John Gribbin & Mary Gribbin: James Lovelock

ONE

The Greenhouse before Gaia

SCIENTIFIC UNDERSTANDING of human-induced global warming is older than you might think. The idea that carbon dioxide released into the atmosphere by burning fossil fuel would warm the planet was clear to at least a few scientists more than a hundred years ago; and that was barely two hundred years after the scientific revolution which, among other things, led to an understanding of atmospheric chemistry. The importance of what is now called the anthropogenic greenhouse effect began to emerge not in the late twentieth century through the work of researchers such as James Lovelock, but in the early nineteenth century through the work of people like Jean-Baptiste Joseph Fourier (usually known as Joseph Fourier).

Of course, nobody could begin to understand the role of carbon dioxide in keeping our planet warm until it was known what carbon dioxide was, and that it was present in the atmosphere. In the seventeenth century, Robert Boyle had begun to appreciate the nature of the atmosphere when he described it as the product of the "exhalations of the terraqueous globe," a rather Gaian description by which he meant the products of volcanic activity, decaying vegetation, and animal life. Although this seems obvious today, it was a profound step forward from the old idea that the atmosphere was made up of some mystical substance known as the ether. It was only in the 1750s that Joseph Black showed that air is a mixture of gases, not a single substance, and isolated one of those gases, then known as "fixed air" but now called carbon dioxide—the first component of the atmosphere to be identified. Two decades later, Daniel Rutherford isolated nitrogen from air, and oxygen was identified by Joseph Priestley and independently by Carl Scheele. In the early

1780s, Henry Cavendish determined the composition of the atmosphere to be almost exactly 79 percent nitrogen and 21 percent oxygen, with just traces of other gases, including carbon dioxide. The scene was set for nineteenth-century scientists to begin to understand how this blanket of air keeps the Earth warm.

Although nobody at the time had any inkling of the role that his discovery would play in the story of global warming, with hindsight that story can be seen to begin in 1800, when the astronomer William Herschel was studying the warming effect of light from the Sun passed through different prisms and colored filters. To his surprise, he found that when sunlight was split up into a rainbow pattern by a prism, a thermometer placed beyond the red end of the spectrum warmed up, even though it was receiving no visible light from the Sun. He had discovered what later became known as "infrared" radiation—radiation like light but with wavelengths longer than red light, invisible to our eyes. But it was a quarter of a century before this invisible radiation was first linked with global warming.

Fourier, who was born in 1768 and died in 1830, came to the study of global warming late in his life, but is the first person known to have appreciated that the atmosphere keeps the Earth warmer than it would be if it were a bare ball of rock orbiting at the same distance from the Sun. Fourier was very interested in the way heat is transmitted, and among other things he calculated an estimate for the age of the Earth based on how long it would have taken for a ball of molten rock to cool to the Earth's present state. His estimate was a hundred million years, a number so staggeringly large that he didn't dare publish it—many people in his day still believed the age of the Earth that had been derived from a literal interpretation of the chronology in the Bible, which comes out at about six thousand years. But Fourier's estimate is small by today's standards, only 2 percent of the best modern estimates for the age of the Earth.

The calculation of how hot (or rather, how cold) a bare ball of rock orbiting the Sun would be is relatively straightforward, and Fourier and his contemporaries got it more or less right. But we don't have to worry too much about the calculation, because there is indeed a bare ball of rock orbiting the Sun at the same distance as the Earth—our Moon—and scientists have measured its average temperature. The surface of the Moon, like that of the Earth, gets colder at night and warmer by day, but averaging over the whole ball of rock, the Moon's surface is a chilly –18°C. Averaging over the entire Earth in the same way, the surface temperature is 15°C. Something keeps the surface of the Earth about 33 degrees Celsius warmer than it would otherwise be—and that something, as Fourier realized, is the atmosphere. He carried out his studies of global warming in the 1820s, and in 1824, summarizing work that he had previously reported in various places, he wrote that "the temperature [of the Earth] can be augmented by the interposition of the atmosphere, because heat in the state of light finds less resistance in penetrating the air, than in repassing into the air when converted into non-luminous heat."[1] In other papers published in that decade he made the analogy that heat is trapped near the surface of the Earth by the atmosphere in the way that heat is trapped inside a hothouse. Specifically, he referred to the warming inside a box with a glass cover exposed to the Sun, and suggested that the glass lid retained the "obscure radiation" (now known as infrared) inside the box. His analogy was wrong, but much later the term *greenhouse effect* came to be almost inextricably associated with global warming—so much so that we shall use it in this way ourselves.

Why was Fourier wrong? The air in a greenhouse gets hot because the rays from the Sun passing through the panes of glass in the greenhouse heat the ground inside the greenhouse, which gives up warmth to the air above it. Hot air rises, and outside a greenhouse air warmed in this way rises and carries the heat away with it, eventually radiating it away into space. But inside the greenhouse the warm air cannot escape and the air gets hotter and hotter. Greenhouses get hot because their roofs suppress convection, which is why gardeners adjust the temperature inside by opening or closing vents in the roof. The first scientist to appreciate the real role of the atmosphere in warming the globe was John Tyndall (1820–1893), an Irish

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[1] An English translation of the 1824 paper was published in the *American Journal of Science* in 1837, so the work was widely known.

polymath who was also one of the first popularizers of science and whose lectures in the United States were almost as popular as those of his contemporary Charles Dickens.

Tyndall, the son of a local policeman, was born in the village of Leighlin Bridge, in Carlow. He received only a basic formal education, but in 1839 he got a job with the Irish Ordnance Survey, and in 1844 he became a railway engineer with a company based in Manchester. All the while, he had been studying and attending lectures in his spare time, and in 1847 he was appointed as a teacher of mathematics, surveying, and engineering physics at Queenwood College, a Quaker school in Hampshire. Just a year later he went to the University of Marburg, in Germany, to study mathematics, physics, and chemistry, graduating in 1850. One of his professors in Marburg was Robert Bunsen, of burner fame. After a spell at the University of Berlin, Tyndall returned to England, where he was made a Fellow of the Royal Society in 1852 and became Professor of Natural Philosophy at the Royal Institution in 1853; in 1867 he succeeded Michael Faraday as Director of the Institution, a post he held until he retired in 1887.

Among Tyndall's many pieces of work, he explained how the blue color of the sky is caused by the way light is scattered in the atmosphere, did pioneering investigations of germs, and wrote the first popular account of the kinetic theory of heat (*Heat Considered as a Mode of Motion*, published in 1863). His lectures in the United states in 1872 and 1873 were not only hugely popular but also a great financial success; Tyndall gave all the profits to establish a trust fund for the benefit of American science. He was also one of the movers behind the inauguration of the science journal *Nature*. But what we are interested in here is his study of the way carbon dioxide interacts with infrared radiation—which grew out of a visit to the Swiss Alps in 1849.

This first visit to the Alps was intended primarily as a vacation, but Tyndall—like many of his contemporaries—became fascinated by glaciers, and made annual visits for several years to study these rivers of ice. At that time, there was great interest in the then-recent discovery that the Earth has experienced one or more great ice ages, when it has been much colder than it is today; with Tyndall's interest in both glaciers and heat it was natural that he should try to find an explanation for why the Earth should sometimes go into deep freeze. In the spring of 1859 he began to study the way various gases interact with infrared radiation. His big discovery was that "perfectly colourless and invisible gases and vapours" such as nitrogen, oxygen, carbon dioxide (which he called carbonic acid), and water vapor behaved very differently when exposed to "radiant heat." He found that although infrared radiation passes right through oxygen, nitrogen and hydrogen with scarcely any effect, carbon dioxide, water vapor and ozone (the triatomic version of oxygen) all absorb infrared radiation very effectively. Water vapor is the strongest absorber of this radiant heat, and since there is a lot of water vapor in the Earth's atmosphere, Tyndall concluded that it is the most important gas in controlling the temperature at the surface of the Earth.

Tyndall discussed his ideas in a presentation to the Royal Institution in 1859, and he presented his detailed results to the scientific community in a lecture given to the Royal Society in February 1861 and published in its *Philosophical Transactions*. "Those who like myself have been taught to regard transparent gases as almost perfectly diathermanous, will probably share the astonishment with which I witnessed the foregoing effects," he told his audience. After pointing out the powerful heat-absorbing effect of water vapor, he concluded that changes in the influence "exercised by the aqueous vapour . . . must produce a change of climate" and that "similar remarks would apply to the carbonic acid diffused through the air." Furthermore, "such changes in fact may have produced all the mutations of climate which the researches of geologists reveal."

Tyndall elaborated and refined his argument in a series of papers on the subject in the *Philosophical Magazine* in the early 1860s—nearly 150 years ago. In his words: "The solar heat possesses, in a far higher degree than that of lime light,[2] the power of crossing an atmosphere; but, when the heat is absorbed by the planet, it is so changed

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[2] "Limelight" was widely used in stage lighting in the 19th century. It is a brilliant white light produced by heating calcium oxide ("lime") in a flame of oxygen and hydrogen.

in quality that the rays emanating from the planet cannot get with the same freedom back into space. Thus the atmosphere admits the entrance of the solar heat, but checks its exit; and the result is a tendency to accumulate heat at the surface of the planet."

In modern language, the argument runs like this. Sunlight passes through the atmosphere almost unaffected, because it is mostly in the wavelengths of visible light, and warms the surface of the Earth. Most of the energy in sunlight is in the form of visible light because the Sun is so hot—its surface is at a temperature of about 6,000°C. Cooler objects radiate energy at longer wavelengths, and hotter objects at shorter wavelengths, in every case with a peak at a wavelength corresponding to the temperature of the object, following a rule known as the black body law. Because the surface of the Earth is much cooler than the surface of the Sun, the Earth radiates energy at much longer wavelengths, in the infrared. And a great deal of this infrared radiation from the surface of the Earth is absorbed by gases such as water vapor and carbon dioxide in the air, warming the atmosphere. When the atmosphere in turn radiates its warmth away, some goes out into space and some goes back down to the surface of the Earth, keeping it warmer than it would otherwise be. This is the mistitled atmospheric "greenhouse effect" that keeps the Earth 33°C warmer than the Moon.

In a paper published in 1862, Tyndall used a rather different, but no less dramatic, analogy: "As a dam built across a river causes a local deepening of the stream, so our atmosphere, thrown as a barrier across the terrestrial [infrared] rays, produces a local heightening of the temperature at the Earth's surface." Significantly, though, as he spelled out elsewhere, "the dam, however, finally overflows, and *we give to space all that we receive from the sun*."[3] For a particular concentration of greenhouse gases in the atmosphere, the planet reaches an equilibrium at a temperature where the cooler outgoing radiation exactly balances the hotter incoming radiation; increasing the concentration of greenhouse gases in the atmosphere is equivalent to raising the height of the dam, thereby deepening the water level (in-

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[3] Our italics.

creasing the temperature) at which this happens. Tyndall described water vapor as: "A blanket more necessary to the vegetable life of England than clothing is to man. Remove for a single summer-night the aqueous vapour from the air . . . and the sun would rise upon an island held fast in the iron grip of frost." Tyndall suggested that changes in the amount of water vapor and carbon dioxide in the atmosphere could therefore cause the kind of climate changes represented by ice ages ("all the mutations of climate which the researches of geologists reveal"), but made no detailed calculation of the size of the suggested effect.

The next step in the development of the understanding of global warming also came about through the search for an explanation of ice ages, when a Swedish chemist—turning his attention to the puzzle for a bit of light relief from his main work—came up with the first calculation of what effect either halving or doubling the amount of carbon dioxide in the air would have on the average temperature at the surface of the Earth.

Svante Arrhenius was born in 1859, the year John Tyndall began to study the way that different gases absorb radiation, and died in 1927. He came from Uppsala, where his father was an estate manager. Although he went to Uppsala University in 1876 intending to study chemistry, he found the teaching in the chemistry department there so bad that he switched to physics for his first degree, then moved on in 1881 to Stockholm to work for a PhD in physical chemistry. This educational path gave him a thorough grounding in physics as well as chemistry, which he later put to good use in his work on global warming, even though he regarded this merely as a hobby. Although Arrhenius received his doctorate in 1883, his thesis did not receive top marks, and this made it difficult for him to get a permanent academic post. For five years he traveled around Europe on a scholarship from the Swedish Academy of Sciences, again broadening his experience more than he might have on a conventional career path, and by the end of the 1880s he was recognized as one of the leading chemists in the world. He returned to Stockholm in 1891 as a lecturer at the Technical Institute (Högskola), a forerunner of Stockholm University, where he became a professor in 1895. Arrhenius received the Nobel Prize for chemistry in 1903, and in 1905 he became Director of the Nobel Institute, where he stayed until shortly before he died. From the time he returned to Stockholm, alongside his work in chemistry Arrhenius developed interests in astrophysics, the origin of life (he suggested that the Earth might have been "seeded" with spores from space, an idea known as panspermia), and climate change.

Climate change was something of a hot topic at the end of the nineteenth century because of the realization, as we have mentioned, that the Earth has experienced several glaciations in the relatively recent geological past. Although other people had noticed the evidence of extensive glaciation before, the person who really started the study of ice ages rolling was Louis Agassiz (1807–1873) who, as the thirty-year-old president of the Swiss Society of Natural Science, astonished the audience for his Presidential Address in 1837 by launching into an impassioned lecture on ice ages—indeed, it was in this lecture that the term ice age was introduced. His colleagues took some convincing, but Agassiz went out on the campaign trail with enthusiasm, typified by this extract from his book *Étude sur les glaciers*, published in 1840:

> The development of these huge ice sheets must have led to the destruction of all organic life at the Earth's surface. The ground of Europe, previously covered with tropical vegetation and inhabited by herds of great elephants, enormous hippopotami, and gigantic carnivores became suddenly buried under a vast expanse of ice covering plains, lakes, seas and plateaus alike. The silence of death followed . . . springs dried up, streams ceased to flow, and sunrays rising over that frozen shore . . . were met only by the whistling of northern winds and the rumbling of the crevasses as they opened across the surface of that huge ocean of ice.

No wonder many people in the later nineteenth century worried about the return of the ice!

Geologists slowly gathered evidence that the Earth has experienced not one but several glaciations in the past few million years, and that there has been a repeating rhythm of ice ages and warmer intervals now known as interglacials. Today, it is clear that more extensive ice cover than we see on Earth now has been normal for at least the past five million years, and warmer interglacials like the one we live in have been relatively short-lived departures from the long-term average. But those discoveries lay far in the future when nineteenth-century scientists struggled to find an explanation for the advance and retreat of the ice.

One idea was that the climate of the Earth is affected by changes in the balance of the seasons caused by the way the Earth wobbles (like a wobbling, spinning top) as it orbits around the Sun, and by small changes in the orbit itself. The orbit changes from more circular to slightly more elliptical, because of the gravitational influence of the other planets. The overall effect is that even though the average amount of heat received by the entire Earth from the Sun in the course of a year stays the same, sometimes our planet experiences hot summers and very cold winters for thousands of years in succession, while at other times in the cycle there are millennia with less difference between the seasons. The timescale of these changes is just the same as the timescale of the rhythm of ice ages and interglacials.

The first person to suggest a link between these astronomical rhythms and ice ages was a French mathematician, Joseph Adhémar (1797–1862), who presented it among a hodgepodge of rather confused ideas in a book, *Révolutions de la mer*, published in 1842. But the person who really put the astronomical theory of ice ages on the scientific map was a Scot, James Croll, born in 1821. Croll is a fascinating figure who came from a poor crofting family, had no formal education, but worked his way up to obtain a post with the Geological Survey of Scotland in 1867 and be elected as a Fellow of the Royal Society in 1876. His first scientific paper on ice ages was published in 1864, but the clearest presentation of his idea appeared in a book, *Climate and Time*, published in 1875.

In a nutshell, Croll argued that what you need to start an ice age is a sequence of very cold winters, allowing snow to pile up at high latitudes and be compressed into ice sheets by the addition of more snow each year. According to his model, if you put the calculations of the astronomical rhythms in, the Northern Hemisphere should have been warming out of an ice age between about 100,000 and 80,000 years ago, when its winters were relatively mild and summers were relatively cool. But by the end of the nineteenth century geologists had evidence to the contrary: exactly at that time between 100,000 and 80,000 years ago, the Earth's temperature was declining—the world was plunging into the latest ice age.

That should have been a clue—it is now clear that for millions of years it has always been cold enough for snow to fall in winter with the potential to build ice sheets. The *natural* state of the planet has been that of an ice age, so it has warmed into an interglacial state only when summers have been really hot—hot enough to melt the ice. Cooling northern summers between 100,000 and 80,000 years ago allowed the normal climate to resume after a short-lived warm spell. But that connection between summer heat and interglacials, which we discuss in more detail later, was not made in the nineteenth century, and Croll's astronomical model for ice ages fell from favor following his death in 1890, before Arrhenius turned his attention to the puzzle of ice ages.

Arrhenius had two big advantages over pioneers such as Tyndall when he started to investigate how heat is trapped by the atmosphere of the Earth. By that time, Josef Stefan (1835–1893) had discovered the mathematical law that relates the temperature of an object to the amount of energy it radiates, and there were accurate measurements of how much energy is trapped in this way by different gases, thanks to Samuel Pierpont Langley, who invented the bolometer—an instrument sensitive enough to measure temperature differences of one hundred-thousandth of a degree Celsius when warmed by radiation over a wide range of wavelengths. Modern versions of these bolometers are flown on many satellites today to monitor the changing heat balance of the Earth from space (and, indeed, on missions to Mars and other planets).

The idea of launching his instruments into space would surely have appealed to Langley, who among other things was an aeronautical pioneer, the man after whom NASA's Langley Research Center and the Langley Air Force Base are named. He was born in 1834 in

Boston, Massachusetts, and was another of the nineteenth century's "self-made" scientists. After leaving high school, he devoured science books from libraries and worked as a civil engineer in Chicago and St Louis before getting his first scientific job as an assistant at the Harvard Observatory. After a spell teaching mathematics at the U.S. Naval Academy in Annapolis, in 1867 he settled as professor of physics and astronomy at the Allegheny Observatory in Pennsylvania, where he stayed for twenty years. He then became director of the Smithsonian Institution in Washington DC, where he spent the rest of his career; he died in 1906.

From the mid-1880s onward, Langley carried out a series of experiments with flying machines. He is thought to have been the first person to build heavier-than-air machines, powered by steam, that were capable of sustained flight, although they were unmanned and uncontrolled. At the beginning of the twentieth century, when he was in his late sixties, Langley built an aircraft powered by a gasoline engine that was intended to carry a human pilot. There is every likelihood that it would have flown, but it was let down (literally) by its catapult launching system. Two test flights, wisely attempted over water, ended in the Potomac River; the second of these launch failures occurred on 8 December 1903, just nine days before the first successful flight of the Wright brothers' machine.

Langley's measurements of infrared absorption by the atmosphere were made in the second half of the 1880s. Langley's bolometer was so sensitive that it could measure the amount of heat falling on it at different wavelengths as it moved along the spectrum—or rather, as the spread-out spectrum from a source like the Sun is moved across the bolometer. Each kind of molecule in the air radiates energy (when it is hot) or absorbs energy (when it is cooler than the radiation passing through it) over specific ranges of wavelengths, known as emission or absorption bands; the bands are the same whether the molecules are emitting or absorbing. Spectroscopic observations revealed the presence of many absorption bands associated with both water vapor and carbon dioxide, and by making observations of the spectra of both the Sun and the Moon Langley was able to pinpoint how much radiation gets trapped in the air.

The question Arrhenius set out to answer in the second half of the 1890s was, how does this trapped energy affect the temperature at the surface of the Earth?

This work involved a great deal of tedious calculation in those days before the advent of electronic calculators (let alone computers), but as early as 1895, in a paper presented to the Stockholm Physical Society, Arrhenius was able to write that; "Temperature of the Arctic regions would rise about 8 degrees or 9 degrees Celsius, if the carbonic acid increased to 2.5 to 3 times its present value. In order to get the temperature of the ice age between the 40th and 50th parallels, the carbonic acid in the air should sink to 0.62 to 0.55 of present value (lowering the temperature 4 degrees to 5 degrees Celsius)." At that time, Arrhenius was chiefly interested in finding an explanation for ice ages—if you like, global cooling. He developed his ideas and carried out more extremely tedious calculations involving a lot of work over the next few years, publishing a weighty textbook, which received little attention, in 1903. By that time he was beginning to appreciate the importance of global warming, and realized that human activities had the potential to change the climate. His colleague Nils Ekholm pointed out in 1899 that human activities had the potential to double the amount of carbon dioxide in the atmosphere, and that this would "undoubtedly cause a very obvious rise of the mean temperature of the Earth." Arrhenius picked up on the idea, and in 1904 he wrote that "the slight percentage of carbonic acid in the atmosphere may, by the advance of industry, be changed to a noticeable degree in the course of a few centuries." But from his historical and geographical position, this seemed like a good thing.

Arrhenius had no idea how rapidly the burning of fossil fuel would increase and how swiftly carbon dioxide would build up in the atmosphere as a result. And from the perspective of Sweden, a slightly warmer world looked desirable. In his popular book *Worlds in the Making* (1906),[4] drawing on work he had done over the previous ten years, Arrhenius explained just how cold the world would be without the "hot-house" effect. Crucially—and significantly in terms

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[4] The English translation did not actually appear until 1908.

of the development of the kind of ideas important for Gaia theory—he included feedback in his calculations. First, Arrhenius calculated that taking all of the carbon dioxide out of the air would cause the average temperature at the surface of the Earth to drop by 21°C. But he realized that such a cooling would also reduce the amount of water vapor in the air, and he calculated that this reduction in water vapor would cause a further cooling of 10°C, giving a total cooling of 31°C, almost all the way down to the figure appropriate for the airless Moon and close to the figure we get from modern calculations.

This is an example of a positive feedback. Cooling the Earth by whatever means takes water vapor, one of the greenhouse gases, out of the air as the water vapor condenses, and makes the planet cooler still. The same thing happens in reverse—when the world warms, for whatever reason, water evaporates from the oceans and infrared heat trapped by the extra water vapor in the air makes the warming bigger than it would be if there were no feedback. There are also examples of negative feedbacks, which act to reduce changes and maintain the status quo; we shall come across these later.

Arrhenius was satisfied that reducing the amount of carbon dioxide in the air could easily explain why ice ages happened, even though that raised the question of why the amount of carbon dioxide in the air should vary. As he developed his ideas, he also pointed out that if the amount of "carbonic acid" in the atmosphere increased slightly from its present level, this might prevent the onset of another ice age, make the climate of Europe more equable, and stimulate the productivity of plants which need carbon dioxide in order to grow, thus providing more food for the world's increasing population. "We would then have some right," he suggested from his chilly northern home, "to indulge in the pleasant belief that our descendants, albeit after many generations, might live under a milder sky and in less barren surroundings than is our lot at present."

This optimistic scenario was based on the assumption that the amount of carbon dioxide added to the air by human activities would be small compared with the natural "reservoir" of the gas in the atmosphere. Arrhenius was able to make the comparison between anthropogenic emission of carbon dioxide and natural processes because one of his colleagues in Stockholm, Arvid Högbom, had been studying the way carbon dioxide cycles in the Earth system work, with the gas being released by volcanoes, absorbed by the oceans, and so on. Arrhenius calculated in 1896 that doubling the quantity of carbon dioxide in the air would warm the world, allowing for feedbacks, by 5°C—which, partly by luck, is very close to the best modern estimates. But he never dreamed how rapidly the world would change in the twentieth century; he thought that at the rate human activities were releasing carbon dioxide in the 1890s it would take three thousand years for industrial activities to produce such a rise. By 1906 he had already revised this estimate down to a few centuries; in fact, the amount of carbon dioxide in the air has already risen, since Arrhenius' day, by more than 25 percent, and the doubling is projected to take place before the end of the present century.

Hardly anyone, though, believed Arrhenius' claim that adding carbon dioxide to the air would make the world warmer. The accepted wisdom of the time—which we now know was based on inadequate measurements made with spectrographs less sensitive than those of today—was that in the parts of the infrared spectrum where carbon dioxide absorbs energy the bands were already "saturated," with all the radiation being absorbed, so there was none left over to be absorbed by additional carbon dioxide. There was also an assumption that any carbon dioxide added to the air by human activities would be absorbed by the oceans. This is true up to a point, but it takes the oceans thousands of years to absorb what human activities can now release in a century.

While the idea of carbon dioxide as a regulator of climate and possible explanation of ice ages languished after the work of Arrhenius, the rival astronomical theory suffered a similar modest rise and rapid fall from grace. The idea was revived by the Serbian Milutin Milankovitch (1879–1958), who devoted most of his career to refining the calculations of how the astronomical effects we have described change the amount of heat arriving at the Earth from the Sun (the insolation) at different latitudes and different seasons. By the time World War I broke out, Milankovitch was a professor at the University of Belgrade and already deep into his laborious calculations, which would eventually reveal how insolation had changed over the past 600,000 years. In the wrong place at the wrong time, on a visit to Hungary when the war broke out, Milankovitch was interned by the Hungarians and spent four years in Budapest with nothing to do but continue his calculations. First he came up with a mathematical model, with every number worked out by hand, describing the climate of the Earth today, then he adapted it to cover Venus and Mars as well.

The fruits of all these labors appeared in a book published in French in 1920. At first, the only person who appreciated the value of what Milankovitch had achieved was a Russian-born German meteorologist, the seventy-six-year-old Wladimir Köppen, who wrote to Milankovitch from Hamburg, initiating a long correspondence. It was Köppen who provided Milankovitch with the key insight that the way to start an ice age in the Northern Hemisphere is to have cool summers, rather than very severe winters. Armed with this insight, Milankovitch embarked on another calculating epic and found that the timing of his climate model matched the geological record. Over the past six hundred millennia, when Northern Hemisphere summers have been at their coolest the Alpine glaciers have advanced.

What became known as the Milankovitch Model of ice ages gained some currency in the 1920s and 1930s, and was summed up in a book that Milankovitch saw published in 1941—ironically, in the German language, just at the time Yugoslavia was being invaded by German forces during World War II. But in truth the geological chronology was too poor to make the match between ice ages and lower insolation convincing to skeptics, and even if the timing of ice ages and astronomical rhythms matched, the size of the astronomical effect seemed too small to account for the size of the climatic fluctuations. The astronomical rhythms might be, as they were later called, the "pacemaker" of ice ages, but they could not on their own *drive* ice age/interglacial fluctuations. So the Milankovitch Model began to lose what modest support it had almost exactly at the time Milankovitch published his big book.

Meanwhile, the carbon dioxide model of ice ages had re-entered the arena of scientific debate, even if it had won few converts. One person who was convinced was the American physicist E. O. Hulburt, who pointed out the flaws in the argument about saturation of the infrared bands in a paper published in the *Physical Review* as early as 1931.[5] But the *Physical Review* was not a journal read by meteorologists, and his paper had no impact at the time. The person who did make meteorologists at least sit up and debate the issue was a British physicist, Guy Stewart Callendar—who, having almost literally learned thermodynamics (the science of heat) at his father's knee, turned his attention to the carbon dioxide greenhouse effect in the late 1930s.

Callendar was born in 1897 and died in 1964. His father, Hugh Callendar, was a professor of physics at McGill College in Montreal at the time of Guy's birth, but he soon returned to his native England as professor of physics first at University College, London, then at the Royal College of Science (now Imperial College), also in London, where he was head of the physics department from 1908 to 1929. The elder Callendar was an authority on thermodynamics and steam power, especially the application of thermodynamics to steam turbines—hugely important to industry and shipping. He had been elected as a Fellow of the Royal Society in 1894. Among his many other scientific interests, Hugh Callendar also invented a kind of electronic thermometer based on monitoring the way the resistance of a platinum wire changes with temperature; this became the sensor in a kind of chart recorder that has been used ever since to record changes in temperature continuously on long rolls of paper.

Under the influence of his father, Guy Callendar studied engineering in London then worked as one of Hugh Callendar's research assistants from 1923 to the end of the 1920s. After his father died in 1930, the younger Callendar took over some of his lecturing duties, and carried out research on steam turbines and fuel cells. From 1942

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[5] The earlier argument against the idea that adding carbon dioxide to the air will make the globe warmer was also wrong because it failed to take account of the way absorption of infrared radiation is affected by temperature, and the temperature of the atmosphere changes considerably with altitude.

until he retired in 1957, he worked for the Ministry of Supply. But all that time his real scientific passion was the study of weather and climate, which he carried out in his own time, strictly speaking as an amateur meteorologist, but one with a thorough grounding in physics and in particular in thermodynamics. His biographer James Fleming sums Callendar up as "a well-trained, extremely competent, pensive, and somewhat reclusive engineer, a loving husband and devoted father."

Callendar's "hobby" bore fruit in 1938 when, already in his forties, he presented a paper to a meeting of the Royal Meteorological Society. He had been collecting weather statistics for years—in particular, temperature data from around the globe, going back to the end of the nineteenth century. Other people had found hints in the partial records available to them that the world had warmed during the first third of the twentieth century, but the statistics Callendar had gathered—from some two hundred weather stations around the world—established this beyond any doubt. That would have been enough of an achievement for most amateur meteorologists, but Callendar went further. He told the meeting that he had an explanation for the warming; the addition of carbon dioxide from human activities into the atmosphere of the Earth was adding to the greenhouse effect. He pointed out that the burning of fossil fuels over the previous fifty years (mostly coal in those days) had released about 150 billion tons of carbon dioxide into the air, and that three-quarters of it was still there, representing an increase of 6 percent in its atmospheric concentration between 1900 and 1936.

When he had first come across the work of Arrhenius, Ekholm and other early proponents of the idea of human-induced global warning, Callendar had not been persuaded by their arguments. But he knew that much better measurements of the properties of the so-called greenhouse gases had been obtained since the beginning of the twentieth century, so rather than dismiss the idea out of hand, in the best scientific tradition he carried out his own calculations to test it. Contrary to his expectations, he found that the effect was real. According to Callendar's calculations of the greenhouse effect, using the latest data on infrared absorption and information about the structure of the atmosphere, a doubling of the amount of carbon dioxide in the air would produce a rise in global mean temperature of at least 2°C, although he noted in his 1938 estimate that the effect might be "considerably greater." Since the world had warmed by just one-sixth of a degree since 1900, this meant that according to his calculation the anthropogenic greenhouse effect could account for between two-thirds and three-quarters of the warming. This is an important point, which was appreciated even by this early pioneer of global-warming studies—nobody claims that *all* changes in climate, even today, are a result of human activities. There are natural fluctuations as well, just as there have always been, with the human influence superimposed on them. What Callendar was saying was that the warming of the world between 1900 and 1936 was three times greater than it would have been without human interference.

Callendar's words are eerily similar to those being used by climatologists today, some seventy years later: "If any substance is added to the atmosphere which delays the transfer of low temperature radiation, without interfering with the arrival or distribution of the heat supply, some rise of temperature appears to be inevitable in those parts which are farthest from outer space." But how should we react to the prospect of such a rise in temperature? Here Callendar, like Arrhenius, struck a very different note from his modern counterparts. In the late 1930s, global warming still seemed like a good thing, and in any case Callendar estimated that the average global temperature increase caused by human activities would be only about 2°C over the next two hundred years. So: "The combustion of fossil fuel, whether it be peat from the surface or oil from ten thousand feet below, is likely to prove beneficial to mankind in several ways, besides the provision of heat and power . . . the return of the deadly glaciers should be delayed indefinitely." In 1939 Callendar reported that "the five years 1934–38 are easily the warmest such period at several stations whose records commenced up to 180 years ago." And this was still seen as very much a good thing, whatever the cause of the warming.

Callendar continued to study the role of carbon dioxide and other greenhouse gases throughout his life. In 1941 he published a paper reviewing the spectroscopic measurements and drawing attention to the absorption bands of carbon dioxide itself, water vapor, nitrous oxide, and ozone, all components of the Earth's atmosphere. The overall effect of his work was to make professional meteorologists appreciate that the absorption of infrared radiation by carbon dioxide in the atmosphere really is important, and a problem worth studying. For this reason, some climatologists have tried to promote the use of the term *Callendar effect* for what is usually known as the anthropogenic greenhouse effect; but they are fighting a lost cause, since, as we have acknowledged, the term *greenhouse effect* is just too catchy. In Callendar's lifetime, though, the study of this greenhouse effect was still only a minority interest. The idea of a human-induced global warming still seemed far-fetched, and those who thought it was real felt it was probably a good thing—not least because the Northern Hemisphere cooled (for reasons we shall discuss later) in the three decades following Callendar's 1938 presentation at the Royal Meteorological Society. Callendar himself continued revising his work and publishing papers on the greenhouse effect until his death in 1964, although nothing had the impact of his early papers. But in 1941, the year Callendar published his review of the data on carbon dioxide absorption and Milankovitch published his epic book on insolation cycles, a young man who would eventually put all these ideas into their proper global perspective was just finishing his degree at the University of Manchester.