

By the Light of the Silvery Moon

Arrhenius, S. (April 1896). On the influence of carbonic acid in the air upon the temperature of the ground. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science Series 5*, 41 (251). 39 pages.

In Arrhenius' 1896 paper we witness the birth of modern climate science. Working with incomplete theoretical basis and a few beams of moonlight, Arrhenius calculated the warming that would result from doubling the CO₂ concentration of the atmosphere, a quantity that modern climate scientists call the climate sensitivity. Granted he may have gotten lucky to get what is essentially the right answer, but more importantly his approach was well guided, and brilliantly creative. Along the way, Arrhenius described the water vapor feedback, which about doubles the impact of changing CO₂, and the ice albedo feedback, which is largely responsible for the intensified warming in high latitudes. Although Arrhenius is best known for the Arrhenius equation, which describes the effect of temperature on the rates of chemical reactions, his 1896 paper contribution stands squarely at the foundation of Earth science.

Fourier described the greenhouse effect resulting from an atmosphere that selectively passes incoming visible light, and absorbs outgoing infrared radiation. Tyndall showed that the capacity to absorb and emit infrared radiation is shared by only a few trace gases in the atmosphere, notably water vapor and CO₂. However, technology was not available in Tyndall's time or Arrhenius' to measure the strength of the absorption by the gases, which as it turns out varies wildly depending on the exact wavelength of the radiation. Putting matters even further out of Arrhenius' reach, the detailed absorption spectrum depends on the pressure of the gas, because of interactions between molecules that alter the vibrational frequencies that the molecules can undergo. The CO₂ absorption spectrum consists of a collection of very narrow peaks, which broaden and coalesce with increasing pressure. Even today, a detailed calculation of the absorption and emission of IR by a column of atmosphere is not trivial; it can be done by computer models known as line-by-line codes, based on megabytes of detailed spectral information for the various greenhouse gases, but these calculations are too computationally expensive, that is to say slow, to be done in the full climate models that are used to predict things such as, say, the climate sensitivity or global warming forecasts. Climate models use approximate codes to calculate the balance of radiation energy. Under these circumstances, what should we suppose were the odds of Arrhenius doing this calculation by hand and getting the right answer?

The basis of Arrhenius' scheme is measurements of the IR intensity of moonlight made by Samuel Pierpont Langley. Langley was trying to estimate the temperature of the moon based on the knowledge that the intensity of IR emission goes up as the temperature of the emitting object rises. He invented and used a device called a bolometer to measure the IR intensity, manifested as a change in temperature of a piece of metal coated with an absorbing layer of soot that was exposed to the light beam, relative to another that was not. Langley selected particular wavelengths by sending the IR through a prism made of salt, which was known to be one of the few solids that is transparent to IR radiation (Fig. 3.1).

Although the measurements were not intended for this purpose, Arrhenius' idea was to use the data to calculate the absorption of IR by the entire atmospheric column of CO₂ and water vapor.

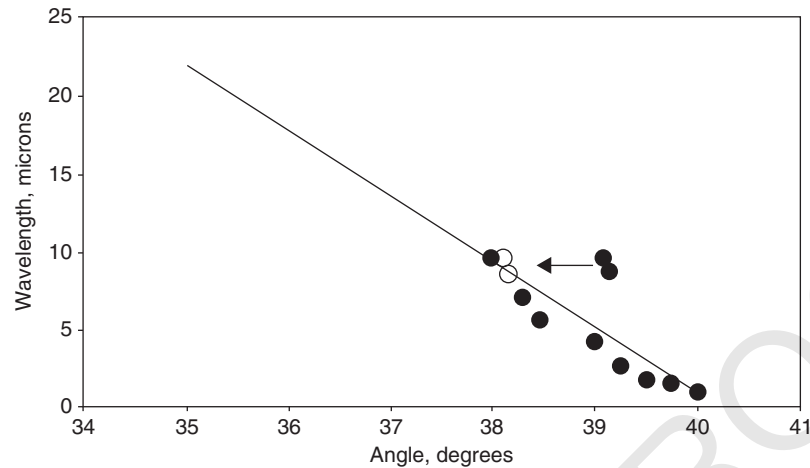


Fig. 3.1 This is the relationship between the deflection angle of Langley's infrared beams and the wavelengths of the light as reported by Arrhenius. The two outliers are probably a misprint; if the angles of $39.xx^\circ$ are replaced by $38.xx^\circ$, they fall on the same relation as the rest of the values quoted. At the time Arrhenius was writing, experimental data relating wavelength to refraction angle through Langley's salt prism was not available for angles below $38.x^\circ$, so Arrhenius estimated the relationship using a linear fit. For Arrhenius' purposes, the exact form of the relationship does not actually matter, since it was only the absorption summed up over all wavelengths that counts for the greenhouse calculation. You can do this sum equally well using the deflection angle or the wavelength. However, where the relationship matters is in comparing the spectral data Arrhenius deduced to modern accurate absorption data for water vapor and carbon dioxide. Jean-Louis Dufresne, in his Habilitation thesis (a sort of super PhD thesis done by advanced researchers in the French academic system) found that the nonlinearities in the wavelength–angle relation are very important to doing the comparison correctly.

The measurements were made over many nights, under differing weather conditions, which meant different amounts of water vapor to absorb the IR. The moon was also at different elevations in the sky on the different nights, sending the moonbeams through the atmosphere either vertically or obliquely, through differing inventories of CO_2 . Regressing the IR intensity data against the varying inventories of CO_2 and water vapor, Arrhenius calculated the apparent absorption coefficients of the greenhouse gases in the atmosphere. One of the many formidable challenges Arrhenius faced was disentangling the water vapor and CO_2 absorption effects. In some parts of the spectrum, this is not really possible using the kind of data available to Arrhenius, but science proceeds by making the best use possible of whatever data there is, and that is what Arrhenius did. Up until recently, the standard wisdom was that Arrhenius did quite well at getting the absorption properties more or less right, but Jean-Louis Dufresne's discovery of the importance of the nonlinearity in the relationship between refraction angle and wavelength has changed that picture. In Fig. 3.2, it is argued that Langley's data was sufficient to allow Arrhenius to do a fairly good job of the water vapor absorption properties near 6.5-micron wavelength, but did not extend far enough into the long-wave infrared to pick up the CO_2 absorption feature near 15 micron, which is the most important one for global warming.

Arrhenius was aware that any substance that can absorb IR will also emit its intensity dependent upon its temperature. Some of the IR light that they measured may have come from emission by gases in the atmosphere rather than coming directly from the moon. This physics passed without comment in Arrhenius' derivation of the absorption coefficients, although it is clearly accounted for in the climate modeling in the second part of the paper. Perhaps Arrhenius was assuming implicitly that the moon is warm enough that any IR emission coming from our own atmosphere would be negligible, or at least that IR emission from our atmosphere would be

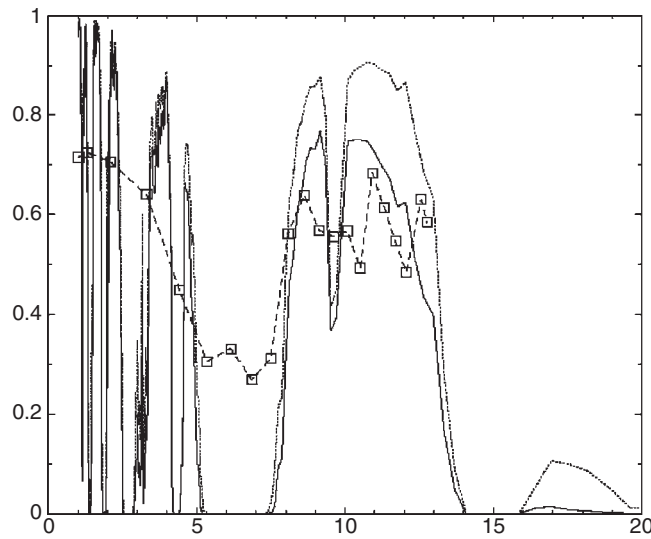


Fig. 3.2a The spectral properties of CO_2 and water vapor in the atmosphere as deduced by Arrhenius compared with results from a modern atmospheric radiation code. Each figure shows the transmission (vertical axis) as a function of the wave number in microns (horizontal axis). A transmission of 1 corresponds to a transparent atmosphere, whereas a transmission of 0 corresponds to a completely absorbing atmosphere. The dashed lines with symbols in each figure give the results of the calculation by Arrhenius using Langley's lunar infrared transmission data. The dotted and solid lines are the results of a modern radiation code, with two different assumptions about the water vapor content of the atmosphere. Figure 3.2a compares results calculated with both water vapor and CO_2 .

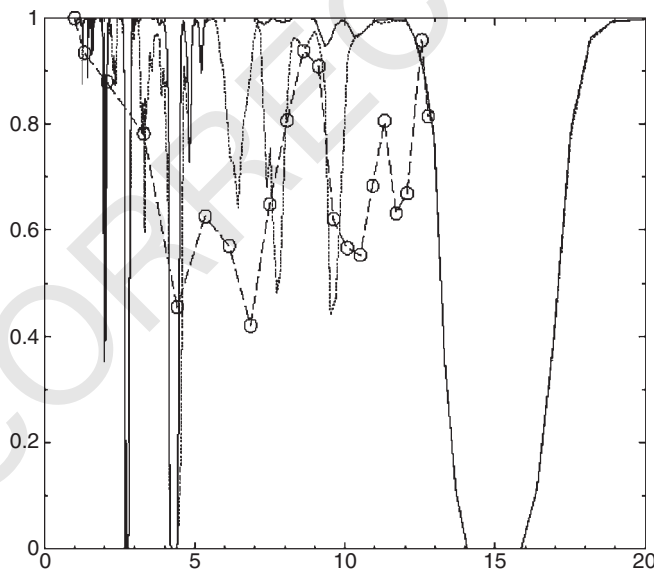


Fig. 3.2b Shows results for CO_2 alone.

reflected in the absorption coefficients that he derived from the data. If the air in the atmosphere were all the same temperature as the surface of the Earth and the moon, then presumably the amount of gas intercepting the moonbeam would have no impact on IR intensity, and the absorption coefficients Arrhenius derived would be small, indicating correctly that the greenhouse

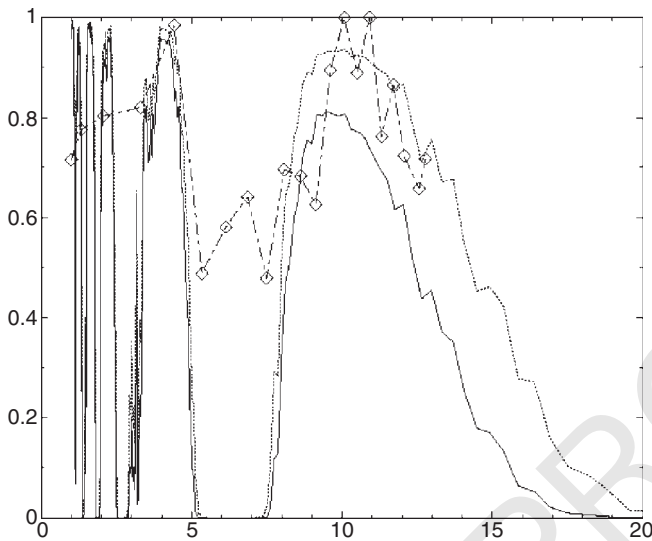


Fig. 3.2c Shows results for water vapor alone. The calculation by Arrhenius does a qualitatively good job of reproducing the main absorption features of water vapor around 5 micron, but the CO_2 spectroscopy bears little resemblance to the correct pattern based on accurate modern laboratory measurements. In particular it completely misses the 15 micron absorption region, which is principally responsible for anthropogenic global warming. There is nothing essentially wrong with the technique used by Arrhenius. The main challenge is to separate water vapor from CO_2 effects, and if Langley's data had extended to the 15 micron region, where the CO_2 effects dominate, the masterful analysis technique Arrhenius employed would have worked very well. These calculations were carried out by Jean-Louis Dufresne (*L'effet de serre: sa découverte, son analyse par la méthode des puissances nettes échangées et les effets de ses variations récentes et futures sur le climat terrestre*. Habilitation thesis, Université Pierre et Marie Curie, 2009) and are used with the kind permission of the author.

effect is weak. This benefit of the doubt is undermined somewhat by the statement that it is “a physical absurdity” for the IR intensity to increase with passage through the gas (page 245), or that “it is not permissible to assume that the radiation could be strengthened by its passage” through the gas (page 252), and the calculation of the near-complete extinction of the radiation intensity by very high gas inventories following Beer's law in Table III (page 251). The main problem with the spectroscopy inferred by Arrhenius was not the effect of atmospheric thermal emission. It was the fact that Langley's measurements did not extend to sufficiently long wavelengths to pick up the principle CO_2 absorption feature near 15 micron (see Fig. 3.2).

Arrhenius was also aware of the band saturation effect, carefully described by Tyndall, in which the absorption depends linearly on temperature for low concentrations or pressures of the gas, but as the absorbing gas inventory increases, eventually all the incoming IR is absorbed, and further increases in gas concentration have only a small impact on the IR flux. One of the chief objections, raised by Angstrom in particular, to the proposition that CO_2 can affect the climate was that the absorption bands of CO_2 were already saturated. This would have been an impossible determination to make in the laboratory at this time, because CO_2 at differing altitudes in the atmosphere has different spectra and therefore differing effects on the IR absorption. Arrhenius' effective absorption coefficients, based on the change in IR intensity with a change in the inventories of the greenhouse gases, actually included the effect of band saturation. Had the gases in the atmosphere been more saturated than they are, the effect of humidity and lunar zenith angle would have been smaller than Langley measured, and Arrhenius would have gotten smaller absorption coefficients. O clever, clever man!

So, Arrhenius obtained the best estimate of the CO₂ and water vapor spectroscopy the methods of his day would permit, but then how to turn that into a calculation of temperature? Basically, what Arrhenius had to do was invent the field of climate modeling, which had never before been done quantitatively for planets with atmospheres. He wrote a model taking into account the radiative energy exchanges between the atmosphere and space, between the atmosphere and the ground, and between the ground and space (owing to transmission of infrared through the atmosphere). The model took into account the fact that the water vapor content of the atmosphere is expected to increase as the atmosphere gets warmer. He used his spectroscopic data to calculate the atmospheric infrared absorption and emission that appears in the energy balance equations. To keep the calculation manageable (remember, he had to do all of this by hand), he wrote a model in which the entire atmosphere was characterized by a single temperature. Arrhenius was not implying that the atmosphere really was isothermal – he was only assuming that the atmosphere’s radiative properties could be characterized by a single vertically averaged temperature of some sort. His discussion shows that he was well aware of the accuracies inherent in a one-layer model of the atmosphere, but given the tedium of the calculations, who could fault him from stopping at one layer, when the results already looked interesting? The one-layer model, and its comparison to modern multilayer models, is described in the Box, The Arrhenius one-layer model of the greenhouse effect.

Arrhenius’ calculation of the impact of changing CO₂ concentration was done in a gridded calculation space, just like modern climate models. The grid in Arrhenius’ case was by latitude and season. Arrhenius recognized that the radiation energy budget does not necessarily balance at any given location on the Earth. More energy comes in at the equator from the intense sunshine than leaves locally by infrared. The difference is carried to higher latitudes by winds and ocean currents, and is ultimately balanced by excess outgoing radiation over incoming at higher latitudes. Arrhenius assumed that the heat fluxes that he could diagnose today from his gridded model would also apply in an altered, double-CO₂ world. This assumption was not precisely correct, but it was certainly the correct place to start.

The impact of clouds on climate is difficult to model even to this day. Clouds scatter and reflect incoming sunlight, and they also act as blackbodies in the atmosphere, absorbing essentially all of the IR radiation that hits them, and re-radiating at an intensity dependent on the temperature of the cloud droplets. Arrhenius does not mention the IR effects of clouds, but he is well aware of the visible (albedo) effect. His solution, as for the heat fluxes, is to assume that the distribution and impacts of clouds will be the same in the altered double-CO₂ world. Again, this was an excellent place to start, given the limited options available. Clouds remain the main uncertainty in modern climate models, but there is no indication that the behavior of clouds has a large biasing effect on the temperature impact of changes in atmospheric CO₂ concentration.

Arrhenius constructed the water vapor feedback by power of pure reason. As the temperature of the Earth rises in response to a doubling of atmospheric CO₂, the saturation vapor pressure of the atmosphere rises following the Clausius–Clapyron relationship. If the air can hold more water vapor, then presumably it will. Arrhenius assumed that the relative humidity, the expression of water vapor content relative to the saturation concentration, would remain the same with a change in climate. If the natural world has an average relative humidity of 80%, then the warmer world will also be 80% saturated, but since the warmer air can hold more water vapor, it holds 80% of a higher concentration, the absolute humidity rising proportionally to the saturation value. The effect of water vapor on climate is therefore to amplify a temperature change, driven in this case by doubling atmospheric CO₂.

Arrhenius also recognized the cooling effect of ice and snow at the Earth’s surface when it reflects incoming visible light, and the fact that a warming world can thaw the ice, leaving a less reflective ground or ocean surface to absorb the incoming sunlight. Ice therefore acts as another positive amplifying feedback in the climate system, leading to a stronger temperature change

from increasing CO₂ concentration, in particular in high latitudes where the ice is. The ice albedo feedback, as it is now called, is the main reason why high latitudes warm more than low latitudes, an effect we see today in the Arctic, and in the forecast for the future, both from modern climate models and in Arrhenius' own results. (The Antarctic, it must be noted, is something of a special case, with cooling in the interior of the continent and little loss of sea ice over the past decades, for dynamical reasons having to do with the intensity of the circumpolar jet in the atmosphere and the loss of stratospheric ozone, a greenhouse gas, known as the ozone hole.)

In the end, Arrhenius predicted that doubling the CO₂ concentration of the atmosphere would raise the temperature of the surface of the Earth by about 6°C. This is hauntingly similar to the climate sensitivity found today. With the benefit of over a century of conceptual advances and an explosion of computer power that would have seemed like magic to Arrhenius, we now expect that the Earth would warm by about 2.5–4°C. However, it must be said that with regard to the specific number he came up with, Arrhenius was more lucky than right. There are two sources of error in his calculation, which were inevitable products of the state of the art at the time. The first source of error is the limitation in the accuracy with which he could estimate the true absorption spectrum of CO₂. The second source of error is in the use of a one-layer model of the atmosphere to compute the greenhouse effect. The one-layer model, used with correct spectroscopy, leads to an underestimate of the true climate sensitivity, mainly because with only one layer water vapor excessively masks the effects of carbon dioxide because a one-layer model lacks the high, cold dry parts of the atmosphere where CO₂ packs the most punch (see Box: The Arrhenius one-layer model of the greenhouse effect.). The inaccuracies in the spectroscopy Arrhenius used, however, bias the sensitivity to the high side, which more than compensated for the low bias of the one-layer model. Thus, if Arrhenius had had correct spectroscopy in his one-layer model, he would have predicted a modest (though still significant) climate sensitivity. If he had used a modern multilevel model with his inaccurate spectroscopy, he would have found an extraordinarily high climate sensitivity, well in excess of the high end of the IPCC range.

Would history have been different in either of those cases? We can only speculate, but given that even the rather alarming climate sensitivity he came up with was insufficient to stir much sense of concern for decades after Arrhenius' seminal paper, it seems unlikely. It is unseemly to dwell too much on the specific number Arrhenius came up with, which was a product of unavoidable technical shortcomings of his day. The genius in the work of Arrhenius is that he turned Fourier's rather amorphous and unquantified notion of planetary temperature into exactly the correct conceptual framework, even going so far as getting the notion of water vapor feedback right. Most importantly, he correctly identified the importance of satisfying the energy balance both at the top of the atmosphere and at the surface. Conceptual errors regarding this point plagued the subject long after the spectroscopy had improved. If the climate theorists and spectroscopists of the next few decades had only fully understood Arrhenius' paper, many false steps could have been avoided. As it stands, correct spectroscopy was not brought together with a correct conceptual framework in a multilevel model until the seminal work of Manabe in the early 1960s. It is rather fortuitous that the number we now have for climate sensitivity is similar to the one that Arrhenius came up with, but what is not fortuitous is that nothing that has come up in the intervening century or more has shaken the basic conceptual foundation of the greenhouse effect that Arrhenius laid down. Not even a little. In this, Arrhenius was prescient and 100% right. While we can now compute the effects of CO₂ on climate at a level of detail and confidence that Arrhenius could hardly have dreamed of, we are basically doing the same energy book-keeping as Arrhenius taught us how to do, but only in vastly elaborated detail with vastly better fundamental spectroscopic data.

Arrhenius was mostly interested in the cause of the ice ages, and he predicted that the CO₂ concentration of the atmosphere during glacial time might have been 150 ppm (we now know it was 180–200 ppm). He recognized the possibility that humans could alter the climate of the Earth,

by “evaporating the coal mines into the atmosphere,” but estimated that it would take 1000 years to double the CO_2 concentration. This was actually a reasonable conclusion at the time. CO_2 emissions have grown exponentially since then, and it takes real courage of conviction, or wild-eyed alarmism, to extrapolate a present-day trend far into the future based on exponential growth. Anyway, as a Swede he felt that perhaps a bit of warming might be pleasant. Not an attitude, we hasten to add, that Swedes today would generally concur with. They seem to like their broad sweeps of Northern tundra and short, sweet summers with berries in the pastures. To say nothing of a century of investment in hydropower designed to make use of the climate of the past century, and not that of the scary new world global warming is taking us into.

Box: The Arrhenius One-Layer Model of the Greenhouse Effect

The one-layer model of Arrhenius represents the atmosphere by a single layer with temperature T_a having emissivity e . According to the laws of radiation physics, the emissivity also gives the absorption, so that the transmission is $(1 - e)$. The emissivity is a function of temperature, because of the temperature dependence of the atmosphere’s water vapor content. Arrhenius solved for the atmospheric temperature assuming only infrared radiative exchanges between the atmosphere and the ground, and between the atmosphere and space. He then used the result to compute the infrared leaving the top of the atmosphere – the *Outgoing Longwave Radiation*, or OLR. In equilibrium, this must balance the absorbed solar radiation. The calculation is laid out in Fig. 3.3.

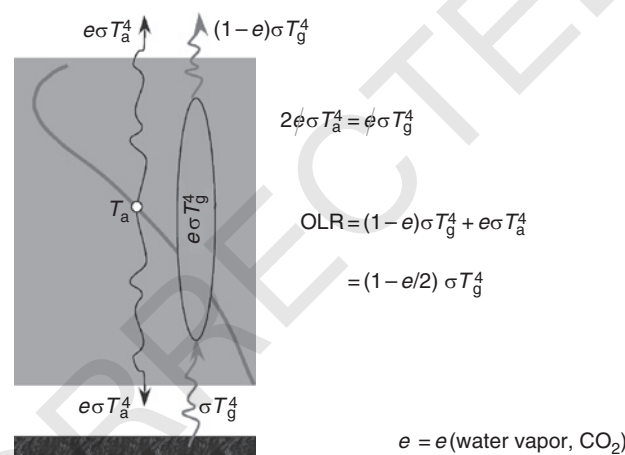


Fig. 3.3 Schematic of Arrhenius’ one-layer atmosphere model.

A modern multilayer model looks like Fig. 3.4, in which a radiation model is used to compute the mean altitude from which infrared escapes to space. The temperature there is T_{rad} , and it gets colder relative to the ground as more greenhouse gas is added to the atmosphere. Adding a greenhouse gas warms the ground because in equilibrium T_{rad} has to stay fixed so as to balance the absorbed solar radiation, but it occurs at a higher altitude, so you have to follow the temperature gradient a longer distance before you hit the ground. Another refinement taken into account in modern models is that heat exchange with the ground is not just radiative, but also contains contributions from turbulent exchange of heat and moisture. The effect of these is to keep the ground temperature close to the overlying air temperature, and so the details of the turbulent transfer are relatively inconsequential.

It is straightforward to insert modern spectroscopy into the Arrhenius one-layer model. All you have to do is to use a modern radiation code to compute the emissivity e of a slab, taking into account the temperature-dependent water vapor content of the slab. Increasing the CO_2 makes the emissivity closer to 1, and therefore warms the surface. In Fig. 3.5, the calculation has been organized graphically.

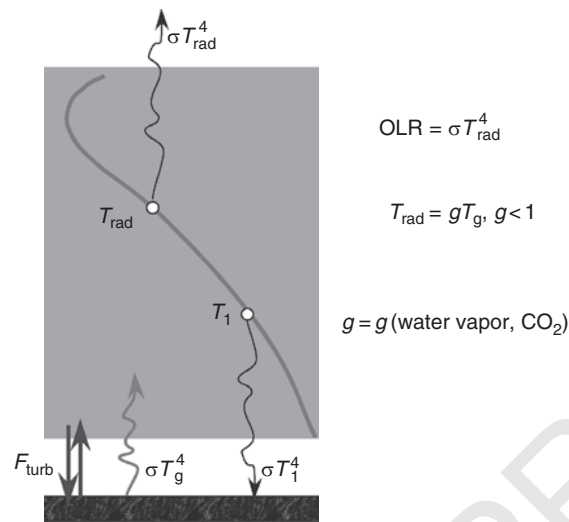


Fig. 3.4 Schematic of a modern multi-layer atmosphere model.

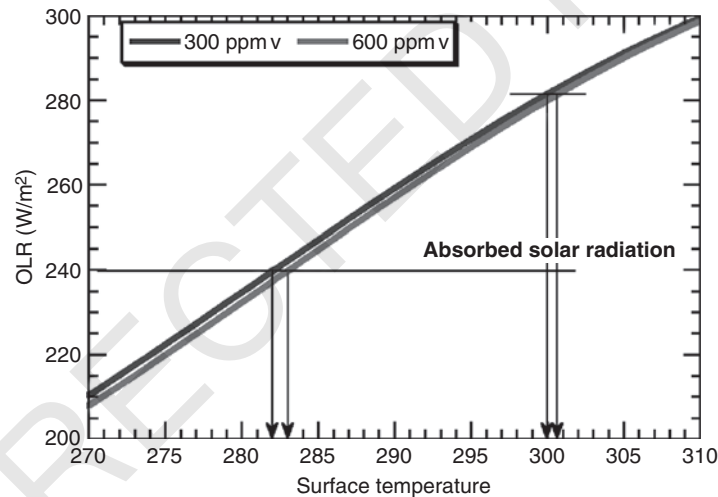


Fig. 3.5 One-layer model with water vapor feedback, using modern spectroscopy.

We specify a surface temperature, use the Arrhenius balance equations to compute the corresponding atmospheric temperature (using the temperature and CO_2 -dependent emissivity), and then use both the surface and atmospheric temperature to compute the infrared emission out of the top of the atmosphere – the OLR. Where the straight line corresponding to the absorbed solar radiation intersects the OLR curve, we read off the equilibrium surface temperature. All climate theory, in essence, amounts to some variant on computing this curve with ever-greater sophistication. The results show that where the absorbed solar radiation yields an equilibrium temperature around 280 K at 300 ppmv CO_2 , doubling the CO_2 would yield about a degree of warming. The warming is somewhat less if the base case corresponds to a typical tropical temperature. These results include the one-layer version of the water vapor feedback. They are smaller than what a multilayer model would give, because the isothermal model of the atmosphere puts too much water vapor high up, and therefore underestimates the increase in the emissivity caused by a doubling of CO_2 .

Box: The Saturation Fallacy

Knut Ångström (1857–1910) was the son of the Swedish physicist Anders Ångström who lent his name to the unit of length widely used in spectroscopy and atomic physics. The younger Ångström, like his father, was very interested in the properties of radiation. If there were a prize for papers that set back the study of global warming, surely Knut's paper on the absorption of infrared by CO_2 and water vapor would be a strong contender. This paper was among the first to introduce what might be called the *Saturation Fallacy* – the idea that at its present concentration CO_2 absorbs as much infrared as it possibly can, so introduction of more CO_2 cannot change the climate. If you put enough infrared absorber into a layer of air, it absorbs everything. You cannot absorb more than 100% of the radiation. Moreover, laws of radiation physics that were well established at the time said that such a perfect absorber would also radiate like an ideal black-body, meaning that addition of more absorber could not change the emission, if you held the temperature of the layer fixed. As a variant on this argument, Ångström also claimed that even without this *saturation* of the CO_2 effect, the absorption by water vapor would be so strong that it would accomplish the same thing, leaving little role for CO_2 changes to affect climate. Such was the force of Ångström's claim that it may well have been instrumental in keeping most atmospheric scientists from taking Arrhenius seriously for nearly a half century. Even today, one sometimes hears the saturation argument used by some less scrupulous global warming deniers.

But Ångström was wrong, and he was wrong on many counts. First, his laboratory measurements of the absorption properties of CO_2 were inaccurate. We know today, from precise laboratory measurements, that CO_2 is not anywhere close to saturated in the Earth's conditions. In fact, it is not even completely saturated for the atmosphere of Venus, which has 300 000 times as much CO_2 in it as the Earth's atmosphere! Second, it turns out that even if CO_2 and water vapor *were* saturated in the sense claimed by Ångström, it would not prevent addition of more CO_2 from warming the climate. The reason is that the temperature and density of the atmosphere decline with altitude, and so there is always some region up there that is tenuous enough and dry enough (by virtue of being cold) that it is unsaturated – and it is from *this* region that infrared escapes to space when the lower atmosphere is saturated. The “thinning, cooling, and drying” argument could have been made using the physics known at the time of Arrhenius, but strangely enough it did not become appreciated until the much later work of Plass and Manabe. The fact that reduced pressure also limits gaseous absorption – and hence saturation aloft – adds to the effect, but is in no way crucial to the “thinning, cooling, and drying” argument. Let us first take a closer look at the absorption properties of CO_2 , using modern laboratory data.

Suppose we were to sit at sea level and shine an infrared flashlight with an output of one Watt upward into the sky. If all the light from the beam were then collected by an orbiting astronaut with a sufficiently large lens, what fraction of a Watt would that be? The question of saturation amounts to the following question: How would that fraction change if we increased the amount of CO_2 in the atmosphere? Saturation refers to the condition where increasing the amount of CO_2 fails to increase the absorption, because the CO_2 was already absorbing – essentially all there is to absorb at the wavelengths where it absorbs at all. Think of a conveyor belt with red, blue, and green M&M candies going past. You have one guy who only eats red M&Ms, and he can eat them fast enough to eat half of the M&Ms going past him. Thus, he reduces the M&M flux by half. If you put another guy next to him who can eat at the same rate, he will eat all the remaining red M&Ms. Then, if you put a third guy in the line, it will not result in any further decrease in the M&M flux, because all the M&Ms that they like to eat are already gone. You would need an eater of green M&Ms to make further reductions in the flux.

Ångström and his followers believed that the situation with CO_2 and infrared was like the situation with the red M&Ms. To understand how wrong they were, we need to look at modern measurements of the rate of absorption of infrared light by CO_2 . The rate of absorption is a very intricately varying function of the wavelength of the light. At any given wavelength, the amount of light surviving goes down like the exponential of the number of molecules of CO_2 encountered by the beam of light. The rate of exponential decay is the absorption factor. When the product of the absorption factor times the amount of CO_2 encountered equals one, then the amount of light is reduced by a factor of $1/e$, that is, $1/2.71282\dots$. For this, or larger amounts of CO_2 , the atmosphere is optically thick at the

corresponding wavelength. If we double the amount of CO_2 , the proportion of surviving light is squared, or about a tenth; if we halve the amount of CO_2 instead, the amount surviving is $1/4$, or about 60%, and the atmosphere is optically thin. Precisely where we draw the line between “thick” and “thin” is somewhat arbitrary, given that the absorption shades smoothly from small values to large values as the product of absorption factor with amount of CO_2 increases.

The units of absorption factor depend on the units we use to measure the amount of CO_2 in the column of the atmosphere encountered by the beam of light. Let us measure our units relative to the amount of CO_2 in an atmospheric column of base one square meter, present when the concentration of CO_2 is 300 parts per million (about the preindustrial value). In such units, an atmosphere with the present amount of CO_2 is optically thick where the absorption coefficient is one or greater, and optically thin where the absorption coefficient is less than one. If we double the amount of CO_2 in the atmosphere, then the absorption coefficient only needs to be $1/2$ or greater in order to make the atmosphere optically thick. The absorption factor, so defined, is given in Fig. 3.6, based on the thousands of measurements in the HITRAN spectroscopic archive. The “fuzz” on this graph is because the absorption actually takes the form of thousands of closely spaced partially overlapping spikes. If one were to zoom in on a very small portion of the wavelength axis, one would see the fuzz resolve into discrete spikes, like the pickets on a fence. At the coarse resolution of the graph, one only sees a dark band marking out the maximum and minimum values swept out by the spike. These absorption results were computed for typical laboratory conditions, at sea level pressure and a temperature of 20°C . At lower pressures, the peaks of the spikes get higher and the valleys between them get deeper, leading to a broader “fuzzy band” on absorption curves like that shown below.

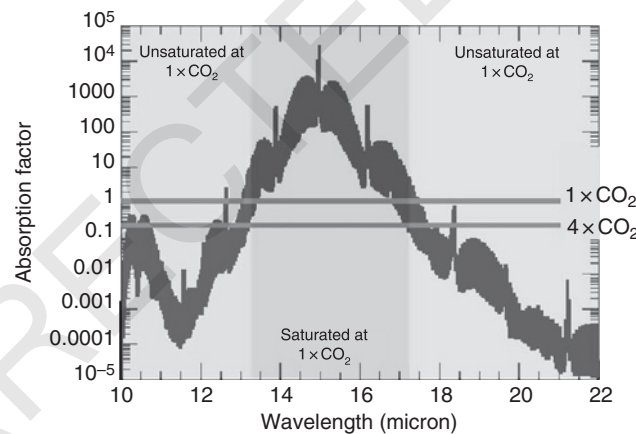


Fig. 3.6 Infrared absorption spectrum of CO_2 with regions of band saturation indicated at 1 and 4 times atmospheric CO_2 concentration.

We see that for the preindustrial CO_2 concentration, it is only the wavelength range between about 13.5 and 17 micron (millionths of a meter) that can be considered to be saturated. Within this range, it is indeed true that adding more CO_2 would not significantly increase the amount of absorption. All the red M&Ms are already eaten. But waiting in the wings, outside this wavelength region, there are more goodies to be had. In fact, noting that the graph is on a logarithmic axis, the atmosphere still would not be saturated even if we increased the CO_2 to 10000 times the present level. What happens to the absorption if we quadruple the amount of CO_2 ? That story is told in Fig. 3.7.

The horizontal blue lines give the threshold CO_2 needed to make the atmosphere optically thick at $1\times$ the preindustrial CO_2 level and $4\times$ that level. Quadrupling the CO_2 makes the portions of the spectrum in the yellow bands optically thick, essentially adding new absorption there and reducing the transmission of infrared through the layer. One can relate this increase in the width of the optically thick region to the “thinning and cooling” argument determining infrared loss to space as follows. Roughly speaking, in the part of the spectrum where the atmosphere is optically thick,

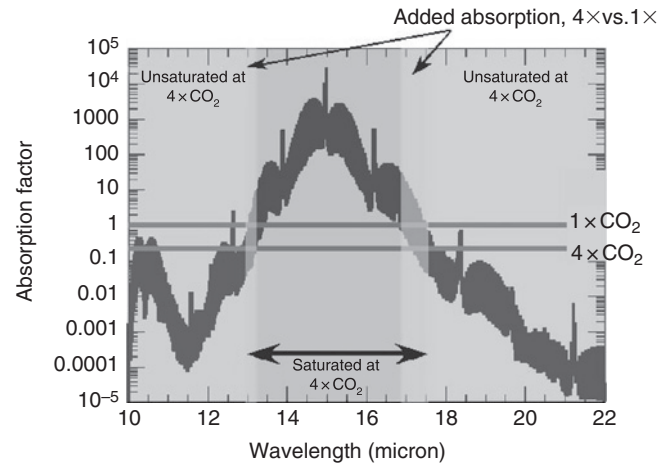


Fig. 3.7 With an increase in atmospheric CO_2 concentration, the saturated band for CO_2 expands.

the radiation to space occurs at the temperature of the high, cold parts of the atmosphere. That is practically zero compared to the radiation flux at temperatures comparable to the surface temperature; in the part of the spectrum that is optically thin, the planet radiates at near the surface temperature. Increasing CO_2 then increases the width of the spectral region where the atmosphere is optically thick, which replaces more of the high-intensity surface radiation with low-intensity upper-atmosphere radiation, and thus reduces the rate of radiation loss to space.

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Angstrom, K. (1900). Ueber die Bedeutung des Wasserdampfes und der Kohlensäure bei der Absorption der Erdatmosphäre. *Annalen der Physik Bd 3*, 720–732. 13 pages.