

UNDERSTANDING EUNICE FOOTE'S 1856 EXPERIMENTS:
HEAT ABSORPTION BY ATMOSPHERIC GASES

by

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The contribution of Eunice Foote (1819–1888) to early understanding of the relationship between atmospheric gases and climate change has become a focus of interest in the scholarly community and more widely on social media. In this article we offer a detailed interpretation of both of her known published papers, focusing particularly on her first and most significant paper of 1856, in which she related changes in the types and amounts of atmospheric gases, including carbon dioxide, to warming and changes in climate. We trace the derivation of her ideas and explore how she constructed, carried out, and interpreted her experiments.

Keywords: Eunice Foote; heat absorption by atmospheric gases;
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INTRODUCTION

Eunice Newton Foote (1819–1888) was an American whose scientific work has been rediscovered only in the last decade.¹ Based on published experiments, she suggested that

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¹ R. P. Sorenson, 'Eunice Foote's pioneering work on CO₂ and climate warming', *Search and Discovery* article #70092 (2011), http://www.searchanddiscovery.com/pdfz/documents/2011/70092sorenson/ndx_sorenson.pdf.html (accessed 18 April 2020);

M. Darby, 'Meet the woman who first identified the greenhouse effect', <http://www.climatechangenews.com/2016/09/02/the-woman-who-identified-the-greenhouse-effect-years-before-tyndall/> (accessed 18 April 2020). The paper by Sorenson includes a contemporary description of Joseph Henry's reading of Eunice Foote's paper at the meeting of the American Association for the Advancement of Science in August 1856. That report was published by David Ames Wells (ed.), *Annual of Scientific Discovery or Year-book of Facts in Science and Art for 1857* (Gould & Lincoln, Boston, 1857), pp. 159–160. It corroborates the report that was written in *Scientific American*, which we refer to in this article, but it may be based on newspaper articles such as that in the *New York Tribune*: 'Section of physics and mathematics', *New York Daily Tribune*, 26 August 1856, p. 7. It provides a few more details, and is consistent with the geological link we examine here, although it goes into fewer details than the *Scientific American* piece. It also makes reference to

greater amounts of carbon dioxide (CO₂) in the atmosphere would increase Earth's temperature.² This statement was made in 1856, five years before John Tyndall (*ca* 1822–1893) made the same suggestion,³ though it has been argued that it is unlikely that he was aware of her work.⁴ Foote published just two known papers, in 1856 and 1857, before her family responsibilities and wider interests in women's rights and as an inventor cut short any further scientific research. Indeed, these are the only two papers in physics published by any American woman before 1889.⁵ Eunice Foote had formal training in science, which she obtained while studying at the Troy Female Seminary, now the Emma Willard School, and by taking classes at a nearby men's science college that would later become Rensselaer Polytechnic Institute,⁶ but she did not have the advantage of an extensive experience or training in experimental physics. This is partly a consequence of the gender norms of her time, and partly of the relatively under-developed state of research in physics in the USA at the time compared with Britain and Europe.⁷

Although Eunice Foote's two papers have previously not been critically discussed in detail, the first, and to a lesser extent the second, have sparked considerable online discussion. Yet they are important not only for our understanding of the history and origins of atmospheric and climate science, but also for foregrounding the contributions of a remarkable woman whose work has been overlooked until recently. We examine both her publications, and contemporary writings about them, to try to reconstruct her thinking and the nature and significance of her experimental results. Elisha Foote (1809–1883), Eunice's husband, also conducted experiments on solar radiation at the time that she was conducting her work. Elisha Foote presented his work at the August 1856 meeting in Albany of the American Association for the Advancement of Science (AAAS), their 10th meeting. Eunice's paper was also presented at the same meeting, but according to a contemporary newspaper report the work was read by Joseph Henry, the first Secretary of the Smithsonian Institution,⁸ which both contemporary and modern science writers agree is an example of the unequal gender norms of the time. However, there is no mention of either paper in the proceedings of the meeting. Neither paper is published by the AAAS nor is either mentioned in the extensive list of papers presented, but not published.⁹ Elisha was, however, elected as a

greater water vapour in the atmosphere over the ocean giving rise to moist air in response to temperature-driven evaporation. Sorenson was not aware of the actual papers that Foote had written, and thus could not be sure how much of what was written by Wells could reliably be attributed to her. He also thought that her work was only an oral presentation and thus forgotten for that reason. See also, e.g., K. Hayhoe, 'John v Eunice - a fascinating tale of early climate science, women's rights and accidental poisoning', 2 September 2016, <https://m.facebook.com/katharine.hayhoe/posts/1744016609156552> (accessed 21 April 2020); J. Halpern (E. Rabett), 'On Edith Foote's Experiment', *Rabett Run* [weblog], 2 May 2018, <http://rabett.blogspot.com/2018/05/on-edith-footes-experiment.html?m=1> (accessed 21 April 2020).

2 Eunice Foote, 'Circumstances affecting the heat of the sun's rays', *Am. J. Sci. Arts* **22**, 382–383 (1856).

3 J. Tyndall, 'The Bakerian Lecture: On the absorption and radiation of heat by gases and vapours, and on the physical connexion of radiation, absorption, and conduction', *Phil. Trans. R. Soc. Lond.* **151**, 1–36 (1861), at pp. 28–29.

4 R. Jackson, 'Eunice Foote, John Tyndall and a question of priority', *Notes Rec.* **74**, 105–118 (2020).

5 *Ibid.*, p. 117.

6 J. Hecht, 'Something's a-Foote with climate science history', *Photonics Focus* **1**, 18–19 (2020), https://spie.org/news/photonics-focus/marapr-2020/tyndall-foote-and-the-greenhouse-effect?utm_id=zrdz&SSO=1 (accessed 21 April 2020).

7 Jackson, *op. cit.* (note 4), p. 118.

8 'Scientific ladies—experiments with condensed gases', *Scient. Am.* **12**, 5 (1856). See also *New York Daily Tribune*, 26 August 1856, p. 7.

9 *Proceedings of the American Association for the Advancement of Science. Tenth Meeting. Held at Albany, New York, August, 1856* (Joseph Lovering, Cambridge, MA, 1857), p. 222. It is the versions in the *American Journal of Science and Arts* that state where the papers were presented. Many papers are listed in proceedings of the meetings as presented but not received or published.

member of the AAAS in 1856.¹⁰ He remained a member until the 14th meeting in 1861 but does not appear in the list of members for the 15th meeting in 1866 (after the American Civil War). Eunice Foote is not listed as a member for any of these meetings.¹¹ Eunice Foote's first paper, 'Circumstances affecting the heat of the sun's rays', was nevertheless published in the *American Journal of Science and Arts*,¹² immediately following the paper by her husband, Elisha Foote 'On the heat in the sun's rays'.¹³ Elisha's paper, but not Eunice's, was then republished in the *Philosophical Magazine* in Britain.¹⁴ However, Eunice's second paper, 'On a new source of electrical excitation', also read by Henry to the AAAS Meeting in Montreal in 1857, was published in the *Proceedings of the AAAS*, the first by a woman.¹⁵ A shorter version was published in the *American Journal of Science and Arts*.¹⁶ Unlike her first paper, this version was then republished in the *Philosophical Magazine*.¹⁷ We remark on the differences between versions below. In addition to this evidence, we consider a report of her first paper published in the September 1856 issue of *Scientific American*,¹⁸ based on the oral presentation of her work by Joseph Henry at the AAAS meeting in August 1856.

EXAMINING FOOTE'S PAPERS

Foote's first paper, 'Circumstances affecting the heat of the sun's rays', from 1856, dealt with the influence of concentration and composition on the warming of atmospheric gases. Her second paper, 'On a new source of electrical excitation', from 1857, evaluated the impact of moisture and gaseous composition on the ability of air to generate static electricity, which she referred to as 'electrical excitation'. We start with her second paper from 1857, as published in the *American Journal of Science and Arts* and in the *Philosophical Magazine*. This paper provides an early, experimental description of the effect of a pressure-driven change on the static electricity of air, presumably due to the effect that the adiabatic temperature change has on gaseous moisture content. An adiabatic change is a pressure-induced change in temperature that arises without the addition or removal of heat. This change in temperature will thus alter the vapour pressure of water in the air.

10 *Op. cit.* (note 9), p. xlvii.

11 The first woman elected a member according to the *Proceedings of the AAAS* was Maria Mitchell, at the 4th meeting in 1850. The second was Almira Phelps, at the 13th meeting in 1859. No other woman is listed as a member before the Civil War.

12 Eunice Foote, *op. cit.* (note 2).

13 Elisha Foote, 'On the heat in the sun's rays', *Am. J. Sci. Arts* **22**, 377–381 (1856).

14 Elisha Foote, 'On the heat in the sun's rays', *Phil. Mag.* **13**, 167–172 (1857).

15 Mrs. Eunice Foote, 'On a new source of electrical excitation', in *Proceedings of the American Association for the Advancement of Science. Eleventh Meeting. Held at Montreal, Canada East, August, 1857* (Joseph Lovering, Cambridge, MA, 1858), pp. 123–126. Intriguingly, she is named here as Mrs. Eunice Foote, not Mrs. Elisha Foote, as she is called in the versions in the *American Journal of Science and Arts* and *Philosophical Magazine*. This is the first paper by a woman published in the *Proceedings of the AAAS*, and the only one before the Civil War. A paper by Miss Morris 'Remarks on the Seventeen year Locust' was communicated by Agassiz at the 4th Meeting in 1850, but was not received for publication. The third paper by a woman mentioned in the *Proceedings of the AAAS* is by Almira Phelps 'On the scientific and religious character of Edward Hitchcock', at the 15th Meeting in 1866. The paper was listed as read but not published. It was common for papers not to be received or published, but no other papers attributed to women are mentioned in the *Proceedings of the AAAS* up to this point. Three newspaper reports note that Foote's paper was read by Henry: *Chicago Daily Tribune*, 20 August 1857, p. 3; *New York Daily Tribune*, 17 August 1857, p. 6; *New York Daily Times*, 18 August 1857, p. 2. They name her respectively as 'Mrs. Foote', 'Mrs. Elisha Foote' and 'Mrs. Elisha Foote'. It is not clear from the reports whether she was present or not, though one imagines that it would have been mentioned if she were.

16 Mrs. Elisha Foote, 'On a new source of electrical excitation', *Am. J. Sci. Arts* **24**, 386 (1857).

17 Mrs. Elisha Foote, 'On a new source of electrical excitation', *Phil. Mag.* **15**, 239–240 (1858).

18 *Op. cit.* (note 8).

In this 1857 paper, Eunice Foote's opening line states: 'I have ascertained that the compression or the expansion of atmospheric air produces an electrical excitation.'

She goes on to explain:

My experiments with this apparatus have extended over about eight months, and I have found the action to bear a strong analogy to that of the electrical machine. In damp or warm weather little or no effect would be produced, whilst at other times, particularly in clear cold weather, the action would be so strong as to diverge the leaves of the electrometer to their utmost extent. *In warm weather when no action would be produced, I have attained the result by cooling the air artificially. A sudden expansion or contraction always increases the effect.* [Authors' emphasis]

She continues later:

Particularly should this be observed in the dry cold regions of our atmosphere above the effects of moisture and vapors; and it was established by the experiments of Becquerel as well as those of Gay Lussac and Biot^[19] that the electricity of the atmosphere increases in strength with the altitude.

It is evident that she had read the literature on atmospheric electricity, although we cannot tell exactly which papers, and she adds further references to observations by Humboldt (who worked with both Gay Lussac and Biot) described in his *Kosmos*, and by de Saussure. From these statements she understood that the amount of static electricity that she could generate in her device was related to the moisture content of the air. Likewise, she noted that she could alter the moisture content of the atmosphere by expanding or compressing the air. This is the effect that adiabatic cooling or warming has on air, as is currently taught to students. Adiabatic cooling and warming are tied to the concept of the ideal gas law, which was developed in 1834, slightly more than two decades before she published her first paper.

This second paper by Foote is notable for a further reason. The version published in the *American Journal of Science and Arts* and in the *Philosophical Magazine* omits a substantial portion that was presented to the AAAS in 1857 and published in the *Proceedings*. This section is concerned with terrestrial magnetism. Foote suggests, referring to the work of Humboldt and Edward Sabine, that the electrical excitations that pass round the Earth daily 'might explain the induced magnetism of the earth and the polarity of the magnetic needle'.²⁰ These positions would not be accepted as correct today, but demonstrate that she was engaged with the scientific literature of the time. She goes on to outline seven pieces of evidence that she felt supported her assertion: the connection between magnetic intensity and electric tension in the atmosphere; the regular increase in magnetic activity at certain times of day; Sabine's discovery of annual changes of terrestrial magnetism depending on the Earth's position relative to the Sun; the dependence

¹⁹ Becquerel described the 'electricity of the atmosphere' and its variation with height in a paper published in *Comptes rendus de l'Académie des Sciences* in April 1838. This was translated and reprinted as 'Instructions for the scientific expedition in the North of Europe. Part relating to the Phenomena of Electricity. Drawn up by M. Becquerel', *Ann. Electr. Magn. Chem.* **3**, 24–31 (1838). In this paper, Becquerel refers to the balloon ascent of Gay Lussac and Biot in 1804, in which they carried out a wide range of measurements, including on atmospheric electricity. The experiments are described in 'Aeronautics', *Encyclopaedia Metropolitana* **14**, 152–155 (1845).

²⁰ Mrs. Eunice Foote, *op. cit.* (note 15). In addition, one newspaper report stated that electrical excitation produced by condensation and rarefaction of the air was at that time 'a fact never heretofore proven', *New York Daily Times*, 8 August 1857, p. 2.

of magnetic intensity on the position of the Moon relative to the Sun; the diurnal variations of the declination of the magnetic needle dependent on the position of the Sun; the maximum of these variations changing sign at the equinox; and the extension of large magnetic disturbances to great distances. She ends the version of the paper published in *Philosophical Magazine* with an enigmatic statement: 'Other phaenomena, which it is believed may be traced to the same cause, will be the subject of another communication', but this third paper has not yet been found, and may never have been published.

We now move on to Foote's first paper of 1856. Joseph Henry, the Secretary of the Smithsonian Institution, presented this paper at the 10th Annual Meeting of the AAAS in August 1856, with a preamble and introduction that praised her expertise. Following that presentation, the September 1856 issue of *Scientific American* included her as the main subject in an article entitled: 'Scientific Ladies—experiments with condensed gases', a nod to Eunice Foote's 1856 experimental paper. Regarding Foote, the *Scientific American* article states: 'So highly gifted is this lady, and so profoundly versed in the sciences, that the late Prof. Caldwell, of Louisville, who had an opportunity of conversing with her, and also seeing her perform some experiments, declared "she was deeply acquainted with almost every branch of physical science."'21

One of the current criticisms of Eunice Foote's 1856 paper with respect to its relationship to understanding of the greenhouse effect is that the glass tubes that she used would allow some solar radiation to pass through, but not the longwave infrared (IR) radiation which is responsible for the atmospheric greenhouse effect. While Eunice Foote did not measure the natural greenhouse effect of the Earth's atmosphere by specifically using longwave IR (as Tyndall did), she did measure the heating of the experimental atmosphere trapped in her apparatus, which was acting like an actual greenhouse. The Earth's greenhouse effect is not generated by the IR radiation coming from the Sun. Incoming shortwave solar radiation is transformed into longwave, outgoing IR radiation (heat) when photons interact with surfaces or gases and are radiated into the atmosphere or lost to space. In the upper atmosphere, some of the longwave IR radiation is then absorbed by greenhouse gases in the atmosphere, and radiated back to the surface, involving both direct molecular-scale vibrational processes, and indirect global-scale, climate feedbacks. As the glass on Eunice Foote's experimental apparatus blocked incoming longwave IR, it would also have blocked outgoing IR generated within the vessel from exiting the device by transmittance. As a result, the gases in the interior would warm, including in response to their greenhouse warming potential, losing heat by conduction through the glass, following a natural logarithmic response. As can be seen from the results below, this explanation fits the observations reasonably well. To be clear, Foote did not explicitly theorize or investigate what we now call the greenhouse effect. While the data from Foote (1856) do not provide a direct measure of the full, natural greenhouse effect, they do provide a measure of the heating resulting at a molecular scale owing to the absorption and radiation of heat by the gases, including what we now know are greenhouse gases—carbon dioxide and water—in her experimental atmosphere.

For her opening line in the 1856 paper, Eunice Foote states: 'My investigations have had for their object to determine the different circumstances that affect the thermal action of the rays of light that proceed from the sun.'²²

21 *Op. cit.* (note 8).

22 Eunice Foote, *op. cit.* (note 2).

Remarkably, the contemporary article in *Scientific American*, published in September 1856, just one month after Eunice Foote's paper was presented at the 1856 AAAS Meeting provides evidence of the motivation for her experiments:

Our constant readers will remember that several articles from different persons appeared in the last volume of the SCIENTIFIC AMERICAN, relating to solar heat at the surface of the earth. The question was introduced by Wm. Partridge, of Binghamton, who took the position, that density of the atmosphere, and not the angularity of the sun's rays, was the principal reason why it was warmer in valleys than on the tops of mountains.^[23] His views were opposed by other correspondents, but none of them supported their opinions with practical experiments to decide the question; this we are happy to say has been done by a lady. A paper was read before the late meeting of the Scientific Association, by Prof. Henry for Mrs. Eunice Foot [*sic*], detailing her experiments to determine the effects of the sun's rays on different gases.^[24]

This contemporary account written in *Scientific American* documents that Eunice Foote's experiments were conducted to address a scientific question regarding whether the heat of the Sun's rays at the surface was affected by the density of the air. She went further to explore how the composition of the air could also affect heating.

Based on her writings, the scientific questions that she seeks to answer are:

1. Does the concentration of gas in the atmosphere affect its warming response to the Sun's rays?
2. Does the composition of the gas in the atmosphere affect its warming response to the Sun's rays?
3. Can the effect of different gases on the warming response of the Sun's rays be ranked?

Unlike John Tyndall, she did not address *how* or *why*, related questions that would get at the specifics of the mechanisms related to the effects that she observed in nature and which motivated her experimental designs, but her experiments do effectively answer the three questions above.

FOOTE'S EXPERIMENTAL DESIGN

The experiments described in the 1856 paper exhibit a sophistication in their construction, although she leaves many unfortunate gaps in the descriptions of her underlying theoretical approach, methods and results. At just two pages, the paper is rather short, providing few insights on the experimental apparatus. The 1856 report in the *Scientific American* article more fully describes her apparatus as 'an air pump and two glass receivers of the same size—four inches in diameter and thirty in length'.²⁵ A thermometer was placed inside each of the tubes to measure its temperature.

The equipment used in the 1857 experiments on electrical excitation differed somewhat from the equipment employed in the 1856 paper, but its use is more fully described:

23 See W. Partridge, 'The rays of the sun', *Scient. Am.* **11**, 219 (1856); PERDEX, 'Philosophical Inquiry', *Scient. Am.* **11**, 162 (1856); 'The rays of the sun', *Scient. Am.* **11**, 188 (1856).

24 Anonymous, *op. cit.* (note 8).

25 *Ibid.*

The apparatus used was an ordinary air-pump of rather feeble power adapted either to compress or exhaust the air. Its receiver was a glass tube about twenty-two inches in height and three in diameter, with its ends closed by brass caps cemented to it. At the bottom was a stop-cock and a screw by which it was attached to the air pump.^[26]

She goes on to describe the electrical components of the apparatus and then to discuss the research that she conducted over the course of eight months and during which she experimented with placing the equipment under vacuum or compression and swapping the atmosphere within the glass tubes for oxygen gas, dry or damp air, and carbonic acid gas (CO₂ gas). The devices from the two papers are not the same size, but she uses them to manipulate gases in the same manner in both experiments. Given the timeframe of the two studies, which are just months apart, it seems likely that the experimental device used in the 1857 paper is a variation of the device used in the 1856 paper.

It is possible that she conducted the experiments at the same time, or that she devised and built the second apparatus after the completion of the work of the first study. The first paper was published in November 1856, but we know that it was presented in August 1856. That would provide enough time to conduct a study of about 8 months for the second paper, assuming a quick turnaround for the publication of the second paper in November 1857.

Analysing the data, we have worked out a way to estimate the uncertainty of the measurements from her apparatus, and the mean temperature at the start of the 1856 experiments. We can also calculate and compare the temperature changes and relative warming for her different experimental atmospheres.

The experimental measurement design was paired as a means of comparing the heating effect of two states on the enclosed gas atmospheres. The pairing design was well conceived, indicating that she understood the importance of a control and experimental treatment to be able to discern an effect experimentally. She also notes the importance of building the two experimental glass vessels as similarly as possible to minimize experimental bias.²⁷

Her pairing design included several factors. She focused on full sun versus shaded measurements, exhausted (vacuum) versus condensed air, dry versus damp air, and common air (ambient atmosphere at observed temperature and pressure) versus carbonic acid gas (CO₂), but her experimental design also allowed the following comparisons: exhausted (vacuum) versus common air (atmospheric pressure), and common air versus compressed air.

The relative effect of each of these gases or atmospheric mixtures can also be compared, but to a limited extent, as we describe below.

FOOTE'S RESULTS AND CONCLUSIONS

First result

'My investigations have had for their object to determine the different circumstances that affect the thermal action of the rays of light that proceed from the sun.'

'Several results have been obtained.'

²⁶ Mrs. Elisha Foote, *op. cit.* (note 16).

²⁷ Elisha Foote also stated in his paper that the two thermometers were 'procured as nearly alike as possible': Elisha Foote, *op. cit.* (note 13), p. 377.

‘First. The action increases with the density of the air, and is diminished as it becomes more rarified.’²⁸

Observations employed: This result is concluded based on comparison of the temperature data from the exhausted tube with the condensed tube.

Associated supposition:

‘This circumstance must affect the power of the sun’s rays in different places, and contribute to produce the feeble action on the summits of lofty mountains.’

Assessment: Her results here demonstrate appropriate transference. She reconstructed in the laboratory an experiment that allowed her to simulate changes in atmospheric pressure as a function of altitude and to infer how that would influence the warming of the atmosphere by the Sun’s rays. She is not able to recreate the experimental conditions at a specific altitude, but appropriately assesses the sign and direction of the effect. This result demonstrates an understanding that the mass of atmosphere present can influence its warming.

Second result

‘Secondly. The action of the sun’s rays was found to be greater in moist air than in dry air.’²⁹

Observations employed: This result is based on the comparison of the dry and damp air temperature runs.

Associated supposition:

‘The high temperature of moist air has frequently been observed. Who has not experienced the burning heat of the sun that precedes a summer’s shower? The isothermal lines will, I think, be found to be much affected by the different degree of moisture in different places.’

Assessment: Her result documents that she had concluded that the atmosphere warmed when additional water vapour was present, although her mechanistic understanding as to why was incorrect. Although she does not use the term, or explain the mechanism, her experiment is appropriately designed to allow her to measure the warming due to water vapour. She provides two suppositions to tie to these experimental results, which document her powers of abstraction. The first is the temporal change in temperature associated with a fall in humidity following an afternoon summer rainfall. This supposition is potentially incorrect because the change in temperature could be associated with moving atmospheric frontal boundaries. The second is planetary in nature. She notes that lines of constant temperature around the globe (isothermal lines) must be influenced by the degree of moisture in the atmosphere. This documents that she had an understanding of contemporary global geographic patterns of atmospheric moisture,³⁰ what we would today refer to as the results of the Hadley Circulation, with alternating bands of moist tropical and temperate rain forests, and deserts.

Third result

‘The highest effect of the sun’s rays I have found to be in carbonic acid gas.’³¹

²⁸ Eunice Foote, *op. cit.* (note 2).

²⁹ *Ibid.*

³⁰ It seems likely that this understanding came from her reading of Humboldt, to whom she refers in her second paper, though not in the first. Humboldt’s invention of isotherms is described in A. Wulf, *The adventures of Alexander Humboldt: the lost hero of science* (John Murray, London, 2015), pp. 177–179.

³¹ Eunice Foote, *op. cit.* (note 2).

Observations employed: This result is based on comparison of the common air (atmospheric pressure) and the carbonic acid gas (CO₂) temperature runs.

Associated supposition:

'The receiver containing the [carbonic acid] gas became itself much heated—very sensibly more than the other—and on being removed [from the sun], it was many times as long in cooling.'^[32] [Bracketed expressions added by authors for context]

'An atmosphere of that [carbonic acid] gas would give to our earth a high temperature; and *if as some suppose, at one period of its history* the air had mixed with it a larger proportion than at present, an increased temperature from its *own action* as well as from [the] *increased weight* [that] must have necessarily resulted.'^[33] [Italics and bracketed expressions added by authors for emphasis and context]

Assessment: Her result here allows her to infer correctly that under her experimental conditions, the carbonic acid gas (CO₂) produced the greatest warming effect. Her reference to the fact that the receiver with the carbonic acid gas (CO₂) became 'sensibly' heated indicates that she understood that temperature is a measure of sensible heat (as opposed to latent heat, the heat incorporated during a phase change for water). Her assessment that carbonic acid gas (CO₂) produced the greatest effect in these experiments is correct, but a limitation of this finding is that she did not know the pressure or concentrations of the various gases in her experiments beyond a general sense, with the exception that we will describe below. To be certain in this effect, one would need to set up the experiments such that the gases in the vessels had the same initial concentration or pressure for an accurate comparison. Despite this shortcoming, she clearly documented in her result that carbonic acid gas (CO₂) was effective at absorbing heat and thus warming the atmosphere that was present in her experimental receivers. She also noted that different atmospheric gases had different warming potentials.

Of particular interest are the suppositions that she draws from this observation of the heating effects of carbon dioxide in the atmosphere. She states that, if there were more carbonic acid gas (CO₂) in the atmosphere, the planet would be warmer. Because she started with an ambient atmosphere of gas at standard pressure and temperature, and to that added the carbonic acid gas (CO₂), her assessment that adding carbonic acid gas (CO₂) to the atmosphere would warm it beyond the 1856 level is correct. She also states that others have speculated that at one period of its history that there was likely more carbonic acid gas (CO₂) in the atmosphere.

She finally synthesizes the results from her experiments and concludes that this warming could have arisen not only from the composition of the carbonic acid gas (CO₂) 'from its own action', but also because of the 'increased weight', or mass of an atmosphere with this added gas present.³⁴ Unfortunately, she did not carry out further experiments that might have allowed her to control for these two variables and make a specific estimate for warming due to carbon dioxide alone.

The use of 'period' and 'history' indicates that she is almost certainly discussing changes over geologic time. Was she making the intuitive leap that she had observed that

32 *Ibid.*

33 *Ibid.* Emphasis added.

34 *Ibid.*

carbonic acid gas (CO₂) can warm an atmosphere in her experiments and that there was prior evidence of warm periods in Earth history, and thus linking the two concepts? Or was she testing an assertion that someone else had made that carbonic acid gas (CO₂) was abundant in the atmosphere during past periods in Earth history? The contemporary description of the significance of her work, written in *Scientific American*, addresses these questions of motivation.

It is believed and taught by geologists that during [the Devonian] the period preceding the carboniferous era,—when the coal bed materials were forming—that the atmosphere of the earth contained immense quantities of carbonic acid [CO₂], and that there was a very elevated temperature of atmosphere in existence, in comparison with that of the present day. Those who believe that this earth was once a fiery ball, attribute this ancient great atmospheric heat to the elevated temperature of the earth; but Mrs. Foote's [*sic*] experiments attribute it to a more rational cause, and leave the Plutonists but a small foundation to stand upon for their theory.³⁵ [Bracketed expressions added by authors for context]

This remarkable passage provides further insight into Eunice Foote's motivation for her experiments, and it explains the status of contemporary geological thinking regarding the history of the Earth and the factors that influenced the warming of its atmosphere. The 1856 *Scientific American* article, which discusses the contribution of women to the advancement of science, and Eunice Foote in particular, states that Eunice Foote's 1856 paper is the earliest known, experimentally verified statement that carbon dioxide concentrations in the atmosphere lead to global warming and can explain warm periods in the geologic past. It also makes it clear that Eunice Foote designed her experiments to test that hypothesis.

The *Scientific American* article provides a rare glimpse into early nineteenth century understanding of climate change in the geologic past, which has perhaps not been widely appreciated in recent years. Geologists at the time surmised that past periods of the Earth were warmer than their time: the Transitional, Secondary and Tertiary, which encompass much of what is now referred to as the Phanerozoic. These conclusions were drawn based on the flora and fauna that had been discovered in association with geologic strata globally: the widely distributed fossils of tree ferns and tropical-like vegetation were taken as evidence of past warm conditions.³⁶ The time in which Eunice Foote was working was coincident with the discovery of dinosaurs, which at the time were thought to be enormous, cold-blooded reptiles that lived in warm, moist, swampy environments. Certainly the earliest dinosaur papers make note of ferns and other tropical vegetation that was found in the same strata.³⁷ As we see from the *Scientific American* article, the Plutonists thought that the warmer temperature of the Earth in these early times emanated from the internal, residual heat that remained after its formation, releasing noxious and humid vapours that contributed to a dense, moist and warm environment. Franz Unger (1800–1870), the Austrian botanist and geologist, in his 1851 *Primitive worlds*,³⁸ collaborated with landscape painter, Josef Kuwasseg (1799–1859), to illustrate a pictorial

³⁵ Anonymous, *op. cit.* (note 8).

³⁶ W. Buckland, 'XXI.—Notice on the Megalosaurus or the great Fossil Lizard of Stonesfield', *Trans. Geol. Soc. Lond.* **S2-1**, 390–396 (1825); G. A. Mantell, 'Notice on the Iguanodon, a newly discovered fossil reptile, from the sandstone of Tilgate forest, in Sussex', *Phil. Trans. R. Soc. Lond.* **115**, 179–186 (1825).

³⁷ G. A. Mantell, *Petrifications and their teachings; or, a hand-book to the gallery of organic remains of the British Museum* (Henry G. Bohn, London, 1851).

³⁸ F.-X. Unger, *Die Urwelt in ihren verschiedenen Bildungs-perioden. 14 landschaftlichen Darstellungen mit erläuternden Text. Le monde primitif à ses différentes époques de formation. 14 paysages avec text explicatif* (Beck, Vienna, 1851).

folio atlas of the geologic past. Unger wrote the explanatory text for the folio based on the current scientific understanding, which postulated that volcanic eruptions emitted humid vapours and carbonic acid (CO₂) gas, which gave Earth the warmer conditions and the CO₂ 'food' needed for ancient plants, dinosaurs and other early animals to thrive:

Small, damp islands, covered with forests inhabited by the greatest and most terrible monsters of the ancient world: such are the scenes which this formation offers to the artist, judging from scientific researches already made. An atmosphere filled with humid vapours and exhalations of carbonic acid was as favourable to this prodigious propagation of the amphibious races, as to the development of Ferns, Cycadeae, Coniferae, and of some Monocotyledons.

The contemporary early nineteenth century work of Franz Unger, which is explored in Rudwick's 1992 book, *Scenes from deep time*,³⁹ corroborates the statements from the *Scientific American* article regarding connections between a dense atmosphere, water vapour, and global warmth. Geologists of the time thought that there were higher concentrations of carbon dioxide in the moist warm past atmosphere, particularly during the Carboniferous Period, but they felt that the water vapour was the cause of the warmth, while the carbon dioxide provided the food for the lush vegetation that gave rise to the vast coal deposits of the Carboniferous Period.⁴⁰

Eunice Foote's experiments tested the hypotheses that increasing atmospheric density and moisture, and the addition of carbon dioxide to the atmosphere warmed it, settling the argument in the contemporary eyes of the writer of the *Scientific American* article. Our modern understanding of volcanic eruptions and their effect on climate documents that sulfate aerosols provide a short-term cooling while carbon dioxide release yields a longer-term warming. While on deep time, tectonic timescales, continental position, seafloor spreading rates, weathering rates and carbon dioxide fluxes dominate the long-term climate trend, aside from catastrophic events, carbon dioxide fluxes by volcanoes are now thought to provide less of an influence on natural climate variability than biospheric processes modulated by orbital variations on Croll–Milankovitch and shorter timescales. Our modern understanding of climate change and observations now also document that the continued burning of fossil fuels, industrial activity and land use changes by human activity, which began during the Industrial Revolution, have warmed the planet considerably, consistent with Eunice Foote's now particularly relevant 1856 paper.

Final result

'On comparing the sun's heat in different gases, I found it to be in hydrogen gas, 104 deg [F]; in common air, 106 deg. [F]; in oxygen gas, 108 deg. [F]; and in carbonic acid (CO₂) gas, 125 deg. [F].'^[41] [Bracketed expressions added by authors for context]

Assessment: This is a tantalizing final statement for several reasons. It makes it clear that there were additional experiments that she conducted, but which are not tabulated. She makes

³⁹ M. J. S. Rudwick, *Scenes from deep time: early pictorial representations of the prehistoric world* (University of Chicago Press, 1992).

⁴⁰ See, e.g., Alonzo Gray, *Elements of geology* (Harper & Brothers, New York, 1853), pp. 269–270; Samuel St John, *Elements of geology* (G. P. Putman & Co., New York, 1854); David Ames Wells, *First principles of geology* (Iverson, Phinney & Co., New York, 1861).

⁴¹ Eunice Foote, *op. cit.* (note 2).

no other reference to experiments with hydrogen or oxygen gas in the 1856 paper, although she mentions experimenting with water vapour, hydrogen and carbonic acid (CO₂) gases in her 1857 paper as well. She also did not include any of these final measurements in her earlier experimental result tables for common air or carbonic acid gas (CO₂), although both those final measurements are higher than the values given in the earlier tables. That suggests that these measurements were either later values from those same runs, or collected during a different series of experiments. Her earlier use of the term ‘from its own action’ documents that she understood that different gases had different warming effects, although she did not discuss a specific mechanism as to why that might be the case, aside from an increase in the density of the air.

Eunice Foote’s atmospheric warming hypothesis can thus be summarized as: The warming of the atmosphere by the Sun’s rays depends on the density of the atmosphere and the composition of the gases in the atmosphere. Foote stated that the lower atmosphere was warmer than the upper atmosphere owing to its density, and, as a corollary, that the addition of water vapour or carbonic acid gas (CO₂) to the atmosphere would further warm the air ‘by their own action’ beyond the density of the air. She also stated that temporal variations in carbonic acid gas (CO₂) explained the presumed warmer conditions of the Earth during the geologic past, thus recognizing the potential impact of carbon dioxide gas on climate. Foote’s hypothesis differs considerably from the modern greenhouse hypothesis, wherein greenhouse gases influence atmospheric warming.

It is not too surprising that her experiments indicate qualitatively that, of these gases, carbonic acid gas (CO₂) produced the greatest warming. It is now known that hydrogen and oxygen gases lack a greenhouse effect because of their inability to generate an asymmetric vibration, which gives rise to the molecular greenhouse effect in carbon dioxide, water vapour or other greenhouse gases. Unfortunately, no further information regarding the time-step or concentration is provided for the measurements cited in this final statement. How interesting it would be to find her laboratory books!

ADDITIONAL INTERPRETATIONS

What was the relative warming for each experimental case that Foote (1856) obtained? Our first effort is to establish the uncertainty of the temporal and temperature measurements generated by her apparatus. Her measurements were conducted using the Fahrenheit scale, and were reported to the nearest degree. But most modern scientific work is conducted in Celsius or Kelvin, which are identical in gradation, but differ in their zero points. As an initial analytical step, all observations are converted from Fahrenheit to Celsius.

We know that her measurements were collected at intervals of 2 to 3 min because she states in her 1856 paper: ‘The observations taken once in two or three minutes’. We can assume that indicates a mean time-step of 2.5 ± 0.5 min. Her experiments were thus conducted over 8 to 18 min depending on the number of time-steps she recorded, which varies by experiment. Figure 1 plots her experimental results as a function of time-step. The data are fitted logarithmically as a function of time-step, because heat transfer from a glass cylinder follows an exponential function. The exponential fits indicate that while the heat transfer was approaching steady-state—the point at which heat gain is balanced by heat loss—none of the experiments was run long enough to reach steady-state.

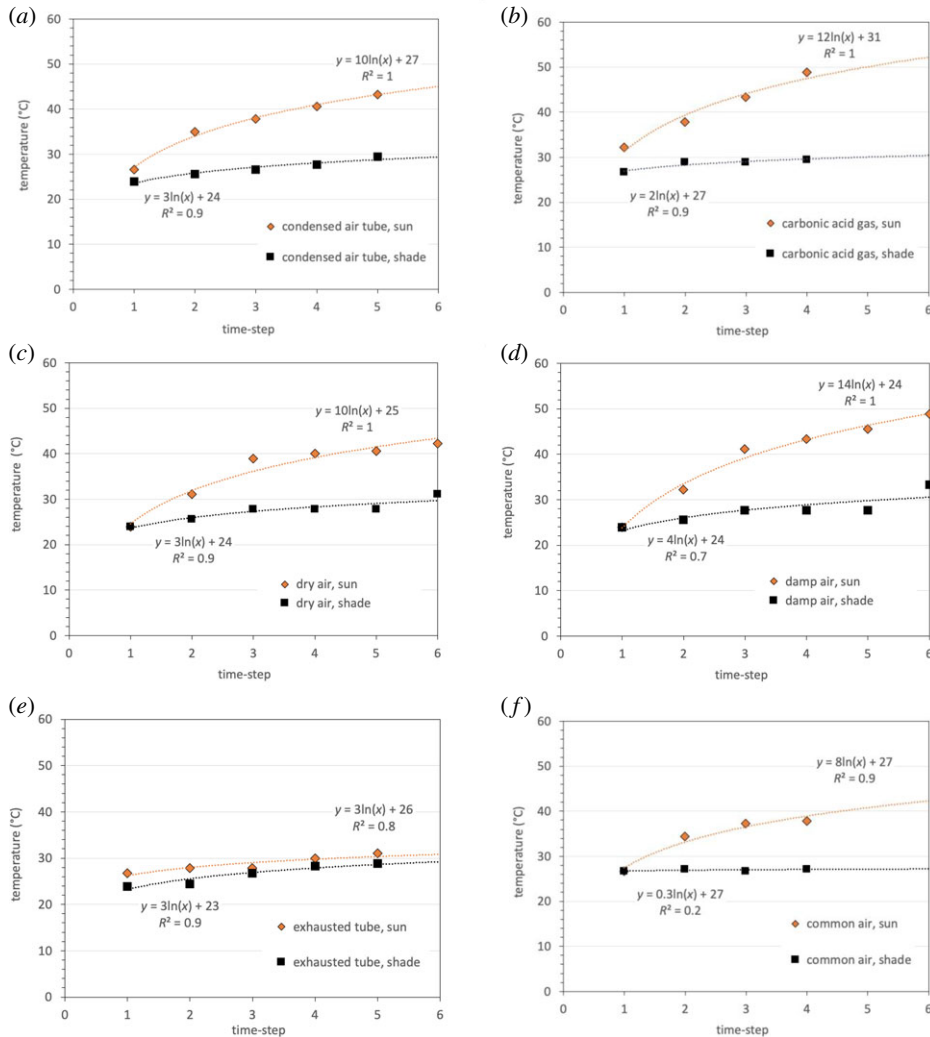


Figure 1. Paired logarithmic fits as a function of time-step relative to the temperature data (°C) from Foote (1856) (in sun and shaded) for (a) condensed air, (b) carbonic acid gas, (c) dry air, (d) damp air, (e) exhausted and (f) common air. The coefficients of determination (R^2) with values >0.95 are shown as $R^2 = 1$, to account for the significant figures available. The heights of the plotted symbols are the size of the $\pm 1^\circ\text{C}$ propagated error bars. (Online version in colour.)

The measurements from the shade experiments plotted as a function of time-step (figure 1) show that the results plot closely together.⁴² By fitting each of the shade series with a

⁴² Modern measurements of air temperature are always made in the shade to avoid direct heating by solar rays. Foote states that she waited for the two devices to equilibrate to the same temperature before starting to take measurements, then placed the tubes at the location where measurements were taken. Owing to the expansion or contraction of the air as she filled the tubes with various gases using the pump, she would likely have seen initial temperature differences. It is possible that she filled the tubes inside a building, then brought them outside to be placed separately in a shady spot or in direct sunlight to start the experiment. If that were the case, then the devices would warm up owing to the difference between the initial location where they equilibrated before they were placed at the start

logarithmic function, it is possible to remove the temporal offsets from the experimental runs. With this information, one can combine and obtain an estimate of the error in the experimental system. The standard error of the resulting temperature residuals can then be propagated, yielding an overall 3-sigma standard error of $\pm 1^\circ\text{C}$. Comparison of the paired data (shade vs sun) and those from the different gas experiments provides a way to quantify the warming effect observed in each series of experimental conditions.

ESTIMATING WARMING EFFECTS FROM THE PAIRED EXPERIMENTS

Eunice Foote's experimental design makes it possible to determine an estimate of the direct, molecular warming effect generated by each of the gases or atmospheres in her experimental setups, with the exception of hydrogen or oxygen owing to the incomplete data provided.

There are two critical pairs that we can compare quantitatively to assess the influence of density, within the limits of her experimental capabilities given the inherent design of her experiment. The key step that Eunice Foote made during her experiments was to evacuate the air from one of her experimental receivers and then compress that atmosphere into another receiver that started at room temperature and pressure. She also made measurements with common air, or the atmosphere at standard temperature and pressure. We know that her measurements were made in the spring or summer because the average temperature of her runs conducted in the shade was $75\pm 3^\circ\text{F}$ ($25\pm 1^\circ\text{C}$). These three cases enable us to experimentally compare the warming due to the composition of the spring or summer-time atmosphere measured in 1856 against the vacuum, and the 'doubled' 1856 spring or summer-time atmosphere generated by her pump. For historical reference, we note that climate scientists now estimate that the carbon dioxide content of the 1856 atmosphere was 286.2 ppm, so an upper limit on the carbon dioxide level in the doubled case would be <572.4 ppm,⁴³ though we cannot draw any quantitative conclusions from this.

Foote's experiments were not conducted for the same number of time-steps. To normalize these results, we fitted the experimental data with logarithmic fits. These natural logarithmic fits are then estimated for 4, 5 or 6 time-steps—the last three time-steps in her experimental runs—to assess the variability in the estimated values for the warming. Obtaining an estimate of the warming effect involves three temperatures and two differences. First, the average temperature for all the shaded measurements at each time-step is taken as the mean temperature of the field testing site at the time of the experiments. The average shaded temperature for each step is then subtracted from each of the experimental values made in the sun for time-step 4, 5 or 6, respectively. The second temperature residual is determined by subtracting the residual temperature (sun minus shade) for the common air experiment from each of the other experimental residuals. That second difference provides a measure of the warming effect of each case relative to that of common air, the ambient 1856 atmosphere. The observed paired temperature data for shade and sun for each experimental case are plotted in figure 1, along with the natural logarithm fits as a function of time-step that were used to interpolate and extrapolate the results for time-steps 4, 5 and 6.

of the experiment. We do know that she moved them to initiate the experiment. It is also possible that they warmed owing to the fact that the atmosphere could not escape from the tubes and thus took in heat from the diffuse lighting that was illuminating them even when they were in the shade.

⁴³ Meure C. MacFarling, D. Etheridge, C. Trudinger, P. Steele, R. Langenfelds, T. van Ommen, A. Smith and J. Elkins 'The Law Dome CO₂, CH₄ and N₂O ice core records extended to 2000 years BP', *Geophys. Res. Lett.* **33**, L14810 (2006).

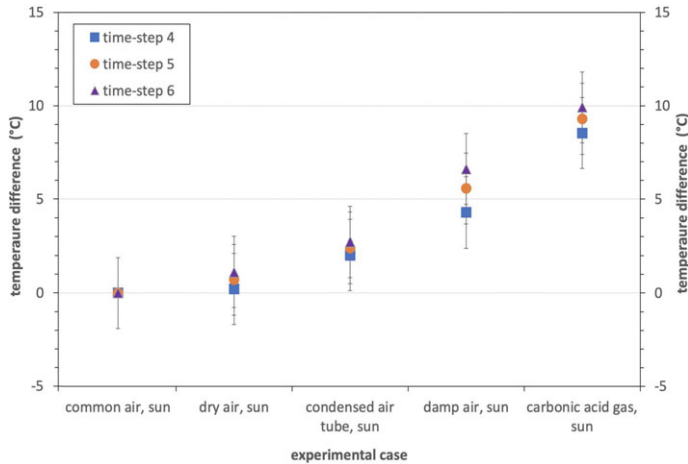


Figure 2. Experimental estimates of warming derived from Foote (1856), based on differences from logarithmically fitted values at time-steps 4, 5 and 6 relative to the common air case. (Online version in colour.)

The resulting comparison of the condensed run to the common air run gives an estimate for the warming effect of the ‘doubled’ 1856 atmosphere, within experimental errors. The other cases indicate whether their warming effects were greater than or less than the warming effect relative to common air, which serves as the zero point of reference for this calculation (figure 2). The estimate of the warming for the ‘doubled’ case calculated in this way ranges from 2°C, at time-steps 4 and 5, to 3°C, at time-step 6. The 3-sigma propagated standard error on these estimates, which includes more comparisons than the individual values, works out to $\pm 2^\circ\text{C}$. We can also evaluate the warming potential for the vacuum relative to the common air estimate. In these experiments, the temperature deviation of the exhausted tube (the vacuum run) ranged from -11 to -13°C depending on time-step.

The warming effects obtained from Foote (1856) qualitatively rank as one would expect given a modern understanding of radiative forcing. The dried-air run produced an estimate not very different from the common air run and less than the condensed air run, as would be expected from the pumping of atmosphere from one vessel into the other. The damp air run produced a greater effect than the dry air and condensed air run, and the carbonic acid gas (CO_2) run produced a higher effect than the damp air, as can be expected for the addition of a large volume of carbon dioxide to an atmosphere that already contained some water vapour and carbon dioxide.

SOURCES OF ERROR IN THESE ESTIMATES

From an experimental standpoint, there are several sources of error in the warming estimates. The experiments were run for a differing number of time-steps, and, while following a natural logarithmic function, did not flatten out entirely, indicating that they did not proceed sufficiently long to reach steady-state. They likely provide a transient experimental estimate of the direct molecular aspects of the warming associated with the absorption and radiation

of shortwave radiation by the asymmetric vibrational modes of the greenhouse gases trapped in the glass tubes and of other means of heat transfer into the gases. The experiments were conducted at the surface in a small experimental environment, on short timescales, where heat transfer from the walls of the apparatus into the gases is particularly important,⁴⁴ whereas the Earth's greenhouse effect occurs in the upper atmosphere where carbon dioxide radiates heat back to the surface and integrates global biogeochemical feedbacks on a variety of timescales. The 'doubled' atmosphere run may be potentially low in warming because the air pump was likely not able to reach a full vacuum, and thus probably left some atmosphere in the initial tube that was exhausted. Indeed, in the 1857 paper that Eunice Foote wrote following the 1856 study, she describes her air pump as 'feeble in its action'. That is no doubt an observation gained from months of experimental work with the device. We do not know how much water vapour was present in the ambient air during her experiments, although the fact that the common air run is indistinguishable in value from the dried air run (figure 2) suggests that the water vapour content was relatively low.

CONCLUSIONS

It is not straightforward to partition the physical effects measured by Foote (1856). Foote did not attempt this in the paper, as far as we know, and neither did Henry, who stated:

Prof. Henry, on concluding the paper, made some gallant remarks [in] regard to the ladies, and to Mrs. Foote in particular and added, that although the experiments were interesting and valuable, there were [many] [difficulties] encompassing [any] attempt to interpret their significance. It was a very delicate and intricate inquiry, well worthy the attention of investigation. With regard to the experiment which Judge Foote had suggested of producing the highest effects of the spyglass by throwing its focus upon a very highly [heated] object, it had already been tried by Dipret, who had thrown the light of a sunglass and burnished mirror on a point heated with a galvanic "flame", and had thus produced a very intense artificial heat ...^[45]

This explains Joseph Henry's perspective following his reading of Eunice's paper and after hearing Elisha's paper. He states essentially that her work was difficult to understand. But that could mean either that it was merely ambiguous, or alternatively that he simply did not comprehend the importance of what she had accomplished. The passage also provides some other important pieces of information. Eunice Foote was presumably present in the room when Henry read her 1856 paper, otherwise he would not have addressed her directly in this fashion. The initial phrase about 'gallant remarks in regard to the ladies and to Mrs. Foote' comes across as patronizing. These concluding remarks also potentially explain why the papers by Elisha and Eunice were not included in the AAAS *Proceedings*. Elisha's paper could have been deemed redundant and thus not an original contribution; Eunice's work may have been deemed a novelty that was uninterpretable. By contrast, the piece in *Scientific American* was effusive in its praise, suggesting that the author had an

⁴⁴ See, e.g., P. Wagoner, C. Liu and R. G. Tobin, 'Climate change in a shoebox: right result, wrong physics', *Am. J. Phys.* **78**, 536–540 (2010).

⁴⁵ 'Section of physics and mathematics', *New York Daily Tribune*, 26 August 1856, p. 7. The scan is of poor quality. Words given in square brackets are the authors' suggested readings of them.

enlightened attitude toward the capabilities of women. Aside from that piece and the newspaper accounts of the 1856 AAAS meeting, we have found only two other references to the work of Eunice Foote in the literature, in addition to the two eight-line summaries in British and German publications that do not appear to have been followed up at the time.⁴⁶ In 1857, David A. Wells, a science writer, republished a newspaper account of the reading of Foote's 1856 AAAS paper in the *Annual of Scientific Discovery*.⁴⁷ The second reference, also published by David A. Wells, in his 1861 textbook, *First principles of geology*,⁴⁸ is a restatement without attribution of the conclusion from Foote (1856) that an atmosphere rich in carbonic acid could explain the warm temperatures during the Carboniferous Period. Unfortunately, Wells did not cite Eunice Foote directly as the source of that finding, although he did cite other researchers by name or publication in the same text.

In principle, there are three processes by which Foote's gases may have been heated, and all may have been operative simultaneously. Foote does not discuss these. First, some of the shortwave IR from the solar radiation incident at ground level may have penetrated the glass and been absorbed by the gases. This process happens in the atmosphere, though it is not responsible for the greenhouse effect. Second, her apparatus will have been heated by the incident solar radiation. In turn, that heat would have been transmitted by conduction from the walls of her apparatus to the gases inside, and then by convection within the gaseous environment. This process is not responsible for the greenhouse effect.⁴⁹ Third, the gases and walls of her heated apparatus would have radiated longwave IR into her experimental atmosphere, which would then have been absorbed by the gases. This is the process that initiates the greenhouse effect in the atmosphere, followed by radiation of heat by the heated gases. To be clear, this paper does not claim that Foote gave any demonstration or explanation of the mechanism of the Earth's global, greenhouse effect. It was Tyndall, a few years later, who showed directly that gases including carbon dioxide can absorb and radiate longwave IR, and who used this to explain the physical basis of the greenhouse effect. What Foote did was to show that carbon dioxide can absorb heat, though she did not determine precisely what was responsible for the heating in her apparatus. She may have assumed, though she does not say so, that the gas was directly absorbing solar radiation, which happens in the atmosphere but is not responsible for the greenhouse effect. She may also have appreciated that the gas could be heated through transfer, by conduction and radiation, from the apparatus itself, which was heated up by the Sun. For our purposes, it is immaterial what precise mechanism was doing the heating. Foote showed that carbon dioxide could absorb heat and she made the reasonable supposition—prompted by geological evidence—that as a consequence, different amounts of carbon dioxide in the atmosphere might affect the atmospheric temperature and hence the climate.

The remarkable scientific work of Eunice Foote was lost to science for some 155 years from 1856 until 2011, when the first hint of its significance was uncovered by Raymond Sorenson. This study provides a reconstruction of her contribution to climate science in hindsight, based on her own publications and contemporary accounts of her work by those

46 See Jackson, *op. cit.* (note 4), p. 112 for more detail on this.

47 Wells, *op. cit.* (note 1). This is almost identical to the account in the *New York Daily Tribune*.

48 Wells, *op. cit.* (note 40), p. 242.

49 The significance of convection in explaining the observed results in experiments like Foote's is described in Wagoner *et al.*, *op. cit.* (note 44).

who recognized its significance. The article in *Scientific American*, written in 1856, summarized her contribution as follows:

The columns of the SCIENTIFIC AMERICAN have been oftentimes graced with articles on scientific subjects, by ladies, which would do honor to men of the highest scientific reputation; and the experiments of Mrs. Foote afford abundant evidence of the ability of woman to investigate any subject with originality and precision.⁵⁰

Foote's work is like a meteor. It shone brightly, then disappeared from view. From the analysis of her experiments, it is clear that Foote was the first to understand that changing amounts of gases such as carbon dioxide and water vapour in the atmosphere could change its temperature and hence the climate—what we now understand as the basis for the greenhouse effect. She carried out the first experiments that demonstrated the absorption of heat by these gases, which was a new discovery, and she confirmed her hypothesis. What she did not do, unlike Tyndall, was to give a detailed physical explanation of her results, or to isolate and detect the physical basis of the Earth's greenhouse effect (the absorption and radiation of longwave IR in the upper atmosphere). Given her experimental arrangement, there are several factors that could have led to her observed temperature changes. That does not detract from the quality and significance of her early contribution to climate science. Though her work did not become part of the history of climate science until recently—only a few references to her experiments and some newspaper articles have so far been found in the decades following her discoveries—we can now do justice to the short scientific career of a remarkable figure.

ACKNOWLEDGEMENTS

The significance and meaning of Eunice Foote's work is currently much discussed on social media. We thank Sarah Myhre, whose tweet on this topic brought the authors together and led to this interdisciplinary collaboration. We appreciate the written contributions of many others who have contributed through social media and related ways, including Katharine Hayhoe, Joshua Halpern and John Perlin, we thank Cyril Hilsum for exchanges that helped point out the complexities of interpreting Foote's experiments, and we thank the two anonymous referees who suggested helpful ways of improving this paper. We thank Michael Hawkins and Joe Cain, whose suggestions led the authors to evidence about discussions on climate, atmosphere, natural history and geology in the early nineteenth century, Norma Rosado-Blake (AAAS Archivist and Records Manager) for specific information on Eunice Foote and the 1856 AAAS meeting, and Beth Hylan (Reference and Education Librarian at The Rakow Library of the Corning Museum), who provided access to scanned archive material with glass formulas from the mid-1800s and other resources on the composition and properties of scientific glass manufactured during the mid-1800s. We dedicate this paper to Eunice Foote and to other women scientists who left their fields of research, and were not able to fulfil their potential, owing to gender norms and societal pressures.

⁵⁰ *Op. cit.* (note 8).