

## Article

# Cosmic connections: James Croll's influence on his contemporaries and his successors

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**ABSTRACT:** This paper examines the astronomical theory of ice ages of James Croll (1821–1890), its influence on contemporaries John Tyndall, Charles Lyell, and Charles Darwin, and the subsequent development of climate change science, giving special attention to the work of Svante Arrhenius, Nils Ekholm, and G. S. Callendar (for the carbon dioxide theory), and Milutin Milanković (for the astronomical theory). Croll's insight that the orbital elements triggered feedbacks leading to complex changes – in seasonality, ocean currents, ice sheets, radiative forcing, plant and animal life, and climate in general – placed his theory of the Glacial Epoch at the nexus of astronomy, terrestrial physics, and geology. He referred to climate change as the most important problem in terrestrial physics, and the one which will ultimately prove the most far reaching in its consequences. He was an autodidact deeply involved in philosophy and an early proponent of what came to be called 'cosmic physics' – later known as 'Earth-system science.' Croll opened up new dimensions of the 'climate controversy' that continue today in the interplay of geological and human influences on climate.

**KEY WORDS:** astronomical theory, carbon dioxide theory, climate change, cosmic physics, ice ages.



It is to be hoped that the day is not far distant when the climate controversy will be concluded. James Croll<sup>1</sup>

James Croll (1821–1890) was the leading proponent of an astronomical theory of climate change. In 1864 he proposed that the 'true cosmical cause' of climate change 'must be sought for in relations of our earth to the sun,' that 'geological and cosmical phenomena are physically related by a bond of causation,' and that changes in the earth's orbital elements, combined with physical feedbacks, were 'sufficiently great to account for every extreme of climatic change evidenced by geology.'<sup>2</sup> He called climate change, 'the most important problem in terrestrial physics ... and the one which will ultimately prove the most far reaching in its consequences,' asking, '[w]hat are the physical causes which led to the Glacial Epoch and to all those great secular changes of climate which are known to have taken place during geological ages?'<sup>3</sup> His insight that the orbital elements triggered feedbacks leading to complex changes – in seasonality, ocean currents, ice sheets, radiative forcing, plant and animal life, and climate in general – placed his theory at the nexus of celestial mechanics, terrestrial physics, and geology.

This paper examines Croll's climate theory and its significant influence on his contemporaries, including John Tyndall, Charles Lyell, and Charles Darwin. It then sketches the subsequent path forward in climate change science, giving special attention to the work of Svante Arrhenius, Nils Ekholm and

G. S. Callendar (for the carbon dioxide theory), and Milutin Milanković (for the astronomical theory). He was an autodidact deeply involved in theistic philosophy and an early proponent of what came to be called 'cosmic physics' – later known as 'Earth-system science.' Croll opened up new dimensions of the 'climate controversy' that continue today in the interplay of geological and human influences on climate.

## 1. Croll

James Croll has not received the full attention he deserves. His hastily prepared autobiographical sketch, dictated to his wife Isabella in his later years, provides evocative outlines of his life of poverty, physical suffering, pain, and neglect. The second son of David Croil, a stonemason and crofter, and Janet Ellis, he entered this world in the village of Little Whitefield, in the parish of Cargill, Perthshire, Scotland, on 2 January 1821. He received almost no formal education, and was by his own account, 'a rather dull scholar.' In 1832, age 11, a favourable encounter with the *Penny Magazine* launched him on a lifetime course of reading, especially in philosophy and science. He writes, 'it was not the facts and details of the physical sciences which riveted my attention, but the laws or principles which they were intended to illustrate.'

In an era when life expectancy was less than four decades, it took Croll fully four decades to settle into his life's work. He was, in turn, a *millwright* (with a tendency to abstract thinking rather than practical details); a *house joiner* (until an inflamed elbow ended his career); a *tea merchant* (a venture terminated by the ossification of his elbow); an *innkeeper* (at a temperance inn with insufficient lodgers); an *insurance salesman* (a profession

<sup>1</sup>Croll (1885, pp. 14–15).

<sup>2</sup>James Croll to John Herschel, 4 February 1865, quoted in Irons (1896, p. 123).

<sup>3</sup>Croll (1885, p. 1); see also Fleming (2006).

not suited to a man who loves solitude); and a *columnist* for a Glasgow weekly paper. At age 26, Croll read and re-read Jonathan Edwards' *Freedom of the Will* (1754) and, as a member of the Church of Scotland, adopted Calvinist theology that led him to discern in the universe 'a unity, plan, and a purpose pervading the whole, which imply thought and intelligence.'<sup>4</sup> During a period of under-employment, in 1857, Croll published his thoughts on causality and determinism into a volume titled, *The Philosophy of Theism*.<sup>5</sup>

In 1859, Croll accepted a humble position as a *caretaker* at Anderson's College and Andersonian Museum in Glasgow. Here, with the time and resources to read, study, and consult with the likes of Sir William Thompson and Lord Kelvin, Croll was able to focus his attention on physical science and published a number of articles on electricity, heat, and, notably, on the astronomical controls on geological climate. His most prominent paper, 'On the physical cause of the change of climate during geological epochs,' published in the *Philosophical Magazine* in 1864, 'excited a considerable amount of attention' among the leading scientists of Scotland and England, including, notably, John Tyndall, Charles Lyell, and Charles Darwin.

Inspired by Joseph Adhémar's work, *Révolutions de la mer* (1842), Croll's theory identified changes in the earth's orbital elements as likely periodic and extraterrestrial mechanisms for initiating multiple glacial epochs. His theory accounted for both the precession of the equinoxes and variations in the shape of the earth's orbit. It predicted that one hemisphere or the other would experience an ice age whenever two conditions occur simultaneously: a markedly elongate orbit, and a winter solstice that occurs far from the sun. Croll rejected several older notions of climate change: that the earth was simply cooling following its hot origin, that the earth's axis had shifted, that the earth had passed through hotter and colder regions of space, and that rearrangement of landmasses was a cause of glacial and interglacial conditions.<sup>6</sup> He assumed only changes in solar insolation were needed, as controlled by the well-established variations in orbital eccentricity and precession of the equinoxes. Later, he added changes in the obliquity of the ecliptic. These cosmical factors provided a mechanism for multiple glacial epochs and alternating cold and warm periods in each hemisphere. In other words, when the Northern Hemisphere was in the grips of an ice age, the Southern Hemisphere would be in an interglacial. As the earth's orbital elements varied, this situation would eventually be reversed.

Feedback mechanisms triggered by orbital variations were critically important in Croll's system, since they served to enhance the climatic changes initiated by the orbital elements. These include radiative effects of the ice fields, enhanced formation of cloud and fog, changes in sea level, and the mixing and redirection of warm and cold ocean currents. According to Croll, '[t]he cause of secular changes of climate is the deflection of ocean currents, owing to the physical consequences of a high degree of eccentricity in the earth's orbit.' His colleague J. Horne opined, 'to Dr. Croll belongs the rare merit of showing that, though glacial cycles may not arise *directly* from cosmical causes, they may do so *indirectly*!'<sup>7</sup>

In 1867, Croll accepted a position as the secretary and accountant of the Scottish Geological Survey in Edinburgh. His routine duties included ordering, printing, colouring, and selling maps, and keeping the accounts and stores in order. Survey Director Archibald Geikie encouraged Croll to carry out his

own research on orbital theory, but to write it up on his own time. Croll also made field excursions on glacial deposits and discovered a pre-glacial riverbed running from Edinburgh to Glasgow. His typical day involved working in the office from ten to four, home at five for dinner and an hour's rest, then a leisurely stroll in the countryside with pencil and paper, after which he read and wrote at home for about an hour. Although he had long been afflicted with severe head pains that increased with mental exertion, still he produced numerous papers and books on climate change, glacier motion, geological time, ocean currents, astrophysics, and his first love, theistic philosophy.

In 1875, Croll summarised his theories in *Climate and time*, a book widely admired by geologists around the world.<sup>8</sup> Within a year, Croll received, among other accolades, an honorary degree from Saint Andrews and was elected a Fellow of the Royal Society. James Geikie (Archibald's brother) adopted Croll's ideas to advance the theory of multiple glaciations.<sup>9</sup> In 1880, at age 59, Croll resigned from the Geological Survey due to declining health, a decision that reduced his income by over 75%. He published *Discussions on climate and cosmology* in 1885, where he again posed the question he felt he had adequately answered: 'What are the physical causes which led to the Glacial Epoch and to all those great secular changes of climate which are known to have taken place during geological ages?'<sup>10</sup> A reviewer in the *Saturday Review* noted, 'every honest scientific investigator will admit that his writings have had the most influence on cosmological speculation. In certain directions his influence has been nearly as great as that of Darwin's in biology.'<sup>11</sup> Croll, however, had reached his limit, he resolved to terminate his studies, 'not merely in climatology, but also in physical science in general.'<sup>12</sup>

Subsisting on a small pension in old age, Croll turned his attention to writing a book on the philosophical basis of evolution. It was a race with fate. He knew his demise was near when he experienced a debilitating stroke:

I fell on the floor and lay insensible for above an hour; and when I recovered consciousness, I found I was not so strong either physically or mentally as formerly. I have since then had four or five cases of unconsciousness. What I am suffering from is a slow loss of power in the heart. This state of things will probably go on till the heart stops, an event which I am enabled to contemplate with the utmost composure, as it will be but the way of entrance to a better land.<sup>13</sup>

On his deathbed, Croll was able to hold a copy of *The Philosophical Basis of Evolution* (1890) and heard a favourable review of it read to him.

## 2. Tyndall, Lyell, and Darwin

John Tyndall, Charles Lyell, and Charles Darwin were three of the most influential scientists connected to and influenced by Croll. Tyndall (1820–1893) exchanged scientific ideas with Croll and supported him in later life in his application for a government pension. In 1859, Tyndall began a notable series of experiments at the Royal Institution on the radiative properties of various gases, demonstrating that 'perfectly colorless and invisible gases and vapours' were able to absorb and emit radiant heat. He identified the importance of atmospheric trace

<sup>4</sup>Irons (1896, p. 24).

<sup>5</sup>Croll (1857); For an account of Croll's metaphysical interests, see Finnegan (2012).

<sup>6</sup>Croll (1864, pp. 122–23).

<sup>7</sup>Irons (1896, p. 228); J. Horne, quoted in Irons (1896, pp. 113, 510).

<sup>8</sup>Croll (1875).

<sup>9</sup>Hamlin (1928).

<sup>10</sup>Croll (1885, p. 1).

<sup>11</sup>*Saturday Review*, October 1887, cited in Irons (1896, p. 438).

<sup>12</sup>Irons (1896, p. 41).

<sup>13</sup>Croll to C. G. Foster, 3 November 1890, quoted in Irons (1896, p. 482).

constituents as efficient absorbers of long wave radiation and as important factors in climatic control. Specifically, he established beyond a doubt that the radiative properties of water vapour and carbon dioxide were of importance in explaining meteorological phenomena such as the formation of dew, the energy of the solar spectrum, and possibly the variation of climates over geological time. Tyndall, who was a master word stylist, appreciated Croll's deft use of metaphor to describe the dynamical theory of heat, writing to him in 1863: 'Your letter was interesting to me as an illustration of power to seize a definite physical image – the molecules acting as hammers was capital.'<sup>14</sup> Tyndall approved the 'philosophic tone' of Croll's manuscript and noted that there are many remarks in it to which I would heartily subscribe.<sup>15</sup> Tyndall was well aware of Croll's astronomical theory, but thought the problem of ice ages was a complicated one. Based on his laboratory experiments, he held that changes in the amount of any of the radiatively active constituents of the atmosphere – water vapour, carbon dioxide, ozone, or hydrocarbons – could have produced 'all the mutations of climate which the researches of geologists reveal ... they constitute true causes, the extent alone of the operation remaining doubtful.'<sup>16</sup>

Historians Bernard Lightman and Michael S. Reidy mention a possible link between Tyndall's work on radiation and Croll's astronomical theory of climate change: 'It would be difficult to believe that the ongoing conversation about the origins of the ice ages – and, in the 1860s about James Croll's new orbital theory of ice ages – did not partially inform John Tyndall's work on radiation.'<sup>17</sup> There is no need to be tentative here or for these historians to invoke a double negative. It is widely known that Tyndall shared his ideas with Croll on the propagation of luminous heat and non-luminous heat through the atmosphere, and the two men shared the general principle (and greenhouse metaphor), 'that an atmosphere forms a local dam which elevates the temperature of the planet.'<sup>18</sup> This was one of Croll's important feedback mechanisms. Also, use of the term 'ice ages,' plural, is anachronistic in the 1860s since, although postulated earlier by Adhémar (1842), evidence of multiple advances and retreats of the glaciers was documented by geologists and widely accepted only in subsequent decades.<sup>19</sup> Moreover, it is well established that late-19th- and early-20th-Century theories of multiple glaciation identified atmospheric radiation and orbital elements as two of the leading candidates.<sup>20</sup>

Charles Lyell (1797–1875) held steadfastly to his theory of the geographical determination of climate, first articulated in 1830 in the first edition of the *Principles of geology*:

Lyell assumed a constant proportion of dry land to sea and only 'trifling variations' in the mean and extreme height of the land and the depth of the sea. Most important to Lyell was the grouping of the continents, with an ice age possible only with continentality at high latitudes.<sup>21</sup> Lyell rejected catastrophism, championing the uniformitarian idea that earth was shaped by known and still observable natural processes over vast expanses of geological time. He was dismissive of notions that climate had changed much for any reason in historical times since the elapsed period was insufficient and human agency was too

ineffective to change the leading features of the physical geography of the globe.

In 1865, Lyell had to confront Croll's astronomical challenge to his geographic theory. Based on the advice of John Herschel and the Astronomer Royal, George Biddell Airy, Lyell tentatively agreed that changes in eccentricity could result in a 20% reduction or augmentation of the entire heat the earth received from the sun, but considered the mechanism 'quite subordinate to geographical causes.'<sup>22</sup> The question for Lyell was geological dating of the combined effect of astronomical and geographical causes, with the latter dominant.<sup>23</sup> Croll had always maintained that the glacial epoch could not possibly have been caused *directly* by any change in the eccentricity of the earth's orbit, but by the combined physical effects of 'certain agencies which were brought into operation by means of the change,' that is to say, by physical feedbacks.<sup>24</sup> Croll thought Lyell had treated his astronomical theory in a 'highly complimentary way' by including a new 37-page section in the tenth edition of *Principles* (1866).<sup>25</sup> Although they championed different geological systems, Lyell and Croll agreed on many points.

Charles Darwin (1809–1882) was much taken by Croll's arguments on geological time. On this point, Darwin wrote to Croll,

I have never, I think, in my life, been so deeply interested by any geological discussion. I now first begin to see what a million means .... I thank you cordially for having cleared so much mist from before my eyes.<sup>26</sup>

Croll's orbital elements theory of alternating cold and warm hemispheres provided Darwin with a mechanism to support the accumulation of modifications needed for natural selection.<sup>27</sup> He included these ideas in the fifth edition of his *Origin of Species* (1869) as a rationale for accelerating the pace of evolution.<sup>28</sup> For Darwin, Croll's conclusions had 'a most important bearing on geographical distribution,' and he was pleased to add his name in nomination of Croll's election to the Royal Society.<sup>29</sup>

### 3. Arrhenius, Ekholm, and Callendar

A new branch of climate theory dealing with the effects of carbon dioxide emerged after Croll's demise. Its geological aspects were developed by Svante Arrhenius, Nils Ekholm, and their Swedish associates, and the full implications of human activities was first documented by G.S. Callendar. Both threads, the geological and the human, have since become major components of the 'climate controversy.'

Svante Arrhenius (1859–1927) received a Nobel Laureate in chemistry for the theory of electrolytic dissociation; he also pursued broad interests in meteorology and 'cosmic physics,' defined as the physics of the earth, sea, and atmosphere.<sup>30</sup> In 1895, based on earlier work by John Tyndall, Arrhenius suggested that a reduction or augmentation of about 40% in the concentration of a minor atmospheric constituent, carbon dioxide, might trigger feedback phenomena that could account for the glacial advances and retreats. In an important article, 'On the influence of carbonic acid in the air upon the temperature of the ground,' he developed an energy budget model that considered the

<sup>14</sup>Irons (1896, p. 104).

<sup>15</sup>Tyndall to Croll, 9 May 1865, quoted in Irons (1896, p. 147).

<sup>16</sup>Tyndall (1861, pp. 276–77).

<sup>17</sup>Lightman & Reidy (2014, p. 40).

<sup>18</sup>Tyndall to Croll, 19 May 1866, quoted in Irons (1896, p. 148); Tyndall to Croll, 15 February 1867, quoted in Irons (1896, p. 153); cf. Tyndall (1867, p. 418).

<sup>19</sup>Hamlin (1982); Fleming (1998a, b, pp. 147–55).

<sup>20</sup>Crawford (1997).

<sup>21</sup>Lyell (1872, vol. 1, p. 264).

<sup>22</sup>Lyell (1872, vol. 1, p. 277); Lyell to Darwin, 1 March 1866 (Darwin Correspondence Project, <https://www.darwinproject.ac.uk>).

<sup>23</sup>Lyell (1872, p. viii).

<sup>24</sup>Croll to Lyell, 28 September 1866, quoted in Fleming (1998a).

<sup>25</sup>Croll to Lyell, 30 November 1866, quoted in Fleming (1998a).

<sup>26</sup>Darwin to Croll, 19 September 1868, quoted in Irons (1896, p. 200).

<sup>27</sup>Liepmann (1981).

<sup>28</sup>Burchfield (1974); Croll to Darwin 23 June 1869, quoted in Irons (1896, p. 222).

<sup>29</sup>Darwin (1869, pp. 451–52), cited in Finnegan (2012).

<sup>30</sup>Crawford (1996).



radiative effects of carbon dioxide and water vapour at ambient temperatures and studied the response of his model to changes in the carbon dioxide concentration.<sup>31</sup> Arrhenius devoted five pages of his article to the work of his friend and colleague, the geologist Arvid Gustaf Högbom, who worked on the carbon cycle and the geochemistry of carbon.<sup>32</sup>

In 1901, Arrhenius's close colleague, Nils Ekholm (1848–1923), published a long review article 'on the variations of the climate of the geological and historical past and their causes.' He dismissed astronomical theories out of hand, mentioning Croll by name, but did not consider Croll's invocation of feedback mechanisms.<sup>33</sup> He did, however, acknowledge Croll's 'indisputable priority' for his theory that the obliquity of the earth's axis was a controlling factor in the climate of high latitudes.<sup>34</sup> Ekholm proposed that the principal variations of the climate of the past, over the course of at least 100 and perhaps 1000 million years, were probably due to long periodical, and perhaps also accidental, variations of the quantity of carbonic acid in the atmosphere. He foresaw this leading to a possible future ice age, but also pointed to the 'remarkable' human influence on climate, noting that the present burning of pit-coal is so great that in one year it gives back to the atmosphere about 1/1000 of its present store of carbonic acid, which would eventually cause a very obvious rise of the mean temperature of the earth. Ekholm ended his long essay on the speculative note that Man might someday 'control' climate by artificially increasing or decreasing the supply of carbonic acid, 'according to his wants and purposes.'<sup>35</sup>

The work of the Swedish geoscientists marks the emergence of the climate dioxide theory of climate change. They were not motivated by increasing levels of carbon dioxide due to the burning of fossil fuels; instead, they were attempting to explain temperature changes at high latitudes that could account for the onset of ice ages and interglacial epochs. They took a track that largely diverged from the orbital theory of Croll, yet in their own way, engaged in a quest to develop an alternative cosmic physics that linked the heavens and the earth.<sup>36</sup>

Guy Stewart Callendar (1898–1964) identified the link between the artificial production of carbon dioxide, enhanced sky radiation, and global warming. Today, this is called the 'Callendar Effect,' or, in popular jargon, anthropogenic global warming. Callendar was one of Britain's leading steam and combustion engineers and a specialist in infrared physics. He formulated a coherent theory of infrared absorption and emission by trace gases, established the 19th-Century background concentration of carbon dioxide at 290 ppm, and argued that its atmospheric concentration was rising due to human activities, which was causing the climate to warm. He did this in 1938!<sup>37</sup> In 2005, Dave Keeling recalled his correspondence with Callendar in the 1950s: 'He was a careful investigator and a major contributor to keeping alive interest in the CO<sub>2</sub> Greenhouse Effect during decades when it had almost been forgotten by the science community.'<sup>38</sup>

#### 4. Milanković

In the 20th Century, the Serbian mathematician and geophysicist Milutin Milanković (1879–1958), who was trained and worked in

civil engineering, took on a cosmic problem, setting out to place the astronomical theory of climate on a firm mathematical basis for the inner planets of the solar system and calculate the impact of earth's secular orbital cycles on climate change. He started working on the astronomical theory of climate in 1912, but his work was interrupted by the outbreak of World War I and was severely constrained by his house arrest in Budapest and the subsequent devastation of Belgrade. In 1920, Milanković published, in French, his *Mathematical theory of thermal phenomena produced by solar radiation*. In it, he credited Croll for recognising, more precisely than his predecessors, the influence of the eccentricity of the earth's orbit on the duration of the seasons. He provided a short technical critique of the astronomical part of Croll's theory, but commented only briefly on the core of Croll's contribution, his climatological ideas, regarding glacier formation in high latitudes.<sup>39</sup>

Two years later, Milanković received an invitation from the distinguished climatologist Wladimir Köppen and his son-in-law Alfred Wegener, to collaborate in calculating the influence of changes in earth's solar insolation on the ice ages. Milanković wrote one chapter and published his radiation curves for high latitudes in Köppen and Wegener's *Die Klimate der geologischen Vorzeit* (1924).<sup>40</sup> To codify this work, he decided to compile all of his previously published papers on palaeoclimatology into a single work, *Canon of Insolation and the Ice-Age Problem*, originally published in German in 1941, a work completed between the outbreak of World War II and the bombing of Belgrade, including the building that housed his typeset pages. The periodic orbital variations (eccentricity, obliquity, precession) he calculated in his canon of insolation, along with their climatic influences, today are called Milanković cycles.

In the *Canon*, Milanković referred to Croll's theory as the 'most remarkable' of the early ice age theories, since it 'correctly recognizes the influence of the eccentricity of the earth's orbit upon the duration of the astronomic seasons.' However, because of uncertainties in the timing of ice ages and in the stratigraphic record, and because Croll's theory predicted glaciation in only one hemisphere, the theory was largely disregarded for at least three decades. According to Milanković, the inadequacy of Croll's theory, 'lies in the fact that the influence of the variability of the obliquity upon the insolation is not sufficiently taken into account.'<sup>41</sup>

Milanković's work was inspired by a grand vision of an integrated cosmic science that could be applied to very specific problems in geology and climatology. His distinguished predecessor Croll, working from the holistic perspective of natural philosophy, also pointed out the necessary coherence of astronomy and geology. Yet, Milanković lost supporters in the 1950s when the new technique of carbon-14 dating of palaeontological materials showed a significant divergence from his theory. According to him, 'science is a continuum, and we never know if it has spoken its final word.'<sup>42</sup> Today's calibration of orbital cycles derives from evidence buried deep in the earth, in ice cores and ocean sediments. The artificial cardiac 'pacemaker' was invented in 1950, so this metaphor, applied to the astronomical theory, although memorable, is a very recent one.<sup>43</sup> Croll referred to climate change as 'the combined effect' of all the astronomical causes.<sup>44</sup>

<sup>31</sup>Arrhenius (1896).

<sup>32</sup>Högbom (1894); see also Berner (1995).

<sup>33</sup>Ekholm (1901, p. 2).

<sup>34</sup>Ekholm (1901, 45–46).

<sup>35</sup>Ekholm (1901, 60–61).

<sup>36</sup>Crawford (1996, pp. 145–55); Crawford (1997, p. 11).

<sup>37</sup>Callendar (1938); Fleming (2007).

<sup>38</sup>D. Keeling to J. R. Fleming, 9 February 2005, quoted in Fleming & Fleming (2007, box 2, notebook 1939-40-T1).

<sup>39</sup>Milanković (1920, pp. 248–53).

<sup>40</sup>Köppen & Wegener (1924).

<sup>41</sup>Milanković (1998); see also Petrović (2008).

<sup>42</sup>Milanković (1995, p. 85).

<sup>43</sup>Hays *et al.* (1976); Maslin (2016).

<sup>44</sup>Croll to Darwin, 2 December 1868 (Darwin Correspondence Project, <https://www.darwinproject.ac.uk>).

Over the years, Croll's work has been subjected to harsh judgement as 'wrong',<sup>45</sup> or merely a precursor of Milanković, but there are far more interesting historical perspectives on his work. Croll recognised the incomplete nature of the geological record of climate, and the evidence for climate change hidden in marine deposits:

But no doubt in the deep recesses of the ocean, buried under hundreds of feet of sand, mud, clay, and gravel, lie multitudes of the plants and animals which then flourished on the land, and were carried down by rivers into the sea. And along with these lie the skeletons, shells, and other exuviae of the creatures which flourished in the warm seas of those periods.<sup>46</sup>

The ability to reconstruct such climate chronologies came only in the 1970s when interdisciplinary teams began to analyse such data.<sup>47</sup>

In 2013, the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC), which focuses primarily on anthropogenic climate change, noted that 'recent modeling work provides strong support for the important role of variations in the earth's orbital parameters in generating long-term climate variability'.<sup>48</sup> Rather than viewing the astronomical and the carbon dioxide theories as two separate entities, they are now intimately linked, with cooling and warming orbital configurations seen as conditions for the sequestration and release of greenhouse gases.

## 5. Conclusion

The life and legacy of James Croll cannot be constrained to his scientific accomplishments. He is best known for his climate theories, but too narrow of a focus on this aspect of his work, and neglect of his considerable influence on his contemporaries and successors, threatens to reduce his contributions to only one dimension of his worldview. He was a natural philosopher and cosmic thinker whose legacy is not limited to climate science, but can be felt throughout Earth-system science. His was a personal quest for a general theory of the unity of nature, and, as an independent scholar and autodidact, he approached the problem from the perspectives of religion, philosophy, and natural science. In fact, Croll considered his scientific work to be a diversion from his primary interest in philosophy and theology. 'Little did I suspect,' wrote Croll in 1888, that working on climate change was the beginning of a path 'so entangled that fully twenty years would elapse before I could get out of it'.<sup>49</sup> Croll repeatedly declared his preference for philosophy over physics, and gave 'cosmological width of sweep' to his geological inquiries.<sup>50</sup> In the year of his election to fellowship in the Royal Society of London, Croll declined an invitation to speak at a meeting of the British Association for the Advancement of Science, writing,

I have not been at a scientific meeting for upwards of half a dozen of years. The real truth is, there is a cold materialistic atmosphere around scientific men in general, that I don't like. I mix but little with them. There is, however, indication of a reaction beginning to take place towards something more spiritual in science; and the day, it is to

be hoped, is not far distant when religion, philosophy, and science will go hand in hand.<sup>51</sup>

What Darwin did for life forms, Croll accomplished for climate change. Croll's 'tangled bank' was not constrained to organic nature, but invoked the vicissitudes of the earth's orbital path around the sun and the seemingly incalculable complexity of all the feedbacks it triggered, physical and biological, from the molecular to the planetary levels. There is 'grandeur' in Darwin's view of life, but so too in Croll's cosmic view of nature. Both men focused on natural laws, and both (Croll more than Darwin) invoked a First Cause who set into motion the complex dance of the material world. Irons wrote of Croll in 1896,

He was by nature a philosopher rather than a scientist. He was ever straining toward the most abstract, the origin of the material universe or the great First Cause .... The time has, perhaps, not yet arrived when an accurate estimate of the lasting value of his researches and speculations in science and philosophy can be formed.<sup>52</sup>

Perhaps the time has still not yet arrived, but by learning more about his cosmic connections, we are getting closer.

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<sup>45</sup>Weart (2003, p. 5).

<sup>46</sup>Croll (1875, pp. 288–89).

<sup>47</sup>Imbrie & Imbrie (1979); Burchfield (1980).

<sup>48</sup>IPCC (2013).

<sup>49</sup>Irons (1896, pp. 24, 33, 41).

<sup>50</sup>G. C. Baxter, quoted in Irons (1896, pp. 477–78); see also Finnegan (2012).

<sup>51</sup>Croll to Morison, 17 August 1876, quoted in Irons (1896, p. 312).

<sup>52</sup>Irons (1896, pp. 491, 493).

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MS received 13 December 2020. Accepted for publication 5 February 2021. First published online 10 May 2021