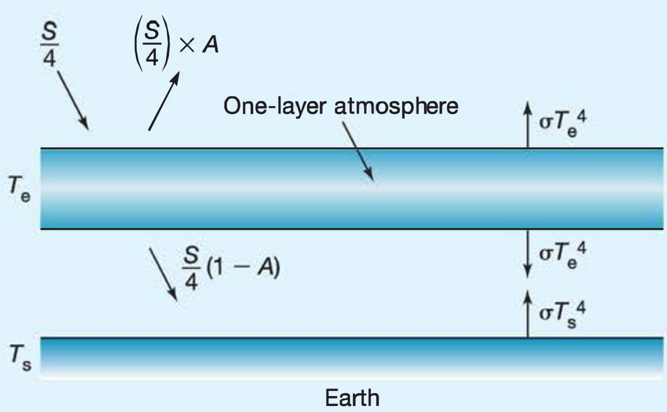
THINKING QUANTITATIVELY

How the Greenhouse Effect Works: The One-Layer Atmosphere

Although we calculated that Earth's greenhouse effect provides 33°C of surface warming, our method of obtaining this result (by subtracting the calculated effective radiating temperature from the observed mean surface temperature) provides little insight into the physical mechanism that causes the warming. We can remedy this by doing a simple calculation that demonstrates how the greenhouse effect actually works.

Suppose we treat the atmosphere as a single layer of gas and that this gas absorbs (and reemits) all of the infrared radiation incident on it (Box Figure 3-2). Let us assume that it absorbs and emits infrared radiation equally well at all wavelengths, so that we can treat it as a blackbody, and that it has an albedo A in the visible spectrum, just like that of the real Earth. What are the temperatures of the gas layer and of the surface beneath it? We will call the layer temperature T_e and the surface temperature T_s, because these quantities are exactly analogous to those discussed in the text.

We can determine the values of T_e and T_s by balancing the energy absorbed and emitted by both the surface and the one-layer atmosphere. Let the amount of sunlight striking the planet be equal to $S/4$ (the globally averaged solar flux). The surface absorbs an amount of sunlight equal to $S/4 \times (1 - A)$, along with a flux of downward infrared radiation from the atmosphere equal to σT_e^4. The atmosphere absorbs an amount of upward infrared radiation from the ground equal to σT_s^4, and it emits infrared radiation in both the upward and downward directions at a rate of σT_e^4. (The real atmosphere also absorbs some of the incoming solar radiation, but we ignore that complication here.) Thus, we can write the overall energy balance in the form of two equations:



BOX FIGURE 3-2 The greenhouse effect of a one-layer atmosphere.

For the surface,

$$\sigma T_s^4 = \frac{S}{4}(1 - A) + \sigma T_e^4;$$

for the atmosphere,

$$\sigma T_s^4 = 2\sigma T_e^4.$$

(The factor 2 in the second equation arises because the atmosphere radiates in both the upward and downward directions.) If we now substitute the second equation into the left-hand side of the first equation and substract σT_e^4 from both sides, we obtain

$$\sigma T_e^4 = \frac{S}{4}(1 - A),$$

which is just the familiar energy-balance formula. But dividing the atmospheric energy-balance equation by σ and then taking the fourth root of both sides yields an additional result:

$$T_s = 2^{1/4}\, T_e.$$

Thus, the surface temperature is higher than the one-layer-atmosphere temperature by a factor of the fourth root of 2, or about 1.19. For $T_e = 255$ K, as on Earth at present, we get $T_s = 303$ K, and we calculate a greenhouse effect of

$$\Delta T_g = T_s - T_e = 48 \text{ K}.$$

This is higher than the actual greenhouse effect on Earth by about 15 K.

This example is not meant to be realistic. The real atmosphere is not perfectly absorbing at all infrared wavelengths, so some of the outgoing IR radiation from the surface leaks through to space. This effect tends to make ΔT_g smaller. Conversely, a more accurate calculation would subdivide the atmosphere into a number of different layers. Including more layers tends to make ΔT_g bigger and is the reason why a thick atmosphere, like that of Venus, can produce a really huge amount of surface warming. The calculation does, however, illustrate the basic nature of the greenhouse effect: By absorbing part of the infrared radiation radiated upward from the surface and reemitting it in both the upward and downward directions, the atmosphere allows the surface to be warmer than it would be if the atmosphere were not present.