Joseph Fourier, the 'greenhouse effect', and the quest for a universal theory of terrestrial temperatures

James R. Fleming

The central role that the theory of terrestrial temperatures played in Fourier's mathematical physics has not received the attention it deserves from historians, although his cryptic allusions to the heating of a greenhouse, taken out of context, have been widely cited by subsequent authors.

Jean Baptiste Joseph Fourier (1768–1830) was known by his contemporaries as a friend of Napoleon, administrator, Egyptologist, mathematician and scientist whose fortunes rose and fell with the political tides. He was a mathematics teacher, a secret policeman, a political prisoner (twice), governor of Egypt, prefect of Isère and Rhône, baron, outcast, and perpetual member and secretary of the French Academy of Sciences[1]. His reputation is largely based on his 'Fourier series', a widely used mathematical technique in which complex functions can be represented by a series of sines and cosines. Among physicists and historians of physics, he is also known for his book *Théorie analytique de la chaleur* (1822), an elegant work that Lord Kelvin described as 'a great mathematical poem'.

Recently, Fourier's article of 1827, 'Mémoire sur les températures du globe terrestre et des espaces planétaires', published in the *Memoirs* of the French Academy, has been mentioned repeatedly as being the first reference in the literature to the atmospheric 'greenhouse effect'. Here I will review the origins of this practice and demonstrate that most of these citations are unreliable, misdirected and anachronistic. While there are indeed greenhouse analogies in Fourier's writings, they are not central to his theory of terrestrial temperatures, nor are they unambiguous precursors of today's theory of the greenhouse effect. Of greater significance, I will clarify what Fourier actually wrote on the subject of terrestrial temperatures and locate this topic within the context of his analytical theory of heat.

James Rodger Fleming

Is Professor of Science, Technology and Society at Colby College, Maine. He has published extensively on the history of meteorology and geophysics, including social and military aspects and climatic change. He serves as a consultant for the American Meteorological Society and is chair of its history committee. His books include *Meteorology in America, 1800–1870* (Johns Hopkins University Press, 1990), *Science, Technology, and the Environment* (Akron University Press, 1994), *International Bibliography of Meteorology* (Diane Publishing, 1994), *Historical Essays on Meteorology* (American Meteorological Society, 1996) and *Historical Perspectives on Climate Change* (Oxford University Press, 1998). He lives in China, Maine (not mainland China!) with his wife Miyoko and two sons, Jamitto and Jason.
e-mail: jrflemin@colby.edu

Most people writing on the history of the greenhouse effect merely cite in passing Fourier's descriptive memoir of 1827 as the 'first' to compare the heating of the Earth's atmosphere to the action of glass in a greenhouse. There is usually no evidence that they have read Fourier's original papers or manuscripts (in French) or have searched beyond the obvious secondary sources. Many authors, perhaps relying on secondary sources, mistakenly cite Fourier's paper of 1827 as his first on the subject of terrestrial temperatures; some claim that it is only available in French. In fact Fourier presented his paper on terrestrial temperatures to the Académie Royale des Sciences in 1824 and published it that same year in the *Annales de Chimie et de Physique*; it was reprinted in 1827 and translated into English in the *American Journal of Science* in 1837 (Ref. 2). Secondary sources typically do not acknowledge references by Fourier to greenhouses in his magnum opus of 1822 or in his earlier papers. Moreover, existing accounts assume far too much continuity in scientific understanding of the greenhouse effect from Fourier to today. Even his biographers fail to emphasize the quest for a universal theory of terrestrial temperatures as a key motivating factor in all of Fourier's theoretical and experimental work on heat.

Fourier's article of 1824

In an article published in 1824, Joseph Fourier presented some 'general remarks' on the temperature of the Earth and interplanetary space. Fourier provided no equations, and he told his readers that 'the analytic details which are omitted here are found in the works which I have already published'; he called this work a 'résumé' that included results from several earlier memoirs. According to John Herivel, one of Fourier's biographers, this essay was 'largely expository in character and added nothing essentially new' on the subject of terrestrial temperatures[3].

In the article, Fourier discussed the heating of the Earth by three distinct sources: (1) solar radiation, which is unequally distributed over the year and which produces the diversity of climates; (2) the temperature communicated by interplanetary space irradiated by the light from innumerable stars; and (3) heat from the interior of the Earth remaining from its formation (Figure 1). He examined in turn each of these sources and the phenomena they produce.

The article contains an extended discussion of the distribution of solar heating over the globe caused by the periodic and latitude-dependent nature of the sun's irradiance. This section of the paper, based on results established much earlier by Fourier, was a classic application of Fourier's analytic techniques. Fourier also discussed another factor controlling terrestrial temperatures: the internal heat of the globe and its secular cooling, but he determined this to be a trivial amount: no more than three-hundredths of a degree during the course of recorded history.

The balance of the article is devoted to an examination of a third factor: the temperature of space and its effect on the temperature of the Earth. Here reside most of Fourier's comments on the heating of the atmosphere. According to Fourier, 'the influence of the stars, is equivalent to the presence of an immense hollow sphere, with the earth in the center, the constant temperature of which should be a little below what would be observed in polar regions[4].' In his most memorable analogy, Fourier compared the heating of the atmosphere to the action of an instrument called a heliothermometer. This instrument, designed and used in scientific mountaineering in the 1760s by

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Figure 1 Heat sources affecting terrestrial temperatures according to Fourier. 'The earth receives the rays of the sun, which penetrate its mass, and are converted into non-luminous heat; it likewise possessed an internal heat with which it was created, and which is continually dissipated at the surface; and lastly, the earth receives rays of light and heat from innumerable stars, in the midst of which is placed the solar system. These are the three general causes which determine the temperature of the earth'. Joseph Fourier, 1824 (Ref. 2).

Horace Benedict de Saussure, consisted of a small wooden box lined with a layer of black cork. Sunlight entered the box through a window covered with three panes of glass separated by air spaces. This arrangement served to magnify the heating effect of the Sun's rays (measured by a thermometer enclosed in the box) while eliminating the cooling effect of wind currents. In 1774, simultaneous heliothermometric observations taken at different locations by Saussure and an assistant demonstrated an appreciable increase in solar heat with altitude[5].

For Fourier, the atmosphere was like a giant heliothermometer, sandwiched between the surface of the Earth and the imaginary cap provided by the finite temperature of interstellar space. The interior of this heliothermometer, especially the fluid and aerial components, possessed radiative properties of its own: 'The transparency of the waters appears to concur with that of the air in augmenting the degree of heat already acquired, because luminous heat flowing in, penetrates, with little difficulty, the interior of the mass, and non-luminous heat has more difficulty in finding its way out in a contrary direction'. Fourier admitted, however, that it is 'difficult to know how far the atmosphere influences the mean temperature of the globe; and in this examination we are no longer guided by a regular mathematical theory'. Fourier's statement most suggestive of the greenhouse effect, and most cited out of context, was the following: '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'.

Fourier concluded by claiming that he had 'united in this article all the principal elements of the analysis of terrestrial temperature' and had summarized the results of his earlier researches, 'long since given to the public'. While raising the possibility that new properties of radiating heat or causes modifying the temperature of the globe might yet be discovered, he was positive that 'all the principal laws of the motion of heat are known'[6]. In his mind, this essay of 1824 on terrestrial temperatures, although providing no equations, had rendered more complete his magnum opus of 1822 on the analytical theory of heat.

Earlier comments by Fourier on terrestrial temperatures and greenhouses

The question of terrestrial temperatures was on Fourier's mind as early as 1807, when he wrote on the unequal heating of the globe. By 1816, he had composed a manuscript of 650 pages on the subject[7]. His magnum opus of 1822 discusses the problem of terrestrial temperatures and the principles governing the temperature of a greenhouse ('serre'). In his writings, Fourier acknowledged earlier works on heat by John Leslie, Count Rumford, and others. One of the earliest such references was to the work of Edme Mariotte who wrote in 1681 that although the Sun's light and heat easily passed through glass and other transparent materials, heat from other sources ('chaleur de feu') did not[8].

Fourier made observations on the heating power of the Sun and on night-time refrigeration. He conducted experiments on the heating and cooling of objects of different composition and shape, and on the transmission, absorption and reflection of radiant heat. He employed basic physical principles and formulated mathematical laws to explain and predict universal phenomena, such as 'the progressive extinction of heat rays in the atmosphere'[9].

In his *Théorie analytique de la chaleur* (1822), Fourier used these results to introduce the elements of a comprehensive mathematical theory of heat: the differential equations describing the movement of heat in solids and fluids, the variations introduced by external periodic heat sources, and the transmission of heat by diaphanous substances. While these topics were all contributions to basic physical theory and have been read as such by generations of physicists and historians of physics, they were also the elements of Fourier's theory of terrestrial temperatures, with the Earth as the cooling body, the Sun as the periodic heat source, and the atmosphere as the diaphanous intermediary[10].

It is clear that Fourier considered himself the Newton of heat: 'The principle of heat penetrates, like gravity, all objects and all of space, and it is subject to simple and constant laws'. As an example of these laws, he cited the distribution of solar heat over the globe: the daily, yearly and longer periodic variations that heat both the surface and the interior of the Earth, which cause variations beneath the surface and control the grand movements of the oceans and the atmosphere. For Fourier the analytical theory of heat constituted a 'rational law of atmospheric motion, ocean motion, change of seasons, and so on – a grand geophysical law confirmed in the laboratory and expressed by calculus'[11].

Citation patterns

In 1836 the physicist C.S.M. Pouillet, following in Fourier's tradition, wrote a memoir on solar heat, the radiative effects of the atmosphere, and the temperature of space. Tenth on his list of 16 related objectives was to determine the 'general conditions of equilibrium of temperature of a body protected by a diathermanous covering analogous to the atmosphere'. Pouillet argued that the equilibrium temperature of the atmosphere must be higher than the temperature of outer space and lower than the temperature of the Earth's surface. This was mainly because the atmosphere exerts 'unequal absorbing actions' on 'rays of heat derived from space' as well as those emitted from the Earth's surface. He credited Fourier with this insight, which was based on earlier experimental work by Saussure:

> M. Fourier is, I think, the first who has had the idea of regarding the unequal absorption of the atmosphere as exercising an influence on the temperatures of the soil. He had been led to this by the beautiful experiments made by De Saussure, in 1774, on some elevated summits of the Alps and in the adjacent plains, with a view to compare the relative intensities of solar heat. On that

occasion [1824] M. Fourier states in a precise manner one of the principles which have served me to establish the equations of equilibrium[12].

Pouillet compared the atmosphere to experiments he had done on solid and liquid diathermanous screens, for example, panes of glass and layers of water, concluding that 'the atmospheric stratum acts in the manner of screens of this kind, and ... exercises a greater absorption upon the terrestrial than on the solar rays'. He called this the 'effect of diathermanous envelopes'. Pouillet, however, had not arrived at a final theory of terrestrial temperatures. Like Fourier, Pouillet was also quite interested in what was called 'the temperature of space' and the quantities of heat the Earth received from the Sun, from space, and from other 'celestial bodies', factors that we have shown were more central to the theory of terrestrial temperatures than was the greenhouse effect.

John Tyndall referred to Fourier's work in his 1861 essay 'On the Absorption and Radiation of Heat by Gases and Vapours'. Tyndall credited Fourier and others with the notion that 'the interception of terrestrial rays [by the atmosphere exercises] the most important influence on climate'. By now, however, Tyndall had identified a mechanism. His laboratory experiments showed that water vapor, although transparent to light rays, was the best absorber of 'calorific rays' and that 'every variation of this constituent must produce a change of climate'. He thought similar effects could be caused by carbon dioxide and by 'an almost inappreciable admixture of any of the hydrocarbon vapours'. Without venturing quantitative estimates, he suggested that changes in the amount of radiatively active gases in the atmosphere could have produced 'all the mutations of climate which the researches of geologists reveal'[13]. In his 1896 essay 'On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground', Svante Arrhenius began the practice of citing Fourier's 1827 reprint as the first mention of the greenhouse effect: 'Fourier maintained that the atmosphere acts like the glass of a hot-house, because it lets through the light rays of the Sun but retains the dark rays from the ground[14]. Arrhenius's famous essay, more than any other, seems to be the proximate source of the misquotations and the tendency to conflate current and historical understandings.

Today many scientific review articles and textbooks contain brief historical allusions, typically drawn from secondary rather than original sources. This trend can be identified in recent citations of Fourier's work. In a 1988 review essay, V. Ramanathan, an authority on atmospheric radiation, cited Fourier's 1827 article, claiming, 'The greenhouse effect of the atmosphere was pointed out, perhaps for the first time, by Fourier, who also suggested that human activity can modify climate'[15]. Again in 1988, Ramanathan repeated the claim that perhaps Fourier's 1827 article was a famous first:

> Fourier's (1827) paper is basically a discourse on the processes governing the heat balance of the atmosphere, the surface, and the interior of the Earth. Fourier pointed out that the atmosphere behaves like the transparent glass cover of a box (exposed to the sun) by allowing sunlight to penetrate to the Earth's surface and retaining the longwave radiation (or 'obscure radiation' according to Fourier) from the Earth's surface. This inference is perhaps one of the earliest suggestions of the now well-known greenhouse effect of the atmosphere[16].

M.D.H. Jones and A. Henderson-Sellers cited Ramanathan rather than Fourier in their 1990 article, 'History of the Greenhouse Effect', asserting the following:

> The French physicist, Fourier, was probably the first person, in 1827, to allude to the greenhouse effect when he compared the influence of the atmosphere to the heating of a closed space beneath a pane of glass[17].

In *Dead Heat*, Michael Oppenheimer and Robert Boyle also cited Fourier's 1827 article but severely garbled the citation[18]. In their notes the authors quoted an English translation of a section of Fourier's article that, although relevant, does not mention the greenhouse effect directly and that stops just short of Fourier's important statement that 'the effect of solar heat upon air confined within transparent covers has long since been observed'[19]. Ian Rowlands repeated this error in his otherwise excellent book, *The Politics of Global Atmospheric Change* (1995); he briefly cited the 1827 article and cited it wrongly in his notes in a way very similar to Oppenheimer and Boyle. History was not his focus, however; he covered the 130 years from Fourier to Roger Revelle in one page[20].

Revelle himself alluded broadly to Fourier's pioneering work on the greenhouse effect but did not give references; William Kellogg cited Revelle. Wilfrid Bach said Fourier (1827) '[w]as probably the first to discuss the CO_2 [*sic*]/ greenhouse effect and compare it with the warming of air isolated under a glass plate'. Never mind that the radiative properties of CO_2 were not investigated until the mid-19th century[21].

Spencer Weart, a historian of physics, cited Fourier (1827) and claimed that the greenhouse effect was 'discovered' in 1896 by Arrhenius. His article, a stimulating comparison of nuclear issues and global warming, followed the established pattern of citing Fourier: 'In 1827 [*sic*], French physicist Jean-Baptiste Fourier had suggested that the Earth is kept warm because air traps heat, as if under a pane of glass'[22].

Mark Handel and James Risbey have improved the situation somewhat by noting that Fourier's essay was in fact published in 1824 and reprinted in 1827. The following annotation appears in their very helpful bibliography:

> This was the first paper to qualitatively describe the greenhouse effect. Compares the effect of the atmosphere of the earth to that of a pane of glass covering a bowl. (It is easier to find the 1827 version than the nearly identical 1824 version. In French. No known published translation, though unpublished ones exist.)[23]

Several corrections are in order here. Both the *Annales de Chimie et de Physique* and the *Mémoires de l'Académie Royale des Sciences de l'Institut de France* are easy to find in most major libraries. The 1827 article also appeared in the *Oeuvres de Fourier*, a readily available source[24]. As mentioned earlier, an English translation of Fourier's 1824 essay, by Ebeneser Burgess, was published in the *American Journal of Science* for 1837.

As I have demonstrated, Fourier's article of 1824 was not the first in which he mentioned the behavior of greenhouses. Nor was this article in essence about the greenhouse effect. According to Jones and Henderson-Sellers, 'the history of the greenhouse effect is not well known outside the atmospheric sciences'[25]. We may also safely say that it is not well known inside the atmospheric sciences.

Conclusion

Understanding of Fourier's scientific worldview has steadily eroded over the years and is just now being recovered. His article of 1827, cited by Arrhenius and by many others since as containing the 'first' allusion to the greenhouse effect, was merely a reprint of a descriptive memoir published three years earlier. Moreover, Fourier did not actually use the term 'serre' (greenhouse) in his essay of 1824 in which he discussed the behavior of the heliothermometer. For Fourier the 'temperature of space', more than the 'greenhouse effect', was a primary factor controlling terrestrial temperatures. Those seeking to understand Fourier's scientific contributions must be willing to look well beyond the secondary literature and well before 1827 to place his quest for a universal theory of terrestrial temperatures in the context of his work on the analytic theory of heat.

Notes and references

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18 Oppenheimer, M. and Boyle, R.H. (1990) *Dead Heat: The Race Against the Greenhouse Effect*, p. 34, Basic Books. They provide the following citation on p. 222, Fourier, J. (1824) [*sic*] Les temperatures [*sic*] du globe terrestre et des espaces planétaires, *Memoires* [sic] *de L'Academe* [sic] *Royal des Sciences de L'Institut de France* 7, 569–604. The correct citation is given in Ref. 2

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