James Croll in Context: The Encounter between Climate Dynamics and Geology in the Second Half of the Nineteenth Century[1]

James Rodger Fleming

Science, Technology, and Society Program
Colby College, Waterville, Maine USA

jfleming@colby.edu

Introduction

This paper provides historical context and illuminates the roots of the work of Milutin Milankovic' by examining early contributions to climate dynamics by James Croll (1821-1890), the leading proponent of an astronomical theory of climate change in the nineteenth century.[1] Inspired by Joseph Adhémar's work, *Révolutions de la mer* (1842), and taking into account precession of the equinoxes, variations in the eccentricity of the orbit, and tilt of the axis, Croll 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."[2] Although Croll's theory of orbital elements has often been criticized as "wrong," and characterized as a precursor of Milankovic', there are far more interesting historical perspectives on his work. His fundamental insights into the interplay of astronomical and geological factors – into cosmic physics and climate dynamics -- were extremely influential, especially in the case of the leading geologist of his day, Charles Lyell, who revised his *Principles of Geology* in response to Croll's theory.

In order to examine the interplay of climate dynamics and "science dynamics" on centuries-to-decades time scales, the paper concludes with a comparison between the carbon dioxide theory and the astronomical theory of climate change, both of which experienced eclipse and reformulation before reemerging transformed in the twentieth century.

[1] Reprinted by permission of the Serbian Academy of Sciences and Arts from *Milutin Milankovic Anniversary Symposium: Paleoclimate and the Earth climate system, Belgrade, 30 August - 2 September 2004: invited lectures.* A. Berger, M. Ercegovac, and F. Mesinger, ed. (Belgrade, 2005), 13-20.

Biographical

James Croll, the second son of David Croil, a stonemason, and Janet Ellis, entered this world in the village of Little Whitefield, in the parish of Cargill, Perthshire, Scotland on 2 Jan 1821. He was raised on a farm, had almost no formal education, and was by his own account "a rather dull scholar," when in 1832, age 11, a favorable encounter with the *Penny Magazine* launched him on a lifetime course of reading, especially in philosophy and science.[3] He writes that, "even at the commencement of my studies, 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." Geology, with its emphasis on detailed observation, held no attraction for Croll, and his employment in 1867, at age 46, with the Scottish Geological Survey, was "more by accident than by choice," although it proved to be of "immense advantage" for his climatological studies.

Yet in an era when life expectancy was less than four decades, it took Croll fully four decades to find his life's work. He was in turn a *millwright* (yet a poor one because his mind tended to abstract thinking rather than practical details); a *house joiner* (until an inflamed elbow at age 25 ended his career as a physical laborer); a *tea merchant* (a venture terminated by the ossification of his elbow joint); an *innkeeper* (at a temperance inn with insufficient lodgers); an *insurance salesman* (a profession not suited to a man who loves solitude); a *newspaperman* with a temperance weekly; and a *caretaker* at Andersonian College and Museum in Glasgow.

Croll's physical disabilities and his "strangely checquered career" allowed him time for reading and writing in his favorite subjects, metaphysical and physical.[4] His first book, *Philosophy of Theism,* was published in 1857 at age 36, during his employment as an insurance salesman; his situation at Anderson's College surrounded him with a fine scientific library, brought him the acquaintance of Sir William Thompson, Lord Kelvin, and provided him "a good deal of spare time for study." This led to a number of scientific publications on electricity, heat, and notably, on astronomical controls on geological climate. His 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. "Little did I suspect," wrote Croll, that this was the beginning of a path "so entangled that fully twenty years would elapse before I could get out of it."[5]

In 1867 Croll turned down a field position in the Scottish Geological Survey, but accepted a job in Edinburgh as the survey's secretary and accountant. Croll's duties included ordering, printing, coloring, and selling maps and keeping the accounts and stores in order. The Director, Archibald Geikie, encouraged Croll to carry out his own research, but to write it up on his own time. According to Croll, "the duties of the office were not at all laborious, either physically or mentally."[6] In addition to his work on orbital theory, Croll made field excursions on glacial deposits and discovered a pre-glacial river bed running from Edinburgh to Glasgow. He also encouraged James Geikie to advance the theory of multiple glaciations. He shared this opinion with the famous evolutionary theorist Alfred Russell Wallace, who wrote, "It is, I think, now beyond question that the Glacial epoch consisted of a succession of cold and warm periods, which must be accounted for in any theory of geological climate"; and with the even more famous evolutionist Charles Darwin, who wrote, "It is strange that many geologists are so reluctant to admit Interglacial periods, which so much upset the [received] theories of climate."[7]

Croll's 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 later in life he was afflicted with head pains that became unbearable with mental exertion, still he produced numerous papers on climate change, glacier motion, geological time, ocean currents, and astrophysics.

In 1875 Croll published his major book, *Climate and Time*, a work delayed several years due to ill health, but a work widely admired for the profound impression it produced on geologists around the world.[8] The appearance of this book heralded his election as a Fellow of the Royal Society and his receipt of an LL.D. from Saint Andrews University -- which charged him 10 pounds 10 shillings for the honor, or more than $1000 today.

Croll was a very private man. A combination of poor health and modesty led him to turn down an invitation to lecture at the Royal Institution; his avowed dislike of what he called subterfuge, namedropping, and public displays kept him away from meetings of the British Society for the Advancement of Science. By 1871 he was "getting tired of geological subjects." He thought there were "more noble and ennobling studies than science" which he considered too narrow minded. After a good rest he wanted to return to his "old favorite study of philosophy."[9]

In 1880 Croll further strained his heart and retired from the Survey, expecting to draw a full pension because of his advanced age. To his chagrin, he received credit for only thirteen years of employment and saw his income plummet from 350 pounds to 75. This dire financial situation forced the Crolls to give up housekeeping and go into rented lodgings.

In retirement Croll wrote two more scientific books: *Discussions on Climate and Cosmology* (1886) and *Stellar Evolution and its Relations to Geologic Time* (1889). The former served largely as a reply to his critics and an opportunity to develop, illustrate, and confirm his theory of the secular change of the earth's climate. According to Irons, "even if [Croll's theory] be not in all respects faultless and complete, it will forever be acknowledged as having opened up the way for any thorough explanation of the phenomena with which it deals."[10] With his health failing, Croll was finally able to return to his first love, philosophy, and saw the publication of his fifth book, *The Philosophical Basis of Evolution* (1890), a response to Darwinism and Spencerianism, through the press in the year of his death.

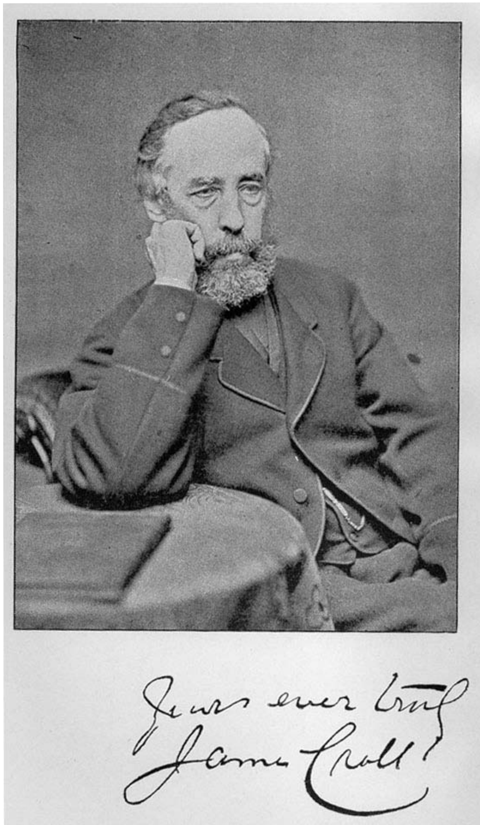

Fig. 1. Croll from Irons, frontispiece.

Fig. 2. Croll from Irons, facing p. 405.

Croll's Theory

In 1864 Croll published an article in the *Philosophical Magazine* "On the Physical Cause of the Change of Climate During Geological Epochs." In this paper Croll introduced changes in the earth's orbital elements as likely periodic and extraterrestrial mechanisms for initiating multiple glacial epochs. Two decades earlier, in *Révolutions de la mer* (1842), Joseph Adhémar had considered only the climatic effects of the present amount of eccentricity, not the effect of its changes. Moreover, Adhémar was a catastrophist. He extravagantly assumed that when the earth was gripped by an ice age the polar ice-cap rested on the bottom of the ocean, rising to the enormous height of twenty leagues (~100 km). After 10,000 years, warming conditions, triggered by precession, allow the oceans to erode the base of the polar ice cap, causing it to collapse catastrophically into the ocean. According to Adhémar, this sudden motion of such a massive body of ice causes a dramatic shift in the earth's center of gravity, dragging the oceans along with it and smashing everything on the surface of the globe with a massive tidal wave of death and destruction.[11]

Unlike Adhémar, Croll was an actualist, but unlike Charles Lyell, he was willing to consider cosmic causes for earth processes. Croll wrote that he had "studiously avoided introducing into his theories anything of a hypothetical nature," and had set out to prove that "the theory of secular changes of climate follows, as a necessary consequence, from the admitted principles of physical science."[12]

Employing the calculations of Leverrier and Lagrange of the maximum eccentricity of the Earth's orbit, and extending them over the course of four million years (Figure 3), Croll proposed that this "eccentricity was sufficiently great to account for every extreme of climatic change evidenced by geology."[13] His theory of ice ages took into account 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.[14] 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 (see Figure 4).

Feedback mechanisms, such as 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 (see Figure 5) would serve to enhance the climatic changes initiated by the orbital elements. According to Croll, "The *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." That is, "glacial cycles may not arise *directly* from cosmical causes, they may do so *indirectly*!" [15]

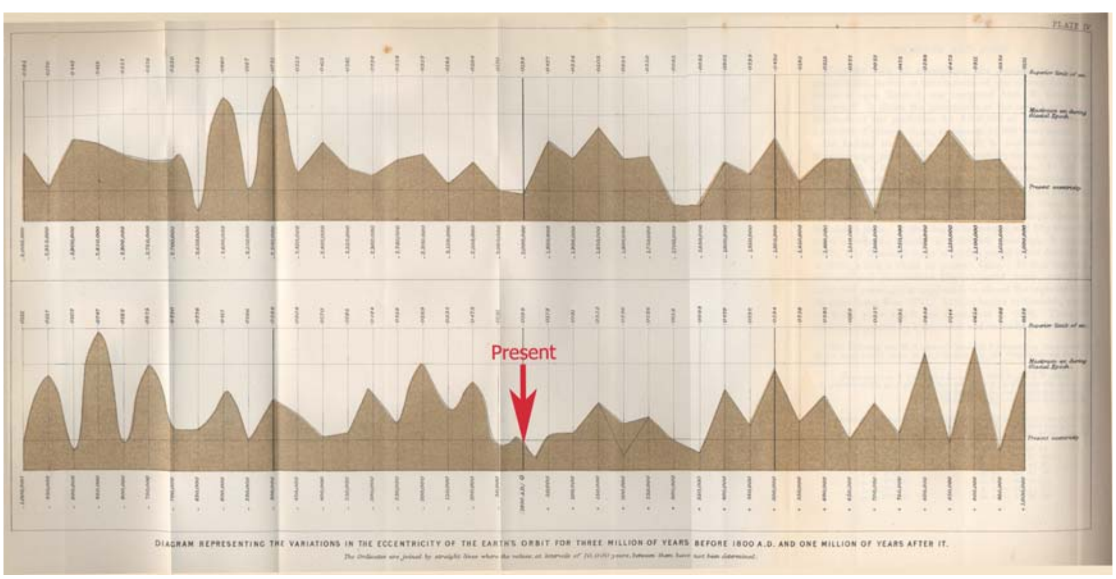

Fig. 3. Variations in the earth's orbit for three million years before 1800 A.D. and one million years after it, from Croll, 1875, following p. 312.

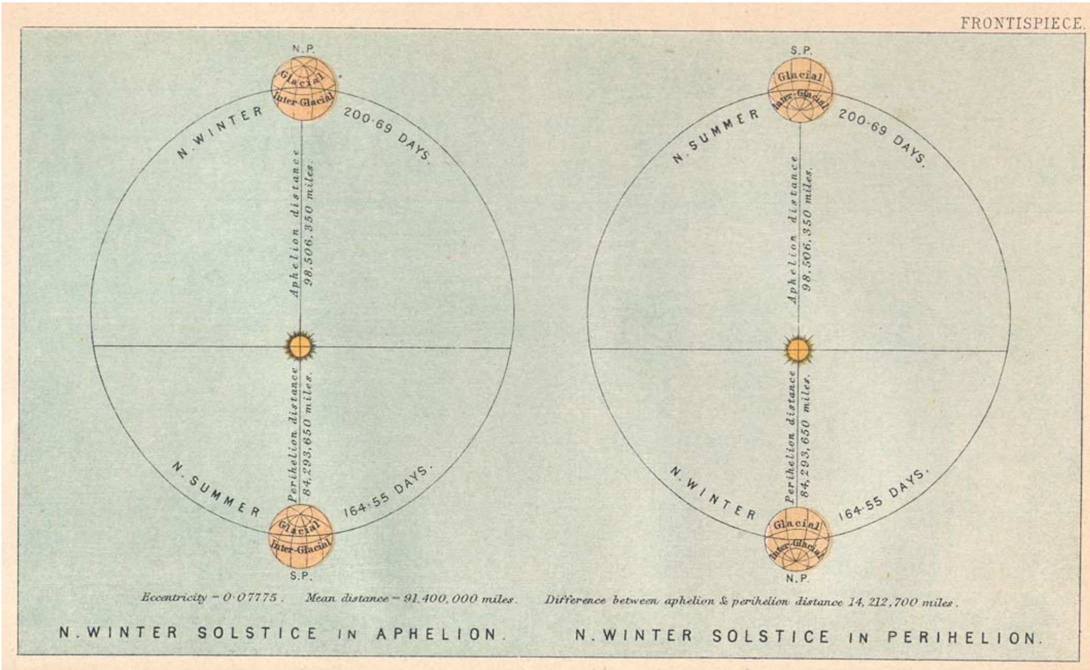

Fig. 4. Glacial and interglacial conditions when eccentricity is at its superior limit, from Croll, 1875, frontispiece.

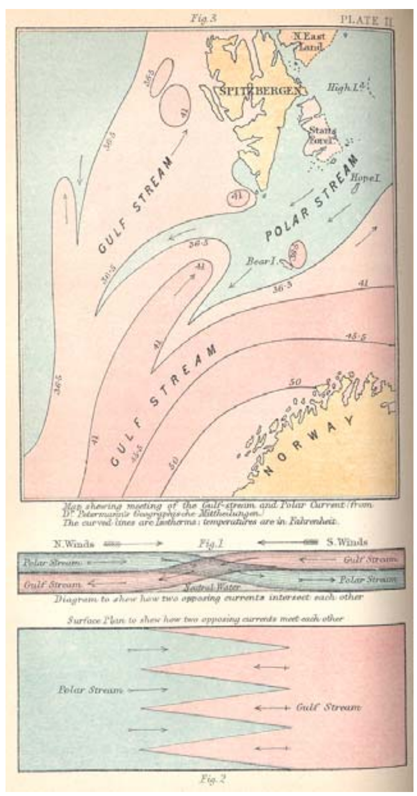

Fig. 5. Warm and cold currents, one of the key feedback mechanisms causing climate change, from Croll, 1875, facing p. 219.

Croll and Lyell

Croll's astronomical challenge to the geographic theory of climate change caused an uproar amongst Charles Lyell and his associates. In 1865, as he was preparing the important tenth edition of his *Principles of Geology*, Lyell sought expert advice on how to deal with the new contender. He asked Sir John Herschel's opinion on the reliability of Croll's "facts and reasons," adding, "Of their applicability to Geology I may perhaps form an independent opinion. . . . I feel more than ever convinced that changes in the position of land & sea have been the principle cause of past variations in climate, but astronomical causes must of course have had their influence & the question is to what extent have they operated?"[16] Herschel replied that astronomical causes could provide huge temperature fluctuations, "quite enough to account for any amount of glacier and coal fields…. Suppose a distribution of land favorable to cold, suppose an extreme e[ccentricity], and suppose the aphelion to coincide with the winter first in one hemisphere and then in the other, and any amount of glacier you can want is at your disposal…"[17] Lyell responded to Herschel with a twenty-two page letter explaining why geographic causes had to predominate over astronomical ones. He *knew* the enormous influence on climate of varying configurations of land and sea from direct accounts and observations; the effects of varying eccentricity had yet to be proven.[18] Lyell conducted a similar correspondence with the Astronomer Royal, Sir George Biddell Airy, concerning the "ancient state of the Earth's orbit."[19]

By 1866 Lyell, on the advice of Herschel and Airy, had tentatively accepted Croll's theory as a true, but minor cause of climatic change. Lyell wrote to Charles Darwin that he considered Croll's maximum eccentricity for the glacial period, "quite subordinate to geographical causes or the relative position of land and sea and abnormal excess of land in polar regions."[20] Darwin was much more enthusiastic than Lyell about the astronomical theory. He accepted it in part because it provided a valuable mechanism for speciation. Darwin thanked Croll for sending him his papers from the *Philosophical Magazine*. "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."[21] He further agreed with Croll that the advocates of the iceberg theory (such as Lyell) had formed "too extravagant notions regarding the potency of floating ice as a striating agent."[22]

In September 1866, Croll received Lyell's proof sheets for the climate chapters of the tenth edition of the *Principles of Geology*.[23] Croll wrote back immediately 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 the physical feedbacks of climate dynamics.[24] Two months later, upon receipt of the tenth edition of the *Principles* in November, Croll sent Lyell a thank-you note for the handsome gift and for the "highly complimentary way" in which his astronomical theory had been treated.[25] Lyell had indeed agreed with Croll on many points. Although they still had deep disagreements, Croll attributed their differences to basic incompatibilities in the approaches of physics and geology.[26]

Compared to earlier editions, Lyell's tenth and subsequent editions devoted more than twice as much space to climatic change. While the previous edition had had about 58 pages on climate and its vicissitudes, the tenth edition had 130, including a new chapter on astronomical influences with a 37-page section on Croll. Quoting Lyell: "Mr. Croll's suggestion as to the probable effects of a large excentricity in producing glacial epochs is fully discussed, and the question is entertained whether geological dates may be obtained, by reference to the combined effect of astronomical and geographical causes"—with the latter dominant.[27]

Theory Emergence, Eclipse, and Reemergence

The astronomical theory of climate change emerged between 1864 and 1890 with the work of James Croll. Milankovic' 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."[28] 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 Milankovic', 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."[29]

The astronomical theory reemerged from eclipse and was formulated into a mathematical theory of insolation by Milutin Milankovic' between 1920 and 1941. Notwithstanding the precision of the "Canon of Insolation," even the Milankovic' theory "had an uneven run" and was in partial eclipse until the 1960s, in part because of thermal lags in the climate system and in part because of the unexplained lack of continental glaciation prior to the Pleistocene. In 1976 the theory received new confirmation from the paleostratigraphic work of James Hayes, John Imbrie, Nicholas Shackelton, and others who documented the astronomical signals in a number of independent proxy climate records.[30]

The carbon dioxide theory of climate change followed a similar trajectory. It emerged in the nineteenth century as a consequence of the experimental work of John Tyndall (ca. 1859) and the global model published by Svante Arrhenius (1896) before falling into dispute and eclipse in the early decades of the twentieth century. The work of G.S. Callendar from 1938 to 1961 revived and reformulated the theory. It was further brought out of eclipse by the work of Gilbert Plass (ca. 1953), Charles David Keeling (from 1958), Budyko (in the 1970s) and many others. In recent decades the carbon dioxide theory has moved from a scientific question, to a scientific concern, to a "scientific consensus" and a dominant public policy issue.[31]

There are further parallels between the two theories. Compare Tyndall's statement about atmospheric trace gases:

> Changes in the amount of any of the radiatively active constituents of the atmosphere—water vapor, carbon dioxide, ozone, or hydrocarbons—could have produced "all the mutations of climate which the researches of geologists reveal…

with an early statement by Croll about the astronomical theory:

> 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."

Almost a century later, faced with the difficulties of reviving the carbon dioxide theory and establishing the astronomical theory G.S. Callendar wrote: "How easy it is to critique and how difficult to produce a constructive theory of climate change!" (1957), and Milankovic' observed:

"If my theory is good, it will live by its strength" (1958).[32] Today both theories are part of mainstream science. Major reference works cite the *Callendar Effect* :

> Climatic change brought about by anthropogenic increases in the concentration of atmospheric carbon dioxide, primarily through the processes of combustion. The actuality of such changes was proposed in 1938 by the English scientist G.S. Callendar." (*Encyclopedia Britannica*),

and the *Milankovic' Theory*:

> A theory connecting climate changes and glaciations with cyclic variations in the earth's orbit (*Oxford English Dictionary*).

Conclusion

During Croll's lifetime the Great Ice Age had been discovered and notions of multiple glacial and "Crollean" interglacial epochs were being debated. Many of the major mechanisms of climatic change had been proposed, if not yet fully explored: changes in solar output, changes in the Earth's orbital geometry, geographical changes, and changes in atmospheric transparency and composition. New climate theories were being introduced and new work was being done on heat budgets, spectroscopy, and the carbon dioxide content of the atmosphere. The stratographic sequence had not been worked out and many geologists still thought that glacial "drift" deposits had been carried by icebergs. Through such tempestuous theoretical waters, Croll kept a steady course, negotiating between cosmic and terrestrial physics on the one hand (as exemplified by Herschel and Lord Kelvin) and geology on the other, as practiced by Lyell, Darwin, and the Geikie brothers.

The historical literature on climate change has not yet received adequate attention.[33] Most historical accounts criticize James Croll for being "wrong" or refer to him merely as a heroic precursor of Milankovic'. Recently, calling Croll a "British" geologist (fighting words to a Scottish natural philosopher) Spencer Weart dismissed him with the following words, "Most scientists found Croll's ideas unconvincing, and his timing of the ice ages wholly wrong."[34] However, as documented here, Croll had a significant influence on such luminaries as Lyell, Herschel, Darwin, and the Geikie brothers, to name just a few. As the *Saturday Review* noted, "every honest scientific investigator will admit that [Croll's] writings have had the most radical influence on cosmological speculation. In certain directions his influence has been nearly as great as that of Darwin's in biology.[35]"

Both Croll and Milankovic' were visionaries, both were extremely disciplined and principled; both had to face and overcome extreme challenges to advance their theories; both had the Herculean task of trying to unite heaven and earth; both provided "missing link(s) between celestial mechanics and geology."[36] As Milankovic' noted:

> [Astronomical causes of climate change] lie far beyond the vision of the descriptive natural sciences. It is therefore the task of the *exact* natural sciences to outline this scheme, by means of its laws ruling the universe and by its developed mathematical tools. It is left, however, to the *descriptive* natural sciences to establish an agreement between this scheme and geological experience.[37]

This sentiment applies to Croll in context. I argue that Croll's ideas on climatic change can only be understood and evaluated properly in light of nineteenth-century science in general and geology in particular. If Croll's theory that the earth's climate "revolves" around the sun started a Copernican revolution in climate dynamics, then Milankovic' served as the Newton of this field. On the occasion of the 125th anniversary of the birth of Milutin Milankovic' in 1879, a year in which James Croll was actively defending his book, *Climate and Time*, historians will readily agree that the contributions of *both* individuals are best evaluated in context.

References

Adhémar, Joseph, 1842. *Révolutions de la mer, déluges périodiques*. Paris.

Bard, Edouard, 2004. "Greenhouse effect and ice ages: historical perspective," *C.R. Geosciences* 336: 603-38.

Croll, James, 1857. *Philosophy of Theism*. London.

Croll, James, 1864. "On the Physical Cause of the Change of Climate During Geological Epochs," *Philosophical Magazine* 28: 121-37.

Croll, James, 1867. "On the Change in the Obliquity of the Ecliptic, its Influence on the Climate of the Polar Regions and on the Level of the Sea," *Philosophical Magazine* 33: 426-45.

Croll, James, 1875. *Climate and Time in Their Geological Relations. A theory of secular changes of the earth's climate*. New York.

Croll, James, 1886. *Discussions on Climate and Cosmology*. New York.

Croll, James, 1889. *Stellar Evolution and Its Relations to Geological Time*. London.

Croll, James, 1890. *The Philosophical Basis of Evolution*. London.

Darwin, F. and A.C. Seward, ed., 1903. *More letters of Charles Darwin*, 2 vols. London.

Fleming, James Rodger, 1998. *Historical Perspectives on Climate Change*. New York.

Fleming, James Rodger, 2007. *The Callendar Effect*. Boston.

Hamlin, Christopher, 1982. "James Geikie, James Croll, and the Eventful Ice Age, *Annals of Science* 39: 565-83.

Hays, J.D., J. Imbrie, and N.J. Shackleton, 1976. "Variations in the Earth's Orbit: Pacemaker of the ice ages," *Science* 194: 1121-32.

Herschel, John, Papers. Royal Society Library. London.

Imbrie, John and Katherine Porter Imbrie, 1986. *Ice Ages: Solving the mystery*, 2d ed. Cambridge, Mass.

Irons, James Campbell, 1896. *Autobiographical Sketch of James Croll with Memoir of his Life and Work*. London.

Lyell, Charles, Papers. Special Collections Department, Edinburgh University Library [Cited in endnotes as Lyell Papers].

Lyell, Charles, 1866-68. *Principles of Geology*, 10th ed. London.

Milankovic', Milutin, 1998. *Canon of Insolation and the Ice-Age Problem*. Belgrade.

Milutin Milankovic´ 1879-1958, 1995. European Geophysical Society.

Petrovic', Aleksandar, 2002. *Insolation and Climate: Milutin Milankovic' and the Mathematical Theory of Climate Changes*. Belgrade: Ministry for Protection of Natural Resources and Environment of the Republic of Serbia.

Tasch, Paul, 1986. "James Croll and Charles Lyell as Glacial Epoch Theorists," *Earth Sciences History* 5: 131-33.

Weart, Spencer, 2003. *The Discovery of Global Warming*. Cambridge, Mass.

Endnotes

[1] A common alternative spelling is Milankovitch; the outline of Croll's life was derived from his "Autobiographical Sketch," in Irons, 9-41.

[2] Croll, 1864, 129; Croll, 1867, 443; Croll to John Herschel, 14 Feb. 14, 1865, in Irons, 123.

[3] The quoted material in this section is from Irons, 9-41.

[4] Irons, 493.

[5] Croll, in Irons, 31-33.

[6] Ibid., 35.

[7] Croll to A.R. Wallace, 24 July 1880, in Irons, 359; Croll to Charles Darwin, 3 Nov. 1886, in Irons, 431.

[8] J. Horne in Irons, 517.

[9] Croll to Rev. Osmond Fisher, 28 Aug. 1871, in Irons, 261-62; and 17 June 1875, in Irons, 282-83.

[10] Irons, 493-94.

[11] Croll 1875, 544-45.

[12] Croll, 1875, 22.

[13] Irons, 123.

[14] Croll 1864, 122-23.

[15] Irons, 228; J. Horne in Irons, 510.

[16] Charles Lyell to John Herschel, 31 Jan. 1865, Herschel Papers.

[17] Herschel to Lyell, 6 Feb. 1865; Herschel to Lyell, 15 Feb. 1865, both in Herschel Papers.

[18] Lyell to Herschel, 11 Feb. 1865, Herschel Papers.

[19] Cited in Lyell to Herschel, 28 April 1865, Hershel Papers.

[20] Lyell to Darwin, 1 Mar. 1866, in Darwin and Seward.

[21] Darwin to Croll, 19 Sept. 1868, Irons 200.

[22] Darwin to Croll, 24 Nov. 1868, in Darwin and Seward.

[23] Croll to Lyell, 24 Sept. 1866, Lyell Papers.

[24] Croll to Lyell, 28 Sept. 1866, Lyell Papers.

[25] Croll to Lyell, 30 Nov. 1866, Lyell Papers.

[26] Croll to Lyell, 12 Dec. 1866, Lyell Papers.

[27] Lyell 1866-68, viii.

[28] Milankovic', 1998, 500-02.

[29] Ibid.

[30] *Milutin Milankovic´ 1879-1958*, 1995, 158-59; Hays, et al., 1976; Imbrie and Imbrie, 1986.

[31] For details, see Fleming 1998.

[32] G.S. Callendar to Gilbert Plass, 13 May 1957, Callendar Papers, University of East Anglia, for details see Fleming 2007; Milankovic' cited in Petrovic', 15.

[33] Notable exceptions include Hamlin and Tasch.

[34] Weart, 5.

[35] *Saturday Review*, Oct. 1887, cited in Irons, 438.

[36] Milankovic' cited in Petrovic', 3.

[37] Imbrie and Imbrie, 172-73.