Temperature & Energy
Warming the Earth and the Atmosphere

In this section we shall begin by looking at the concept of temperature and how it is recorded. We'll then see how the Sun radiates energy in different forms to the Earth by an amount that is characteristic of all hot bodies; how the balance between visible radiation and IR is crucial to maintaining the temperature of the Earth at its present level and how the atmosphere plays a central part in the radiation balance through the greenhouse effect. I am going to spend some time talking about radiation because it is the single most important factor determining climate and weather. The textbook covers these topics in chapter 2.

Temperature

What is temperature? You may say it's what you read when you put in a thermometer! This is really a circular definition. Temperature measures how *hot* or cold an object is. Heat is a form of energy and energy is measured by an average speed (or energy of motion, called *kinetic energy*) of molecules in a solid, liquid or gas. So, in effect temperature is a measure of an average speed of motion of atoms or molecules.

[Aside: we experience hot and cold sensations by how quickly our skin experiences a change of temperature. If you put a piece of metal (at room temp) against your warm skin, the metal feels colder than a piece of wood at the same temperature. This is because the metal conducts heat better and the temperature of your skin lowers more quickly against the metal. Our feelings for hot and cold are not a very reliable measure of temperature.]

Cooling a body, or a mass of air, means taking away heat energy and reducing the average speed of molecules. [For the more experienced physicists and chemists in the audience, heat energy generally consists of both kinetic energy and potential energy, the potential energy representing the stretching of inter-molecular and inter-atomic bonds]. Cooling cannot be carried on indefinitely, because there is only a certain amount of energy present. When all the kinetic energy that can be taken away has been extracted, the absolute zero of temperature is reached. [Note the careful wording. Einstein pointed out many years ago that even at absolute zero atoms have residual motion that can't be removed. This motion is known as "zero point energy"]. Absolute zero temperature is a long way below normal room temperature, as we'll soon see.

There is a basic law of the study of heat called, grandly, the second law of thermodynamics, that states what is obvious from everyday experience as a fundamental 'law': "bodies can only transfer heat energy to colder bodies", or, to put it the other way around, "cold bodies can't heat hotter bodies". I'll mention this again later.

Temperature scales

The usual temperature scale employed the world over in meteorology is °C, i.e. degrees Celsius (not Centigrade, which is a local British name); e.g. 20°C.

You will find degrees Fahrenheit, °F, in the USA and in historical British records, where the Fahrenheit scale is used. If I said "which is bigger, a change of 1 degree Fahrenheit or 1 degree Celsius?" what answer would you give? Most people in Britain know that there are more degrees Fahrenheit between the temperatures of ice and boiling water than degrees

Celsius but as far as modern science is concerned, degrees Fahrenheit are of historical interest only, like ounces for mass and guineas for money.

It's worth saying a bit here about the history of thermometers, both out of general interest - thermometers are one of the few scientific instruments that have become part of everyday life - and because climate records of the past were clearly made using thermometers of past-times and not present day instruments. The Fahrenheit scale pre-dated the Celsius scale. Daniel G. Fahrenheit (1686 – 1736) spent his early life in Gdansk in Poland but lived in The Netherlands for most of his adult life, earning a living mainly as a thermometer and barometer maker. He invented the mercury-in-glass thermometer in 1714 and worked on his scale over the following decade. What made Fahrenheit's thermometers particularly notable in his day was that they were consistent, unlike the slightly earlier alcohol thermometers that tended to vary, in part because the alcohol used was sometimes a mixture of alcohol and water. Fahrenheit's scale was quickly taken up in Britain as well as The Netherlands, and later spread to America and British colonies.

Fahrenheit sold many thermometers as a valuable aid to doctors, one of the few innovations in medical practice in the early 1700s that was effective and would still appeal to anyone today. A number of different devices that registered temperature changes had been around in the 1600s. Nowadays you commonly see in gift shops reproductions of Galileo's 'thermometer'. It consists of a jar of liquid with many weighted glass balls in it that sink when the temperature goes up and rise when it goes down. Each ball is supposedly calibrated to sink at a particular temperature. Such devices are more 'thermoscopes' than 'thermometers' in that they haven't got a convenient scale to read off the temperature. Galileo's version and a number of other 17th century ideas were too inaccurate or bulky or fragile to form a convenient meter for measuring temperature, a meter that was portable, versatile, cheap, reproducible, reliable and all you expect from a thermometer.

Imagine the impact of being able to supply good thermometers into a world that didn't really have them. The new thermometers of the 1700s were taken all round the world. One result was that people who lived in temperate climates like ours found that when you measured the temperatures in the tropics, they weren't as sweltering as personal experience suggested; when you measured the temperatures in cold parts of the world, they weren't generally as frigid as had been imagined. People realised that plants from hot parts of the world could indeed survive in glass houses in countries like Britain and Holland, and so began the eighteenth century passion for collecting plants from all over the world and growing exotic species. Botanical knowledge blossomed, to make an appropriate analogy. So did a wide range of chemical activities. Many chemical reactions depend sensitively on temperature. Once you have good thermometers, then you have accurate control over what you are doing with chemical reactions, in industry and in daily life. Imagine cooking in an oven without having much of an idea of the oven's temperature. Quality control improved in the brewing industry and many other industries besides. Without the thermometer, meteorology would not be a science.

If you think about it, the basic laws of optics, mechanics, planetary motion and so on were discovered in the 17th century but not the basic laws of science that involve temperature. These were 18th and 19th century discoveries, because the thermometer as a tool of science was a later invention. We don't tend to think of the humble liquid in glass thermometer found in almost every house as a sophisticated instrument but it came on the scene a lot later than mechanical clocks, microscopes, telescopes and a good number of other scientific instruments. That's enough of a diversion on thermometers. Pause when you next see one and reflect what an elegant, simple but effective device it is. In the early days of thermometry there were almost as many scales as there were inventors and improvers in the field. A Swedish Professor of Astronomy, Anders Celsius (1701 - 1744), developed his alternative scale not long after Fahrenheit's work. The Fahrenheit and Celsius scales emerged as the survivors. Then the world had two different devices to do the same job – a bit like the videotape scenario facing Betamax and VHS in the early days of electronic video recording, or the current clash between Blu-ray and HD DVD. Although Fahrenheit was the more inventive pioneer, his scale is surely doomed to become a historical curiosity in future. Now, back to the topic of temperatures in meteorology and climatology.

In basic relations in physics, such as the ones we are about to see for radiation, temperature is measured *from absolute zero* in degrees Kelvin, K. E.g. 293 K is 20°C. Notice that no degrees (°) symbol is used when a temperature is in Kelvin. A change of one Kelvin degree is the same as one Celsius degree; the only difference between the scales is that the Kelvin scale starts at the lowest possible temperature, absolute zero. The general conversion between Celsius and Kelvin is:

$$\text{temp in K} = \text{temp in °C} + 273$$

The constant '273' is a good enough approximation for this course. If you need to, you can find the more exact figure in tables of physical constants. Kelvin was one of the great Scottish physicists, a leading world figure in science in the 19^{th} century. He was professor of Natural Philosophy at Glasgow for more than 50 years from 1846-1899. 2007 was the centenary of the year of his death and it is a mark of the esteem he was held in that his tomb is in Westminster Abbey near that of Isaac Newton. One of the areas that made him famous was the study of heat and energy. His personal name was William Thomson and in the index of many a general physics book you will find the 'Joule-Thomson effect', 'Thomson on thermo-electricity' and so on.

Sun's radiation

We shall skip a few pages of the textbook to look first at the Sun's radiation before looking at heating in the atmosphere. Take away the Sun's radiation for 12 hours and it is dark and gets noticeably colder. A traditional NE saying embodies the same idea applied to approaching winter: *as the nicht lengthens, the caald strengthens*. Take away the Sun's radiation for a month and the Earth would become uninhabitably cold. You can get an inkling of this by looking at the Moon. A lunar night lasts almost 14 Earth days. During the lunar night the Moon's surface cools to -100°C. In polar regions on Earth the Sun does disappear for more than a month at a time and it does get exceedingly cold in the dark polar winter. However, it's still warmer than -100°C because, as we shall see, polar regions are heated by a transfer of energy from nearer the equator. Turn that off too, and the carbon dioxide in the air could freeze out. In short, to maintain the Earth's climate, we need the enormous input of energy from the Sun we now get.

Blackbody radiation

Solar energy reaches us mainly in the form of *radiation* across the electromagnetic spectrum. A spectrum is a plot of how much radiation is emitted against the wavelength of the radiation. The Sun's spectrum is *continuous*. It covers a large wavelength range. Only a small fraction of the total range is the visible spectrum. The Sun's spectrum extends from UV right through to the radio spectrum. The slide shows roughly how much of the energy is in different wavelength regions. This curve follows the famous Planck radiation law, whose details won't be covered in this course. The Sun's spectrum peaks in the visible. Almost half of Sun's output, 44%, is visible light; 7% is UV; 48% is in the IR. A very small fraction of the energy from the Sun is generated by means other than blackbody radiation. For instance, you can image the Sun at X-ray wavelengths by its own radiation but I shan't discuss the details here. You can hear more about this in our Space Science (PX2011) course at level 2, if anyone would like to follow this up.

All bodies radiate electromagnetic (EM) energy. The Sun is not special. Hotter bodies clearly must emit more radiation than colder bodies, from the 2nd law of thermodynamics. Never minding the spectrum for the moment, exactly how much radiation do bodies emit and absorb?

What is a blackbody?

We are going to answer the question of how much radiation a body emits for the special but very important case of a 'blackbody'. This is a technical term. A blackbody is one that absorbs all the radiation that falls on it. You can see why the Sun is treated as a blackbody even though it is glowing incandescent. Any radiation that falls on it is absorbed. The Sun of course re-radiates by an amount appropriate to its temperature. Coal fires and furnaces are other examples of glowing blackbodies. Any radiation that falls into the hole at the front or top of a furnace bounces around and is absorbed inside.

Many bodies don't absorb all the radiation that falls on them. This is the underlying reason why bodies are grey, white or coloured. The amount of radiation they emit is correspondingly reduced from that emitted by a blackbody. This reduction is taken account of by introducing the idea of the *emissivity* of the body, a factor less than 1 that may vary with wavelength. The result is that the radiation from most bodies is less than from blackbodies and departs from the Planck radiation curve if the emissivity depends on wavelength. However, the blackbody radiation curve shows how the radiation varies by factors of thousands over the wavelength range; the emissivity describes relatively minor departures from this.

Total radiant energy

When physicists ask 'how much?' they expect not a descriptive answer but a numerical answer in well-defined units. It is the surface of a body that emits; hence the total radiation depends on the number of square metres (m^2) of surface. The total radiant energy emitted by a square metre of surface per second is measured in Watts. It increases dramatically with temperature.

$$\boxed{E = \sigma T^4} \qquad \boxed{\sigma = 5.67 \times 10^{-8}\ \mathrm{Wm^{-2}K^{-4}}}$$

This is the **Stefan-Boltzmann Law**. Notice T is in K and remember that room temperature in K is quite significant. The slide shows the amount of energy radiated per m^2 at different temperatures. At 300 K (27°C) a blackbody emits 450 Wm^{-2}. If we were blackbodies, we'd emit a bit more, since blood heat is nearer 37°C or 310 K. That is a lot of energy and since we have a surface area around 2 m^2, such radiation would be equivalent to a 1 kW fire. You don't seem to be getting as much as this from your neighbour. What is happening?

Radiation example

Two things are going on. Firstly, objects that aren't blackbodies emit less radiation: typically 0.1 to 0.9 of the rate of blackbodies. As we've seen, the emissivity is a simple reduction factor that multiples the Planck emission rate. For simplicity here, we'll assume that the same emissivity is good enough to cover the whole range of wavelengths, or at least the bit of it that's most important.

More importantly, we are not only emitting radiation all the time but receiving radiation from our surroundings. What counts is the *difference* between radiation received and emitted. There will be no net radiation received or emitted by a body if it is at the same temperature as its surroundings. A body that is hotter than its surroundings emits more radiation than it receives.

- e.g. A blackbody at 310 K (37°C) emits 524 Wm^{-2}. The surroundings at 273 K (0°C) emit 315 Wm^{-2}. The difference is 209 Wm^{-2}.

- A person at 37°C whose emissivity is 0.2 and area 2 m^2 emits a net amount of energy at the rate of 88 W (i.e. Js^{-1}). Moral: don't stand around in swimming shorts or a bikini in the snow unless you're feeling very hot.

Clothes cut down on the radiation we might emit in two ways:

a) they provide an inner surface at nearly skin temperature that radiates back;

b) they support a temperature gradient across them by virtue of being poor conductors.

Global warming requirement

If the earth were a blackbody at 288 K and you heated it by 1 K, then it would need to provide 5.4 Wm^{-2} to sustain the increased radiation. It's our everyday experience that if you heat something up it won't stay hot unless you sustain the source of heat. Take away the source and it will naturally cool. Radiation is the phenomenon that ensures it will. How, then is sustained global warming possible?

The Earth's surface is not far off being a blackbody at the IR wavelengths it gives off. The net result is that if the Earth is getting warmer, then some process must be supplying the extra heat energy to sustain the higher temperature, and supplying lots of it. 5 Wm^{-2} is equivalent to 5 MW km^{-2}, 500 GW over the whole of Scotland; and there are a lot more square kilometres on the Earth's surface. Indeed, to keep Britain 1°C warmer requires more energy than all the power stations in the country generate, by a factor of many times. We'll come back to the Earth's energy requirements later.

I should add here that the Earth is **not** a blackbody when it comes to absorbing incident sunlight, for the reflectivity of the surface alters depending on the surface cover (e.g. ice or soil, trees or corn, etc.). The variation in reflectivity alters the amount of sunlight absorbed and hence the heating effect of the sun's rays. This effect is crucial to models of global warming.

Wavelength of maximum radiation

So far we have said nothing about the spectrum of radiation at cooler temperatures than the Sun. We may be emitting radiation but we're not glowing yellow hot or white hot. Where is this radiation in the EM spectrum? It is all at longer wavelengths than visible light. How much longer? When you walk near to a radio set you are listening to, you don't hear a hiss, or see spotty interference all over a TV screen. That's because the radiation we emit isn't as long as the wavelength that domestic radio or TV receivers are tuned to. The wavelengths we mainly emit are between the microwave and visible regions of the electromagnetic spectrum, namely in the infra-red.

One simple way of giving an answer is to ask where the peak of the spectrum is. For the Sun it is in the green part of the visible spectrum. Some people have suggested that it is no accident that our eyes are most sensitive to light at around the very same wavelength. To see, eyes must absorb light. Molecular absorption of light always covers a narrower range than the complete visible spectrum. To maximise the sensitive of the eye, it makes some sense to optimise the absorption of receptors at the back of the eye (the retina) to the wavelength of maximum energy in sunlight. That's a digression.

The peak wavelength of emission for cooler bodies than the Sun moves off to the infra-. There is a very simple relationship that lets you find where it is:

$$\boxed{\lambda_{max} = \frac{3000}{T}} \qquad \lambda \text{ in } \mu\text{m}, \; T \text{ in K}$$

e.g. for the Sun at 6000 K: $\lambda_{max} \sim 0.5\ \mu m$
for our surroundings at 300 K: $\lambda_{max} \sim 10\ \mu m$

This law was discovered by Wilhelm Wien and is known as *Wien's displacement law*. It and other work that Wien did was considered so important in moving physics forward at the start of the 20th century that he was awarded the Nobel Prize in Physics in 1911 "for his discoveries regarding the laws governing the radiation of heat".

This maximum radiation by the Earth in the far infra-red has a very important consequence for the temperature of our surroundings, the temperature of the biosphere.

Long and short wave radiation

You've seen in an earlier slide the wavelength distribution for the Sun's emission. The sunshine reaching the ground reaches us at comparatively short wavelengths that are transmitted right through the atmosphere. The far infra-red and beyond (shorter than 1.5 μm) is known to meteorologists as *long wave radiation*. Notice the difference in the important wavelength regions of emissions between Earth and Sun. This difference comes in to our own story soon.

Radiation balance

There is one other difference between Sun's energy and the Earth's radiation. Sunlight is received at the outer atmosphere in one direction only, give or take 0.25°, which is the spread of the Sun across the sky. The Earth re-radiates all round because the spinning Earth spreads out the incoming radiation over all longitudes (i.e. all the way around the Earth). Since the Earth remains at a stable temperature - overall it is neither getting hotter or colder on a time-scale of years - then the Earth re-radiates as much energy as it receives. You need to allow that the Earth reflects some 30% of the incident sunlight away without any absorption. Equating the incident energy received by the Earth to the radiation emitted by a body at temperature T given by the Stefan-Boltzmann law, you can calculate the average temperature of the Earth. It turns out to be 255 K or -18°C. This is very odd, because meteorological measurements at the surface of the Earth and over the ocean show that the average temperature on the Earth's surface is close to 288 K or 15°C. What is going on?

Apart from the Sun, the rest of space into which the Earth radiates is very cold, about 3 K. Are we getting any useful heat from the stars? Or heat from the ground? On holiday in the Greek island of Lesbos a few years ago, I found at the edge of one beach a pool that was almost too hot to bathe in. It was hotter than a freshly run bath. Geothermal energy comes to the surface in select parts of the world but, overall, it makes a negligible difference to the Earth's energy balance. We are not getting any worthwhile energy to heat the biosphere from any source other than the Sun.

Greenhouse effect

What is going on is a bit like what is happening when you wrap yourself up to combat the cold on the snow slopes. Remember how your clothes re-radiate your IR radiation back to you, keeping you warm. The Earth needs a blanket to keep warm and that blanket is our atmosphere. The mechanism is different with a real blanket but the effect on the Earth is similar. It is hotter under the blanket than on top. The atmosphere is pretty opaque to a significant amount of IR, because of the particular molecules it contains. The absorption spectra of the important molecules are shown in the textbook in chapter 2 and I'll show a slide later on. These molecules re-radiate IR back to the Earth.

With a person, the heat you are trying to keep in is heat generated by metabolic activity. With the Earth, the heat energy you are trying to keep in is warmth created originally by the Sun's rays. The blanket, our atmosphere, must let through the Sun's visible light but stop much of the re-radiated IR, just as the glass in a greenhouse lets in the Sun and keeps the warmth within. This analogy has led to the effect being called the *atmospheric greenhouse effect*. [It is unfortunate that the main reason a greenhouse keeps things warm is that it keeps the wind out and confines the circulation of warm air. The physical barrier of the glass is even more important than the IR barrier. The atmosphere restricts heat radiation, not particularly heat convection. Inspite of this difference, everyone uses the term 'greenhouse effect'].

The greenhouse gases in the atmosphere are H_2O, CO_2, O_3, N_2O, CH_4 and CFCs in decreasing order of influence. The reason these molecules are greenhouse gases whereas the major constituents of the atmosphere, N_2, O_2 and Ar, are not is that they have more than 2 atoms per molecule and the extra bond-bending internal motions within the molecule happen at infra-red frequencies. The textbook diagram Fig. 2.11 (depending on the edition) shows their IR absorption bands. Remember that the wavelength of maximum emission, λ_{max}, by the Earth is ~10 μm. Water is by far the most prominent greenhouse gas. Satellites look down on the atmosphere in the IR and what do they see? Their view is blocked by water vapour, not CO_2. Likewise, look up from the Earth in the IR and it is water vapour and water droplets that absorb most of the IR, not CO_2. We'll come to the rôle of CO_2 later.

The greenhouse effect is essential to life on Earth as we know it. Without the atmospheric greenhouse effect the Earth would be largely a frozen waste with frozen oceans. Fortunately, there is a plentiful and largely constant supply of water molecules, though, as we shall see, the water vapour content of the atmosphere varies a lot in one area.

Because the greenhouse effect is so important to our climate, I want to summarise what I've said in a different way.

The Earth from Space

If the Earth had no atmosphere, like the Moon, the incident sunlight would keep the Earth's temperature at an average of 255K. At this temperature the radiation from the Earth's surface equals the energy input from the Sun.

Add an atmosphere transparent to sunlight

The atmosphere partially absorbs some of the outgoing IR. This heats it up and it radiates energy both inward to the Earth and outward into space. The Earth now receives radiation from two sources – the original sunlight plus IR from the atmosphere. This is more radiation than it did before there was an atmosphere and hence the Earth's surface heats up. That, quite simply, is the greenhouse effect.

What of the media's greenhouse effect?

Media's greenhouse effect

The media have equated the overall warming of the Earth over the past century or so, which has certainly taken place, with an increase in the greenhouse effect resulting from all causes, notably changes (increases) in the concentration of greenhouse gases. Molecules involved are H_2O, water, because in a warmer world there is more evaporation, CO_2, which is increasing at the rate of about *0.5% of its concentration* annually, or ~2 part per million in the atmosphere, and some CFCs, which have absorption bands close to the peak of IR wavelengths emitted by the Earth. However, you are the next generation of scientific literate people and you should see several separate issues in global warming, some of which I've teased out in the next section of the course. First, global warming and climate change – what is the evidence that says it has taken place and is continuing to take place? Secondly, what is the spectrum of possible causes? Can we say how much each component contributes? As we'll see, the greenhouse effect is only one of a range of influences on global temperatures.

Sun's short-wave energy

Before looking at climate change, look at the final two slides. They present the big picture of the Earth's energy budget. Global warming is concerned with changes down at the few % level. The total amount of radiation coming from the Sun to the Earth is about 1367 W m^{-2} for each m^2 perpendicular to the Sun's rays averaged over the year. This equates to 342 W m^{-2} on average over the surface of the Earth. Satellite measurements (notably from the Earth Radiation Budget Experiment – ERBE) show that on average 104 W m^{-2} is reflected away, leaving a net absorbed flux of 238 W m^{-2} to heat the Earth. The Sun's short-wave energy heats us up. 30% goes back into space; 19% is absorbed by the atmosphere and, on average, 51% is absorbed at ground level. Where the Sun's rays have to travel through more atmosphere, particularly in our latitudes and further North, less than 51% reaches the ground.

Notice again one global influence of cloud. It reflects sunshine directly into space. It sends away energy that would otherwise have warmed us. If the Earth were to be completely cloud covered instead of having less than 50% cloud, as at present, then the world’s climate would turn very cold and harsh. This is the basis of the catastrophe that would follow a major asteroid strike when the resulting dust, ash and condensation would envelope the globe. Volcanic eruptions on a large scale can have the same effect and some past species extinctions are believed to be due to this effect.

Ground - Atmosphere energy balance

The diagram in the textbook is worth your study. Energy equal to 147% of the incident solar energy reaches the Earth's surface. That's why the average surface temperature is as high as 15°C. Only 51% comes directly from the Sun; 96% comes from the atmosphere, including clouds. Of course 147% must depart from the surface and the right-hand-side of fig. 2.15 shows on average how that goes: 117% in IR; 23% in (latent) heat of evaporation of water (more later) and 7% by convection and conduction through the air. Convection is heat transferred by bodily motion of warm air away from the surface. If you add up all these figures, you’ll see that the energy radiated equals energy received.

Climate change and other environmental issues are inter-linked

This slide is just a nice graphic to introduce our next section, which discusses climate change over various time-scales and touches on a range of environmental issues.

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