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Some observations on the greenhouse effect at the Earth's surface

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ABSTRACT

It is shown that the greenhouse gases carbon dioxide and water vapour reflect back to the surface, all IR radiation originating at the surface within their respective spectral bands. This reflection occurs in a very thin layer at the surface, not much over 12 cm in thickness. Heat is lost from the surface by heat exchange with the atmosphere and by loss of radiation. About 52% of radiation leaves the surface in two principal window regions but this is not enough to account for the earth's equilibrium temperature. This window radiation seems to disappear quite quickly and is replaced by black body radiation. It is this which eventually contributes to the earth's radiation balance, and has to originate approximately between 40 and 50 km altitude where the temperature is about correct, near 255 K. Doubling the CO_2 concentration increases the surface temperature by about 0.9 °C and this need not have any influence higher up in the atmosphere. The surface temperature seems indeed to have no direct influence on the earth's external radiation balance.

1. Introduction

Earlier articles discussing the greenhouse effect seemed to favour the idea of absorption of energy by the IR active gases in the atmosphere with consequent rise in temperature. Recently, the idea of reflection of energy by the IR active gases seems to have taken its place but with energy balance diagrams requiring substantial proportions of reflected energy [1]. From the meteorological point of view the picture is a little different as heat exchange via thermals is more important [2]. The surface also loses energy by radiation and the question is how much of this is lost by both processes, how much is reflected by the IR active gases, over what distance and how does this contribute to the Earth's energy balance? The principal IR active gases near the surface at low altitudes are carbon dioxide and water vapour. At the time of writing, the concentration of carbon dioxide is near 400 ppmv, which it is convenient to express as 1×10^{16} molecules cm^{-3}. Water vapour varies widely in concentration according to place, weather conditions and, to a degree, time of day. It is usually expressed as a vapour pressure obtained from temperature and relative humidity levels. Converting these into units of molecules cm^{-3} for comparison with CO_2 levels, we get a range of values of 2 to 6 $\times$ 10^{17} molecules cm^{-3} as typical here in inland Provence.

In this paper, using a random walk approach, we examine the way reflection of IR energy in the CO_2 and H_2O bands may occur at the surface and to what extent. We then describe a number of simple measurements whose results support the idea of reflection as involving quite short distances, and enable us to estimate the fraction reflected and the mean free path of radiation at the greenhouse gas frequencies. The work arose from the observation that different sized blackened, back insulated metal plates attained different temperatures when exposed to the sun, the largest being the warmest by up to 20 °C.

1.1. Previous Measurements of Radiation Near the Surface

It is appropriate to survey some early and later radiation measurements made near the surface of the earth. Bell and co-workers in 1960 described instrumentation for low resolution IR measurements of radiation downwelling from the sky and that observed at some distance from the surface and leaving the earth at low angles [3,4,5]. His results have been much quoted by workers attempting to produce surfaces which reflect sunlight perfectly and re-radiate only where radiation can escape to space in Simpson's window, the object being to obtain air conditioning with zero power consumption [6]. Bell's results show little downwelling radiation in the window for clear skies but flanked by strong radiation in the CO_2 and H_2O bands which I suggest is due to random walk diffusion of energy from the sides of his periscope tubes. Certainly, recent developments [7] in the instrumentation for the atmospheric radiation measurement project (ARM) avoid the periscope tubes and give much lower intensities in these bands. Unfortunately, Bell's upwelling measurements were made at large distances and tell us nothing about what happens in the first few cm or so, which I will show, is where full reflection takes place. No measurements appear to have been made of upwelling radiation very close to the surface.

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1.2. IR Energy Upwelling From the Surface

Now we must look at the spectrum of the energy that leaves the surface, for a surface temperature of 290 K, Fig. 1. There are two Planck functions which could describe the spectrum, I(λ), which varies as λ^5 and I(υ), which varies as υ^3. An I(λ) spectrum of upwelling radiation is seen by Bell [5] and this overlaps significantly with the water vibration band. I(υ) has very little overlap with the water band and, it will be shown, water has an important effect. The spectrum depicted in Fig. 1 is thus an I(λ) spectrum. The positions of the water (W) and CO_2 (C) vibration bands are marked, as is that of the water rotation band (Wr). The limits of these bands were determined as follows: for the CO_2 band I used the HITRAN data, which are logarithmic in intensity, and took the limits at 0.8% of the maximum intensity. These were 13.3 to17.2 μm [8]. For the water vibrational band the limits were found from a logarithmic plot of intensities of an actual spectrum and were 4.8 to 7.9 μm. The bands were made rectangular. The justification for this will be found in the discussion below. The main intensity for the water rotation band appears to start at about 23 μm [9]. There are two regions E where energy escapes though I am not at all certain where it goes. The escape gap from about 7.9 to 13.3 μm corresponds approximately with Simpson's window [10,11]. Note that the spectral intensity is significant out to 60 μm and the water rotation band contains a significant part of the total energy. If we measure the areas of each band (by counting squares, error ± 5%) we find that the areas of W, W_R and C are a fraction 0.485 of the total and we will show, cause total reflection of the energy in their bands back to the surfce. To my surprise, all the texts I have read ignore the spectral region to the long wave side of the centre of the CO_2 band, though this obviously plays an important part. Nor is the part played by the water rotation band discussed, though much attention is given to the weak water continuum at shorter wavelengths which is probably the skirts of the many rotation bands [12] and so should have the same properties as the rotation bands. It is not clear how to deal with the water rotation band, though it is likely to cause reflection of energy and we will show below that it does not transfer energy radiatively to the water vapour.

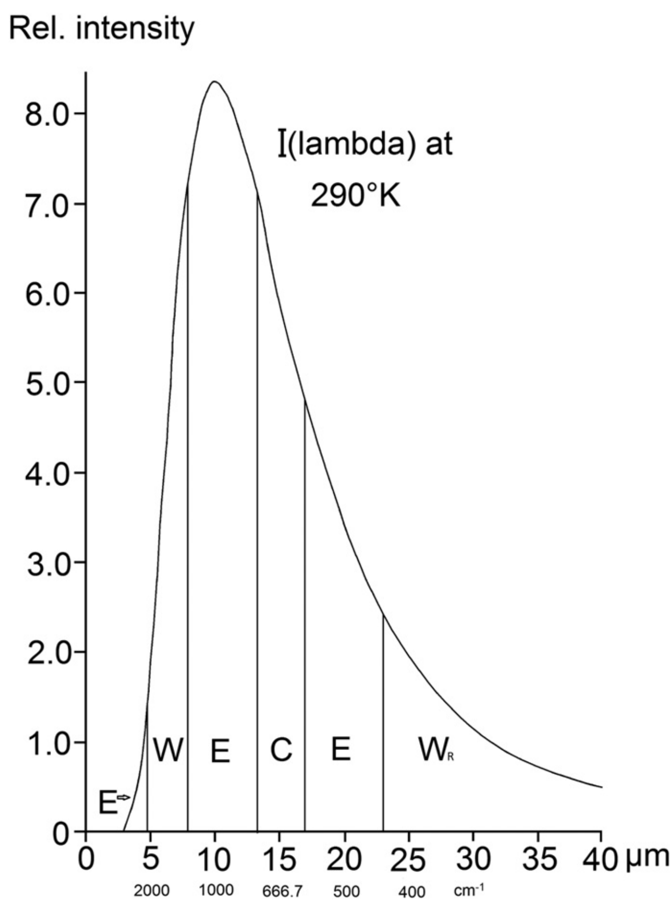

Fig. 1. A plot of the Plank function I(λ) for the radiation of a surface at a temperature of 290 K, plotted as a function of wavelength so that area under the curve is equivalent to total energy emitted. It is divided schematically into various regions. E shows where radiant energy can escape the surface, C is the CO_2 vibration band and W is the water vibration band, W_R is the water rotation band. Total reflection of radiation occurs in the vibration bands and, probably, in the rotation band too.

A simple calculation is often used to demonstrate the need for a greenhouse effect. The earth receives energy from the sun at the rate of $\pi r^2(1\text{-}a)S$, where S is the solar constant, a is the earth's albedo and r is the radius of the disc seen by the sun. The earth reaches an equilibrium temperature, T and emits energy, via IR radiation from its whole surface area, of $4\pi r^2\sigma T^4$. These two quantities must be equal, so, $S(1\text{-}a) = 4\sigma T^4$. Inserting appropriate values of S, a and σ, we obtain $T = 255$ K or −18.2 °C, which is about 33° too cold. Hence not all the re-radiated heat gets away from the earth. We can estimate approximately how much needs to be held back by writing $S(1\text{-}a) = 4\sigma T^4(1\text{-}g)$, where g is the proportion held back. By putting $T = 288$ K, we get that g has to be about 0.39. So, the amount held back at the surface as calculated from Fig. 1 is far too great to account for the greenhouse effect observed. The weakness of this calculation is that we do not know if it is the surface which radiates this energy or some layer higher in the atmosphere.

2. Theoretical the Random Walk

This approach is based on the ideas used to estimate the time it takes for radiation to travel from the centre of the sun to its surface, using a random walk from nucleus to nucleus [13]. This radiation can go round and round the centre on its way to the surface which it takes an incredible time to reach. The difference here is that the terrestrial thermal radiation starts from an opaque surface and that any radiation that tries to go around the starting point, returns to the surface, is stopped and absorbed. That is, it has been reflected back to the surface by the greenhouse gases. We see already that reflection of radiation from the surface back to the surface might well be 100% in the presence of an agent capable of provoking a random walk.

We allow a packet of photons with frequencies in the appropriate CO_2 and water vibrational bands, to leave the surface of the earth. These will travel on average for a distance of a mean free path (MFP) when they will encounter greenhouse gas molecules and promote these to exited vibration states. Two things may then happen: either excess photons may promote stimulated re-emission or, spontaneous re-emission may occur. In the first case the re-emitted photons take the same direction as the stimulating photons and reflection cannot happen since these are all moving away from the surface. In the second case the re-emission is isotropic and there is reflection of part of the energy back to the surface. Since the photon flux from the surface of the earth is quite low, this is the likely outcome, a conclusion supported by the experimental evidence below which detects reflection.

It is possible to argue that reflection in an IR band is 100% as follows. Batches of photons which are re-emited isotropically in a layer one MFP thick above the surface can return to the surface. Or they can stay in the same layer and re-emit again, more energy is lost to the surface, the intensity is reduced and becomes zero after a number of re-emissions. Or they may move up into the next layer where they will also be attenuated. Since the model simply transfers energy temporarily to the gas molecules, this means all the energy is reflected to the surface. This occurs within a few MFPs and so is very short range, as envisaged by Barrett and as we will show experimentally [14].