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Stokes, Tyndall, Ruskin and the nineteenth-century beginnings of climate science

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Although we humans have known since the first smokey campfires of prehistory that our activities might alter our local surroundings, the nineteenth century saw the first indications that humankind might alter the global environment; what we currently know as anthropogenic climate change. We are now celebrating the bicentenaries of three figures with a hand in the birth of climate science. George Stokes, John Tyndall and John Ruskin were born in August 1819, August 1820 and February 1819, respectively. We look back from the perspective of two centuries following their births. We outline their contributions to climate science: understanding the equations of fluid motion and the recognition of the need to collect global weather data together with comprehending the role in regulating terrestrial temperature played by gases in the atmosphere. This knowledge was accompanied by fears of the Earth's regression to another ice age, together with others that industrialization was ruining humankind's health, morals and creativity. The former fears of global cooling were justified but seem strange now that the balance has tipped so far the other way towards global warming; the latter, on the other hand, today seem very prescient.

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George Stokes was born in August 1819. His career was in mathematics and physics. In an 1845 paper [1], he derived equations that had earlier been written down by Navier—and by Cauchy, Poisson and Saint Venant—and set them on a clear footing. These equations, now known as the Navier–Stokes equations, describe the movement of a fluid.

Stokes was keenly interested in both nature and art, and his scientific eye, on occasion, spotted errors in the reproduction of nature by an artist. The following tale is told by his daughter Isabella, who wrote a biographical memoir of her father [2]

> He rejoiced in silent companionship, often taking one of us on his long quick walks, perhaps not saying a single word for miles. Then some day his interest would be aroused by something heard or seen, and he would have a sudden fit of eloquence. One day it would be caused by the humming of the telegraph posts, on several occasions by the beauty and interest of rainbows, especially by one near Bray Head when we were sitting close to the cliff's edge and saw a far larger part of the arc than is usually seen. He then told me that he once had to speak at one of the Royal Academy dinners, and took as his text the help which Science might be to Art, criticizing a fine landscape on the walls, much spoilt to him by a rainbow with its colours in the wrong order. He said that Millais stood up and owned to the rainbow, which he said he would amend, and made a very amusing speech

The artwork in question is Millais' *The Blind Girl*, showing a double rainbow; the amended version is seen in figure 1.[1] Larmor, editor of Stokes' correspondence, also noted Stokes' appreciation of the natural environment [2]

> The pleasure felt by Prof. Stokes in beautiful natural surroundings moved him to public action on various occasions. When a suggestion was made to abolish the rivulet which runs down by the side of the footpath in Trumpington Street, he was active in dissent. At the Hills Road end of Lensfield Road a beautiful poplar tree, now, unfortunately, docked from age, stood out in the footway: a proposal to remove it called forth a protest in the form of a circular of which the following constituted the preliminary portion of the draft:
>
> A scheme has for some time been in motion pleading for certain improvements (as they are called) in this Road to which it would be well to draw the attention of the inhabitants.
>
> In common as I know with many others, I have often been struck with the beauty of this Road in walking from Downing Terrace towards the Hills Road. The eye rests on a beautiful line of plantation on the right, while the grounds of Downing lie on the left. Short as the road is, I cannot but regard it as one of the ornaments of the Town. The fine poplar tree at the corner is also a highly ornamental object as seen from St Andrew's Street and elsewhere...

Stokes' character, however, was not such as to extrapolate from his appreciation of the natural world any general idea of applying science to nebulous enterprises. According to his daughter Isabella again [2]

> It was interesting to notice in my father's discussions with scientific men the horror he had of theorizing from unproved facts; he would always say, 'But have you proved your facts?' and then would often show them that this had not been done. He could not bear 'scientific romancing,' as he called it.

[1] We presume that Millais had the rarer outer bow wrong, but we cannot find definite confirmation of this. The Pre-Raphaelite movement of which Millais formed a part was deeply interested in weaving science into their art 'How did the group harness empirical methods to create its work? Take arguably the most famous Pre-Raphaelite painting, Millais's Ophelia (1851–25). At first glance, this seems a sentimental portrayal of the tragic suicide of the character in William Shakespeare's Hamlet. However, every plant depicted, from purple loosestrife to wild roses, is the product of more than three months of painstaking observation as Millais worked on the banks of the Hogsmill River in Surrey. Other artists had painted in the open air before, but never in such meticulously wrought detail.' [7]. Ruskin, champion of the Pre Raphaelites, wrote in 1884 that, although the brotherhood's work might 'seem to be the reaction of a desperate fancy...against the incisive scepticism of recent science', they were in fact 'a part of that science itself' [8].

Figure 1. John Everett Millais, *The Blind Girl*, 1856, after its correction, and a double rainbow photographed by one of the authors (JC). Millais corrected the colour sequence on Stokes' prompting, but did not really bring out the difference in intensity between the primary and secondary bows, which is of order 1:0.43 [3], or the greater width of the secondary bow. Compare John Constable's *London, from Hampstead Heath in a Storm; with Double Rainbow Seen beneath Purple Masses of Cloud* of 1831, which shows correctly these aspects [4]. It is worth noting that Keats' poem *Lamia*, which complains of 'cold philosophy' that would 'unweave a rainbow' was written in 1819 and published in 1820 [5] and so is also celebrating its bicentenary. Stokes developed asymptotics to make rigorous Airy's mathematical treatment of rainbow optics [6]. (Online version in colour.)

John Ruskin was born in February 1819, just a few months before Stokes. He graduated in classics and maths from Oxford. Although his career was to be in art and literature, he was throughout his life interested in botany, geology and meteorology. In 1839, as a young man involved in the beginnings of the Meteorological Society, he wrote [9]

> There is one point, it must now be observed, in which the science of meteorology differs from all others. A Galileo, or a Newton, by the unassisted workings of his solitary mind,

> may discover the secrets of the heavens, and form a new system of astronomy. A Davy in his lonely meditations on the crags of Cornwall, or in his solitary laboratory, might discover the most sublime mysteries of nature, and trace out the most intricate combinations of her elements. But the meteorologist is impotent if alone; his observations are useless … It is perhaps for this reason that the cause of meteorology has hitherto been so slightly supported; no progress can be made by the most gigantic efforts of a solitary intellect, and the co-operation demanded was difficult to obtain, because it was necessary that the individuals should think, observe, and act simultaneously, though separated from each other by distances on the greatness of which depended the utility of the observations. The Meteorological Society, therefore, has been formed, not for a city, nor for a kingdom, but for the world.
>
> …It desires to have at its command, at stated periods, perfect systems of methodical, and simultaneous observations ; it wishes its influence and its power to be omnipresent over the globe, so that it may be able to know, at any given instant, the state of the atmosphere at every point on its surface.
>
> …each, who alone would have been powerless, will find himself a part of one mighty Mind,—a ray of light entering into one vast Eye,—a member of a multitudinous Power, contributing to the knowledge, and aiding the efforts, which will be capable of solving the most deeply hidden problems of Nature, penetrating into the most occult causes, and reducing to principle and order, the vast multitude of beautiful and wonderful phenomena…

Ruskin was certainly prescient in calling for global data collection and recognizing that it would transform meteorology. The basis of weather and climate forecasting today relies on having such a global network, and checks of model accuracy are made with hindcasting, using the historical data that began to be collected in the decades following his plea.

Forty-five years on, in 1884, Ruskin gave two lectures to the London Institution, 'The Storm-Cloud of the nineteenth century' [10] in which he presented his theory of a new type of cloud, never before seen, which he termed a *plague cloud* 'pitch dark, with no blackness—but deep, high, filthiness of lurid, yet not sublimely lurid, smoke-cloud; dense manufacturing mist.' He shows a number of sketches of clouds, both storm clouds—see figure 2 —and others, but not one of the plague cloud that is the subject of his lectures. 'I should have liked to have blotted down for you a bit of plague-cloud to put beside this; but Heaven knows, you can see enough of it nowadays without any trouble of mine', he said. However, he lists 'the phenomena characteristic of the plague-wind': (1) 'wherever the plague-wind blows, be it but for ten minutes, the sky is darkened instantly' (2); it is 'unconnected with any one quarter of the compass'; 'its own favourite quarter, however, is the south-west'; (3) 'it always blows tremulously'; (4) 'it is also intermittent'; (5) 'it degrades, while it intensifies, ordinary storm'; (6) 'in bringing on their peculiar darkness, they blanch the sun instead of reddening it'.[2]

Ruskin turns to contemporary science to see what it has to say about his cloud, and finds science wanting. He lays into the scientists. He picks on Stokes 'The Lucasian professor of Cambridge' for his turn of phrase in this excerpt from one of Stokes' papers, 'On the Change of Refrangibility of Light' [11]:

> Nothing then seems more natural than to suppose that the incident vibrations of the luminiferous ether produce vibratory movements among the ultimate molecules of sensitive substances, and that the molecules in turn, swinging on their own account, produce vibrations in the luminiferous ether, and thus cause the sensation of light. The periodic times of these vibrations depend upon the periods in which the molecules are disposed to swing, not upon the periodic time of the incident vibrations.

[2]It is an interesting, but difficult, exercise to try to relate these characteristics to science. For instance, perhaps 'tremulous' might be related to turbulence; 'the anemometer can only record for you how often it has been driven round, not at all whether it went round steadily, or went round trembling. And on that point depends the entire question whether it is a plague breeze or a healthy one', said Ruskin [10].

Figure 2. Ruskin's 'sketch of the sky in the afternoon of the 6 August 1880, at Brantwood, two hours before sunset. You are looking west by north, straight towards the sun, and nearly straight towards the wind.' Ruskin made the following entry in his diary: 'In the afternoon the most overwhelming, wonderful hours of increasing prismatic light, like a painted window in heaven, pale but intent; and in one or two cases, even deep rose colour, passing into orange, barred or interstained with pale emerald green, passing here and there into olive but not violet except in some dark grey clouds which became violet by being touched with the ruby: these very rare and small, like Turner's lightest spray of dark touches in Flint Castle. All this on the edges above the sun, at about 12–15° above him; he, some 20° above horizon; and all sky interwoven with muslin and netting of divinest cirri cloud, over infinite shoals and sands of mackerel cloud; but all flying, failing, melting—re-appearing—twisting and intertwisting—faster than eye could follow; and, after some 3 h of this play (5–8), ending in two great ranks of storm-cloud—lower, pale against higher, dark (or backing of dark): the latter with long locks and tresses, as of hair at its edge; and both overlying the range of hills, exactly like the Hesperides dragon—ending northward in a clear sky against a black monster cloud—half dolphin, half tiger (which?) rolled and rose, and finally toppled and tumbled—the face of it, or where, had it been a beast, the face would have been, falling forward like a gloomy and slow avalanche and melting, as it was torn down or dragged, into nothingness.' In his lecture, he presents this as a storm cloud that is not a plague cloud, yet in his diary there is the note 'I believe these swift and mocking clouds and colours are only between storms. They are assuredly new in Heaven, so far as my life reaches. I never saw a single example of them till after 1870.' Which appears to indicate that he thought then they might be; it is not clear.

Ruskin quotes this excerpt (with some slight imprecision), and continues

> It seems to me a pleasant conclusion, this, of recent science, and suggestive of a perfectly regenerate theology. The 'Let there be light' of the former Creation is first expanded into 'Let there be a disposition of the molecules to swing,' and the destinies of mankind, no less than the vitality of the universe, depend thereafter upon this amiable, but perhaps capricious, and at all events not easily influenced or anticipated, disposition! Is it not also strange that in a treatise entering into so high mathematical analysis as that from which I quote, the false word 'swing,' expressing the action of a body liable to continuous arrest by gravitation, should be employed to signify the oscillation, wholly unaffected by gravity,

> of substance in which the motion once originated, may cease only with the essence of the body?

He goes on to pay a back-handed compliment to Stokes

> It is true that in men of high scientific caliber, such as the writer in this instance, carelessness in expression does not affect the security of their conclusions. But in men of lower rank, mental defects in language indicate fatal flaws in thought. . .. So that, before you consider whether a scientific author says a true or a false thing, you had better first look if he is able properly to say anything,—and secondly, whether his conceit permits him to say anything properly.

However, Ruskin reserves the full vigour of his attacks for John Tyndall, like Stokes an Irish physicist, and another contemporary (1820–1893)[3] of himself and Stokes. Tyndall had recognized, in work starting in 1859, the important role of carbon dioxide and methane alongside water vapour in atmospheric warming:

> if, as the above experiments indicate, the chief influence be exercised by the aqueous vapour, every variation of this constituent must produce a change of climate. Similar remarks would apply to the carbonic acid diffused through the air; while an almost inappreciable admixture of any of the hydrocarbon vapours would produce great effects on the terrestrial rays and produce corresponding changes of climate. It is not therefore necessary to assume alterations in the density and height of the atmosphere, to account for different amounts of heat being preserved to the earth at different times; a slight change in its variable constituents would suffice for this. Such changes in fact may have produced all the mutations of climate which the researches of geologists reveal.

wrote Tyndall [13,14]. It should be noted that Eunice Foote, whose bicentenary also falls in 1819 (1819–1888), had also shown in work published in 1856 the ability of carbon dioxide and water vapour to absorb heat and made a link between the amount of water vapour and carbon dioxide in the atmosphere and changes in the climate [15]

> The highest effect of the sun's rays I have found to be in carbonic acid gas. . .. An atmosphere of that 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 increased weight must have necessarily resulted

Tyndall and later workers do not appear to have known of her work, which was only recently rediscovered [16]. Foote's experiments were on solar heating of samples of air with amounts of water vapour and carbon dioxide and comparing them with samples of the same composition in the shade. Tyndall's much more precise experiments were using radiated (infrared, i.e. long wavelength) heat. Climate was not the main thrust of Tyndall's work in this area; he was more concerned with the physics of the gases. However, Tyndall was also a leading alpinist, and he knew well recent geological work that had shown that the Earth had passed through an ice age. The discovery of past ice ages was part of the initial impetus for considering the causes of climate change. The fear in Victorian science was that the glaciers that he climbed over in the Alps might advance once more over the whole continent in a new ice age [17]. Tyndall mentioned that his research was motivated by glaciology and by previous work on the temperature of the Earth by de Saussure, Fourier and Pouillet [18]; he stressed that, without a natural balance of water vapour in the atmosphere, the Earth would be 'held fast in the iron grip of frost' [19].

Tyndall and Stokes, although members of different circles of scientific friends, were on amicable terms [20]. Ruskin and Tyndall were not. Ruskin writes about Tyndall's popular book

[3]Tyndall believed that he had been born in 1820, but it is not absolutely certain [12].

based upon both Tyndall's physics and his Alpine experience, *The Forms of Water in Clouds and Rivers, Ice and Glaciers* [21]

> in this point of the diffraction of light I am stopped dead by their confusion of idea also, in using the words undulation and vibration as synonyms. 'When,' says Professor Tyndall, 'you are told that the atoms of the sun vibrate at different rates, and produce waves of different sizes,—your experience of water-waves will enable you to form a tolerably clear notion of what is meant.' 'Tolerably clear'!—your toleration must be considerable, then. Do you suppose a water-wave is like a harp-string? Vibration is the movement of a body in a state of tension,—undulation, that of a body absolutely lax. In vibration, not an atom of the body changes its place in relation to another,—in undulation, not an atom of the body remains in the same place with regard to another. In vibration, every particle of the body ignores gravitation, or defies it,—in undulation, every particle of the body is slavishly submitted to it. In undulation, not one wave is like another; in vibration, every pulse is alike. And of undulation itself, there are all manner of visible conditions, which are not true conditions. A flag ripples in the wind, but it does not undulate as the sea does,—for in the sea, the water is taken from the trough to put on to the ridge, but in the flag, though the motion is progressive, the bits of bunting keep their place. You see a field of corn undulating as if it was water,—it is different from the flag, for the ears of corn bow out of their places and return to them,—and yet, it is no more like the undulation of the sea, than the shaking of an aspen leaf in a storm, or the lowering of the lances in a battle.
>
> 'And the best of the jest is, that after mixing up these two notions in their heads inextricably, the scientific people apply both when neither will fit; and when all undulation known to us presumes weight, and all vibration, impact,—the undulating theory of light is proposed to you concerning a medium which you can neither weigh nor touch!

It is a worthwhile exercise for the student to dissect this paragraph and thereby to understand why Tyndall and Ruskin were at cross purposes in viewing these different types of waves. It is moreover ironic that here Ruskin might have looked once more to Stokes, who in 1847 had shown how particles in waves may move between the arrival of one wavefront and the next in what we now call Stokes drift [22].

Ruskin's new cloud was swiftly derided in the pages of *Nature* in an article by the meteorologist William Clement Ley entitled 'Mr Ruskin's Bogies' [23]:

> Professor Ruskin's utterances are perhaps to be taken least seriously when he is himself most serious, and probably he was never more in earnest than in his jeremiad on modern clouds, delivered at the London Institution on the 4th and 11th inst. Probably none of the readers of Nature have been terrified by the storm cloud of the nineteenth century, but should it be otherwise we hasten at once to their relief. Twenty years before the date fixed by Mr Ruskin for the first appearance of his portentous 'plague-cloud,' the writer of the present article commenced a series of observations on the forms and structures of clouds, followed a few years later by such daily charts of wind and weather as could be constructed from the data, somewhat meagre, that were then accessible. As might be expected, cyclone and anticyclone were then as they are now. The dimensions and densities of the cloud layers have not altered, neither has our moral degeneracy nor the increased smoke of our manufacturing towns developed any new form of cloud. Neither (until the phenomenal sunrises and sunsets of the last three months) has Nature, in painting the clouds, employed upon her palette any fresh tints, whatever artists may have done. Further, we have not observed, nor met with any one, except Mr Ruskin, who has observed, that the wind during the last thirteen years has adopted a 'hissing' instead of a 'wailing' tone, or that the pressure anemometer indicates that the motion of the air has become more tremulous than heretofore.

The phenomenal sunrises and sunsets were down to the eruption of Krakatoa that had taken place in 1883, and had injected large amounts of dust into the atmosphere.

Indeed, it is easy to mock Ruskin's anti-science polemics, but what was he seeing? Was he just imagining things? Ruskin insisted that he was not:

> In many of the reports given by the daily press, my assertion of radical change, during recent years, in weather aspect was scouted as imaginary, or insane. I am indeed, every day of my yet spared life, more and more grateful that my mind is capable of imaginative vision, and liable to the noble dangers of delusion which separate the speculative intellect of humanity from the dreamless instinct of brutes: but I have been able, during all active work, to use or refuse my power of contemplative imagination, with as easy command of it as a physicist's of his telescope: the times of morbid are just as easily distinguished by me from those of healthy vision, as by men of ordinary faculty, dream from waking; nor is there a single fact stated in the following pages which I have not verified with a chemist's analysis, and a geometer's precision.

Although he describes his cloud variously as 'Manchester devil's darkness', 'a nasty solution in a bottle', and 'sulphurous chimney-pot vomit', he distinguishes his cloud from smog, which he refers to as a *London Particular*; London was known for its pea-souper fogs owing to air pollution from coal burning. Ruskin dismisses the idea that his cloud is 'just' pollution in his typically extravagant prose:

> It looks partly as if it were made of poisonous smoke; very possibly it may be: there are at least two hundred furnace chimneys in a square of two miles on every side of me. But mere smoke would not blow to and fro in that wild way. It looks more to me as if it were made of dead men's souls — such of them as are not gone yet where they have to go, and may be flitting hither and thither, doubting, themselves, of the fittest place for them.

So, was Ruskin simply blaming air pollution on the devil? Ruskin's biographer notes the fact that [24]

> From 1869 through 1889 the temperature in London was below average for 18 of the 21 years; rainfall was abnormally heavy from 1875 through 1882; reliable figures for sunshine are available only after 1879, but 16 of the 20 autumns and winters from 1880 through 1889 were below average, and the total sunshine was below average for more than 60 per cent of the decade;

We should note here that it was Stokes who improved the sunshine gauge now known as the Campbell–Stokes recorder or Stokes sphere [25–27]. Ruskin's comment [10] on that instrument is

> you have your sun-measure, and can tell exactly at any moment how strong, or how weak, or how wanting, the sun is. But the sun-measurer can not tell you whether the rays are stopped by a dense shallow cloud, or a thin deep one. In healthy weather, the sun is hidden behind a cloud, as it is behind a tree; and, when the cloud is past, it comes out again, as bright as before. But in plague-wind, the sun is choked out of the whole heaven, all day long, by a cloud which may be a thousand miles square and five miles deep.

If we examine the annual temperatures in central England over time—see figure 3—we can appreciate this interval of cooler weather. Another trigger for Ruskin may have been the abnormal weather after the eruption of Krakatoa in August 1883, as Ley had mentioned in his letter to *Nature*. But again, Ruskin denied this: 'those sunsets were, in the sense in which I myself use the word, altogether "unnatural" and terrific: but they have no connection with the far more fearful, because protracted and increasing, power of the Plague-wind.' A further general factor lies in Ruskin's nineteenth-century anti-industrialist environmentalism. Ruskin hated the way in which the industrial revolution was polluting the environment, 'the sacred fume of modern devotion which now fills the inhabited world', as well as being a dehumanizing influence and

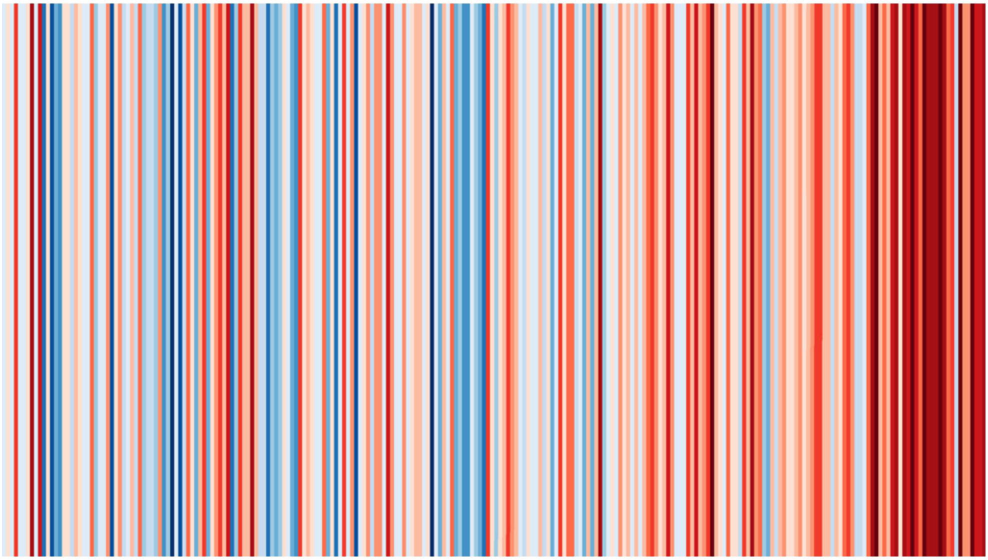

Figure 3. Warming stripes: Annual temperatures in central England from 1772 to 2017. The colour scale goes from 7.6°C (dark blue) to 10.8°C (dark red) (E. Hawkins). One can clearly see the local cooling in the central part corresponding to the years Ruskin was concerned with as a concentrated blue zone. While not optimal for quantitative analysis, this image may be appreciated for its aesthetic qualities; we do not know, of course, whether Ruskin would concur. Reproduced under a CC licence. (Online version in colour.)

one inhibiting creativity. One cannot say for certain what Ruskin was seeing, or thought he was seeing, but all of these aspects may have come together in his plague cloud.

Ruskin was by no means a pioneer in these remonstrances, but was following in a long tradition: people had been complaining of air pollution for a long time by the latter half of the nineteenth century. We imagine that early man—and woman—protested about the smokey air from fires in their caves and tents. Seneca the Younger, in his Moral Letters to Lucilius, wrote (letter 104) of leaving Rome circa 64 CE [28,29]

> As soon as I escaped from the oppressive atmosphere of the city, and from that awful odour of reeking kitchens which, when in use, pour forth a ruinous mess of steam and soot, I perceived at once that my health was mending.

We should add that as far back as the classical world there was some understanding that climate might change over time, and both astronomical and human factors were proposed as being involved in changes in climate [30].

Eleanor of Provence, Henry III's queen, left Nottingham castle because of the smoke in 1257 [31]. Their son, Edward I, had a law enacted in 1307 banning the use of coal in London [29,32]. Many similar attempts at legislating the problem in London were made in succeeding centuries [29]. In 1661, John Evelyn wrote *Fumifugium, or the The inconveniencie of the aer and smoak of London dissipated together with some remedies humbly proposed by J.E. esq. to His Sacred Majestie, and to the Parliament now assembled* [33] in which he described air filled with 'Columns and Clouds of Smoake'

> That hellish and dismal cloud of sea coal [means] that the inhabitants breathe nothing but an impure and thick mist, accompanied by a fuliginous and filthy vapour, which render them obnoxious to a thousand inconveniences, corrupting the lungs and disordering the entire habit of their bodies. . .

> Those who repair to London, no sooner enter into it, but they find a universal alteration in their Bodies, which are either dryed up or enflam'd, the humours being exasperated and made apt to putrefie, their sensories and perspiration so exceedingly stopp'd, with the losse of Appetite, and a kind of general stupefaction, succeeded with such Cathars and Distillations, as do never, or very rarely quit them...

And John Graunt's *Natural and political observations ...upon ...mortality* of 1662 notes mortality attributed to air pollution in London [34,35].

Moving forward to the nineteenth century, in 'The miseries of an artist' [36], an anonymous artist in 1820 London recounted what it was like to

> slink home through a fog as thick and as yellow as the pea-soup of the eating house; ...the fog,...being a compound from the effusions of gas pipes, tan yards, chimneys, dyers, blanket scourers, breweries, sugar bakers and soap boilers...

Luke Howard, a meteorologist who introduced the present system of cloud nomenclature, published *The Climate of London* in 1818–1820 [37], in which he noted both the concentration of smog, which he termed 'city fog', and what is now known as the heat-island effect of human alteration of the climate in a city. He wrote in the second edition of 1833 on another instance of London smog from January 1826 [38]:

> At one o'clock yesterday afternoon the fog in the city was as dense as we ever recollect to have known it. Lamps and candles were lighted in all shops and offices, and the carriages in the street dared not exceed a foot pace. At the same time, five miles from town the atmosphere was clear and unclouded with a brilliant sun.

Alexander von Humboldt (1769–1859), whose 250th anniversary was celebrated in 2019, in 1843 cautiously linked human activity to climate change [39]

> I could have concluded the considerations on the absorptive and emissive powers of the soil, on which the climate of the continents generally depends and the decrease of the heat in the air by the examination of the changes which man produces on the surface of the continents by cutting down the forests, modifying the distribution of water, by pouring large masses of vapours and gaseous substances into the atmosphere in the centres of industrial culture. These changes are undoubtedly more important than is generally admitted, but in the immense variety of causes which act at once and on which the type of climates depends, the most important are not restricted to small localities: they depend on relations of position, configuration and height of the ground, and the preponderance of the winds over which civilization exercises little sensible influence.[4]

Charles Dickens mentions a great deal of fog in his work. *Bleak House* [40] (1852) begins

> Fog everywhere. Fog up the river, where it flows among green aits and meadows; fog down the river, where it rolls defiled among the tiers of shipping and the waterside pollutions of a great (and dirty) city. Fog on the Essex marshes, fog on the Kentish heights. Fog creeping into the cabooses of collier-brigs; fog lying out on the yards and hovering in the rigging of great ships; fog drooping on the gunwales of barges and small boats. Fog in the eyes and throats of ancient Greenwich pensioners, wheezing by the firesides of their wards; fog in the stem and bowl of the afternoon pipe of the wrathful skipper, down in his close cabin;

[4]'J'aurais pu terminer les considérations sur les pouvoirs absorbants et émissifs du sol, dont dépend en général le climat des continents et le décroissement de la chaleur dans l'air par l'examen des changements que l'homme produit à la surface des continents, en abattant les forêts, en modifiant la distribution des eaux, en versant dans les centres de culture industrielle de grandes masses de vapeurs et de substances gazeuses dans l'atmosphère. Ces changements sont sans doute plus importants qu'on ne l'admet généralement, mais dans l'immense variété de causes qui agissent à la fois et dont dépend le type des climats, les plus importantes ne sont pas restreintes à de petites localités: elles dépendent de rapports de position, de configuration et de hauteur du sol, de la prépondérance des vents sur lesquels la civilization exerce peu d'influence sensible.'

fog cruelly pinching the toes and fingers of his shivering little 'prentice boy on deck. Chance people on the bridges peeping over the parapets into a nether sky of fog, with fog all round them, as if they were up in a balloon and hanging in the misty clouds.

In chapter 3 when Esther arrives in London, she asks of the person meeting her

...whether there was a great fire anywhere? For the streets were so full of dense brown smoke that scarcely anything was to be seen. 'O, dear no, miss,' he said. 'This is a London particular.' I had never heard of such a thing. 'A fog, miss,' said the young gentleman.

Stokes' only pertinent comment on smog in his published correspondence seems to be one in a letter to his wife, which ends 'Poor Mary! left in the fogs of London while I am enjoying the fresh air and quiet of Cambridge. God keep you. Your loving husband. Pembroke College, 18 December 1857' [2]. Stokes certainly studies the effects of fogs on light absorption, but characteristically he makes no comments whatsoever that could be construed as 'scientific romancing'.

Thus, by the time Ruskin was thinking about his plague cloud, there was already a mass of evidence pointing towards the effect of human activity on the weather of the metropolis. Writing in 1880, shortly before Ruskin, Russell [41] wrote on London fogs in a very clear fashion

It may be a wise doctrine, that no ancient and long-tolerated institution deserves to be condemned without a fair inquiry into the evidence for and against its existence. A London fog, like most disagreeable things and persons, may have its merits, and, doubtless, also its firm partisans, who would be prepared to defend it in a general way before a Royal Commission as a beneficial visitation. But the proofs of its utility, if they exist, must be brought to light, and as yet we have had none. It may be upheld as a nebulous and mysterious witticism, a gigantic piece of national humour, an enormous practical joke, and we cannot dispute the plea that it may be a source of amusement to its passing acquaintance. But those who know it well have had enough of it. It has hitherto been spared, because, like other evils of greater magnitude, its ill effects have not been very startling and sudden, and it was hard to believe that so harmless-looking and quiet a thing could do much mischief. The unseen and little-noticed causes of death and disease, however, are by far the most fatal. The small germ of typhoid or drain fever slays its thousands every year; but this fact attracts less general attention than the drowning of five hundred by a collision or by a flood. Yet of these the first is the most easily preventable evil. So we have been content to pour the refuse from our domestic fires into the open air, and leave the work of scavenging to unaided natural forces; to disregard 'matter in the wrong place,' so long as it has not killed its hundreds or thousands at a time, and have tolerated something like suffocation, so long as it performed its work slowly, made no unseemly disturbance, and took care not to demand its hecatombs very suddenly and dramatically. And smoke in London has continued probably for many years to shorten the lives of thousands, but only lately has the sudden, palpable rise of the death-rate in an unusually dense and prolonged fog attracted much attention to the depredations of this quiet and despised destroyer.

and

Haziness, if not fog, prevails in London on nearly every day in the year. London haze is quite a different thing from that which occurs naturally in the country, though at times very similar to it in appearance. It is absent only during part of the night and early morning. Every one who has seen the metropolis in the small hours of a fine morning knows the totally changed and unfamiliar appearance of the town when nothing interrupts the vision. On fine, hot, breezy Sundays in summer, when factories are stopped and fires not so much used for cooking, the clearness is so unusual that prominent objects such as St. Paul's Cathedral and the Albert Hall may be seen from distant suburbs. In the daytime, a sightseer on Primrose Hill or Hampstead Heath, even if he be a poet, will be fortunate if more than a small number of 'distant spires' reveals itself to his gaze.

> Smoke-haze is bluish, dirty-grey, or brown in colour, may be smelt if thick, and renders the outlines of clouds murky and ill-defined. The last distinction is the best, and if clouds are overhead, the peculiar grey dirtiness of smoke blurring their edges is almost unmistakable. The dweller in the distant suburbs only rejoices in these town-fogs and town-hazes during the prevalence of certain winds or currents. Generally he may assume coal-smoke to be present when unusual darkness of a peculiar yellowish or brown tint prevails. This darkness is caused by the minute particles of carbon, a substance which, unlike the water particles which compose a pure fog, is incapable of reflecting and transmitting light. He will recognize smoke also in the yellow murky clouds which occasionally pass over his head, with a clear air below, carried by a different current from that prevailing on the ground. In the south-western suburbs, a change from westerly to a north-east wind is commonly preceded by a smokiness sufficient to conceal distant objects. Many people are apt to mistake the darkness caused by banks of smoke resting above them for the effect of thunder clouds, or naturally gloomy weather, and one frequently hears remarks upon the thundery appearance of the sky, and predictions of a storm, when the weather simply happens to be calm enough to allow the refuse of our fires to accumulate and drift slowly above our heads. These dense banks of smoke sometimes pass over a great extent of country, and produce a gloomy appearance at distances of thirty, forty, and even fifty miles or more from the metropolis, for smoke is far less changeful and less easily dissipated than clouds. These dark murky days, which are bright and fine in the windward districts and in the far country, frequently occur in the suburbs, and with especial persistence during fine, calm, and cold winter weather. A London fog may be very unequally distributed, and may even be dense in one quarter while the sun shines brightly in another. It may move slowly in masses, so that at any one spot we have alternations of light and obscurity. This movement and aggregation depends upon the feeble circulating and variable currents which are most favourable to the development and continuance of a thick fog, and upon the tendency of condensed vapour and all small particles to aggregate in defined patches wherever there is sufficient movement.

Post Ruskin, Oscar Wilde in *The Decay Of Lying* (1889) [42] satirized Ruskin by suggesting that the fault of the altered climate in London was art itself

> VIVIAN. . . . All that I desire to point out is the general principle that Life imitates Art far more than Art imitates Life, and I feel sure that if you think seriously about it you will find that it is true. Life holds the mirror up to Art, and either reproduces some strange type imagined by painter or sculptor, or realizes in fact what has been dreamed in fiction. Scientifically speaking, the basis of life—the energy of life, as Aristotle would call it—is simply the desire for expression, and Art is always presenting various forms through which this expression can be attained. Life seizes on them and uses them, even if they be to her own hurt. Young men have committed suicide because Rolla did so, have died by their own hand because by his own hand Werther died. Think of what we owe to the imitation of Christ, of what we owe to the imitation of Caesar.
>
> CYRIL. The theory is certainly a very curious one, but to make it complete you must show that Nature, no less than Life, is an imitation of Art. Are you prepared to prove that?
>
> VIVIAN. My dear fellow, I am prepared to prove anything.
>
> CYRIL. Nature follows the landscape painter, then, and takes her effects from him?
>
> VIVIAN. Certainly. Where, if not from the Impressionists, do we get those wonderful brown fogs that come creeping down our streets, blurring the gas-lamps and changing the houses into monstrous shadows? To whom, if not to them and their master, do we owe the lovely silver mists that brood over our river, and turn to faint forms of fading grace curved bridge and swaying barge? The extraordinary change that has taken place in the climate of London during the last ten years is entirely due to a particular school of Art. You smile. Consider the matter from a scientific or a metaphysical point of view, and you will find that I am right. For what is Nature? Nature is no great mother who has borne us. She is our creation. It is in our brain that she quickens to life. Things are because we see them, and what we see, and how we see it, depends on the Arts that have influenced us. To look at a thing

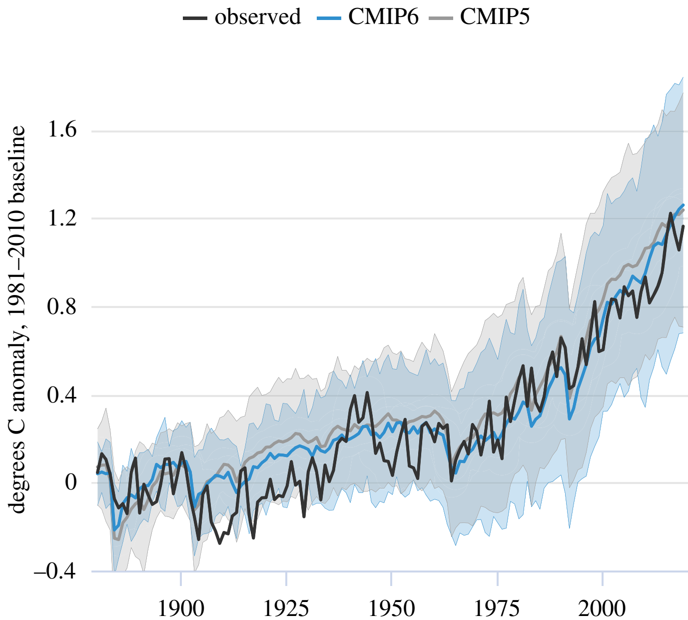

Figure 4. Global surface temperatures 1880–2019: historical observations (from NASA GISTEMP) are shown in the black line along with the results (hindcasts) from numerical climate models of the ultimate generation (blue line; CMIP6) and the penultimate (pre-2013) generation (grey line; CMIP5). The lines for the modelling results are the mean across different numerical models and the shaded areas indicate the variation between model predictions (technically, the two-sigma range). Chart by Carbon Brief (https://www.carbonbrief.org/cmip6-the-next-generation-of-climate-models-explained) using Highcharts (https://www.highcharts.com/). Reproduced under a CC licence. (Online version in colour.)

> is very different from seeing a thing. One does not see anything until one sees its beauty. Then, and then only, does it come into existence. At present, people see fogs, not because there are fogs, but because poets and painters have taught them the mysterious loveliness of such effects. There may have been fogs for centuries in London. I dare say there were. But no one saw them, and so we do not know anything about them. They did not exist till Art had invented them. Now, it must be admitted, fogs are carried to excess. They have become the mere mannerism of a clique, and the exaggerated realism of their method gives dull people bronchitis. Where the cultured catch an effect, the uncultured catch cold. And so, let us be humane, and invite Art to turn her wonderful eyes elsewhere. She has done so already, indeed. That white quivering sunlight that one sees now in France, with its strange blotches of mauve, and its restless violet shadows, is her latest fancy, and, on the whole, Nature reproduces it quite admirably. Where she used to give us Corots and Daubignys, she gives us now exquisite Monets and entrancing Pissaros.

Ruskin, then, was very much in the minds of people who were thinking about man's effect on his environment. Ruskin contributed to the environmental aspect of climate science; the moral idea that we, humans, ought not to be polluting the environment, which could have consequences for the local and even the global climate.

Our three protagonists, Stokes, Tyndall and Ruskin, are bound together as pioneers of climate science, yet none of the three would have recognized this label. Stokes' work on establishing the Navier–Stokes equations, Tyndall's work on the warming effects of gases and Ruskin's environmentalism, as well as his prescient call for the collection of global weather data for meteorology, subsequently came together in the twentieth century, from which emerged climate science, including an understanding of human effects on the climate, even at the global scale. All three were accidental climate scientists.

Unlike Ruskin and Tyndall, Stokes' character was such that he would never have joined a public debate into these matters, but it was his work, in particular the Navier–Stokes equations, that, with the advent in the twentieth century of numerical simulations using computers, has permitted both weather and climate modelling. A present day (2019) climate model is basically a whole-Earth weather model at the core of which there are the Navier–Stokes equations solved on a spatial grid typically of size some tens of kilometres and with a time step typically of half an hour for the atmosphere. So-called sub-grid processes are input as parameters into the model (and constitute one source of uncertainty in both weather and climate modelling). Such a model is run to simulate decades or centuries of time with, for example, different amounts of carbon dioxide in the atmosphere. Over many runs statistics are obtained of the probable effect of one or another variable on the global climate. The newest models today, Coupled Model Intercomparison Project Phase 6, CMIP6, are compared with earlier pre-2013 models, CMIP5, in figure 4 in what is termed hindcasting (in contradistinction to forecasting) against historical data of global surface temperatures 1880–2019.

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