5.4 So, what determines the GMST?

5.4.1 An overview of energy gains and losses

Figure 5.14 is what we have been working towards: a diagram giving an overview of the rates of energy gain and loss by the Earth's surface and atmosphere. The component parts of this diagram are Figures 5.7 and 5.13, which have already been discussed, but this synthesis will now be explored in some detail.

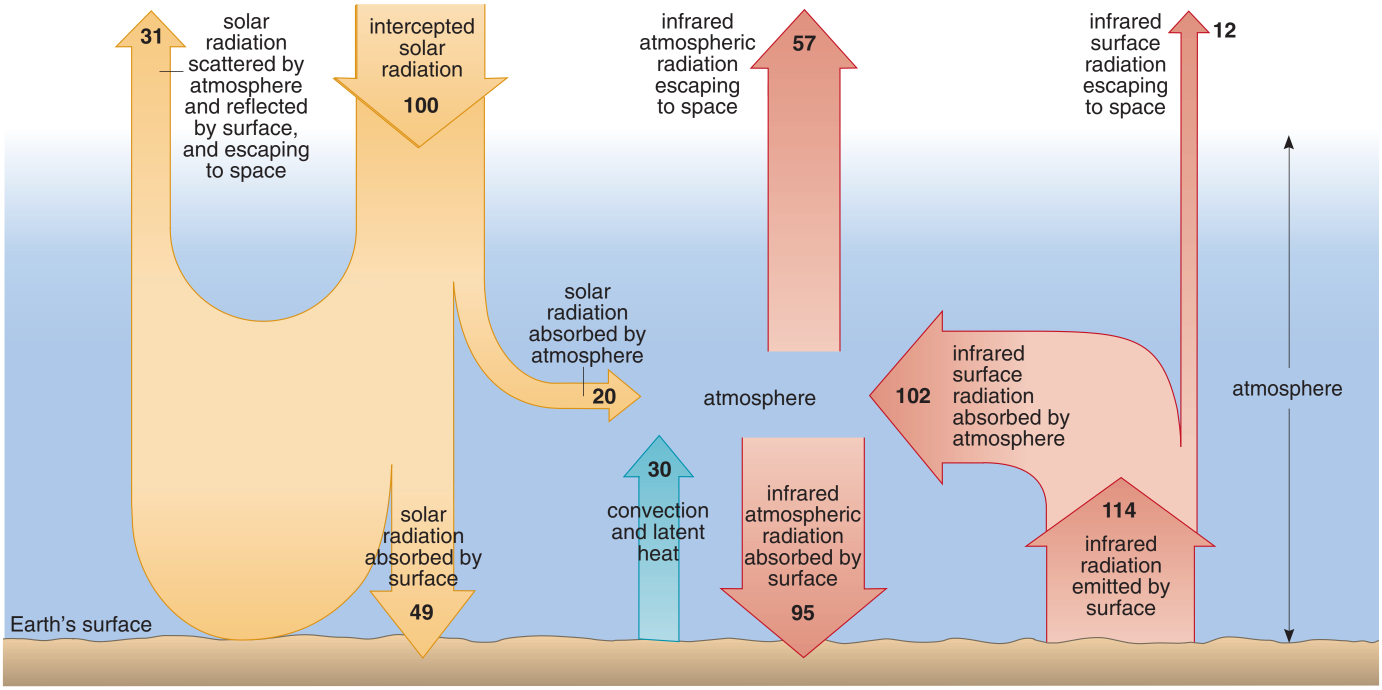

Figure 5.14 Rates of energy gain and loss by the Earth's surface and atmosphere. Note that even though the arrows starting and stopping in the atmosphere do so in a small region in the centre, the atmospheric energy gains and losses that they represent take place throughout the atmosphere. 100 units represent the rate at which solar radiation is intercepted by the Earth. The width of each arrow is proportional to the rate of energy transfer.

The left-hand side of Figure 5.14 shows the rates of energy gain and loss by the Earth's surface and atmosphere that involve solar radiation *directly*. Remember that 100 units represent the rate at which solar electromagnetic radiation is intercepted by the Earth: of these 100 units, 49 units are absorbed by the surface and 20 units by the atmosphere, and the rest (31 units) escapes back to space.

The central part of Figure 5.14 (coloured green) shows the rate of energy transfer from the Earth's surface to the atmosphere by a combination of convection and latent heat. There are 30 units transferred in this way, and it is a loss from the surface.

The right-hand side of Figure 5.14 involves the infrared radiation described in Section 5.3, but now values have been added to the arrows. If we start at the extreme right, then we see that 114 units are emitted by the Earth's surface, with 12 of the 114 units escaping to space, and the rest, the major part, 102 units, being absorbed by the atmosphere. The atmosphere emits infrared radiation at a rate of 152 units. Of this, 57 units escape to space, and the remaining 95 units are absorbed by the surface.

At this point, a question might spring to mind: if the Earth intercepts solar radiation at the rate of 100 units, how can 114 units be emitted by the Earth's surface, and 152 units be emitted by the atmosphere? Tackling the following question should help you understand this apparent paradox.

Question 5.7 (a) From Figure 5.14 calculate the difference between the rate of energy gain and the rate of energy loss for:

(i) the Earth as a whole (consider the solar radiation intercepted by the Earth, and the radiation returning or escaping to space from the atmosphere and the surface);

(ii) the Earth's surface;

(iii) the Earth's atmosphere.

(b) From your calculations in part (a), what do you conclude about the GMST? ◀

The answer to Question 5.7a(i) shows that there is no net energy gain or loss by the Earth, and the answers to the rest of Question 5.7a show that this is also the case separately for the surface and the atmosphere. Everything is in a dynamic steady state: in spite of all those energy flows there is no net accumulation of energy in any part of the system, and no net loss. It is perhaps now less puzzling that some of the rates of energy exchange in Figure 5.14 exceed the rate at which solar energy is intercepted by the Earth. The rates of energy exchange between different parts of a system in a steady state can be as high as you like, as long as the rate of energy gain by each part equals the rate of energy loss by the same part, so the net energy transfer is zero. In other words, the rates of circulation of energy *within* a system can be greater than the rate of flow into and out of a system. In a rather extreme analogy, there's a good deal of blood flow inside you, but (we hope) a negligible flow of blood out or in.

If you are still puzzled by the high rates of energy exchange between the surface and the atmosphere then it might help to return to a water-based analogy. In Figure 5.15 the flow from the tap is the analogy of the solar radiation intercepted by the Earth, and the flow from the base of the lower tank is the analogy of all of the radiation returning or escaping from the Earth to space. Each of these two water flow rates represents energy transfer at a rate of 100 units. It would be possible to represent the rest of Figure 5.14 in the form of a water analogy, but this would give us a plumber's nightmare assemblage of tanks, pipes and pumps. Fortunately the much simpler plumbing in Figure 5.15 suffices to illustrate the general notion that there can be higher rates of internal circulation than the rates of flow in and out. Thus, water is leaking from the upper to the lower tank at a rate of 300 units, and, to maintain a steady state, water is being pumped from the lower to the upper tank at a rate of 200

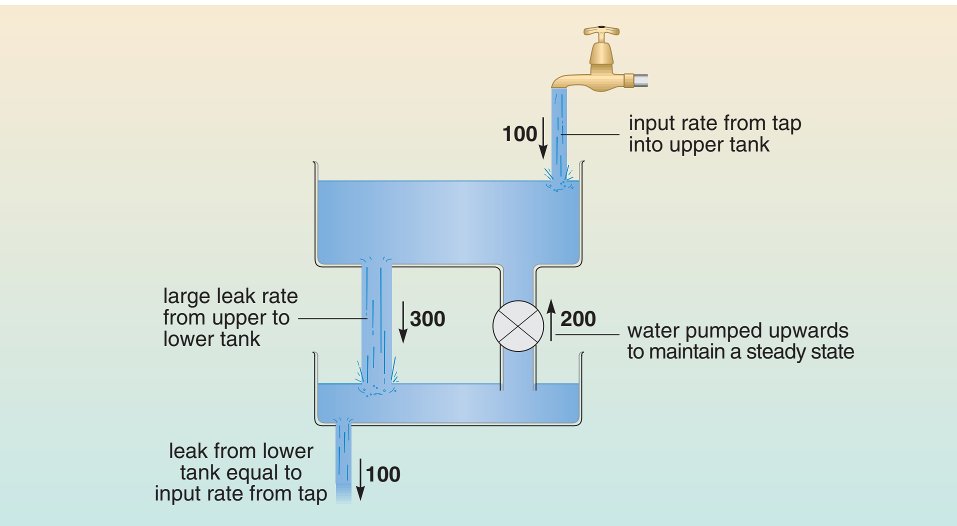

Figure 5.15 A water analogy to illustrate that the rate of flow within a system can exceed the rate of flow into and out of a system.

units. Note that, just as the Sun is the source of all the energy flow rates in Figure 5.14, so the tap is the source of all the water flow rates in Figure 5.15.

5.4.2 Why the GMST has a particular value

In broad terms, we can see from Figure 5.14 that the value of the GMST depends on:

- the rate at which the Earth intercepts solar radiation: this rate is obtained by multiplying the area over which radiation is intercepted (the grey disc in Figure 5.4) by the solar constant;
- the properties of the atmosphere, particularly those that influence:

  the scattering and absorption of solar radiation;

  the absorption of the radiation emitted by the Earth's surface (which is at infrared wavelengths);

  the emission of radiation by the atmosphere (also at infrared wavelengths);

  the rate of energy transfer via convection and latent heat;
- the properties of the Earth's surface, particularly those that influence:

  the reflection and absorption of solar radiation;

  the emission of radiation by the surface (which is at infrared wavelengths);

  the availability of water for evaporation.

If any of these factors is changed, then the GMST will change, unless, in changing several things at once, there is overall compensation in which case there is no net effect on the GMST.

Let's examine the case of the solar constant, and perform a 'thought experiment'. Suppose that initially there is a steady state with the Sun shining as it is today, when suddenly, as in the top graph in Figure 5.16, the solar constant increases to a slightly higher value, with no change in atmospheric and surface properties. What would happen? At once, the Earth's surface would receive more solar radiation than before, and because the surface would absorb the same *fraction*, it would therefore absorb more solar radiation. At the instant that the solar constant changed there would be no change in the rate of energy loss by the surface, so the GMST would start to rise, as in the middle graph in Figure 5.16. This rise in GMST would cause the surface to emit more infrared radiation (Figure 5.12) and so the rate of energy loss would increase as the temperature increased, as in the bottom graph in Figure 5.16. If there were no atmosphere, the GMST would continue to rise until the rate at which energy was lost by the surface equalled the new rate of energy gain by the surface. There would then be a new steady state, with the GMST higher than before.

The presence of an atmosphere makes things more complicated, because the surface also receives infrared radiation from the atmosphere, and loses energy through convection and latent heat. But the outcome would be similar, that an increase in the solar constant would cause an increase in GMST.

The solar constant does indeed vary! Recall that the value we quoted earlier is an average value over several years. If we compare these averages then it is found that the solar constant varies by about 0.1% over a decade or so, and by rather more in the

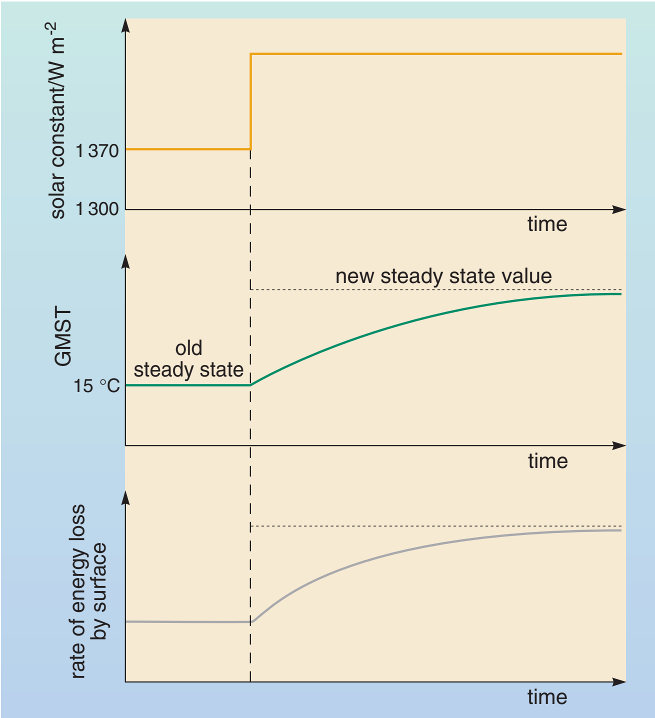

Figure 5.16 The response of the GMST to an increase in the solar constant, and the consequent increase in the rate of energy loss from the Earth's surface. Note that the solar constant axis does not start at zero, so the solar constant is increased only slightly.

longer term. The steady state in Figure 5.14 is therefore slightly disturbed in reality, and as a consequence the GMST does vary. Variations in the solar constant have been a contributory factor to the past variations in the GMST that you met in Sections 2 and 3. But there is a host of other ways of disturbing the steady state. To conclude this section we will consider just one more — the effect on the GMST of changing the rate at which the atmosphere absorbs and emits infrared radiation: this brings us to the much publicized greenhouse effect.

5.4.3 The greenhouse effect

In order to discuss the greenhouse effect, it is convenient to distinguish between the radiation emitted by the Earth's surface and the radiation emitted by the Sun.

- Which radiation is characterized by longer wavelengths?
- The radiation from the Earth's surface.

Moreover, the radiation from the Earth's surface is confined to the longer wavelength part of the infrared region of the spectrum, whereas the solar radiation in the infrared region is at shorter wavelengths. Consequently, the radiation from the Earth's surface is often called *longwave* infrared radiation. The atmosphere also emits longwave infrared radiation.

- From Figure 5.14, write down the fraction of the radiation emitted by the Earth's surface that is absorbed by the atmosphere. Express the fraction in decimal form, and as a percentage.
- The fraction is $\frac{102}{114} = 0.89$. As a percentage this is $0.89 \times 100\% = 89\%$.

Thus, most of the radiation emitted by the Earth's surface is absorbed by the atmosphere. By contrast, only 20% of the incoming solar radiation is absorbed. The fractions (or percentages) absorbed are called the absorptivities.

Suppose that, somehow, the atmospheric properties were suddenly adjusted so that the *only* change was a reduction in longwave infrared absorptivity: suppose that all other atmospheric properties, the solar constant, and all the surface properties remain the same. The atmosphere would therefore absorb a smaller proportion of the infrared radiation emitted by the surface. In Figure 5.14 the 114 units of energy emitted by the Earth's surface would no longer divide into 102 units absorbed by the atmosphere and 12 units escaping to space. The amount absorbed by the atmosphere would be less than 102 units and the amount escaping to space would be correspondingly more. It turns out that the atmosphere would then *emit* less infrared radiation. This means that there would be less radiation for the Earth's surface to absorb: it would absorb less than the 95 units in Figure 5.14. Nothing else has changed at the surface, so the Earth's surface would be losing energy faster than it would be gaining it.

- So, what would happen to the surface temperature?
- It would fall — the surface would cool.

The cooling would not, however, continue indefinitely. The cooler the surface, the lower the rate at which it emits radiation. (It is also possible that the rate of energy loss via convection and latent heat would fall.) The cooling of the surface thus continues until the rate of energy loss by the surface equals the new, lower rate of gain. A new steady state is then in place, with the surface at a new, lower temperature, as in Figure 5.17.

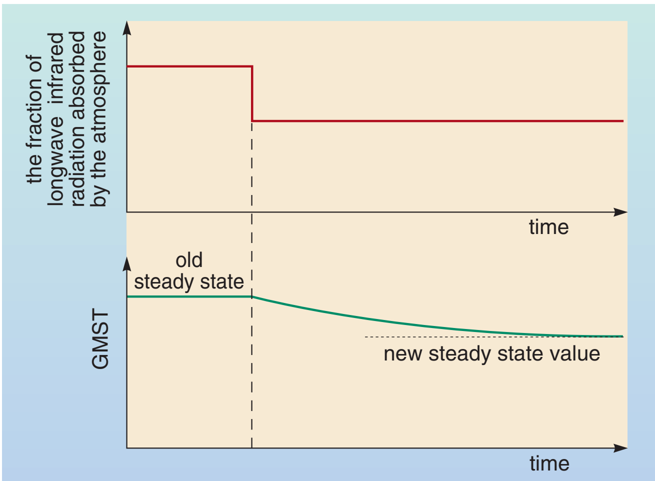

Figure 5.17 The change in the GMST when the atmospheric absorptivity of longwave infrared radiation is reduced, with all else remaining the same.

For the Earth today, if there were no radiation emitted by the atmosphere, and if all else stayed the same, the GMST would be about twenty degrees below 0 °C. Life as we know it would not exist on Earth, and perhaps there would be no life here at all. Our atmosphere thus acts as a powerful 'radiation trap', and the GMST is considerably higher as a consequence.

The rise in surface temperature that results from the radiation emitted by the atmosphere is called the **greenhouse effect**.

Box 5.2, *Greenhouses and the greenhouse effect*, explains why it has this name, though the explanation is not essential for our story.

Box 5.2 Greenhouses and the greenhouse effect

The greenhouse effect gets its name from the higher temperature in an unheated greenhouse than in the air outside. Much of this difference is nothing to do with the greenhouse effect, but arises from the containment of warm air that would otherwise convect upwards and be replaced by cooler air. A small part of the difference is because the glass panes in a greenhouse behave towards radiation rather like the Earth's atmosphere (Figure 5.18). The panes absorb a large fraction of the longwave infrared radiation emitted by the plants, soil and other surfaces within the greenhouse. Radiation emitted by the panes then makes a small contribution to the rise in temperature in the greenhouse.

The high transparency of glass to solar radiation is obvious from our ability to see through it so well. Therefore little solar radiation is absorbed. But what about the longwave infrared absorption? If you have a glass jug (*not* plastic or metal) and an electric cooker you can demonstrate that the longwave infrared absorption of glass is high, as follows.

Switch on a hot-plate but do not let it get so hot that it glows. It is then emitting predominantly longwave infrared radiation. Place your hand to one side of the hot-plate (not too near!) so that you can feel the warmth: your skin has infrared sensors. Do not place your hand above the hot-plate or you will also be receiving energy by convection. Take the glass jug and cover your hand with it, but not too near the hot-plate or the jug might crack. You should at once experience a loss of warming in your hand. The sensation of warmth is restored when the jug is removed. This shows that glass blocks longwave infrared radiation. You cannot tell whether the radiation is being absorbed or reflected. In fact some is reflected but the greater part is absorbed.

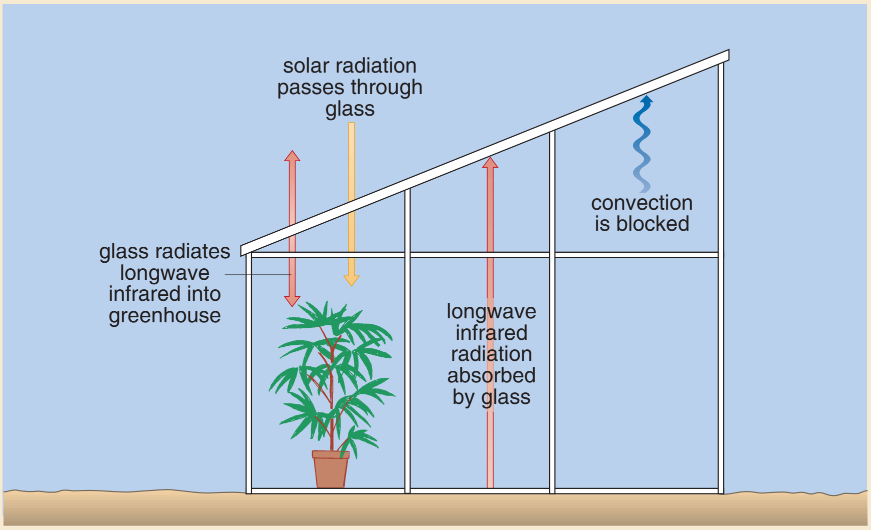

Figure 5.18 How a greenhouse can be warmer than the surrounding air.

For the Earth, the fact that the GMST is considerably higher than it would be if the atmosphere allowed longwave infrared radiation to escape to space shows that the greenhouse effect is not a 'bad thing': indeed, it is a 'good thing'! It is *changes* in the greenhouse effect that could have undesirable consequences for us. The greenhouse effect depends on atmospheric gases that strongly absorb longwave infrared radiation. These are called **greenhouse gases**. The greater the amount of a greenhouse gas in the atmosphere, the higher the GMST (if everything else stays the same). We clearly need to look more closely at the Earth's atmosphere to identify the greenhouse gases, and also to gain a deeper understanding of the other atmospheric properties that influence the GMST. This is a major task for Section 6.