Part I

Climate Physics

1

The Greenhouse Effect

Fourier, J. (1827). Mémoire sur les Températures du Globe Terrestre et des Espaces Planétaires. *Mémoires de l'Académie Royale des Sciences*, 7, 569–604. 25 pages.

Joseph Fourier (1768–1830) is generally credited with the discovery of what is now known as the greenhouse effect. In fact, his contribution to the study of planetary temperature is even more profound than that. Fourier introduced the problem of planetary temperature as a proper object of study in physics, and established a largely correct physical framework for attacking the problem. His work set the stage for most of the further developments in this area over the remainder of the nineteenth century. Indeed, it was only toward the end of that century that physics had caught up to the point that the first quantitative estimates of the Earth's temperature based on Fourier's concepts could be attempted.

If much of Fourier's reasoning in this paper seems qualitative, it should be recognized that most of the areas of physics that Fourier needs to call on were in their infancy in Fourier's day. Infrared radiation (called "dark heat" or "dark radiation" at the time) had been discovered in 1800 by the astronomer Sir Frederick William Herschel, and it was the subject of intense inquiry. Infrared was the "dark energy" of its day and it was perhaps no less mysterious to physicists of Fourier's day than is the dark energy talked about by today's physicists. There was some understanding from the work of Fourier's contemporaries, Dulong and Petit, that the rate of heat loss by infrared radiation increases with temperature, and it was known that infrared could carry heat through a near-vacuum. There was, however, only a limited ability to do quantitative calculations involving infrared heat transfer. Thermodynamics was in its infancy. The very nature of heat was still being hotly debated; the landmark energy conservation experiments of Joule that showed the equivalence of mechanical work and heat would not be carried out until 1843. Against this context, the general correctness of Fourier's great leap of intuition seems all the more remarkable.

In his 1827 paper, Fourier introduces five key concepts:

1. The temperature of the Earth, or indeed any planet, is determined by a balance between the rate at which the energy is received and the rate at which the energy is lost. There is therefore a need to determine the sources and sinks of a planet's energy.
2. There are three possible sources of heat: Sunlight, heat diffusing from the hot interior of the planet, and heat communicated from the general "temperature of space." Of these, the amount of heat leaking out of the Earth's interior is too small to play a significant role in the Earth's surface temperature.
3. Emission of infrared radiation is the only means by which a planet loses heat. Since the rate of energy loss by infrared radiation increases with the temperature of the body, the planet can come into equilibrium by heating up until the rate at which it loses energy by infrared emission equals the rate at which it gains energy from its energy sources.
4. Visible light is converted into infrared light when it is absorbed at a solid or liquid surface.
5. The atmosphere has an asymmetric effect on the incoming sunlight and the outgoing infrared, because the atmosphere is largely transparent to sunlight but is relatively opaque

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> to infrared. This retards the rate at which the planet loses energy, for any given temperature. The result is that the atmosphere keeps the planet warmer than it would have been if the atmosphere had been transparent to infrared radiation.

Fourier's inferences concerning the minimal influence of the Earth's interior heat on climate are drawn from observations of the way temperature varies with depth below the Earth's surface. Of all Fourier's claims in the 1827 paper, this is the one that is most backed up by quantitative reasoning, though the actual mathematical analysis appears in Fourier's other papers and is not reproduced in the 1827 essay. Fourier's greatest work as a mathematical physicist was the formulation of the partial differential equation describing the diffusion of heat within a body, and the development of the mathematical techniques required to solve it. The full range of these developments were engaged in Fourier's interpretation of the Earth's subsurface temperature variations. Indeed, Fourier states that the problem of planetary temperatures provided the main impetus for his formulation of the analytical theory of heat. His theory of heat was applied to the problem in two basic ways. First, since the rate of heat flow is proportional to the temperature gradient, the measured increase of time-mean temperature with depth itself shows that the interior of the Earth is hotter than the surface, and gives an estimate of the heat flux, provided that one can estimate the thermal conductivity of the Earth. The flux Fourier arrived at using this procedure was an overestimate compared to modern calculations because he used the thermal conductivity of iron, but his calculation nonetheless showed the diffusion of heat from the interior to be an insignificant factor in surface temperature. The second kind of problem Fourier did was to impose the observed time-periodic daily and seasonal fluctuations of temperature at the surface as a boundary condition, and then calculate what the subsurface temperature fluctuations should look like. It was this kind of calculation that led Fourier to develop what we now call Fourier series, so as to decompose the complex time-periodic boundary condition into a sum of simple sines and cosines for which the problem is analytically tractable. This calculation correctly predicts that the diurnal variation of temperature should decay rapidly with depth and the annual variation more slowly. The calculation also gives an estimate of the amount of heat that flows into and out of the surface from sunlight in the course of the diurnal and seasonal cycle, and thus provides an additional check on the importance of solar energy in determining the Earth's surface temperature.

It takes away nothing from Fourier's brilliance to point out the one stupendous blunder in his paper. Fourier thought that the heat the Earth receives from the general temperature of interplanetary space was a crucial factor in the Earth's climate, on a par with energy received from the Sun. He thought the temperature of space to be somewhat below the minimum temperatures observed in Winter in the Arctic – roughly 200 K in modern terms. He viewed this as one of his principle discoveries, and claimed that without this source of heat, the Earth would become infinitely cold at night and in the winter, and that no life would be possible. In essence, Fourier's view was that 200 K was the natural temperature that all Solar System planets would relax to if there were no absorption of sunlight. Conceptually, he was not entirely wrong, though the correct number for the "temperature of space" in this sense would be more nearly 5 K than 200 K, but Fourier's estimate of the temperature of space was based on highly dubious reasoning that did not justify his level of certainty by any means. The assumption that Arctic night temperatures represent the temperature of space neglects the role played by the long time required for the ocean to cool down ("thermal inertia") and by the ability of air and ocean currents to transport heat from warmer parts of the planet to the poles. Fourier knew about these effects, and even mentions them explicitly elsewhere in the essay. Evidently, he thought they were too ineffective to account for the observed winter and night-time temperature, though his reasons for preferring the more exotic solution of a high temperature of space remain obscure.

In any event, Fourier's misconception about the temperature of space was corrected by Claude Pouillet in 1838. Pouillet's main contribution to science was a largely correct measurement of the

Solar Constant, though his estimate of the corresponding temperature of the Sun was in error because of shortcomings of then-current representations of blackbody radiation. In the course of these measurements, Pouillet found that the temperature of space was far below the value supposed by Fourier, and nothing more was heard thereafter about the role of the temperature in space in climate.

de Saussure's Hot Boxes

In thinking about the effect of the atmosphere on the Earth's energy balance, Fourier drew on the behavior of a simple device invented by the Swiss Alpinist Horace-Bénédict de Saussure (1740–99). This device, called a *heliothermometer*, consisted of a wooden box insulated with cork and wool, with a lid consisting of one or more panes of transparent glass (Fig. 1). The interior walls were painted black so as to absorb nearly all the sunlight entering the box, and a thermometer was placed in the box so that its temperature could be determined. de Saussure devised this instrument as a means of measuring the intensity of sunlight, so that he could test the hypothesis that it is colder atop mountains because the sunlight is weaker there. The idea was to trap the energy of sunlight inside the box, and keep the interior isolated from the surrounding so that the temperature in the box would be responsive to the intensity of the sunlight rather than the temperature of the surroundings. Using the heliothermometer, de Saussure correctly concluded that sunlight becomes, if anything, more intense at higher elevations, so that some other physical process must come into play. "Hot-Boxes" such as de Saussure's were popular toys among scientists throughout the nineteenth century, and many succumbed to the temptation to use them as solar cookers. de Saussure writes that "Fruits ... exposed to this heat were cooked and became juicy." Herschel himself took a hot-box with him to South Africa in 1830, and reported: "As these temperatures [up to 240°F] far surpass that of boiling water, some amusing experiments were made by exposing eggs, meat, etc. [to the heat inside the box], all of which, after a moderate length of exposure, were found perfectly cooked. ... [On] one occasion a very respectable stew of meat was prepared and eaten with no small relish by the entertained bystanders."

Neither de Saussure nor Fourier hit on the correct explanation of the decline of temperature with altitude, which involves the cooling of air parcels as they are lifted and expand. Nonetheless, the behavior of the heliothermometer provoked a lot of useful thinking about the energy carried by sunlight. Fourier's use of the analogy was to show that if one keeps the rate of energy *input* by sunlight the same, but retards the rate of energy *loss* by putting on a pane of glass, then when the system comes into equilibrium its temperature will be greater than it would have been without the glass in place. Fourier knew that the glass was transparent to sunlight and largely opaque to infrared, but he also knew that in the typical experiment the glass retards heat loss, in part, by simply trapping warm air in the box and keeping it from blowing away. He alludes to the fact that the experiment would still yield an elevation of temperature even if performed in a vacuum, but his use of the subjunctive in the original French suggests that this is a thought experiment, rather than one he actually carried out.

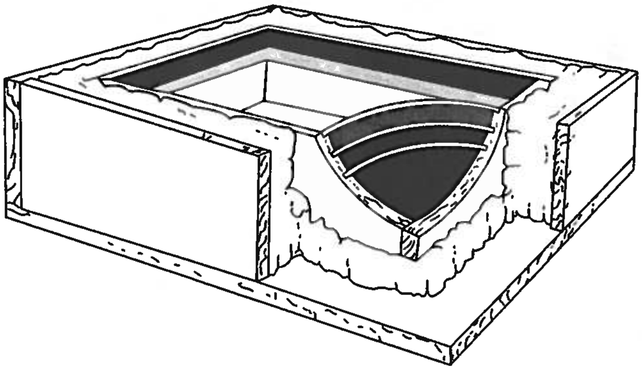

Fig. 1.1 **Artist's conception of the Saussure's improved hot box.**

What Fourier Did Not Do

One thing Fourier did not do was coin the term "greenhouse effect," though his use of de Saussure's heliothermometer as an analogue could be considered similar to a greenhouse analogue. de Saussure's box is indeed a kind of miniature greenhouse. In any event, Fourier showed a clear awareness of the imperfection of the analogy, stating explicitly that the temperature in the hot box was influenced by turbulent heat transfers that have no proper counterpart in the planetary temperature problem.

Further, Fourier did not compute the temperature of the Earth in the absence of an atmosphere and concluded that it was colder than the observed temperature. In fact, he never actually computed the Earth's temperature based on a balance between incoming sunlight and outgoing infrared, though he could have attempted this using the Dulong–Petit radiation law. It is not clear why Fourier thought the atmosphere had to have a warming role. Rather than this being demanded by too cold temperatures in the absence of an atmosphere, Fourier seems to be inferring that the atmosphere ought to act like a pane of glass in being transparent to sunlight but opaque to infrared; he shows awareness of the downward infrared radiated by the atmosphere, but it is not clear what the basis of Fourier's leap of intuition about the atmosphere was. In any event, he was right, and his work stimulated a great deal of further research on the effect of the atmosphere on infrared, and ultimately Tyndall's definitive experiments to be discussed next.

2

Wagging the Dog

Tyndall, J. (1861). On the absorption and radiation of heat by gases and vapours, and on the physical connexion of radiation, absorption, and conduction. *Philosophical Magazine Series 4*, **22**, 169–194, 273–285. 12 pages.

Technical Innovation

John Tyndall labored long and hard, he would have us be assured, to improve the technology for measuring the interactions of gas molecules with infrared radiation, what he called "radiant heat." He measured the absorption of IR by the cool gas, and the emission of IR by the gas when it is heated. Gases in his study that absorb also emit a principal now known as Kirkhoff's law. Tyndall also demonstrated that when a gas is very dilute or at low enough pressure, the absorption increases proportionately with the concentration of the gas, but at a high enough concentration the gas absorbs all of the IR, a phenomenon now called the band saturation effect.

Figure 2.1 shows results from Tyndall's Tables I and II, demonstrating the difference between a saturated and an unsaturated gas. When the gas is unsaturated, the absorption of the radiation by the gas varies linearly with the amount of gas in the cell. At high gas concentration, further increases in the amount of the gas have little effect on the IR absorption.

The basic idea behind the measurement of infrared energy flux or intensity is still used today, for example, in electronic thermometers that peer into a baby's ear (much recommended over the other method). The incoming radiation warms up one pole of a device called a thermopile. A thermopile has two poles, and it produces a measurable voltage that is proportional to the temperature difference between the poles. A thermopile is a collection of thermocouples, consisting of junctions of dissimilar metals at each pole, wired together to produce a stronger, more easily measured voltage.

Tyndall measured the signal from the thermopile using a galvanometer, which measures electrical current, a device now usually called an ammeter. Presumably, the voltage from the thermopile was driven through a resistor to produce an electric current. The galvanometer consists of a rotating part on springs, and a fixed part. A set of permanent magnets are mounted on the fixed part, surrounding the rotating part. The electricity flows through a coil on the rotating part, inducing a magnetic field and causing the rotating part to twist slightly, straining against the springs. A needle mounted on the twisting part allowed a measurement to be recorded, which Tyndall expressed in units of degrees of deflection.

Many of the technical improvements that Tyndall developed have to do with improving the sensitivity of the galvanometer. In addition to improving the intrinsic sensitivity of the device by replacing the dye in the silk used to insulate the coil (he claimed it had a magnetic field), Tyndall figured out that if he balanced the two sides of the thermopile against each other, he could obtain greater sensitivity of measurement. Let us suppose that a gas absorbs 1% of an incoming IR beam, and you use the thermopile to compare the intensity of the IR beam to the intensity of IR from the cool surroundings, just the lab walls shining in. To measure the impact of the absorbing gas,

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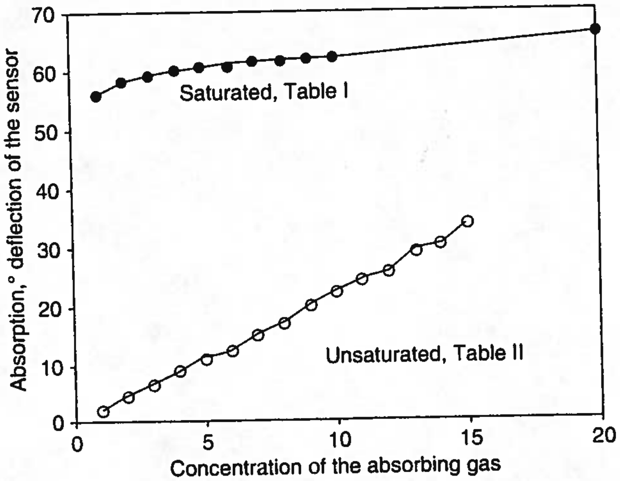

Fig. 2.1 **Tyndall's measurements demonstrated the band saturation effect, which causes the absorption of light to be insensitive to the amount of gas that the light traverses, if the gas concentration is high enough. If virtually all the light is absorbed, then adding more gas has only a small effect. The difference between the data in Tables I and II is that the concentrations of gases in Table I are higher, and therefore saturated. Tyndall also recognized that the atmosphere could be either saturated or unsaturated.**

you would have to be able to detect a small signal change of only 1%. Tyndall's idea was to balance the two sides of the thermopile against each other, by setting up an IR source to the reference side that is the same intensity as the beam on the sample side, before the gas has been introduced. The 1% change in the absolute intensity of the sample beam produces a much larger relative signal against the balanced reference beam of the thermopile. Tyndall needed this increased sensitivity to detect the IR absorption of dilute mixtures of greenhouse gases, such as in air.

Conceptual Breakthroughs

Tyndall's laboratory labors were well informed, driven even, by questions of the Earth's climate and the greenhouse effect. The most jaw-dropping implication of his study was that most (or, as it subsequently turned out, essentially all) of the greenhouse activity of the atmosphere is due to a few trace gases such as water vapor and carbon dioxide. Tyndall realized that this discovery opened the door to an easy way to change the climate of the Earth through time. Instead of waiting for the entire size or mass of the atmosphere to change, all that needs to change is the concentration of a few trace gases. When it comes to the trace greenhouse gases, a little goes a long way.

Scientists are still working out the factors that control the CO_2 concentration of the atmosphere. Tyndall nods to CO_2 as a potential agent of climate change, but points out in particular the variability of the humidity of the air, and speculates about the role that water vapor as a greenhouse gas might play in climate. As it turns out, the Earth's temperature is affected by greenhouse forcing from humidity, but the averaging of the temperatures over wide areas and around the year tends to eliminate much simple correlation between temperature and day-to-day humidity variations. Tyndall was correct in his conclusion that water vapor is the most powerful greenhouse gas in the atmosphere, but as it turns out water vapor is not considered to be a primary climate forcing, because the average water vapor concentration of the atmosphere is now thought to be closely controlled by the hydrologic cycle, in that if the air gets too humid, it rains. For this reason running a garden sprinkler does not lead to global warming in the way that running a gasoline-powered leaf blower does (by emitting CO_2). However, water vapor acts as a positive feedback in the climate system, amplifying a temperature change driven by any other factor such as rising CO_2 concentration.

Tyndall took a few steps in the direction of working out why some gases interact with IR light and some do not. The IR-transparent ones are all simple single-element gases like O_2, N_2, and H_2. The molecular formulas of the gases were not available to Tyndall, so he assumed these to be simple atoms, as opposed to molecules comprised of multiple copies of the same element. The IR behavior of these gases was very different from that of the compound gases like H_2O, CO_2, and ethylene (C_2H_4), which he found to be IR active. Tyndall interpreted his results as evidence for chemical bonds, as in, for example, ammonia as opposed to a mixture of nitrogen and hydrogen gases. The flaw in his conclusion is that diatomic molecules such as N_2 and O_2 have chemical bonds also, it turns out, but are not greenhouse gases because their electronic symmetry when they vibrate does not present an electric dipole to the electromagnetic field, and thus does not produce light. Tyndall phrased it that the compound gases "present a broader side" to the mysterious, gelatinous, gooey substance known as the ether, the medium within which light was thought to propagate, while "the simple atoms do not, – that in consequence of these differences the ether must swell into billows when the former are moved, while it merely trembles into ripples when the latter are agitated. . . ." It is difficult to read this sentence today without a bit of mirthful joy, but if we substitute "electromagnetic field" for "ether," and "electromagnetic radiation" for the billows and ripples, Tyndall's intuition was clearly in the right direction.

3

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 CO_2 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 CO_2, 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 CO_2. 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 CO_2 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 CO_2 and water vapor.

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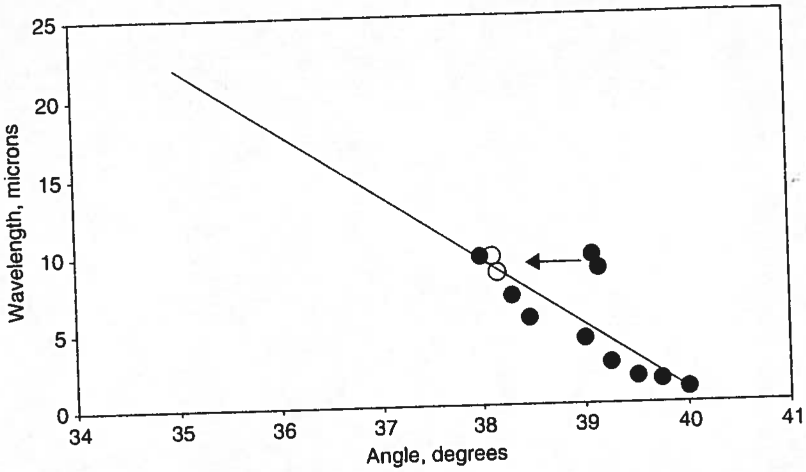

Fig. 3.1 **This is the relationship between the deflection angle of Langley's infrared beams and the wavelengths of the light as reported by Arrhenius. The two outliers are probably a misprint; if the angles of 39.xx° are replaced by 38.xx°, they fall on the same relation as the rest of the values quoted. 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°, 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

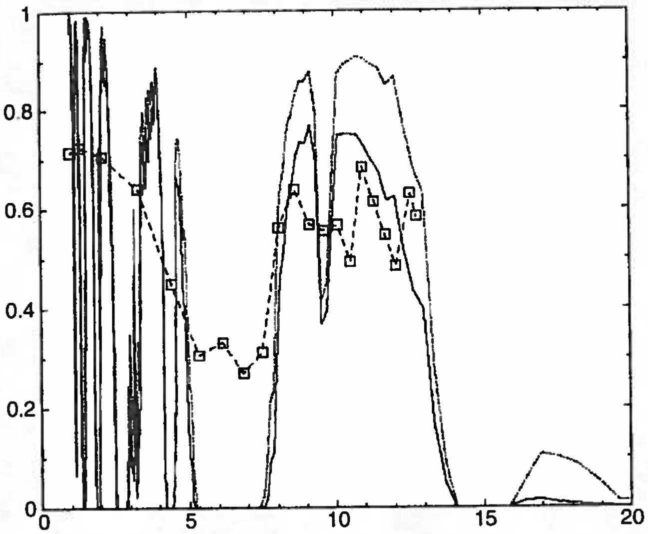

Fig. 3.2a **The spectral properties of CO_2 and water vapor in the atmosphere as deduced by Arrhenius compared with results from a modern atmospheric radiation code. Each figure shows the transmission (vertical axis) as a function of the wave number in microns (horizontal axis). A transmission of 1 corresponds 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.**

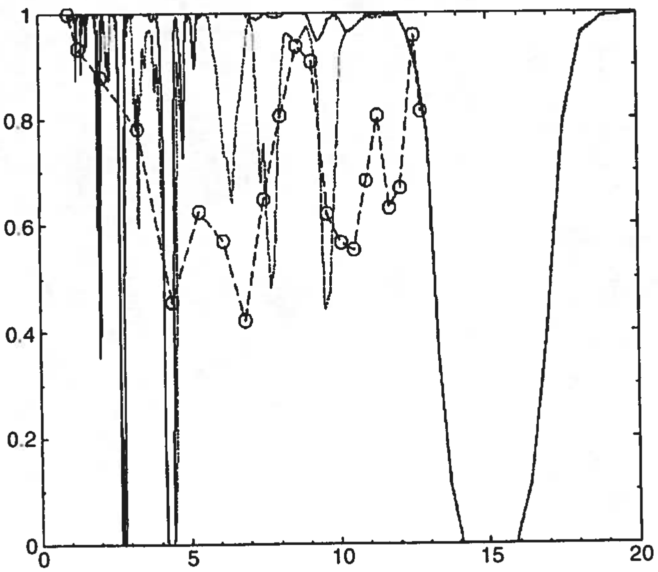

Fig. 3.2b **Shows results for CO_2 alone.**

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

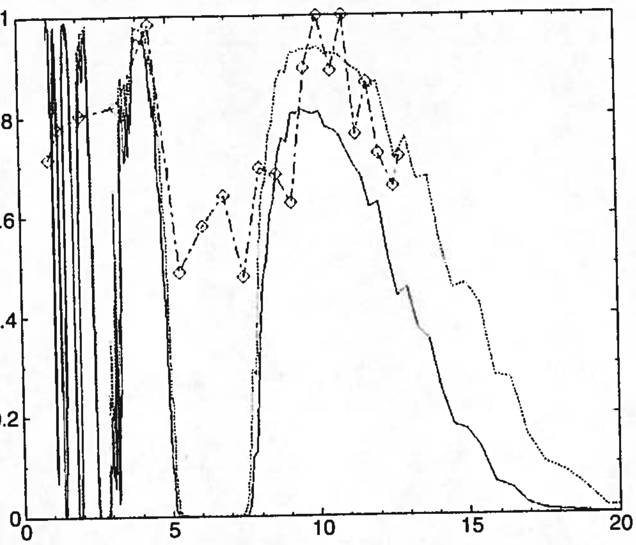

Fig. 3.2c Shows results for water vapor alone. The calculation by Arrhenius does a qualitatively good job of reproducing the main absorption features of water vapor around 5 micron, but the CO_2 spectroscopy bears little resemblance to the correct pattern based on accurate modern laboratory measurements. 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 climate 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!

from increasing CO_2 concentration, in particular in high latitudes where the ice is. The ice albedo feedback, as it is now called, is among the reasons 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 CO_2 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 CO_2. 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 CO_2 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 CO_2 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 CO_2 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.

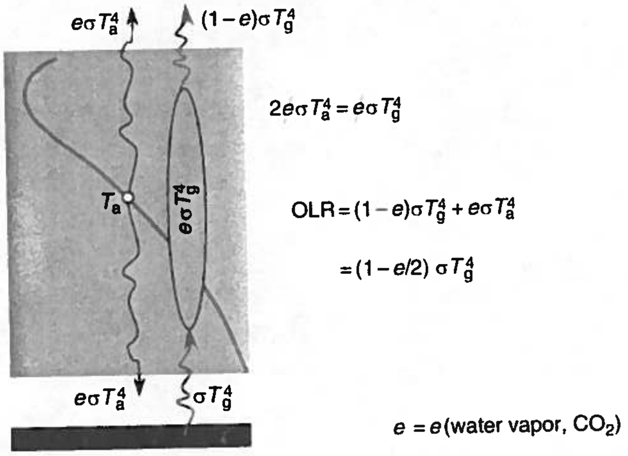

Fig. 3.3 **Schematic of Arrhenius' one-layer atmosphere model.**

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.

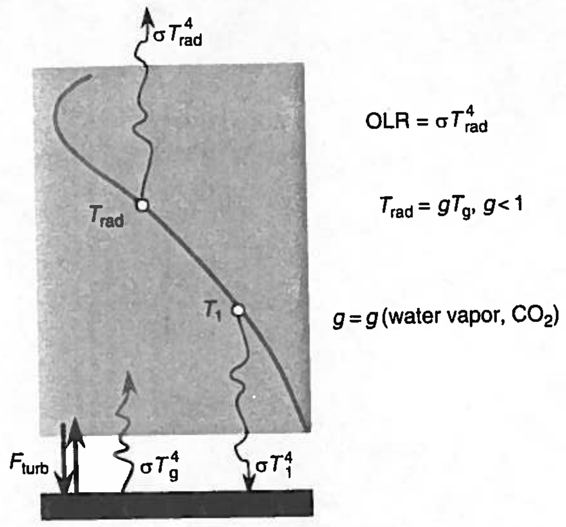

Fig. 3.4 **Schematic of a modern multi-layer atmosphere model.**

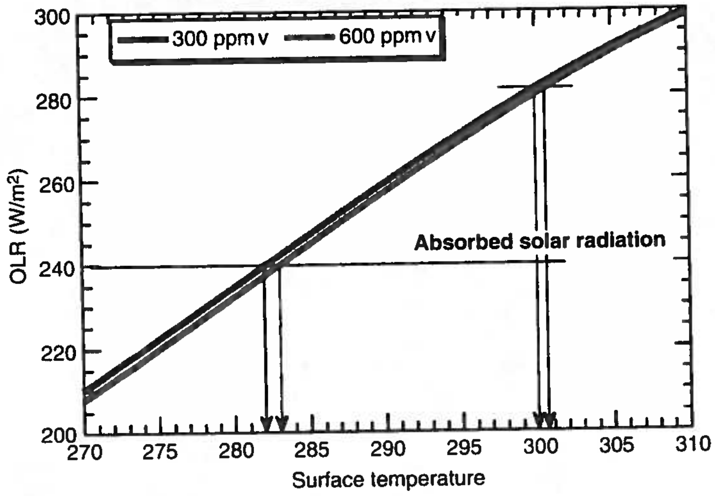

Fig. 3.5 **One-layer model with water vapor feedback, using modern spectroscopy.**

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 300000 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.... 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 $1/\sqrt{e}$, 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.

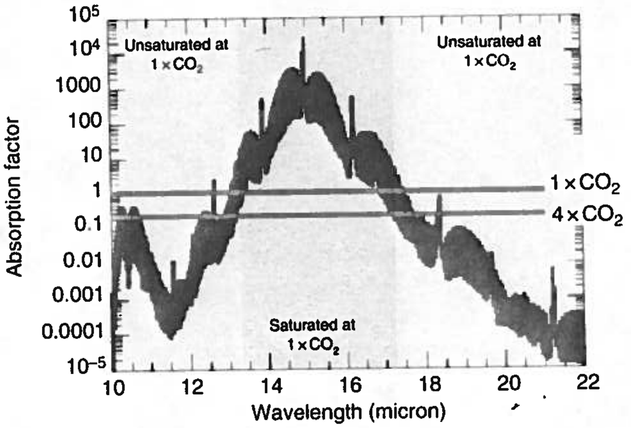

Fig. 3.6 **Infrared absorption spectrum of CO_2 with regions of band saturation indicated at 1 and 4 times atmospheric CO_2 concentration.**

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 thick grey lines give the threshold CO_2 needed to make the atmosphere optically thick at 1× the preindustrial CO_2 level and 4× 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,

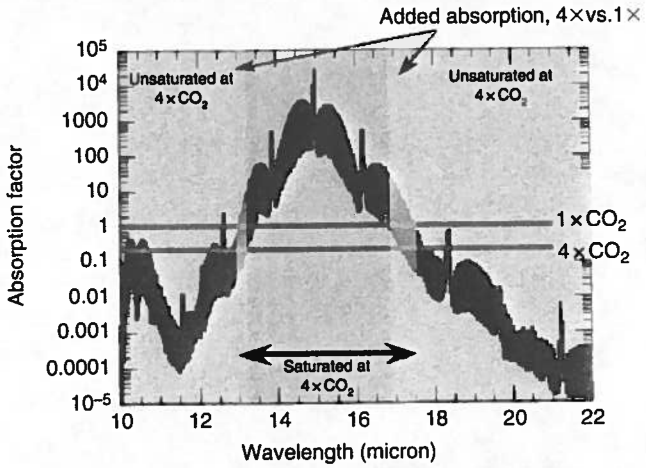

Fig. 3.7 **With an increase in atmospheric CO_2 concentration, the saturated band for CO_2 expands.**

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.

This box is based on material that originally appeared on RealClimate.org. © 2007 R.T. Pierrehumbert, used with permission of the author.

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.

4

Radiative Transfer

Plass, G.N. (1956). The influence of the 15 μ carbon-dioxide band on the atmospheric infra-red cooling rate. *Quarterly Journal of the Royal Meteorological Society*, **82**, 310–324.

The first half of the twentieth century was anything but a fallow period for radiative transfer. Astronomers and astrophysicists in particular showed an intense interest in this subject, and some of them dabbled in applications to the Earth's atmosphere as well. Observational astronomers were motivated to study absorption and emission spectra by the need to correct for the effects of the Earth's atmosphere. They also needed a good understanding of such things in order to interpret the infrared spectra of solar system planets, which during the early part of the century could be increasingly well observed from telescopes on the Earth.

In 1908, Frank Very published some wide-ranging thoughts on the operation of the greenhouse effect on the Earth and other planets, with a particular emphasis on multilayer models of radiative transfer (The greenhouse theory and planetary temperatures. *Philosophical Magazine*, **6**, 16, 478). Astrophysicists were primarily motivated by the problem of stellar structure, which required an understanding of how energy was transported radially by radiation and convection within the star – a problem that has very close affinities with the problem of determining the temperature of a planet. In 1906, Karl Schwartzchild (of black hole fame) presented his paper "On the equilibrium of the solar atmosphere," in which he set forth the basic equations of radiative transfer that bear his name today, and which are extensively used in the study of the Earth's energy balance. The Swiss physicist Jacob Robert Emden took this work further during the subsequent decade, and developed solutions bearing on the vertical structure of the Earth's atmosphere. (Radiative transfer seems to have been something of a family affair – Emden was the uncle of Martin Schwartzschild, Karl's son, and a noted astrophysicist in his own right.) The British atmospheric physicist E. Gold was also active in the early twentieth century, and made substantial contributions to the understanding of the vertical temperature structure of the atmosphere. In 1950, the great Chandrasekhar published his definitive tome on radiative transfer, building on the work of the previous half century.

Radiative transfer was a very active field of inquiry in Earth atmospheric science as well, both because it was necessary to the understanding of the vertical temperature structure of the atmosphere, and because it was recognized that accurate radiative heating and cooling rates were a necessary prerequisite for weather prediction beyond a day or so. Hugh Elsasser, Richard Goody, and Lou Kaplan were active in this area in the 1940s and beyond, and their papers provide a window into the thinking of the day. With very few exceptions, the effect of increasing CO_2 on climate did not seem to be particularly near the top of the list of reasons for studying radiative transfer during this time. A notable exception is George Callendar, who dabbled in radiative transfer in an effort to bring better spectroscopy and vertical resolution into Arrhenius' calculation.

By the time Gilbert Plass came along, much more accurate data on the infrared spectroscopy of CO_2 had become available. Equally importantly, computer power had advanced to the point that this data could be made use of in multilevel-multiband radiative transfer calculations. Plass was the first to put all that together, in our next paper of this collection. Because of the use

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of advanced computers, Plass was able to dispense with many of the approximations that compromised the accuracy of earlier work on the subject. He also fully took into account the pressure-broadening effect, which makes CO_2 infrared absorption less "saturated" at high altitudes than it is at the higher surface pressures. Plass only dealt with the effects of CO_2, however. The state of understanding of water vapor spectroscopy had not yet caught up to the point where a similarly detailed treatment of water vapor could be accomplished. From the standpoint of global warming, Plass' breakthrough accomplishment was the determination of the infrared cooling rate and the top-of-atmosphere emission, and the way these quantities are affected by changes in atmospheric CO_2. The key results are found in his Fig. 7, which can be said to be the first accurate calculation of the CO_2 radiative forcing.

Plass did a superb state-of-the-art job with CO_2 radiative transfer, but when it came to applying his results to the warming or cooling expected from changes in CO_2 he became ensnared in the Surface Budget Fallacy (see Box, The Surface Budget Fallacy), just as did George Callendar before him. Namely, he computed the surface warming by holding the atmospheric temperature fixed, and looking at the warming that would result from the increase in downward infrared flux into the surface that would occur when the atmosphere is made more emissive through doubling CO_2. This approach ignores the fact that doubling CO_2 throws the top-of-atmosphere budget out of balance, and would ultimately cause the atmospheric temperature to increase. It is the increase in atmospheric temperature that gives rise to most of the heating of the surface, and that heating is communicated to the surface by turbulent as well as radiative heat transfer. Interestingly, the *Quarterly Journal* published a discussion of Plass' paper by Goody, Kaplan, and Callendar, none of whom flagged the error in the temperature calculation. In fact, there is no indication that these luminaries considered that to be a particularly important part of the paper.

In some historical accounts, Plass is seen has having improved on Arrhenius' estimate through the use of a state-of-the-art multilayer radiative calculation incorporating realistic CO_2 spectroscopy and the pressure-broadening effect. Plass deserves credit for advancing the state of the art in computation of CO_2 effects on radiative transfer, and also deserves credit for helping to revive interest in the effects of doubling CO_2. However, he never used the top-of-atmosphere radiative forcing computed in his paper, nor did he appear to be aware of its significance. Thus, his update of Arrhenius' estimate of surface temperature change is a stumble down a garden path, not a waypoint on the way to the truth. Plass had better spectroscopy and radiative transfer calculations than Arrhenius, but Arrhenius had a much more correct concept of how to translate all that into changes in surface temperature.

Box: The Surface Budget Fallacy

A common fallacy in thinking about the effect of doubled CO_2 on climate is to assume that the additional greenhouse gas warms the surface by leaving the atmospheric temperature unchanged, but increasing the downward radiation into the surface by making the atmosphere a better infrared emitter. A corollary of this fallacy would be that increasing CO_2 would not increase temperature if the lower atmosphere is already essentially opaque in the infrared, as is nearly the case in the Tropics today, owing to the high water vapor content of the lower atmosphere. This reasoning is faulty because increasing the CO_2 concentration while holding the atmospheric temperature fixed reduces the OLR. This throws the top-of-atmosphere budget out of balance, and the atmosphere must warm up in order to restore balance. The increased temperature of the whole troposphere increases all the energy fluxes into the surface, not just the radiative fluxes. Further, if one is in a regime where the surface fluxes tightly couple the surface temperature to the overlying air temperature, there is no need to explicitly consider the surface balance in determining how much the surface warms. Surface and overlying atmosphere simply warm in concert, and the top-of-atmosphere balance rules the roost.

Arrhenius properly took both the top-of-atmosphere and surface balances into account in his estimate of the effect of doubling CO_2, though he did so using a crude one-layer model of the atmosphere. Guy Stewart Callendar (1938) and Gilbert Plass (1959) employed more sophisticated multi-level models, but when it came to translating their radiation results into surface temperature change both got mired in the surface budget fallacy. The prime importance of the top-of-atmosphere balance was emphasized with crystal clarity in Manabe's work of the early 1960s, but one still encounters the surface budget fallacy in discussions of global warming from time to time even today.

Figure 4.1 shows how the budgets change when CO_2 is doubled from 300 ppmv. The case shown is typical for the Earth's tropics, for which water vapor makes the lower atmosphere optically thick. The system starts off in balance, at a surface temperature of 300 K. If CO_2 is immediately doubled, the downward radiation into the surface increases by a mere 1.2 W/m^2. However, the OLR goes down by over 4 W/m^2. The atmosphere-ocean system is receiving more solar energy than it is losing, and so it warms up. The top-of-atmosphere balance is restored when the surface air temperature has warmed to 302 K. This increases the radiation into the ground by an additional 7.3 W/m^2. Part of this increase comes from the fact that the warmer boundary layer contains more water vapor, and therefore is closer to an ideal blackbody. Most of the increase, however, comes about simply because the low level air temperature T_{sa} increases, and hence σT_{sa}^4 increases along with it. This increase occurs even if the boundary layer is an ideal blackbody – that is, completely opaque to infrared. In addition, the increase of T_{sa} would increase the turbulent heat fluxes into the surface if the surface temperature were to stay fixed, and this increase also contributes to the warming of the surface.

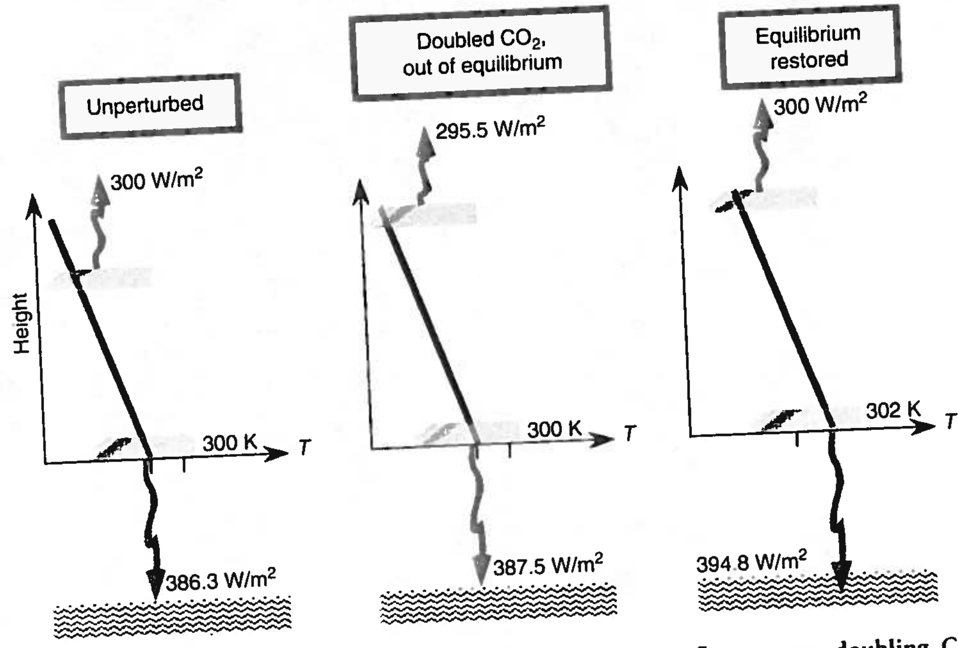

Fig. 4.1 **Changes in top-of-atmosphere and surface radiative fluxes upon doubling CO_2. Calculations were carried out with the radiation model used in the National Center for Atmospheric research climate model, employing an idealized representation of the vertical temperature and humidity variations in the atmosphere. The low level relative humidity is fixed at 80%, while the relative humidity in the free troposphere is 50%. (Figure and associated discussion in this box are reproduced from Pierrehumbert RT 2010: *Principles of Planetary Climate*, Cambridge: 780pp. © 2010 R.T. Pierrehumbert; used with permission.)**

5

The Balance of Energy

Manabe, S. & Wetherald, R.T. (1967). Thermal equilibrium of atmosphere with a given distribution of relative humidity. *Journal of the Atmospheric Sciences*, **24** (3), 241–258. Times Cited: 692. 18 pages.

Budyko, M.I. (1969). The effect of solar radiation variations on the climate of the Earth. *Tellus*, 611–619.

Sellers, W.D. (1969). A global climatic model based on the energy balance of the Earth-atmosphere system. *Journal of Applied Meteorology*, **8**, 392–400.

Three more building blocks had to fall into place before a proper, quantitative estimate of the effect of CO_2 changes on temperature could be carried out. First, the spectroscopy of water vapor had to be mapped out as comprehensively as had been done for CO_2 at the time of Plass. This was quite challenging, since the absorption of infrared by water vapor has a very complex dependence on wavelength, extending over a far greater range of wavelengths than is the case for CO_2. Second, a means had to be found to represent the effects of convection on the temperature structure of the atmosphere. For the most part, investigators had been content to compute the radiation fluxes for an observed or hypothetical temperature profile, without determining the effects of convection in a self-consistent way. Third – indeed the keystone building block of the edifice – the forgotten importance of the top-of-atmosphere energy balance had to be reintroduced into the calculation. All of this had to be knit together in a numerical model sufficiently efficient to permit solution on the computers of the day. This was achieved in the remarkable 1967 paper by Manabe and Weatherald, which we include in the following. Manabe and Weatherald (1967) can with confidence be described as the first fully sound estimate of the warming that would arise from a doubling of CO_2.

The required groundwork on water vapor had been laid in the preceding years. Manabe himself was involved in one of the very first computations of pure radiative equilibrium including accurate water vapor spectroscopy (Manabe and Möller (1961), cited in the paper we include below). This paper did not include a representation of convection, though. That came with Manabe and Strickler (1964), which introduced *convective adjustment* – the first parameterization of convection, and one which is still widely used today. At the same time Manabe was doing all that, he was developing the world's first general circulation model, the first results of which were published in Manabe, Smagorinsky, and Strickler (1965). In the 1967 paper below, the convective adjustment scheme and the numerical representation of both water vapor and CO_2 radiative effects were knit together in a numerical model, which was used to find solutions that satisfied the required top-of-atmosphere energy balance. The changes of water vapor in a changing climate are represented using the same assumption of fixed relative humidity as introduced by Arrhenius. The paper is as remarkable for its clarity of exposition as for its scientific content. Notably, it introduces the use of a curve of outgoing longwave radiation (OLR) vs. surface temperature as a means of graphically explaining how a change in CO_2 leads to surface warming, and also as a means of explaining how the water vapor feedback increases climate sensitivity. Graphs of this sort are the basis of most enlightened modern discussions of climate variations on the

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Earth and other planets. With Manabe and Weatherald, the study of global warming can be said to have entered the modern era. It represents the culmination of the art of the radiative-convective model, in which the entire climate of a planet is represented by a single column subjected to vertical heat exchange by radiation and by convection.

We also include two short papers playing variations on the theme of energy balance. These papers, one by Budyko and the other by Sellers, introduce the very simplest kind of model in which the effects of the pole to equator temperature gradient can be represented. The models in these papers do not try to solve the fluid equations governing atmospheric heat transport in the horizontal, but instead use a simplified representation of heat transfer, based on heat diffusion. Models of this type are generally called *energy balance models*, though the term is a misnomer since all proper climate models are in some sense energy balance models. The key defining features of the ones introduced here are the simplified representation of horizontal heat transfer and the simplified representation of infrared cooling, which is parameterized as a function of surface temperature. The most important insight to come out of such models is the nature if ice-albedo feedback. These papers show quantitatively the destabilizing effect of ice-albedo feedback: if it gets colder, more of the planet is covered by ice, which reflects more sunlight, which in turn leads to further cooling. The papers are also important in introducing the notion of an ice-albedo bifurcation, and multiple equilibrium. For the same conditions of illumination by the Sun, the Earth can support at least three different states: a stable state with little or no polar ice, an unstable state with a large polar ice cap, and a stable globally glaciated state. The last of these has come to be referred to as Snowball Earth. At the time of Budyko and Sellers, the Snowball state was just thought of as a mathematical curiosity, but it has in recent years become a subject of intense inquiry, as strong geological evidence has emerged indicating that the Earth may have indeed passed through Snowball states during the Neoproterozoic (around 700 million years ago) and during the Paleoproterozoic (about 2.5 billion years ago). Energy balance models similar to those introduced by Budyko and Sellers are still important tools for exploratory work in climate science, though they have been supplanted by general circulation models for those cases in which quantitatively accurate predictions are needed.

6

The Birth of the General Circulation Climate Model

Manabe, S. and Wetherald, R.T. (1975). The effects of the doubling CO_2 concentration on the climate of a general circulation model. *Journal of the Atmospheric Sciences*, 32 (1), 3–15. Times Cited: 404. 12 pages.

Hansen, J., Lacis, A., Rind, D., *et al.* (1984). Climate sensitivity: Analysis of feedback mechanisms. In *Climate Processes and Climate Sensitivity*, AGU Geophysical Monograph 29, Maurice Ewing, Vol. 5 (eds. J.E. Hansen & T. Takahashi), pp. 130–163. American Geophysical Union.

Manabe and Wetherald's estimate of the warming expected from a doubling of CO_2 was the first such estimate to be based on completely sound and quantitatively accurate implementations of radiative and convective physics, and it is an estimate that has stood the test of time very well. Even that remarkable paper had its limitations, though, stemming from the representation of the entire atmosphere by a single column. The need to go further is very well articulated in the abstract to our next landmark paper, Manabe and Wetherald (1975). The temperature of the Earth's surface is far from uniform, and to obtain a more complete picture of climate change one needs to be able to predict the geographical distribution of the warming. Further, many climate impacts descend from rainfall changes (drought, flood) rather than just temperature, so one needs to characterize changes in the hydrological cycle. The factors governing atmospheric humidity and hence the all-important water vapor feedback are also intimately connected with the hydrological cycle; it would be highly desirable to replace the assumption of fixed relative humidity with a calculation more closely tied to the basic physics leading to moistening and drying of the atmosphere. Melting of sea ice and snow provides an important feedback on climate, one that was recognized already by Arrhenius but that is virtually impossible to treat accurately in a one-column model. Ultimately, one needs to be able to predict changes in cloud patterns as well, though this challenge was not taken up in Manabe's 1975 paper.

The next step, required to treat these processes, was a very big step indeed. It involved nothing less than solving the full three-dimensional fluid dynamical and thermodynamical equations governing transfer of heat, moisture, and momentum around the globe. The fluid equations needed to be coupled to equations governing the physics of radiation, convection, and thermal exchange with the surface. The result is known as a *General Circulation Model* (GCM). Now, Manabe had to solve his radiation problem not for just a single column, but for thousands of columns, and a grid of these columns had to be linked through the air currents that transport heat, momentum, and moisture from one column to another. This was a problem to tax the very biggest computers of the time, which were in fact physically behemoths but mere mice by the standards of today's computer power. The Univac 1108 on which Manabe's original GCM was developed had all of half a megabyte of RAM – not even enough to store a single MP3 track. It took 20 min to simulate a single day of the atmospheric circulation (Fig. 6.1).

Manabe's prose speaks for itself, but it is worth highlighting a few of the accomplishments of the paper. The work rediscovered *polar amplification* first predicted by Arrhenius – the fact that the high latitudes (especially the Arctic) warm more than low latitudes. In addition to the obvious explanation of this as being due to feedback from melting ice and snow, Manabe invokes a clever and little-

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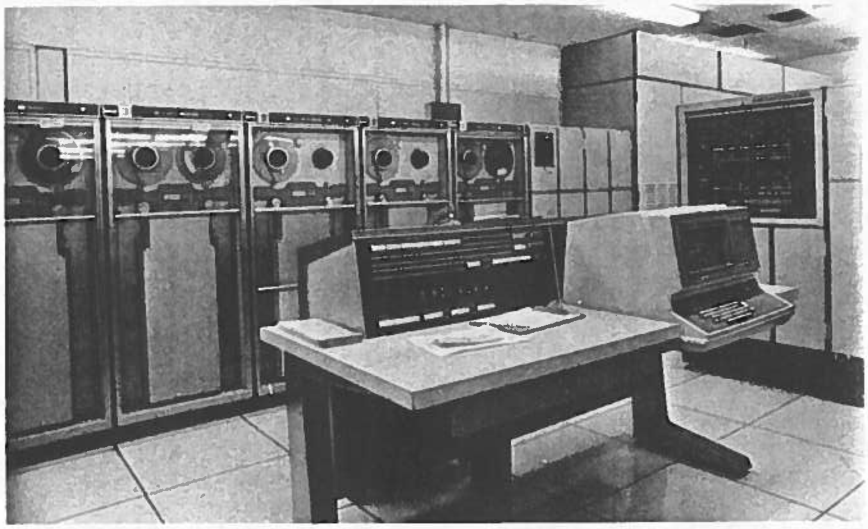

Fig. 6.1 **A Univac 1108 computer which ran Manabe's original GCM climate model.**

remembered hypothesis involving the bottom-heavy vertical structure of polar warming. Manabe and Wetherald (1975) also discovered that land warms more than ocean; this is quite important, given that land is where most people live and where all agriculture is carried out. The paper also for the first time demonstrated that global mean precipitation increases as the world warms.

Manabe's GCM was the first to be able to handle a doubling of CO_2, but others gradually came on the scene. NASA's Goddard Institute for Space Studies (GISS) was an important early entrant to the field. GISS, whose modeling effort was led by James Hansen (from whom we will hear more anon), was an offshoot of NASA's main climate lab left behind above Tom's Diner in New York when diehard Manhattanites balked at making the move to the wilds of suburban Greenbelt, Maryland. The paper we include by Hansen *et al.* represents a landmark in analysis of GCMs, particularly with regard to quantitative analysis of climate feedbacks. This paper is particularly notable in that it provided one of the early indications that cloud feedbacks had the potential to affect the climate sensitivity greatly. Another important result of the paper was the analysis of the nature of the delay in warming caused by ocean heat storage, and the consolidation of the notion of "committed warming," which is basically warming that is in the pipeline and will be realized even if CO_2 concentrations are frozen. The very clever discussion of the intimate relation between climate sensitivity and the time required for climate to reach equilibrium repays careful study even today.