Solar radiation and the atmosphere

The radiation from the Sun makes this planet inhabitable. But solar radiation does not simply provide warmth; it powers the dynamics of the atmosphere. This includes the wind systems, the water cycle and therefore the weather.

Energy from the sun

Solar energy is transmitted from the sun as radiation. This flows outward from the sun; the rate of flow of energy per unit area (the *irradiance*) falling with distance. Simple geometry shows that the irradiance I at a distance R from the sun is related to the *solar emittance* I_S by

$$I = I_S \, (R_S / R)^2 \qquad (1)$$

where R_S is the radius of the sun. This is a typical example of an inverse square law.

Since the mean distance of the earth from the sun is $200R_S$, I (Earth) = $I_S / 40000$. This is known as the *solar constant, S* and is equal to 1353W/m^2. The total power received by the earth is this quantity multiplied by the cross-section of the planet. This is πR_E^2 where R_E is the radius of the earth , 6358km. The average power received per unit area over the surface of the planet is therefore ;

$$P = \pi R_E^{2} S / 4\pi R_E^{2} = S/4 = 336\text{Wm}^{-2}$$

This is a crude estimate; the solar radiation is not received uniformly over the planet (the equator receives much more than the poles). In addition to this, the time of day matters for the same reason- the sun is low in the sky. It is not just a question of the angle of the rays of the sun with respect to the earth (i.e. the same amount of energy is spread over a variable area); also the greater the angle, the longer the path of the sun through the atmosphere and so the greater the absorption of radiation by the atmosphere. Finally, of course, it gets dark at night!

The seasons.

The reason why winter is colder than summer has nothing to do with the variation of the distance of the earth to the sun. (If it were, summer in northern and southern hemispheres would coincide instead of being six months apart). The orbit of the earth is an ellipse and not a circle but the eccentricity (ratio of the major and minor axes) is small. Seasons arise because the earth's axis is not perpendicular to the plane of the orbit (i.e. parallel to the normal), but 23.5^0 away from the normal. This causes first one and then the other hemisphere to point a little towards the sun. The sun is then high in the sky in summer and low in the sky in winter. Thus the proportion of daylight is greater in the summer and less in winter. This effect is most obvious in the polar regions (midnight sun in summer and perpetual darkness in winter for part of the year within the polar circles). Also in summer the sun's rays are more vertical at the local noon which increases the heating effect as noted before. The opposite is the case, of course, in winter.

The peak of the summer heat and the trough of the winter cold lag behind the apparent position of the sun as seen from earth. (The height of summer is not the summer solstice and the depth of winter not the winter solstice). This is due to the finite time that it takes for the earth to respond to changes in the amount of radiation received (thermal inertia).

This is still only a crude picture; the oceans play a major role in the climate. The most obvious local example is the effect of the Gulf Stream. London is on the same latitude as James Bay in Canada and slightly (less than a degree) south of Warsaw. The climate is, however, quite different from either of these places.

Longer-term solar cycles.

On longer time-scales, the solar radiation flux received at the earth may vary. This may be due to intrinsic variations in the solar output. Small variations in the solar output (about 1%) due to sunspot numbers have been seen. They show a quasi- 11 year cycle, but also there are long-term fluctuations. e.g. in the period 1650-1700 the coldest winters when the Thames froze every winter coincided with *low* sunspot numbers. Also, the ellipticity of the earth's orbit varies over a 100,000 year cycle. This changes the solar flux received at the earth by as much as 30%. Further, the tilt of the earth's axis changes slightly over a 40,000 year cycle. These are the *Milankovitch cycles* named after the man who proposed them as the explanation of the ice ages in the Pleistocene.

Solar radiation

The solar spectrum covers a wide range of wavelengths from the ultra-violet to the infra-red. The curve outside the atmosphere is shown in the handout. However, it is not the wavelength at the top of the atmosphere that is important but the curve at ground level (see the handout). As solar radiation passes through the atmosphere, the molecules in the atmosphere absorb some wavelengths strongly, resulting in a very different spectrum at ground level from that in space. The peak in the spectral intensity at ground level occurs in the visible region (it is not surprising that human vision has maximal sensitivity about the wavelengths of 500nm (yellow-green)).

Except for weak lines of excitation of O_2, and some absorption of O_3 little absorption occurs in the visible portion of the solar spectrum. However, most of the ultra-violet (wavelength less than 370nm) is absorbed and does not reach the ground. This radiation is quickly absorbed by atoms and molecules that become ionised or dissociated

$h\nu$ (UV range) + AB $\rightarrow A^+ + B + e^-$ (or $\rightarrow AB^+ + e^-$ or $\rightarrow A + B$)

This is the role of species in the ionosphere. Less energetic radiation penetrates deeper into the atmosphere until it finds a high enough concentration of gaseous species capable of absorbing it. The deeper the radiation penetrates, the higher the density of absorbers (since the pressure of the atmosphere is increasing). This gives rise to the idea of a characteristic *penetration depth* for radiation of particular wavelengths. Although we are considering penetration of radiation from space, the penetration depth is quoted with respect to the surface of the earth. We define the penetration depth as the height above the surface at which the radiation is reduced to e^{-1} (i.e. $2.71828^{-1}=0.368$) of the original intensity (i.e. 2/3 has been absorbed)

1. At wavelengths close to 300nm, ozone starts absorbing UV radiation and continues to do so down to wavelengths of about 200nm. The result is a cutoff in the wavelength

of radiation reaching the ground at about 300nm. The penetration depth for wavelengths between 200 and 300nm is about 40km (in the stratosphere)

2. Between 250nm and 200nm oxygen absorbs radiation effectively by the process

   $$h\nu\ (200\text{-}250\text{nm}) + O_2 \rightarrow O^*(\,^1D) + O(\,^3P).$$

   i.e. producing oxygen atoms. This is effective for penetration depths greater than 80km.

3. For wavelengths less than 150nm, ionisation processes dominate. Examples include

   $$NO + h\nu \rightarrow NO^+ + e^-\ (\lambda < 134.1\text{nm})$$
   $$O_2 + h\nu \rightarrow O_2^+ + e^-\quad (\lambda < 102.6\text{nm})$$
   $$O + h\nu \rightarrow O^+ + e^-\quad (\lambda < 91\text{nm})$$
   $$N + h\nu \rightarrow N^+ + e^-\quad (\lambda < 85.2\text{nm})$$
   $$N_2 + h\nu \rightarrow N_2^+ + e^-\quad (\lambda < 79.6\text{nm})$$

   The penetration depth for wavelengths in the region 150-100nm is thus seen to vary rapidly with wavelength, indicating ‘windows’ or intervals of wavelength for which radiation is less absorbed. If there are few species capable of absorbing a particular wavelength, more radiation of that wavelength will reach the earth’s surface – hence the spiky nature of the solar spectrum at ground level.

The role of ozone

Ozone plays a key role in sustaining life on earth. It absorbs UV radiation that is harmful to biological molecules (such as DNA, proteins, other nucleic acids). Yet ozone forms only a minute fraction of the total atmosphere. If all the ozone was collected from the stratosphere and brought down to the surface of the earth it would form a surface layer 2-3cm thick. Ozone is now being destroyed by the increasing concentration of man-made chemicals in the upper atmosphere. The main culprits are CFCs (chlorofluorocarbons) and nitrogen oxides such as CNO and N_2O. In the last decade, dramatic falls in the ozone concentration in the stratosphere have been observed, particularly around the South Pole (and more recently around the North Pole). This is the *ozone hole*; one of the major environmental issues of the age.

The spectroscopy of biomolecules

The handout shows the part of the solar flux for λ <340nm combined with the absorption spectrum of two important biomolecules; DNA (the carrier of the genetic code) and α-crystallin (the major protein in the mammalian eye lens.) The UV absorption of these molecules is nearly zero in the near UV (320nm < λ < 400nm) but is intense in the far UV (200nm < λ < 290nm). Only in the region 290nm < λ < 320nm is there significant overlap with the solar flux. It is clearly undesirable that bio-molecules should absorb energetic radiation (and thus risk disruption); this mismatch is presumably a result of natural selection. However, if the spectrum of the solar flux at ground level changes shape?

Solar UV can damage genetic material [*mutagenesis*] and kill cells. The severity of erythema (sun-burn) is strongly dependent on the wavelength of the incoming radiation. Radiation of 260nm is 100,000 times more damaging than radiation of 390nm. The flux of radiation with λ < 290nm in the solar spectrum at ground level is very low because of the ozone layer. Hence reductions ozone levels will lead to increases in the radiation flux with $\lambda < 290$nm and so very rapid increases in skin cancer rates.

The damage done to a biological system by solar UV is calculated from the action spectrum $E(\lambda)$ using the integral

$$D = \int_0^\infty E(\lambda) I(\lambda) d\lambda \qquad (2)$$

where $I(\lambda)$ is the intensity distribution of the solar flux as a function of wavelength. The *action spectrum* $E(\lambda)$ measures the efficiency of radiation of a given wavelength in producing sunburn. Both are strong functions of the frequency. Thus minor changes in $I(\lambda)$ will produce a large change in the damage function D.

The Beer Lambert (absorption) Law

This gives a simple description of the absorption process. If I is the flux intensity per unit area of radiation (irradiance), then dI, the change in intensity due to absorption, is given by

$$dI = -KNIdz \qquad (3)$$

where K is the extinction coefficient (also known as the photoabsorption cross-section and written σ_{Pa}), N is the concentration of absorbing molecules and dz is the pathlength over which the molecules are absorbed. If the light is at an angle β to the horizontal, we replace dz by $dz_0 / \cos\beta$ where z_0 is the vertical distance downwards. For the atmosphere (and assuming that the radiation is vertically downwards)

$$\int_{I_0}^{I_G} \frac{dI}{I} = -\int_0^Z KN(z)dz \qquad (4)$$

where I_0 is the irradiance at the top of the atmosphere, I_G is the irradiance at the ground and Z is the height of the atmosphere. If we assume that K is a constant, then we have

$$\ln\left(\frac{I_G}{I_0}\right) = -K\int_0^Z N(z)dz$$

The concentration of molecules certainly is not constant over the atmosphere. Let us write the integral as N_T, the total number of molecules in the atmosphere over a unit area of ground. Then

$$I_G = I_0 \exp(-KN_T) \qquad (5)$$

The ozone filter

Ozone absorbs almost all radiation with $\lambda < 295$nm due to a strong optical transition centred at about 255nm. This is the *Hartley Band*. Only O_3 absorbs in this region. O_2, N_2 have no absorption here. Thus ozone acts as a UV filter. The *Beer-Lambert (absorption)* law can be used to calculate the effect of ozone depletion. For the ozone layer, this gives

$$I_{out} = I_{in} \exp(-\sigma_{PA} Nx) \qquad (6)$$

where I_{in}, I_{out} are the intensities at the top and bottom of the layer, σ_{PA} is the photoabsorption cross-section, N the density of molecules with the cross-section in the gas and x the thickness of the layer. A simple calculation shows that a 10% depletion of the ozone concentration gives a 45% increase in the UV radiation getting through the ozone layer.

The ozone budget

Ozone is created in the stratosphere by photolysis of oxygen molecules

$$O_2 + h\nu \rightarrow 2O \qquad (a)$$

$$O_2 + O\ (+M) \rightarrow O_3\ (+M) \qquad (b)$$

where M is any molecule. It is naturally destroyed by sunlight and/or molecular collisions which reverse the second reaction.

$$O_3 + h\nu \rightarrow O_2 + O \qquad (c)$$

$$O_3 + O \rightarrow 2O_2 \qquad (d)$$

In the stratosphere, these processes reach a steady state. Reactions (a) and (d) maintain a small but non-negligible proportion of oxygen which is not in the form of O_2. Reactions (b) and (c) tilt the balance of species of this non-O_2 towards ozone at heights of 20-30km. In this region there is enough production of oxygen atoms for the ozone-producing reaction (b) to proceed significantly to the right but the atmospheric pressure is still high enough for three-body collisions (required to remove excess energy from the O_3 molecule) to be reasonably frequent.

CFC's (chlorofluorocarbons CF_nCl_{4-n}; usually n=2) were developed in this century for use in refrigerators and aerosol cans. They are stable and non-flammable at tropospheric heights but in the stratosphere they are broken down by solar UV to produce free chlorine radicals and then chlorine oxides, ClO_x (x=1-3) by reaction with O_3 and O. These catalytically decompose ozone by reactions of the type

$$ClO + O_3 \rightarrow ClO_2 + O_2;\ ClO_2 + O \rightarrow ClO + O_2$$

The effect of this is to greatly increase the rate of reaction (4) above. One ClO molecule may destroy 10^{14}-10^{15} O_3 molecules before it is destroyed by other processes in the stratosphere. Thus small concentrations of CFC's (parts per billion (10^{-9})) can damage the ozone layer. Similarly NO (from nitrate fertilisers) and OH (from various natural processes but also industrial processes such as H_2O_2 production) can catalyse ozone destruction.

There is more to the matter than gas phase chemistry. we need to explain why the holes appear in the polar regions and in particular over Antarctica. This is due to the wind systems in these regions. The *polar winter vortex* is very stable due to the large land mass of Antarctica. The intense cold (183K at heights of 15km) produces clouds of ice crystals on which the reactions occur. These *heterogeneous* reactions are far more efficient than the gas-phase reactions discussed above (for a start you do not need three-body collisions; the ice crystals can carry away the excess energy). CFC's are trapped in the polar vortex and concentrated before being released in the polar spring as the solar radiation illuminates these latitudes once again. As the air warms up, the vortex breaks down. Ozone loss has now been observed at high northern latitudes. The Arctic vortex is much smaller than the Antarctic one and the mechanisms of ozone destruction are probably different. The stratospheric aerosol is expected to play a larger role and bromine compounds are more important.

Responses to the ozone problem

- Prevention - replace further release of CFC's and replace them with 'ozone friendly' species. This was the purpose of the 1987 Montreal Protocol (and more recent meetings in London (1990) and Copenhagen (1995)). The objective is to phase out CFC's by early next century. However, the CFC's already released will remain in the atmosphere for about 75 years so ozone depletion will continue. Further, emission of other gases that attack ozone (CH_4, N_2O) continues
- Adaptation – wear sun cream and sun glasses. This does not solve the problem of the increased UV emissions on plant and animal life.

One unexpected side-effect of ozone depletion is the cooling of the stratosphere. Since ozone absorbs UV radiation, the presence of ozone in the stratosphere heats it up. Thus ozone loss cools it done. This partially offsets the increased greenhouse effect – the behaviour of the atmosphere is a complicated problem.

Terrestrial radiation

Not all the solar radiation incident on the earth is absorbed by the atmosphere or the ground. A large fraction is reflected back into space from the cloud tops and the ground. The fraction of radiation reflected (and hence lost to the earth) is called the planetary albedo, often denoted by the symbol a. A rough breakdown of the energy budget of the earth is as follows

- 100 units of solar flux are incident per unit area on the earth
- 33 units are reflected back into space (mostly from cloud tops [26]; but some from the ground [2.5] and from dust and aerosols in the atmosphere [4.5])
- 22 units are absorbed by the atmosphere (including 3 units absorbed by clouds)
- 32.5 units are scattered by the atmosphere. Of these 28 units subsequently reach the ground and 4.5 units are scattered back into space (the dust and aerosols contribution to the albedo mentioned above). This scattering is responsible for the blueness of the sky.
- 17 units reach the ground directly. Of these, 14.5 are absorbed and 2.5 are reflected back into space.

Note that 45 units reach the surface of the earth one way or another. The annual average rate of input of solar energy per unit horizontal area at the top of the atmosphere is $336 Wm^{-2}$. (This is our 100 units). So the solar input to the earth's surface is $151 Wm^{-2}$. This would rapidly heat the earth's surface to an unbearable temperature if it were all totally absorbed. The rate of absorption of solar energy must be balanced by a re-emission of this energy until a steady state is achieved. This point applies with equal force to the 19 units absorbed by the atmosphere. This re-radiation is *thermal radiation* (i.e. heat). The effect of the earth is to perform a partial conversion of the solar visible and UV radiation (coming in) into the terrestrial infra-red radiation (going out).

Terrestrial radiation

It is not simply a matter of re-radiation straight out into space. The input divides as +45 units to the ground, +19 units to the troposphere and +3 units to the stratosphere. The stratosphere does simply reradiate the energy as long wavelength terrestrial radiation. The troposphere and the surface of the earth reradiate to each other as well as to outer space.

The final balance is therefore a complex matter. The final terrestrial radiation balance works out as follows

- The surface of the earth absorbs 98 units from atmospheric re-radiation and re-radiates 113 units. 108 units of this are absorbed by the atmosphere again and 5 units go to space
- The troposphere absorbs 108 units from the surface radiation of the earth and re-radiates 98 units to the earth and 59 units back into space. There is a net loss of 49 units.
- The stratosphere radiates 3 unit directly to space

If we add the solar and terrestrial contributions, we arrive at an interesting picture. If we count the radiation going into space, we arrive at 67 units. This together with the 33 units that are simply reflected gives 100 – the system is in overall balance. The stratosphere receives 3 units from the solar input and reradiates 3 units of terrestrial radiation. That is in balance. The troposphere receives +19 units of solar radiation and re-radiates (net) 59+98-108 = 49 units. Thus the troposphere loses 30 units. The earth's surface receives 45 units of solar radiation and loses (net) 15 units in terrestrial radiation i.e. overall it gains 30 units. We are clearly missing something. If the earth's surface was really gaining energy at the rate of 30 units (100Wm^{-2}) we would know about it. There is in addition a *non-radiant* heat flux that makes up the difference. This is due to atmospheric convection. We will discuss this in more detail later in the course.

The earth as a black-body radiator

Black-body radiation; a reminder of the main points

1. Any atom or molecule can absorb or emit radiation (and move from one energy level to another). Similarly any body can emit or absorb radiation. If a body is in radiative equilibrium with its environment, it will emit as much energy as it absorbs per unit time. The total emissive power, E^t is then defined as the total radiant energy per unit area per unit time and $E(\lambda)$ the energy emitted between wavelengths λ and $(\lambda + d\lambda)$. Hence $E^t = \int_0^\infty E(\lambda)d\lambda$. Similarly, the absorptivity of a body, $A(\lambda)$, is defined as that fraction of the radiation incident on the body that is absorbed at wavelength λ. Thus the total (integral) absorptivity, $A^t = \int_0^\infty A(\lambda)d\lambda$
2. If a body absorbs *all* the radiation that is incident upon it (i.e. $A(\lambda) = 1$ for all λ) then it will not reflect any light and thus appear black. Such a 'black body' will also be the best emitter at any given temperature. The radiation emitted is called black body radiation and has a characteristic emissivity spectrum which is independent of the material making up the body.
3. Black-body radiation is isotropic and depends only on the temperature of the body radiating
4. The integral radiant emittance E_b^t is governed by the Stefan-Boltzmann law
$$E_b = \sigma T^4 \tag{7}$$
where σ is the Stefan constant, 5.67 x 10^{-8} Wm^{-2}K^{-4}.
5. The frequency distribution of the radiation $E_b(\lambda) = dE_b^t / d\lambda$ is given by the Planck spectrum

$$E_b(\lambda) = \frac{2\pi c^2 h}{\lambda^5}\left(\exp(hc/\lambda k_B T) - 1\right)^{-1} \qquad (8)$$

where k_B is Boltzmann's constant. The more usual (and more natural) way to express the matter is that (7) is a consequence of (8).

6. As the temperature rises, the peak in E_b (λ) becomes shifted to shorter wavelengths. This is the Wein displacement law; $\lambda_{max}T$ = constant ($2.88\text{x}10^{-3}$ mK). In other words, as you heat a body it goes from red to blue-white
7. The radiant energy of any body (non-black in general) is equal to its absorptivity multiplied by the Planck function; i.e.

$$E(\lambda) = A(\lambda)E_b(\lambda) \qquad (9)$$

– *Kirchhoff's Law.*

Effective temperature of the earth

The ideas about black bodies matter because (i) the sun emits as though it were a black body with a (surface) temperature of about 6000K (ii) the earth, clouds, behave as black bodies with appropriate temperatures.

Assuming that the earth emits terrestrial radiation as a spherical black body of radius R_E and temperature T_E, then from the Stefan-Boltzmann relation, the total power output of the planet is $4\pi R_E^2\sigma T_E^4$. The rate of absorption of radiation from the sun is $S(1\text{-}a)\,\pi R_E^2$ where a is the albedo (in fact, the integral absorptivity of the earth, but the symbol is conventional) and S the solar constant. These must balance, and so

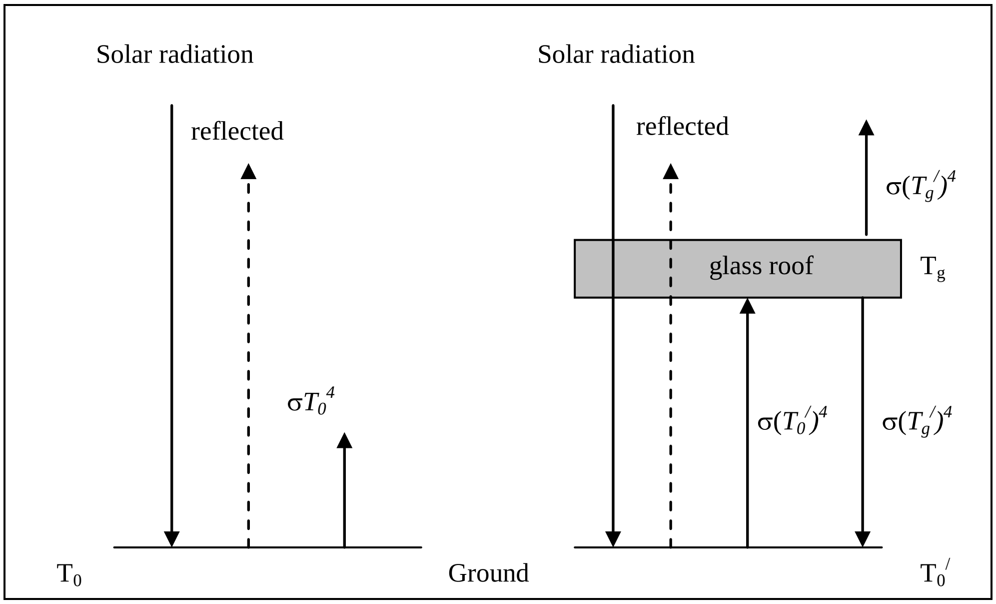
$$4\pi R_E^2\sigma T_E^4 = S(1\text{-}a)\,\pi R_E^2 \qquad (10)$$

from which we can evaluate the effective temperature of the earth as

$$T_E = \left(\frac{S(1-a)}{4\sigma}\right)^{1/4} \qquad (11)$$

Note that T_E is independent of the radius of the body. Given that $a = 0.33$ and $S = 1353\text{Wm}^{-2}$, we find T_E = 251K (-22^0C). This is a bit on the cold side; the mean temperature at the surface of the earth is 288K ($+15^0$C). The problem is that we have neglected the atmosphere entirely; in particular we have neglected the internal energy transfers between the atmosphere and the surface. In effect we have considered the interface between the atmosphere and space and ignored the interface between the atmosphere and the ground.

The elevation of the temperature at the surface of the earth from -22^0C to $+15^0$C is due to the *greenhouse effect*. The name comes from the fact that the mechanism is in many ways analogous to the way that a greenhouse works and the atmosphere can be considered as a greenhouse roof. Consider the diagram below. On the left is the situation that we have considered before which gives a temperature that is far too low. Now place a 'glass roof'

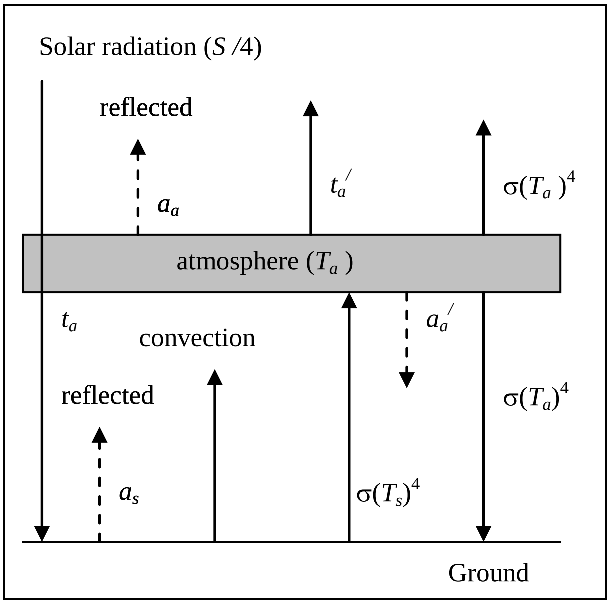


above the ground . The glass lets in the solar radiation but prevents the infra-red radiation from radiating directly to space. This heats the roof to a characteristic temperature T_g and the roof then radiates both to the ground and out into space. The ground is therefore receiving more energy than before and so its temperature will rise until a new equilibrium is achieved in which both the ground and the 'roof' emit as much as they absorb. Thus, in this state, the emission upwards from the glass roof must equal the emission upwards from the ground without the roof (since the balance with respect to outer space must not change. This implies that $T_0 = T_g'$. If we now consider the state of the ground, then the net energy given to the ground directly by the sun must be σT_0^4 (from the diagram on the previous page) and the energy radiated back from the glass roof must be σT_0^4 (since $T_0 = T_g'$). Thus we have

$$2\sigma T_0^4 = \sigma(T_0')^4$$

from the energy balance on the right. Thus the new ground temperature must be

$T_0' = T_0 2^{1/4}$ i.e. 298K (25^{0}C). This is rather too high. However, our model of the atmosphere is still very simple. We have assumed that the 'glass roof' (whatever it is) does nothing except pass solar radiation through and block terrestrial radiation from the surface completely. Moreover, we have assumed that we can treat the 'glass roof' as though it were another black body. If this were true, we could certainly treat the upward and downward radiation from the 'roof' in exactly the same way. However, if this is not the case (and in fact it is not)



we have a more complicated balance to calculate.

Consider the situation in the diagram on the left. This is a more complex model in a number of ways. First, we allow that the atmosphere has a finite ability to transmit radiation (as shown by the *t* coefficients). Second, we treat all downward radiation as pure black-body radiation, but we modify the reflected radiation by an albedo. This is shown by the *a* coefficients. Note that the albedo for upward and downward reflection from the atmosphere is different. We have also incorporated the effects of convective transport discussed above

Net solar flux + heat radiation from atmosphere = radiation emitted from ground (minus reflected from atmosphere) + convection transfer to atmosphere

$$t_a(1 - a_s)\, S/4 \;+\; \sigma T_a^4 \;=\; \sigma T_s^4\,(1 - a_a^{/}) \;+\; C\,(T_s - T_a)$$

Similarly, the energy balance for the *atmosphere* is

Net solar influx + absorption of terrestrial radiation + convective heat transfer to atmosphere = atmospheric emission (up and down)

$$(1 - t_a - a_a)\, S/4 \;+\; (1 - t_a^{/} - a_a^{/})\,\sigma T_s^4 \;+\; C\,(T_s - T_a) \;=\; 2\sigma T_a^4$$

Examples of the application of these equations are

1. Typical values are $a_s = 0.11$, $t_a = 0.53$, $a_a = 0.30$, $t_a^{/} = 0.06$, $a_a^{/} = 0.31$
   $C = 2.5\,\mathrm{Wm^{-2}K^{-1}}$. This give $T_s = 288\mathrm{K}$
2. White (snow-covered) earth $a_s = 0.75$ gives $T_s = 270\mathrm{K}$ (i.e. cold)
3. Dust in atmosphere; $a_a = 0.36$, $a_a^{/} = 0.37$, $t_a = 0.45$, $t_a^{/} = 0.05$ gives $T_s = 283\mathrm{K}$

The greenhouse gases – or where does the roof come from?

We require molecules that can absorb the infra-red radiation coming from the earth (i.e. wavelengths in the range 5-25 microns) but not in visible region. Molecules that do this are H_2O (absorbs in bands <4 microns, an intense band at 6.3 microns and a strong band greater than 9 microns), CO_2 (strong absorption band at 13-17 microns). (O_3 absorbs in both regions; intense narrow band at 9.7 microns). O_3 is only important in the stratosphere. The essential components of the 'roof' are CO_2 and H_2O. The effectiveness of a gas in contributing to the greenhouse effect is measured by the ***Global warming potential***. This is defined as the added surface warming per unit molecule of the gas in the Earth's atmosphere (referred to the effect of CO_2). It is measured in terms of number of molecules of CO_2 equivalent.

Overdoing the greenhouse; the problem of global warming

The huge expansion of industrialisation has led to the prediction that man is now altering the global radiation balance by enhancing the natural greenhouse effect. Industrialisation leads to increased CO_2 emissions and hence increased CO_2 concentrations in the lower atmosphere. Between 1770 and the present, CO_2 concentrations have increased from 280ppm to 350ppm (i.e. an increase of 25%). Moreover, the greatest increase has been in the last 50 years and the concentrations of CO_2 are still increasing. It is certainly the case that the average earth temperature has been rising at about 0.8^0C/yr since 1850. However, this does not demonstrate of itself that increased CO_2 concentrations are the cause. Much work has been done on 'climate modelling' ; modelling the atmosphere and then seeing the effect of changing parameters like CO_2 (or other greenhouse gas) concentrations, mean solar flux and so on. Moreover, if one wants to make predictions about the local climate, the calculations get even worse. The basic ingredients include

1. Modelling the dynamics of the atmosphere by Newton's equations (including such things as mass conservation, hydrostatic effects and so forth
2. Equation of state of the gases in the atmosphere
3. Thermodynamic effects (latent heat of water vapour for example)
4. Clouds and their effect on the radiation equilibrium
5. Convection in the atmosphere
6. Coupling atmospheric effects to the oceans (effects of ocean currents and ice caps)
7. Long term systems (such as El Nino in the Pacific)
8. Effect of different terrains (desert, forests etc)

Also, one must remember that CO_2 is not the only greenhouse gas although it is the largest contributor (about 70%). Sizeable contributions also come from methane (23%) and N_2O (7%).

- *Methane concentrations* before 1800 were about 0.8ppmV (ppm by volume) but since then the concentration has more than doubled and is increasing at about 1%/yr. Although the concentrations of methane are much lower than CO_2 (2ppmV versus 350ppmV), methane is 7.5 times more absorbing than CO_2. Methane emissions come from fossil fuels (100 Mtons/yr), rice paddies (60 Mtons/yr) cows (80Mtons/yr) forest fires and misc. (40Mtons/yr). Methane is removed by chemical reaction with the OH radical and has a lifetime of about 11 yrs.
- *Nitrous oxide* (N_2O) concentrations are 0.3ppmV rising at 0.25% per year. The concentration is now about eight times that of the pre-industrial period. Sources are fertilisers, chemical industry (nylon production), deforestation. Lifetime in the atmosphere about 150yr.
- *CFCs* Concentrations low, but one CFC molecule is 500-10000 times more effective than CO_2. It is possible that CFCs account for up to 20% of global warming. Effect partially offset by the destruction of ozone.
- *Ozone* Increased smogs make O_3 a tropospheric species as well as a stratospheric one. Not clear what the effect will be.
- *Indirect production* from CO,NO, NO_2,which form (and also destroy greenhouse gases). The chemical feedback loops possible are very complex

The relative contribution of various gases to global warming since 1800 is CO_2 (55%); CH_4 (15%); CFC-12 (21%); N_2O (4%); O_3 in troposphere (2%); others (3%).

Various computer models are beginning to converge on a common answer. As the concentration of CO_2 increases, the global average temperature will increase by a few tenths of a degree in the next few years and then by about 1.5^0C over the following 70 years. The slow start is due to the thermal inertia of the oceans. This is a *global average* . There are marked local variations. The northern hemisphere warms about twice as much as the southern and there are strong variations from continent to continent. The amount seems small, but it leads to major climactic changes including desertification in some areas, increased rainfall in others (for example the monsoon region will spread). This has important implications for agriculture.

What can be done is, as always, controversial. There is a commitment that CO_2 emissions will be reduced (that the emissions in 2000 will be no greater than in 1990). However, whether this line can be held is anyone's guess. The same applies to N_2O and CH_4. The effect of the Montreal Protocol will be eliminate (eventually) CFCs but what about the replacements? What are the possibilities of energy conservation and moving away from fossil fuels?

As an example of the consequences of global warming let us consider the rising of the sea level. As it gets warmer, thermal expansion leads to the expanding of the oceans and hence the rising of sea levels (there is also a small effect from melting ice). The amount of thermal expansion strongly depends on the temperature of the water. Cold water expands only a little (the maximum density of water is at 4^0C; ice floats). At 5^0C (i.e. about the UK), a one degree rise in temperature causes a volume increase of 1 in 10^4. At 25^0C (tropics) a one degree rise causes a volume change of 3 in 10^4. This corresponds to 3cm rise in the sea level. The predictions of sea level rise over the next century are in the range 20-50cm. This is enough to make major changes to the coastline.