Environmental Physics for Freshman Geography Students

Professor David Faiman. Lecture 11, v.4.1 (January 20, 2004)

Atmospheric phenomena

In this final lecture we shall address a number of physical phenomena that occur within the earth's atmosphere and their effect on the environment in which we live. The major constituents of the air we breathe are: Nitrogen (N_2) 78%, Oxygen (O_2) 21% and Argon (Ar) (1%). These percentages have been rounded to whole numbers. Had I used 3-figure accuracy, their sum would have been 99.9%, the remaining 0.1% containing "trace" amounts of other gases. The most important trace gases – from the environmental view point – are: water vapor (H_2O), of varying fraction, depending on geographic latitude and time of year; and carbon dioxide (CO_2), about 0.03%. These gases and their effects will be discussed below.

1. Stratification of the atmosphere

As we move away from the earth's surface, the density of the air decreases, until eventually we find ourselves in the vacuum conditions of space. However, the *temperature* of the atmosphere does not vary smoothly with altitude. Instead, there are a number of distinct layers, as shown schematically in **Fig. 1**. The principal layers are: the troposphere, the stratosphere, the mesosphere, and the thermosphere.

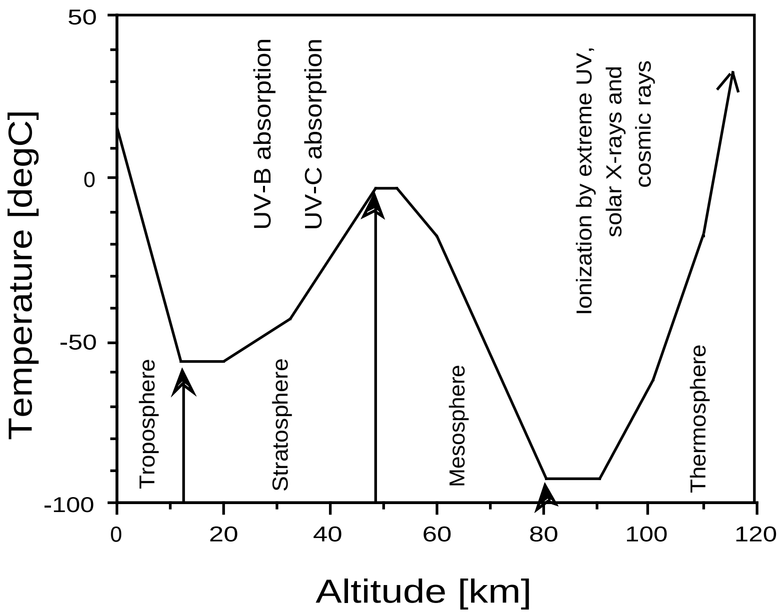

Figure 1: Typical temperature variations with altitude in the troposphere, stratosphere, mesosphere and thermosphere of the earth's atmosphere

1.1 The troposphere (approx. 0-12 km)

The part of the atmosphere that is in contact with the ground is called the *troposphere*. Here the temperature *decreases* with increasing altitude, from ambient values of typically +20 ^{o}C at ground level, to approximately -60 ^{o}C at a height of about 12 km. At this altitude we encounter a transition region known as the *tropopause*, where the air temperature stops falling. The precise values of the tropospheric temperature vary from summer to winter, and the height of the tropopause is different at the equator compared to the poles. But the values given in **Fig. 1** are typical representative values.

The physical reason for this fall in temperature with increasing altitude in the troposphere is that air is basically transparent to solar radiation. Most of the incoming solar radiation is absorbed, *not by the air*, but in the ground, which becomes heated as a result. The warm ground then heats the nearby air via a process of *conduction*, i.e. via the transfer of kinetic energy from the vibrating ground molecules to the less energetic air molecules. Each warmed layer of air then passes on some of its energy to the next layer, etc. However, the further we get away from ground level, the weaker will be this conductive heating because the energy will have been shared among more and more air molecules. For this reason, the temperature of the air will fall the higher we go in altitude. However, as already mentioned, after about 12 km, this cooling stops and something else starts to happen.

1.2 The stratosphere (approx. 12-50 km)

At the height of the tropopause we notice that the temperature of the air stops falling, and then starts to rise! Here, we have entered the *stratosphere*, where the temperature now *rises* the higher we go, reaching almost 0 ^{o}C at about 50 km above ground.

The agent responsible for heating in the stratosphere is the kinetic energy generated by solar *ultraviolet light* (UV). As we shall discuss below, these photons are so energetic that they can break oxygen molecules into free oxygen atoms. It is the energy absorbed from these photons and converted to kinetic energy that causes the atmospheric constituent molecules to heat up within the stratosphere. At the top edge of the stratosphere, we encounter a second transition region, known as the *stratopause* where the air temperature stops rising. Again, this must indicate some new physics.

1.3 The mesosphere (approx. 50-80 km)

By the time we reach the stratopause there are very few oxygen molecules left in the atmosphere. Therefore, solar UV radiation ceases to be an effective heating agent because there are not enough molecules to absorb these energetic photons. We have reached the *mesosphere*, where the atmosphere once more starts to cool off with increasing altitude. Here the temperature drops to nearly -100 ^{o}C at an altitude of 80 km where, at a third transition region - the *mesopause* – the physics changes yet again.

1.4 The thermosphere (above approx. 80 km)

After the mesopause we enter the *thermosphere*, where the air pressure has dropped to 10^{-12} mb. In fact there are so few gas molecules per unit volume that "temperature" loses its normal meaning. However, there are now several agents that can raise the energy of these residual gas molecules; namely, extremely short-wave solar UV radiation, X-rays and cosmic radiation. If one translates the resultant kinetic energy of the gas molecules into "temperatures", using (3/2)kT as the kinetic energy per molecule, one obtains values up to a thousand degrees Celsius, or so! In this region the air molecules become ionized (i.e. stripped of their electrons) by the incoming radiation, resulting in the nocturnal phenomenon of *Aurora*. This phenomenon is observed close to the two poles of the earth because the ionizing radiation becomes trapped by the earth's magnetic field, and near the poles (where the field lines enter and leave the earth's surface) the density of this radiation is highest. More generally, the layers of ionized molecules - the so-called *ionosphere* - causes disturbances to radio transmissions.

Beyond the thermosphere there is no thermopause: the atmosphere gradually merges with the vacuum of space in a region known as the *exosphere*. This has not been included in the **Fig. 1**.

We now consider what happens when short wave UV solar radiation is absorbed by the atmosphere.

2. The ozone layer

Fig. 2 shows the approximate shape of the wavelength spectrum of radiation from the sun that reaches the earth's upper atmosphere (i.e. before any is absorbed).

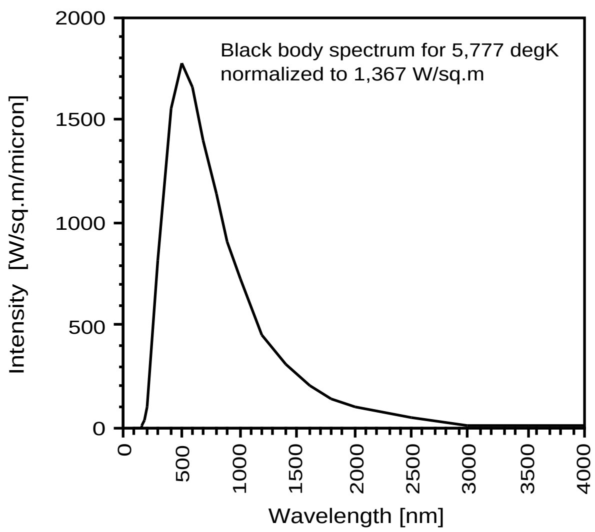

Figure 2: Approximate energy spectrum of solar radiation reaching the top of the earth's atmosphere

The part with wavelengths below about 400 nm (approximately 9% in energy) is referred to as *ultraviolet* radiation, or UV. The part in the approximate range 400 - 700 nm (approximately 55% in energy) is referred to as *visible* light, or VIS, and the part with wavelengths longer than about 700 nm (approximately 36% in energy) is referred to as *infrared* radiation, or IR. As the solar radiation descends through the earth's atmosphere energy is selectively absorbed out by different physical mechanisms among the atmospheric constituents. First, let us discuss the UV part of the spectrum.

2.1. Formation of the ozone layer

Ozone is a gas that is formed when solar ultraviolet light interacts with oxygen molecules. If the incoming solar photons have sufficiently high energy (so-called *UV-C* radiation) they tear apart the oxygen molecules, forming highly reactive oxygen *atoms*. The chemical reaction is:

$$\gamma\,(\lambda < 190\text{ nm}) + O_2 \;\text{->}\; O + O \qquad (11.1)$$

where γ represents a photon with wavelength less than 190 nm (this is the UV-C range of photon energies). These free oxygen atoms quickly attach themselves to neighboring oxygen molecules, forming molecules of ozone gas (O_3). The chemical reaction is:

$$O + O_2 + M \;\text{->}\; O_3 + M \qquad (11.2)$$

In eq. (11.2), M represents a neighboring molecule (such as nitrogen) which must be present in order for the collision process to conserve both momentum *and* energy.

This is the way ozone is formed in the earth's atmosphere. Now, unlike the principal gases in the atmosphere – which are completely mixed together as a result of constant molecular collisions, ozone is *not* thoroughly mixed with the rest of the atmospheric constituents. Instead, it forms a *layer* in the stratosphere.

It is easy to see why this is so. The formation of ozone requires two conditions: First, a plentiful supply of UV-C photons, and second, a plentiful supply of oxygen targets. Far from the earth, there are plently of UV-C photons arriving from the sun, but there are very few oxygen molecules to stop them. Gradually, as the UV-C radiation gets closer to the earth, the density of the atmosphere increases. Therefore, more and more UV-C photons are absorbed until none are left. We thus have a situation in which at low altitudes there are plenty of oxygen molecules but no UV-C radiation to break them up (because it has all been absorbed at higher altitudes). On the other hand, at the highest altitudes there are plenty of UV-C photons but no oxygen molecules to stop them. There will accordingly be an optimal altitude where ozone is produced. This is the so-called *stratospheric ozone layer.* It is the collisions between UV-C photons and oxygen molecules that is responsible for the heating of the stratosphere, as we have seen, to temperatures that are much higher than those at the top of the troposphere.

How thick is this layer? Well, clearly, it will not have well-defined boundaries. It will start off with extremely low density at the top of the stratosphere. It will then become progressively denser as we proceed to lower altitudes, reaching a maximum and then gradually disappearing altogether. The maximum density of the ozone layer occurs at altitudes between 20 km and 30 km above sea level. Now, if we could take all of that ozone and compress it into a spherical shell at standard temperature and pressure (i.e. 273 K and 1 atmosphere), the shell would have a thickness of about 3 mm. Atmospheric physicists have defined a more convenient unit for discussing the thickness of the ozone layer. It is the *Dobson unit* (DU): 3 mm = 300 DU.

2.2 Seasonal changes in the thickness of the ozone layer

Now, in addition to being created by photons, ozone molecules can also be broken apart by photons. For this purpose the energy need not be as high as that of the UV-C photons we discussed above. Photons in the slightly longer wavelength range 290 nm - 320 nm (so-called *UV-B* radiation) have sufficient energy. The chemical reaction here is:

$$\gamma\,(290\text{ nm} < \lambda < 320\text{ nm}) + O_3 \;\text{->}\; O_2 + O \qquad (11.3)$$

The free oxygen atom that is released in reaction (11.3) quickly attaches itself to to nearby molecule, forming O_3 or N_2O. However, the important point about this reaction is that it absorbs out most (but not all!) of the harmful UV-B radiation that reaches us from the sun.

Unlike UV-C radiation, which is all absorbed out by the plentiful supply of atmospheric oxygen, some UV-B radiation does reach ground level because the ozone layer is so thin.

But the thickness of the ozone layer varies with the seasons of the year. In summer time, when the flux of destructive UV-B photons is highest, the ozone layer becomes thinner. On the other hand, in winter, the flux of UV-B is smaller and the ozone layer recovers. It reaches its maximum thickness in the springtime and its minimum thickness in the autumn. Naturally, when the ozone layer is thickest in the northern hemisphere, it is thinnest in the southern hemisphere, and *vice-versa.*

In recent years, it has been discovered that many industrially-produced gases (such as the CFCs used in air-conditioners and spray cans) can break up ozone by chemical means. These agents are believed to be responsible for the so-called *hole in the ozone layer* that has been observed in recent years in the southern hemisphere. It is this effect that has led to the world-wide ban on the use of certain kinds of refrigerant gases.

3. The emission of radiation from hot objects

In the above discussion, we saw how short wave UV-A and UV-B radiation are absorbed by oxygen and ozone, respectively. We now examine the effect on IR radiation that is brought about by the presence of water vapor and carbon dioxide in the atmosphere.

The general shape of the spectrum in **Fig. 2** is characteristic of all so-called “black” objects whether they are stars like our sun or a mere pot of boiling water on a campfire. Of course, if they are very hot indeed (like the element of a 1000 W electric heater when it is switched on) they will no longer appear black, but for this discussion it is assumed that they start off black when cold. The shape of this spectrum is caused - in a manner that is too complicated for me to explain in detail - by the acceleration and deceleration of the electrons as they vibrate back and forth in the hot object. The more energetic those vibrations will be, i.e., the hotter the black body is, the shorter will be the wavelength of the peak in **Fig. 2**. Correspondingly, the cooler the black body is, the lower will be the kinetic energy of its electrons, and the radiation they emit will peak at longer wavelengths.

There is a simple relationship between the temperature of a black body and the peak wavelength of its emission spectrum, known as *Wien’s Law.* It states that *the product of the temperature (in degrees K) and the peak wavelength of the emission spectrum is a constant*. Numerically, it takes the form:

$$\lambda_{peak} \times T = 2900\ \mu\text{m K} \qquad (11.4)$$

where λ_{peak} denotes the wavelength of the peak of the emission spectrum, in units of micrometers (1 μm = 1000 nm), and T denotes the temperature of the black body in degrees Kelvin. The sun's spectrum is quite similar in shape to the emission spectrum of a black body with a temperature of approximately 6000 K. This is interpreted as the mean surface temperature of the sun because its interior is very much hotter indeed.

There is another important radiation law that we must know before we can return to our discussion of atmospheric heating. It relates the temperature of a black body to its total rate of emission of radiation. This law is known as *Stefan's Law*, and takes the simple form:

$$Q' = \sigma T^4 \qquad (11.5)$$

where Q' denotes the rate at which energy is emitted with time, expressed in Joules per per square meter per second = Watts per square meter; T denotes the temperature of the black body, in degrees Kelvin, and σ is the so-called *Stefan-Boltzmann constant* = 5.67×10^{-8} W m^{-2} K^{-4}. We are now in a position to be able to calculate the average temperature of the earth, caused by its absorption of radiation from the sun.

4. The atmospheric greenhouse effect

4.1 The "good" greenhouse effect

The sun emits radiant energy, in the form of photons, at a rate of 3.85×10^{26} J/sec. This energy spreads out uniformly in all directions, and by the time it reaches the earth (i.e. after traveling 1.5×10^{11} m) it has been diluted to an intensity of only 1360 W m^{-2}. This latter number is known as the *solar constant* for the earth, and, as we shall see, is responsible for the temperature we experience on our planet.

Let us form a first estimation of what that temperature is. In order to do this, we shall assume that the earth is a perfectly black body. That is to say, it absorbs radiation from the sun, heats up, and emits radiation to space. We can use Stefan's law to calculate what the equilibrium temperature would be in such a simplified picture.

If R is the radius of the earth and S denotes the solar constant, then the total rate at which the earth receives energy from the sun is:

$$Q'_{in} = \pi R^2 S \qquad (11.6)$$

On the other hand, the rate at which the earth emits energy to outer space is:

$$Q'_{out} = 4 \pi R^2 \sigma T^4 \qquad (11.7)$$

Equating these two rates and inserting numbers gives:

$$T = \sqrt{}\ (S/4\sigma) = 278 \text{ K} = 5\ ^oC \qquad (11.8)$$

Although this number looks extremely reasonable as an average temperature for the earth, we have made two very serious simplifications which must both be corrected. First, the earth does not absorb radiation the way a perfectly black body does - i.e. all the radiation it receives. If it did, then photographs of the earth taken from artificial satellites would be perfectly black! In actual fact, the earth reflects approximately 30% of the sun's radiation back to space without absorbing it. This effect is called the *albedo* effect. *The albedo of a surface is the fraction of the incoming radiation that is reflected from it.* This means that the incoming energy in eq. (11.6) must be reduced by 30%. If we redo the calculation, denoting the albedo by $\alpha = 0.3$, we obtain:

$$T = \sqrt{[(1 - \alpha) S/4\sigma]} = 255 \text{ K} = -18\ ^{o}\text{C} \qquad (11.9)$$

This time our average temperature is clearly too low, because water could not exist in liquid form and there would be no life on earth.

The second simplification that must be corrected is our neglect of the earth's atmosphere. Although most of the atmospheric constituents are transparent to solar radiation, H_2O and CO_2 absorb *strongly* in the IR part of the spectrum. As a result, they absorb part of the radiation that is emitted by the earth, heat up and re-emit radiation - some of it back down again. The resulting equilibrium temperature is accordingly raised to +15 ^{o}C.

This heating of the earth from -18 ^{o}C to +15 ^{o}C by the presence of two trace gases in the atmosphere is known as the *greenhouse effect*, because it is similar to the way glass promotes solar heating in agricultural greenhouses. It is thanks to the greenhouse effect that the temperature of the earth is warm enough to support life. That is the good news.

4.2 The "bad greenhouse effect

The *bad news* is that about 70% of the natural greenhouse warming is caused by water vapor in the atmosphere and about 30% is due to carbon dioxide. That is to say, CO_2 is responsible for about 10 degrees of greenhouse warming. Why is that bad news? Because, the trace amount of natural CO_2 in the atmosphere is steadily increasing due to the burning of fossil fuel. This means that greenhouse-warming is increasing. Therefore, unless we can replace fossil fuel by a non-polluting alternative we may expect to start suffering serious environmental consequences – e.g. the melting of glaciers and a corresponding rise in sea level. The ideal non-polluting alternatives to fossil fuel would be solar energy for the generation of electricity, and hydrogen (generated by the electrolysis of water, using solar-generated electricity) for use as transportation fuel.

Problem set 11 (radiation)

1. A black kettle contains boiling water. What is the peak wavelength of the radiation spectrum it emits?

2. Calculate the value of the solar constant at Mars if that planet is at a mean distance of 228 million km from the sun.

3. If Mars were a perfectly black body, what would be its mean temperature?

4. The Martian atmosphere is rich in CO_2. What qualitative effect would you expect this to have on the temperature of Mars?