How does the Heat Get through the Atmosphere?

Friedrich Herrmann
Abteilung für Didaktik der Physik, Universität Karlsruhe, 76128 Karlsruhe, Germany
friedrich.herrmann@physik.uni-karlsruhe.de

Abstract

When the light of the sun is absorbed at the surface of the Earth, heat is produced. In order to be removed from the Earth into space, this heat has to cross the troposphere. Often it is suggested that the vehicle for this process is infrared radiation. We show, that the dominant mechanism not radiation but convection. We shall introduce an atmospheric model which correctly describes the following phenomena and processes:

- *the vertical temperature gradient;*
- *the dominant heat transport mechanism within the troposphere;*
- *the influence of green house gases.*

1 Introduction

The atmosphere can be considered a thermal insulation of the Earth. The Earth is in a stationary state: it receives energy with the sunlight, and it gives it away with infrared radiation. In the global and temporal average the absorption of sunlight (mainly by the Earth's surface) amounts to 236 W/m^2. For the sunlight, the atmosphere is transparent, for infrared light, however, it is transparent only in a small spectral domain, the *atmospheric window* .That means that the maximum of infrared emission is located at an altitude of about 7 km. At this *emission altitude*, the atmosphere begins to be transparent for IR radiation. Within the troposphere, i. e. the lower atmosphere, temperature decreases with increasing height. The average temperature at sea level is 15 °C, at 7 km it is minus 40 °C approximately. In the following, we shall answer three questions:

1. Why does the temperature decrease with altitude?
2. How does the heat get through the troposphere?
3. How do greenhouse gases constrain this transport?

The atmosphere is a complicated system. In order to understand it, we have to consider models. It is worthwhile to consider several distinct models. Although some of them turn out to be unappropriate, they are useful, since it not only is useful to understand how something works, but also how it does not work, and why it does not work in this way. Therefore, let us begin with some unsuitable models.

2 A solid "atmosphere"

We compare the atmosphere with a thermal insulation layer made of a solid material, e. g. styrofoam. As in the case of the real atmosphere, we heat from below. Since we know the thermal conductivity and the thickness of the thermal insulation layer, we can calculate the temperature difference which is necessary to drive a heat current of 236 W/m^2. The result is 40 000 000 degrees. The temperature gradient obtained in this way is about a million times that of the one observed in the real atmosphere. We conclude that this cannot be the origin of the temperature gradient in the real atmosphere. What is wrong with our model? It is the absence of convection. Indeed, in the real atmosphere we have a thermal "short-circuit" caused by convection. Therefore, we next consider a model which allows for convection: a liquid atmosphere.

3 A liquid "atmosphere"

We first have to define the initial state: We stir up the liquid thoroughly. Usually, we agitate something in order to get a homogeneous composition. However, stirring up has yet another effect: It leads to a sate of indifferent mechanical equilibrium. One might think that thereby all local physical quantities are homogenized. However, this is not true. In our liquid, pressure will not be uniform. At the contrary, a well-defined pressure gradient will establish upon stirring up. Temperature, on the other hand, will homogenize. Let us now heat our liquid from below (as what happens in the atmosphere). That means that we perturb the mechanical equilibrium. The density will decrease in the lower part of the liquid. Thereby, the system becomes unstable and tips over. If we go on heating, a continuous convection establishes. Now, this convection is equivalent to a steady agitation which continuously tries to homogenize density and temperature. Thanks to the convection the indifferent equilibrium is maintained. Is this a good model of the atmosphere? Again the answer is "no". The model does not reflect an important property of the real atmosphere: There is no temperature gradient. Both our previous models are unappropriate. Let us now a try a gas as a model. Finally, that's what our real atmosphere is made of.

4 A gaseous atmosphere

Again we begin by defining the initial state by stirring up. As in the case of the liquid, we get an indifferent layering. And again, pressure did not homogenize. It is remarkable however, that there is yet another quantity which did not homogenize: temperature. Whenever a gas in a gravitational field is stirred up, not only a pressure gradient is establishing, but also a temperature gradient. Notice that we get a temperature gradient without the need of a heat flow. Thus, this temperature gradient has another cause than the one in our styrofoam model. And more important: The numerical value, which follows from theory is in agreement with what is observed in the real atmosphere. Let us again heat from below. What we observe is essentially the same as in the liquid "atmosphere": Convection sets in. As in the liquid, we get a heat transport in the vertical direction. We finally have found a suitable model. Of course, it can be improved. But to do that, we have to consider numerical values.

5 The real atmosphere

The average energy flow per area, which is absorbed by the Earth is 236 W/m ^{2} . This energy must cross the lower atmosphere in the form of heat. In our last model, this transport was supposed to be convective. In reality this is not true to 100!%. The reason is that the atmosphere is not completely opaque for infrared radiation. It is transparent in the spectral domain of the atmospheric window. As a consequence, about a 13% of the 236 W/m ^{2} are radiated directly from the Earth's surface into space. It remains true, however, that convection is the dominant transport mechanism. The reason why convection is so efficient is that it is taking profit of a phase transition: At the surface of the Earth water is evaporated. Thereby it absorbs heat. Together with the nitrogen and oxygen, the water vapor rises to the higher parts of the troposphere. Here it condenses and gives its heat away. This represents about a 35 % of the total heat transport.

6 Greenhouse gases

It is now easy to see how greenhouse gases influence the heat transport. They do so in two ways. If a gas absorbs in the spectral domain of the atmospheric window , then the presence of such a gas tends to narrow or close the window . This is true for chlorofluorocarbons .If the absorption of the gas is outside of the window , i.e. where the atmosphere absorbs anyway , then the gas simply contributes to the absorption of the atmosphere. This is the case for CO_2 . A result is, that the emission altitude increases, the temperature at this altitude becomes lower and the emission weaker .Both effects cause the temperature at the Earth's surface to increase.

7 Summary

We now have the answers to the questions asked at the beginning:

1. Why does the temperature decrease with altitude?
   Answer: It is the natural temperature gradient of a wellstirred-up gas in a gravitational field.
2. How does the heat get through the troposphere?
   Answer: 87 % convection, 13 % direct radiation.

How do greenhouse gases constrain this transport? Answer: 87 % by increasing the emission altitude, i. e. the effective thickness of the atmosphere, 13!% by narrowing the atmospheric window.