In 1896, the Swedish physicist Svante Arrhenius published a scientific paper in which he argued that CO2 released by the burning of coal would warm the climate of the Earth. Arrhenius thought that this was a good thing, because it might prevent the devastation of a new Ice Age.

Arrhenius argument was backed up by years of painstaking measurements (by others) of thermal radiation from the Moon through differing thicknesses of Earth’s atmosphere. Nevertheless his basic argument is easy to understand and forms the basis for a simple understanding of the sensitivity of Earth’s climate to changes in radiation.

Let’s start with the simplest form of the energy balance of the Earth as if it absorbed and emitted radiation as a single point in space. (This is the form we used in the Explain piece previously). We begin by assuming that over time, the rate at which energy is absorbed by the planet is equal to the rate at which it’s energy emitted.

 

Of course all the absorbed absorbed energy on Earth comes from the Sun. A fraction  (the albedo) of the Sun’s radiation is reflected by clouds and ice. If we assume that the Earth as a whole emits energy as a blackbody, then the rate of emission is proportional to the fourth power of the radiating temperature by the Stefan-Boltzmann Law. So we can rewrite (1) as

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On the left-hand side of (2), S0 is called the “Solar constant.” After reflection by bright surfaces, only a fraction (1- Of course solar radiation is absorbed only by the side of the Earth facing the Sun (we call this side day!). The effective area of the Earth receiving solar energy is just the area of the Earth’s disk, *r2*.

The right-hand side of (2) is the rate of emission of radiant energy by the Earth. According to the Stefan-Boltzmann Law, each square meter emits at a rate *T4* (where  = 5.67 x 10-8 is the measured value of the Stefan-Boltzmann coefficient). Thermal radiation is emitted from the entire sphere of the Earth, whose area is given by 4*r2*.

In equation (2), the factor *r2* appears on both sides. We can divide both sides of (2) by 4*r2* to obtain a relationship we’ll call “*F*” for “climate *forcing*.”

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The quantity F is both the rate of absorption and the rate of emission of radiant energy by the Earth, in Watts per square meter (W m-2).

Modern measurements show that the albedo of the Earth is about 30%, meaning that fraction of the Sun’s radiance is reflected and doesn’t contribute to the climate. The solar constant *S0* is measured by satellites to have the value 1367 W m-2. So the numerical value of F is (1367 W m-2) x 0.7/4 = 239 W m-2. Modern satellite measurements confirm that this is in fact also the rate of thermal emission above the atmosphere, verifying the equality (3). As we saw in the Explain slides, this can only be true if the radiating temperature of the planet is (F/)1/4 = 255 Kelvin (about 1 **°**Fahrenheit).

Arrhenius was interested in the *sensitivity* of *T* to *changes* in radiative forcing *F*. His argument was complicated by consideration of the atmospheric content of absorbing gases (carbon dioxide and water vapor). But we can get a simple picture of this sensitivity by taking the derivative of F with respect to temperature.

We can write the derivative of (3) as

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Substituting the numerical values of radiating temperature (T = 255 K) and ( = 5.67 x 10-8 W m-2 K-4), we find that

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where we define *BB* as the sensitivity of blackbody radiation to temperature.

The implication of equation (5) is that it takes almost 4 W m-2 of radiative forcing to warm or cool the Earth by 1 degree Kelvin (Kelvin degrees are the same “size” as Celsius degrees).

At the end of the last Ice Age, average surface temperature rose by about 5 **°**C (9 **°**F). If the blackbody sensitivity were a good measure of true climate sensitivity, that would have required radiative forcing of about (5 K) x (3.8 W m-2 K-1) = 19 W m-2. Is this reasonable?

The albedo of the Earth decreased dramatically due to the melting of the huge continental ice sheets on North America and Europe. Also, the CO2 concentration increased from about 180 ppm to about 280 ppm. The combined radiative forcing from melting the ice (albedo) and increasing CO2 (greenhouse) is estimated to be only about 6.5 W m-2. So it appears that the **climate of the real Earth is about three times as sensitive to radiation as the simple blackbody calculation here**.

That’s what Svante Arrhenius found as well, almost 120 years ago!