cables if they do not contain anything revelatory nonetheless force us to consider the role of public appearances. Is one take home message of this affair (as Zizek notes more generally) that diplomats and political leaders mislead, and sometimes lie, in order to reassure their public audiences that the Arctic region is being governed in a sustainable and peaceful manner? What if the former Danish foreign minister was not joking? What if the Canadians really believed that there are people who really 'don't belong' to the Arctic? Is the spectre of future oil/gas discoveries really driving much of current Arctic policies of Arctic Ocean coastal states? This matters given the claims made by the Arctic Council membership to exercise their environmental, legal and political authority responsibly. Third, do the release of these cables undermine diplomacy, whether Arctic-based or not, by their blatant undermining of the Vienna Convention on Diplomatic Relations, which outlines the confidentiality of diplomatic intercourse? Finally, do the cables, however briefly, talk to the emergence of new knowledge networks and actors engaging with the Arctic region in the www era (more generally, Cull 2011)?

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James Croll: a scientist ahead of his time

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ABSTRACT. James Croll (1821–1890) was a Scottish scientist who made major, although still largely unrecognised, contributions to the theory of the effects of variations in the Earth's orbit on the global climate. He was the first to identify the importance of positive feedbacks in the climate system, especially the ice-albedo feedback, and he placed the astrochronological method on a sound footing. Croll's theory was the first to predict multiple ice ages. However, it was unable to place the end of the most recent glaciation more recently than 80,000 years ago, and as evidence accumulated throughout the 19th century for a much more recent date than this Croll's theory fell into neglect. We argue that this was particularly unfortunate since several of his key ideas were forgotten, and that this has delayed the development of the orbital theory of paleoclimate.

Introduction

James Croll (2 January 1821–15 December 1890) was a Scottish scientist from a modest background who made an outstanding, but insufficiently acknowledged, contribution to science. He contributed to a wide range of disciplines, but his greatest achievement was the development of the orbital theory of paleoclimate. Today, almost 150 years after his work in this area was first published, and a few months after the 190th anniversary of his birth, this achievement is still not as widely recognised as it ought to be.

Croll was born in rural Perthshire in 1821, the second son of a stonemason. At the age of eleven he developed a passion for reading, especially philosophy and science, which remained with him throughout his life. He at first pursued a varied but unsuccessful business career, including spells as innkeeper and tea merchant (Irons 1896) until 1858. In 1859 he became caretaker of Anderson's College and Museum in Glagow, and in 1867 he accepted the post of resident geologist in the Edinburgh office of the Geological Survey, from which he retired in 1880. He had attracted the attention of the scientific establishment through the publication of 'On the physical cause of the change of climate during geological epochs' (Croll 1864). He was elected a Fellow of the Royal Society in 1876, being awarded a doctorate by St Andrew's University in the same year. He died in Perth in 1890.

The orbital theory of paleoclimate was first proposed by the French mathematician Joseph Adhémar (Adhémar 1842), who suggested that ice ages were caused by variations in the Earth's orbit, that is by astronomical effects (Croll, 1875; Imbrie and

Imbrie 1986). Because of the Earth's elliptical orbit around the Sun, winter and summer are not generally of equal length. At present, for example, because the date of perihelion (3 January) is close the northern hemisphere winter solstice, winter is shorter in the northern hemisphere than in the southern hemisphere. Adhémar suggested that glaciations would occur in the hemisphere in which the date of the winter solstice coincided with the aphelion, increasing the seasonal contrasts of insolation in that hemisphere. In other words, that hemisphere would experience long cold winters and short hot summers. In the opposite hemisphere contrasts of insolation would be lower so that mild short winters would be followed by long cool summers. According to Adhémar, long cold winters were the reason for glaciations in the relevant hemisphere, while the other hemisphere would experience an interglacial period.

Adhémar's theory was disputed by the English astronomer John Herschel and also by the outstanding German naturalist Alexander von Humboldt (Croll 1875; Imbrie and Imbrie 1986). They both showed that the average temperature of a hemisphere is determined by the quantity of solar energy received during the whole year, rather than in half a year. And as the change in the annual quantity of solar energy due to precession is equal to zero (thus, for example, reduction in winter insolation is compensated by increase in summer insolation) for either hemisphere, there are no corresponding changes in the climate of either hemisphere. In this way, there are no reasons for global climate change, particularly for the start of glaciations.

Nevertheless, Adhémar's orbital hypothesis was re-examined by Croll 20 years later, in his 'Theory of secular changes of the earth's climate' (Croll 1864, 1867, 1875). Despite the fact that Croll also thought that climatic circumstances, characterised by long winters, would lead to glaciations in the corresponding hemisphere, his theory was a major step forward in the explanation of climate change caused by variations in orbital insolation. Croll's work was characterised by wide erudition and a thorough approach to the problem. He examined the effect of the Earth's inner reserves of heat on its own climate, the planet's passage through hypothesised 'warm' and 'cold' regions of space, possible changes in the solar constant, the effect of the distribution of land and water, and many other hypotheses. He showed that none of these factors could explain glacial–interglacial cycles and he came to the conclusion that the most likely reason for the repeating glaciations was orbital variations of the insolation.

Croll's theory of paleoclimate

Croll had begun his work 20 years after Adhémar's book was published, and from then until the publishing of his main work *Climate and time in their geological relations* . . . .(Croll 1875) science had advanced considerably. Croll was familiar with achievements in astronomy, physics, meteorology and geology. He also knew the views of Humboldt and Herschel, mentioned above, that it was the annual input of heat, rather than that during the winter, that was relevant to the climate. Croll was aware that the direct effect on global climate of changes in insolation through orbital variation is negligible, because the variations of insolation connected with changes in eccentricity of the Earth's orbit are very small and the annual global change of insolation connected with the fluctuation of the two other orbital elements (precession of the equinoxes and obliquity of the ecliptic) is zero (they are 'compensated'). Although he was aware that his idea was unorthodox, Croll believed that it explained the connection between orbital insolation variations and glaciations. He wrote as follows (Croll 1875: 13).

> There is, however, one effect that was not regarded as compensated. The total amount of heat received by the earth is inversely proportional to the minor axis of its orbit; and it follows therefore, that the greater the eccentricity, the greater is the total amount of heat received by the earth. On this account it was concluded that an increase of eccentricity would tend to a certain extent to produce a warmer climate. All those conclusions to which I refer, arrived at by astronomers, are perfectly legitimate so far as the direct effects of eccentricity are concerned, and it was quite natural, and, in fact, proper to conclude that there was nothing in the mere increase of eccentricity that could produce a glacial epoch. How unnatural would it have been to have concluded that an increase of the quantity of heat received from the sun should lower the temperature and cover the country with snow and ice! Neither would excessively cold winters, followed by excessively hot summers, produce a glacial epoch. To assert, therefore, that the purely astronomical causes could produce such an effect would be simply absurd. . . The important fact, however, was overlooked that, although the glacial epoch could not result directly from the increase of eccentricity, it might nevertheless do so indirectly. Although an increase of eccentricity could have no direct tendency to lower the temperature and cover our country with ice yet it might bring into operation physical agents which would produce this effect.

What Croll meant by the term 'physical agents' was positive feedbacks. He wrote further (Croll 1875: 74–75),

> There is one remarkable circumstance connected with the physical causes which deserves special notice. They not only all lead to one result, viz., an accumulation of snow and ice, but they react on one another. . . .in regard to the physical causes concerned in the bringing about of the glacial condition of climate, cause and effect mutually reacted so as to strengthen each other.

Thus Croll was the first to consider the effect of positive feedback, which increased the effect of orbital variation of insolation and transformed that variation into global climate change, that is into glaciations and interglacial periods. That is the main achievement of his theory, and to our mind, is the most important discovery in paleoclimatology. Its consequences are not yet sufficiently recognised.

Croll considered two main mechanisms of positive feedback: between temperature and snow and ice cover (albedo feedback), and between global temperature and displacement of the ocean currents. He believed the second mechanism to be more important, and had previously shown the major influence of the Gulf Stream on the climatic conditions of Europe. The eccentricity e of the Earth's orbit varies, from a low value of about 0.003 to a relatively high value of 0.058 (its current value is 0.017). According to Croll's theory, the feedback mechanism would effectively operate when the eccentricity was high. He also supposed that only particularly long cold winters, connected with an increased value of e and accompanied by unusual falls of snow, would support the mechanism of positive feedback. And it will lead to a further temperature drop, despite the rise in summer insolation having been followed by the corresponding decrease in winter insolation.

To calculate the changes of eccentricity for 3 billion years before the 1800 and 1 billion years after it, Croll used formulas and data of Leverrier. According to his calculation, the highest eccentricities occurred during the period from 980 to 720 thousand years BP and from 240 to 80 thousand years BP. He connected those periods of time with the possibility of glaciations, and deduced that the last terrestrial glaciations ended about 80,000 years ago. Thus Croll was the first to use an astronomical calculation (eccentricity variation) to date paleogeographical events.

The essential predictions of Croll's theory of glaciations were thus that they occurred during periods of high eccentricity. During these long periods (typically about 200 thousand years), both hemispheres were subjected to glaciations, alternating approximately every 10.5 thousand years (half the period of the precession cycle). As we have noted above, the hemisphere experiencing glaciation is the one in which the date of aphelion passage occurs during the winter. Clearly, this kind of glaciation cannot be regarded as truly global. Periods of time with intermediate eccentricity values were interpreted by Croll as interglacial periods and were compared with deposits between glacial horizons.

Croll also included in his book a chapter on the climatic impact of variations in the obliquity ε, which he did not take into consideration in his preliminary theory. At the time he was developing his theory, data on the variation of ε were not well established, having to wait until the work of Stockwell in 1873 and Pilgrim in 1904 (Croll 1875; Imbrie and Imbrie 1986). Nevertheless he recognised the importance of taking into consideration variation of this orbital element. He wrote at the beginning of the 25th chapter of his book (Croll 1875: 398):

> There is still another cause which, I feel convinced, must to a very considerable extent have affected climate during past geological ages. I refer to the change in the obliquity of the ecliptic. This cause has long engaged the attention of geologist and physicist, and the conclusion generally come to is that no great effect can be attributed to it. After giving special attention to the matter, I have been led to the very opposite conclusion. It is quite true, as has been urged, that the changes in the obliquity of the ecliptic cannot sensibly affect the climate of temperate regions; but it will produce a slight change on the climate of tropical latitudes, and a very considerable effect on that of the polar regions, especially at the poles themselves.

Croll discussed the climatic influence of variations in obliquity using Meech's calculations (Croll 1875: 399, 400). According to these calculations, when the obliquity increases, the annual quantity of solar heat input increases at high latitudes and decreases at low latitudes. The relative changes of heat are much more significant at high latitudes than at low latitudes. Based on these calculations, Croll showed that reduction in the obliquity should promote glaciations at high latitudes in both hemispheres, because the reduction in ε would lead to the reduction of temperature, increase of snow and ice cover, and the influence of positive albedo feedback, reinforcing the initial fall of temperature. Conversely, increase in ε should lead to warming and to thawing of snow and ice in polar regions. (It should be noted that at that time this was an unconventional result, because some researchers, who were criticised by Croll, thought that increasing obliquity would lead to the opposite result, that is a fall in temperature at high latitudes, caused by lowering the latitude of the polar circle).

Variations in the obliquity ε lead to single phase changes of climatic conditions at high latitudes in both hemispheres. Thus it could reinforce the climatic influence of the precession mechanism of glaciations, as suggested by Croll's theory, in one hemisphere and reduce it in the other. For example, a decrease in temperature in one hemisphere would be reinforced, if the point of the winter solstice at aphelion matched the minimum value of angle ε; while it would be reduced if the angle of inclination were at its maximum value at that time. We think that Croll realised that this fact made his theory more complicated, though he did not discuss the point in detail. Nonetheless, he pointed out one more phenomenon connected with increasing obliquity: an increase in sea level caused by thawing of snow and ice in polar regions. It is important to note that to prove his conclusions Croll made extensive use of the geological data available at that time.

Failure of Croll's theory

By the end of 19th century empirical evidence had been accumulated that posed difficulties for Croll's theory. Research in both America and Europe pointed to the fact that the last glaciations had finished about 10 thousand years ago rather than the 80 thousand years implied by the theory. This divergence of the theory from the empirical data was the main reason for the failure of Croll's theory to be accepted. At the present time we can say that the biggest mistake in his theory was the assumption that glaciations depend only on seasonal contrasts of insolation, and conditional precession, modulated by eccentricity changes. This conclusion comes from the now widely accepted fact that Pleistocene glaciations occurred in both hemispheres simultaneously. It also fails to match the antiphase influence of precession, but coincides with the minimum eccentricity, at the same time that the precession changes are minimum, and not maximum as predicted by Croll's theory. Furthermore, oxygen isotope analysis of deep water cores shows that precession has the least influence on global changes over the last billion years.

Such criticisms have the benefit of considerable hindsight, but in the second half of the 19th century when geologists had just started to realise the scale of geological time changes, when only the first steps had been taken in studies of the nature of heat and of heat exchange, and when the planet Neptune had been discovered not long before, Croll's theory was a huge step towards realising how interactions between astronomical and terrestrial factors determine the climatic conditions of our planet during the last billion years. His work was ahead its time, especially in introducing the role of positive feedback in determining the intensity and globalism of the orbitally induced variations in insolation in climate changes.

Croll and Milankovitch

It should not be forgotten that Milutin Milankovitch began his research 50 years after Croll. His interpretation of orbital theory of paleoclimate was different from the earlier theories of Adhémar, Croll and others in using mathematically accurate calculations of the effect of variations in orbital conditional insolation at the upper atmospheric boundary. The main idea of his theory is that he attached a direct paleoclimate value to calculated specific (for the summer caloric half-year and at latitude 65° N) insolation variation during last 600 thousand years. For instance, the smallest values of summer insolation at latitude 65° N were interpreted by him as glaciations. Moreover, he supposed that there was

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a linear relation between the calculated summer and winter insolation at different latitudes and the summer and winter temperatures at these latitudes (Milankovitch 1930). In this way, the theory of Milankovitch had a dual effect on the development of the orbital theory of paleoclimate.

On one hand, it was a step forward, through the mathematically accurate calculation of insolation. However, on the other hand progress in orbital theory regressed to the times of Adhémar, because Milankovitch did not take into consideration the reasonable conclusions made by Herschel and Humboldt. To explain the global climate fluctuation he used calculations of semi-annual insolation at a particular latitude. Therefore in his research Milankovitch had no need of the theory and development of positive feedback mechanisms suggested by Croll. (He used it mostly to identify the effect of obliquity on climate variation, which Croll had already done.) Imbrie (1982: 413) criticised this aspect of Milankovitch's theory, adopted also by some later scientists:

> There has also been a tendency for investigators to believe they could model the response of the system from a radiation curve representing the input at a single latitude and season (for example Milankovitch 1941; Kukla 1968; Broeker and van Donk 1970). Since no one could be sure which insolation curve, if any, was the crucial one, investigators had great freedom to choose a curve that resembled a particular set of data. Understandably the resulting ambiguity did much to undermine confidence in the validity of the time domain prediction. Starting in 1976, with the advent of numerical models that integrated the effect of insolation changes over all latitudes and seasons, this situation was much improved.

However, the point of view founded on discrete insolation variations has prevailed.

It thus becomes clear why the famous publication by Hays and others (1976) discovered significant contradictions between the Milankovitch theory and empirical data (Imbrie and others 1993; Bol'shakov 2003 a, 2003b). Attempts made by followers of Milankovitch to solve these contradictions led to new problems (Bol'shakov 2008). The main problem in their approach (Berger and Loutre 1991; Berger and others 1998; Imbrie and Imbrie 1980; Imbrie and others 1993) and many others is the use of mean monthly or even daily insolation variation at a single latitude for paleoclimate interpretation and simulation. This is clearly even worse than the use of semi-annual insolation by Milankovitch. We suggest that it could be one of the main reasons for the problems with the theory of Milankovitch and his followers, such as the 100 thousand year period problem, and the problem of the Middle Pleistocene Transition.

Conclusions

We conclude by summarising what we believe to have been the most important aspects of Croll's work. Firstly, he should be regarded as the author of the astrochronological method because he was the first to evaluate the age of glaciations by comparing the time of their occurrence with theoretically calculated periods of maximum eccentricity. He was among the first to pay attention to the fact that any theory should explain not only the existence of glaciations but also interglacial periods, and he showed the advantages of orbital theory in explaining the multiplicity of glaciations. He was the first to suggest common mechanisms by which all three orbital elements could influence the climate. And, most importantly of all, he recognised that orbital variation of insolation could not, by itself, lead to the known global climate fluctuations. He concluded that these fluctuations could occur only as a result of the added effect of what he termed 'earth physical agents', that is of positive feedback, reinforcing the effect of insolation variations during the developing of climate changes. He suggested specific feedback mechanisms.

However, many of his achievements have been forgotten. In particular, he is inadequately recognised as being among the founders of the astrochronological method. But the biggest regret is that his main achievement has not been appreciated at its true value; the discovery of positive feedback in the climate system. At the same time, the reason why Croll began his examination of positive feedback has also been forgotten. The reason was the necessity to consider the influence of the full annual hemispherical variation of insolation on global climate fluctuations. This last point was strongly demonstrated in the progress of the Milankovitch theory and his followers.

This, the falling into oblivion of the main points of Croll's paleoclimatic theory, prevented the progress of the orbital theory of paleoclimate. We have no doubt that, if the effect of the positive feedback on climate, discovered by Croll, had been taken seriously into consideration, modern paleoclimatology would be at a more advanced stage of development. Unfortunately, it seems that an outstanding discovery made by James Croll appeared far too early.

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