is performed by SMHI (http://www.smhi.se/) at Norrköping and Vindeln.



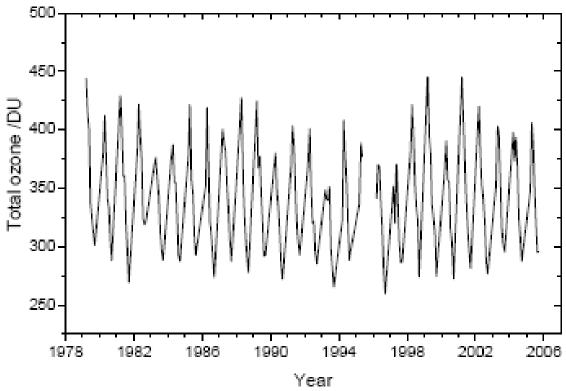
International environmental standards, ozone
WHO: http://www.who.int
Example: O_3 *(ozone)–A problem in the environment nearby*

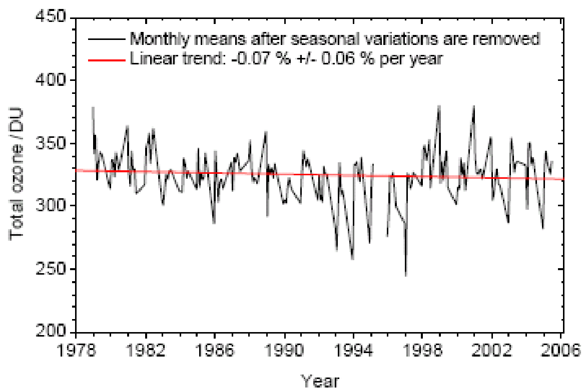
Background concentrations of O_3 in remote and relatively unpolluted parts of the world are often in the range of 40 to 70 mg/m^3 as a one-hour average.
In cities and areas downwind of cities, maximum mean hourly concentrations can be as high as 300 to 400 mg/m^3. High O_3 concentrations can persist for 8 to 12 hours per day for several

days, when atmospheric conditions favour O_3 formation. At poor dispersion conditions, O_3 is normally present at higher concentrations in ambient air outdoors, than in indoor air.
O_3 is a relatively water-insoluble gas. It reacts and produces toxic effects on small airway surfaces. The dose-delivery is greatest in terminal and respiratory bronchioles. Unlike NO_2 and SO_2, there is very little difference in lung function responsiveness between asthmatics and healthy subjects. There is, however, a great variability in individual responsiveness that is not yet understood.

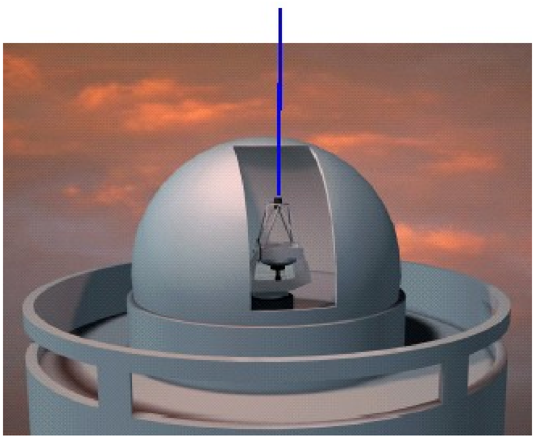
Observations showing signs of the ozone layers recovery has been from the mid 1990:s in most of the world. However there is still an uncertainty, particularly at high latitudes and in the Arctic region. This has been observed by the ALOMAR laboratory at Andöya and is probably partly due to the high natural variability in that region and the effect of decreasing temperatures in the stratosphere. For comparison, the KTH ozone measurements would be an excellent site for observations of the ozone development in this particular important and critical region, somewhat towards to the South compared to ALOMAR.

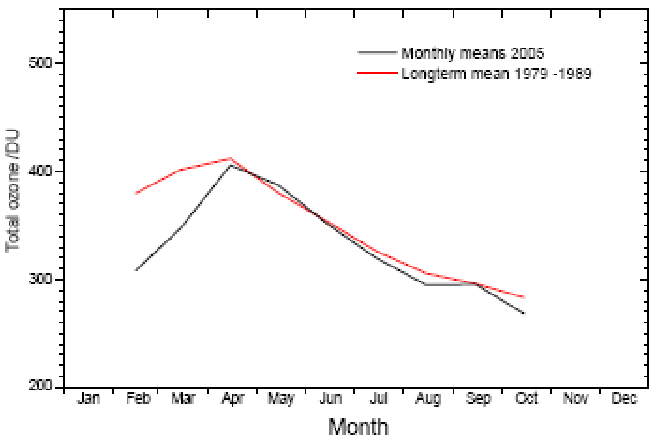
At Andöya, LIDAR instruments as well as ordinary ozone spectrometers have performed measurements. The figure below shows the measurements from Andöya during 2005:





In the graphs we observe that the variations in ozone concentration is rather high and fluctuates between 250 DU to 450 DU. On a long term basis we see that there is a decrease with a slope of about – 0.07 % annually during the 25 last years.





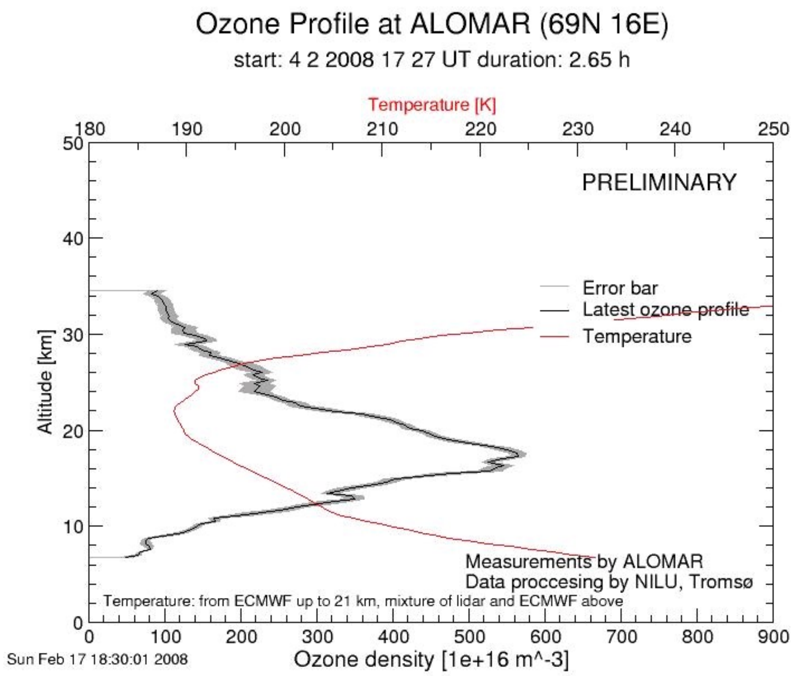
In the diagram one sees that for January, November, and December (polar night) there were not sufficient data to calculate monthly means. The comparison between the long-term mean and the monthly mean ozone values for 2005 shows that the ozone values are close to the long-term mean for most of the year except for the spring months. In this period the ozone values are significantly lower than the long-term mean.

Globally the ozone layer is thinner close to the Equator (around 250 DU) and thicker towards higher latitudes (300-400 DU). Nowadays, the annual ozone hole over Antarctica has lead to a lower mean value of the ozone layer is even thinner than over the Equatorial region.

The annual variation as well as the daily variation is smaller at the Equatorial region but prominent at higher latitudes, depending on air transport with different ozone content. The ozone layer over Scandinavia is thickest during springtime, around 400 DU and it becomes thinner during the summer and reaches as minimum during fall, around 280 DU.

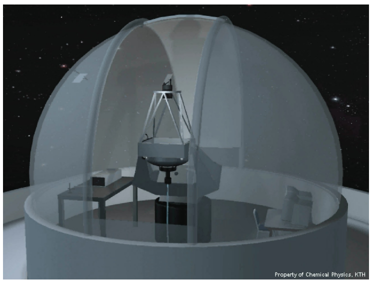
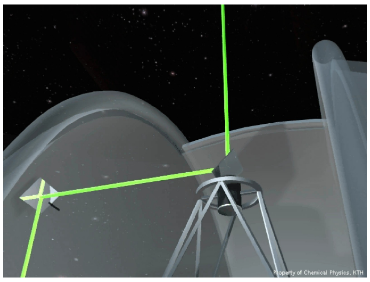
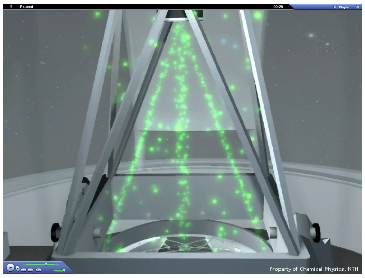
Over Scandinavia it is common with 10 to 20-percent ups and downs from one day to another. Thus, the monthly values can vary ± (5-10)% around a long time average without being anormal. The largest variations occur during winter and spring.

At ALOMAR several observations were made, showing that very different stratospheric winters have occurred in recent years: a generally warm winter (2003/04) without noticeable ozone depletion, a winter (2004/05) with a relatively long cold period with significant ozone depletion, and a winter (2005/06) with a very cold early phase.



For observations of the ozone layer, one can use a LIDAR setup of several lasers with wavelengths partially absorbed by the ozone molecules. Ozone absorbs at 300 nm, at 550 nm and at 10 µm. It is common to use a pulsed Excimer laser (XeCl) operating at 308 nm for the absorption measurements together with a pulsed frequency tripled Nd:YAG laser operating at 355 nm for testing the scattering processes, but not absorbed by the ozone molecules. The laser beams operate synchronously and parallel to the telescope fundamental optical axis. The end mirrors of the laser beams are connected to the telescopes optical axis making scanning relatively simple, once when the axes are brought together.

The measurements of the ozone and CO_2 molecules can be mapped by using the telescope in a configuration as seen in the Figure below.

Chlorofluorocarbons (*CFC*s) have many technical uses; as cooling media in e.g. refrigerators and air conditioners, in the manufacture of plastic foam and formerly as propellants in spray cans. Because they are chemically stable and non-poisonous *CFC*s have been considered ideal from the environmental viewpoint.

Mario Molina and Sherwood Rowland showed in 1974 that *CFC* gases are transported up to the ozone layer, where they meet such intense ultraviolet light that they decompose. The liberated chlorine atoms contribute to a depletion of the ozone layer.

The Ozone Hole over Antarctica

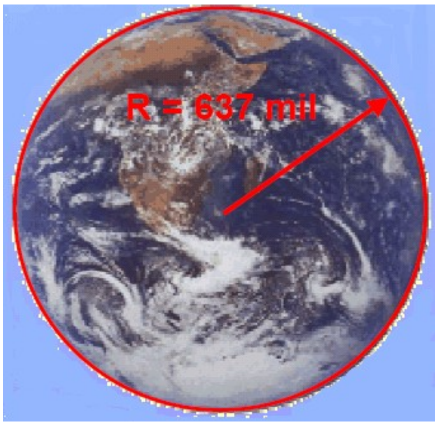
A large depletion of the ozone layer (an "ozone hole") has appeared over Antarctica in the past few years, especially during the Austral spring months September and October. This depletion is caused by the chemical decomposition of ozone, a process that is augmented by the low temperatures (below –80 °C) in the stratosphere during the winter months. During this period the air over Antarctica is isolated from the milder air at lower latitudes.

Extremely low temperatures over Antarctica lead to the condensation of water and nitric acid to form "polar stratospheric clouds" (*PSC*s). Through chemical reactions on the surface of the cloud particles large quantities of chlorine and bromine, derived from *CFC*s and other industrially produced gases, are liberated. As the ultraviolet light increases during the spring months there is an increased depletion of ozone.

2.6 Geothermal heat flow

How much does the heat from the inner parts of the earth affect the surface temperature on the surface Earth?

The heat flow from the inner parts of the Earth has been measured to be $\Phi = 42 \times 10^{12}$ W. Let us suppose that there is no radiation from the Sun. The radius of the Earth is $R = 6{,}370$ km. We can then calculate the flow (W/m^2) from the inside through the surface (area A) to be: $\Phi/A = \Phi/4\pi R^2 = 82$ mW/m^2, which shows that the major part of the heating of the surface of the Earth is through solar radiation.

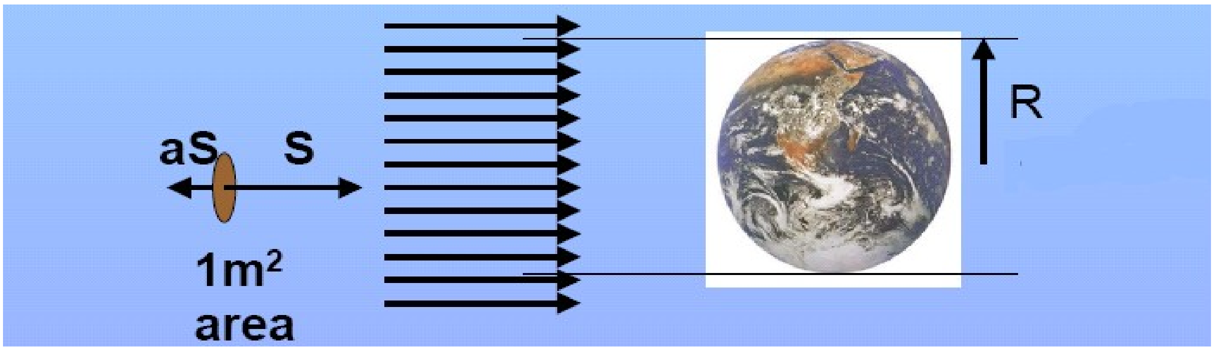


Let us anyhow calculate the temperature of the surface of the Earth with this energy flow. At equilibrium we have:

Energy in = Energy out: $\Phi/4\pi R^2 = \sigma\, T^4$

This leads an extremely low temperature of T = 35 K = - 238 $^{\rm O}$C.

Let us now try to calculate the temperature T, of the Earth's surface by using the solar influx of radiation:



After equilibrium, the incoming energy from the Sun will equal the emitted energy from the Earth:

$Energy_{in} = Energy_{out}$ in the form of radiation:

$$(1-a)S\pi R^2 = \sigma T^4 4\pi R^2$$

The constant a stands for the so called albedo and has been measured by satellite observations to be a = 0.30, and S is the so called solar constant, S = 1370 W/m^2, the influx of radiation. Thus we have:

$$(1-a)\frac{S}{4} = \sigma T^4$$

This results in a temperature of **T = 255 K = - 18$^{\rm O}$C.**

However, the actual mean value of the temperature of the Earth is **T = 288 K = 15$^{\rm O}$C**

This difference in temperature is caused by the Greenhouse effect!

Without the Greenhouse effect the temperature of the Earth would be too low for life to develop like the life we have today. The Greenhouse will be discussed more in detail in Chapter 3.

2.7 Incoming and outgoing radiation

We can compare the black body spectrum of the radiation coming from the sun (5800 K) with the spectrum we get when we study the outgoing radiation from the surface of the Earth having a temperature of 288 K or 15°C.
Applying Wien´s law we get a wavelength maximum at

$\lambda_{\max Earth} = 2898 \times 10^3 \frac{1}{T}$ nm $= 2898 \times 10^3 \frac{1}{288}$ nm ≈ 10060 nm ≈ 10 µm to be compared with the wavelength maximum from the solar radiation at

$$\lambda_{\max Sun} = 2898 \times 10^3 \frac{1}{5800} \text{nm} \approx 499.7\text{nm} \approx 500\text{ nm}$$

The emitted radiation from the Earth has an intensity maximum around 25 W/(m^{2}µm) using the Planck formula and the corresponding intensity of the Sun is 0.85x10^8 W/(m^{2}µm). The total emission can be calculated by using the Stefan-Bolzmann law where

$$e = \sigma T^4 \qquad \sigma = 5.67\text{x}10^{-8}\ \text{W}/(\text{m}^2\text{K}^4)$$

With the above data we obtain: $I_{Earth} = 390$ W/m^2 and $I_{Sun} = 64$ MW/m^2, respectively.