JAMES CROLL – SCIENTIST, WHO LEFT HIS TIME BEHIND

In January 2011 it will be 190 years since an outstanding Scottish scientist James Croll was born. He was versatile researcher and was interested both in life science and humanities (for instance, philosophy). However, he made the most contribution for the development of the orbital theory of paleoclimate. Nevertheless, it seems that this achievement is not recognised enough yet. It became even more obvious nowadays, after almost 150 years since his first work was published.

The orbital theory of paleoclimate was first proposed by J. Adhemar [Adhemar, 1842]. This theory was created to explain the existence of glaciations in the geological past [Croll, 1875; Imbrie, Imbrie 1986]. J. Adhemar connected the climate change with the precession of the equinoxes and thought that glaciations would occur in that hemisphere, where the day of winter solstice coincides with aphelion. That will increase the seasonal contrasts of insolation in the certain hemisphere, in other words long cold winter and short hot summer. In the opposite hemisphere contrasts of insolation will be lower so that mild short winter will be followed by a long chilly summer. According to J. Adhemar, precisely long cold winter is the reason of glaciations in the first mentioned hemisphere. Therefore, in the other one there will be interglacial period.

However, his theory was denied by English astronomer J. Herschel and also by an outstanding German naturalist A. Humboldt [Croll, 1875, Imbrie, Imbrie, 1986]. They both showed that the average temperature of hemisphere can be defined by the quantity of solar energy calories, which it gets during ***the whole year***, but ***not half a year***. And as the change of annual quantity of solar energy combined with the precession, equal to zero (thus, for instance, reducing of winter insolation is compensated with increase of summer insolation) for any of hemispheres, therefore there are no contrary changes in climate of that hemispheres. In this way, there are no reasons for global climate change, particularly for the start of glaciations.

Nevertheless, J. Adhemar's orbital hypothesis was claimed once more by J. 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 climate circumstances, characterised by long winter, lead to the glaciations in the exact hemisphere, his theory was a big step forward explanation of orbital insolation variation impact on global climate changes. Wide erudition and thorough approach to the problem attracts attention to the author. Since the beginning Croll examined impact Earth's inner reserves of heat on its own climate hypothesis, Earth's passage in "warm" and "cold" parts in outer space hypothesis, possible change of Sun constant hypothesis, distribution of land and water hypothesis and many others. In fact, he showed, that all mentioned factors could not be a reason for a glacial–interglacial cycles. He came to the conclusion that the most possible reason for the repeating glaciations could be orbital variation of the insolation.

Croll had begun his work 20 years after the book of J. Adhemar had been published and till publishing of his main work "Climate and time in their geological relations" [Croll, 1875] science have moved on a lot. He knew achievements of astronomy, physics, meteorology and geology very well. He also knew point of view of Humboldt and Herschel mentioned bellow, that year

quantity of heat during the analyses of global climate fluctuation should be counted. Croll understood that ***direct*** insolation impact of orbital variation on global climate is meaningless, because eccentricity of insolation is very few and annual global changes of insolation connected with the fluctuation of 2 other orbital elements (precession of the equinoxes and obliquity of the ecliptic) is zero. He recognised his idea was eccentric; nevertheless he was sure it explained the connection between orbital insolation variation and glaciations. He wrote [Croll, 1875, p. 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."

By physical agents Croll meant feedbacks. He wrote [Croll, 1875, p. 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 causers concerned in the bringing about of the glacial condition of climate, cause and effect mutually reacted so as to strengthen each other." Thereby J. Croll was the first one who took into consideration influence of positive feedback, which increased orbital dependent variation of insolation and transformed that variation into global climate change – glaciations and interglacial periods. That is the main achievement of his theory, and to our mind, is the most important discovery in paleoclimatology. And its consequences are not recognized enough yet.

Croll examined mostly two mechanism of positive feedback: 1) between temperature and area of snow cover and ice cover (Albedo connection), and 2) between global temperature and displacement of ocean stream. He placed the second mechanism as more important, and previously had shown the big influence of Gulf Stream on the climate conditions of Europe. High value of orbit's eccentricity *e* is the precondition of proposed mechanism realization, he thought. Also he supposed that only particularly long cold winters, connected with increased value e and accompanied by unusual fall of snow, would support the mechanism of positive feedback working. And it will lead to a further temperature drop; *despite that winter insolation drop have been followed by the relevant rise of summer insolation.*

To calculate the changes of eccentricity during 3 billion years before 1800 year and 1 billion year after, J. Croll used formulas and data of Le Verrier. According to his calculation, the highest eccentricity value was during the period of time from 980 till 720 thousand years ago and from 240 till 80 thousand years ago. Exactly with those periods of time he connected the possibility of glaciations. Therefore, J. Croll was the first one who used astronomic calculation (eccentricity variation

calculation) for paleogeoraphy events geological age assessment. In accordance with J. Croll, the last glaciations on Earth have finished around 80 thousand years ago.

Thereby, according to the theory of J. Croll, glaciations had happened especially during the periods of high eccentricity value. Both of the hemispheres were subject to glaciations during these long periods of time alternately, approximately every 10,5 thousand years (time of half-cycle precession), and particularly that hemisphere, in which according to precession changes, the day of winter solstice matched with the passage Aphelion. At the same time, in the opposite hemisphere conditions were extremely warm. Obviously, that kind of glaciations cannot be named global. Periods of time with intermediate eccentricity values were interpreted by J. Croll as interglacial periods and were compared with deposits, divided glacial horizons.

In his book J. Croll created a special chapter for climate impact of obliquity variation ε, which he did not take into consideration in his theory preliminary. Partly the reason was that exact data of changes of angle ε during the time were known later than data of precession and eccentricity by Stockwell in 1873 and Pilgrim in 1904 [Croll, 1875; Imbrie, 1982]. Nevertheless Croll recognized the importance of taking into consideration variation of mentioned orbital element.

He wrote in the beginning of 25th chapter of his book: "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 climate influence of variation obliquity using calculations of Mr. Meech [Croll, 1875, pp. 399, 400]. In accordance with those calculations, when obliquity increases, the annual quantity of Sun heat rises up in high latitudes and goes down in the low latitudes. Though, relative changes of heat are much more significant in the high latitudes than in low latitudes. So based on these calculations, Croll have shown that reduction obliquity should help glaciations in high latitudes of both hemispheres, because reduction **ε** would lead to the reduction of temperature, grow of snow and ice cover and influence of mentioned positive feedback, reinforcing the initial fall of temperature. Thereafter, increase **ε** should lead to warming and snow and ice thawing in polar areas. (It should be noted that at that time it was unconventional result, because some of the researchers, who were criticized by J. Croll, thought that increase obliquity leads to the opposite result as fall of temperature in the high latitudes, for instance caused by lowering latitude of polar circle).

Fluctuation of terrestrial axis incline leads to single-phase changes of climate conditions in high latitudes of both hemispheres. So, it could reinforce climate influence of precession-eccentricity glaciations mechanism, suggested by J. Croll theory, in one hemisphere and reduce it in another. For example, fall of temperature in mentioned hemisphere would reinforce, if point of winter solstice in Aphelion matched with the minimum value of angle **ε**; and it would go down, if the incline angle was in its maximum value at that time. Croll realized that this fact makes his theory more complicated, though he did not discuss it in more details. Nonetheless, he pointed one more phenomenon connected with the increase obliquity – grow of ocean level caused by thawing of snow and ice in Polar

Regions. It's important to mention that to proof his conclusions Croll widely used geological data available at that time.

However, in the end of 19th century essential contradictions between the theory and empiric data were discovered. Both American and European scientists came to the conclusion that the glaciations had finished 10 thousand years ago but not 80 thousand years ago as it was according to the theory. That was the main reason for the J. Croll theory to fail. Divergence of the theory with the empiric data shows its inefficiency and invalidity. At the present time we can say that the biggest mistake in his theory was assumption that glaciations are depended only on seasonal contrasts of insolation, conditional precession, modulated eccentricity changes. This conclusion comes from the common nowadays fact that Pleistocene glaciations occurred in both hemispheres simultaneously. And it doesn't match with antiphased influence of precession, but coordinate with minimum eccentricity value, exactly in the time when the precession changes are minimum, and not maximum as J. Croll theory said. Besides that, oxygen isotope analysis of deep-water columns data showed that precession has the least influence on global changes of the last billion years.

Of course it's easy to come to this conclusion nowadays, from the position of modern knowledge. But in the second part of the 19th century when geologists had just started to realize the scale of geological time changes, when only first steps in studies of heat nature and heat exchange have been done, when the planet Neptune have been discovered not long time ago, J. Croll theory was a huge step towards realizing of interaction between astronomic and earth factors determine climate conditions of our planet during the last billion years. His work passed ahead its own time, especially in part of introducing factors of positive feedback, determined intense and globalism of orbital variation insolation.

In the end of examination of J. Croll's theory, we would like to underline the main results of his work.

1. J. Croll agreed that only orbital variation of insolation could not lead to the global climate fluctuations. Though he made a conclusion that these fluctuations could occur with an extra impact of "earth physical agents". He was the first one who took into consideration positive feedback, reinforcing insolation variation impact during developing of climate changes, and suggested their concrete action mechanisms.

2. J. Croll is the author of astrochronology method, because he was the first one who evaluated the age of glaciations through the comparison of time of their existence with theoretically calculated intervals of maximum eccentricity value time.

3. He was the first one who suggested common mechanisms of climate variation influence of all three orbital elements.

4. He was among first who paid attention to the fact that any of boulder-period theory should explain not only existence of glaciations but also inter-glacial periods, and has shown the advantages of orbital theory in explaining multiplicity of glaciations.

However, many of his achievements have been forgotten. In particular, his name has been never mentioned among the founders of astrochronologic method. But the biggest regret is that his main achievement has not been appreciated at true value – discovery of positive feedback in climate system. At the same, the reason why J. Croll had started examination of positive feedback was also forgotten. The reason was *necessity of recording of hemispheres full annual insolation variation influence in explanation of global climate fluctuations.* The last thesis has been strongly proven in the progress of Milankovich theory and his followers.

Not forget to mention that M. Milankovich had started his research 50 years later than J. Croll. His interpretation of orbital theory of paleoclimate was different from previously developed theories of Adhemar, Croll, and others in part of orbital conditional

insolation variation mathematically accurate calculations at the upper atmosphere border. The main idea of his theory is that he attached direct paleoclimate value for counted discrete (for the summer caloric half year and in latitude 65 North) insolation variation during last 600 thousand years. For instance, the least value of summer insolation in latitude 65 North was interpreted him as glaciations. Moreover, he supposed there's linear relation between calculated summer and winter insolation of different latitudes and summer and winter temperature in these latitudes [Milankovich, 1930]. Hereby, theory of Milankovich has made dual effect on the development of orbital theory of paleoclimate.

From one hand, it was a step forward, related with mathematically accurate calculation of insolation. However, from the other hand progress of orbital theory had been discarded in far past, to the times of Adhemar, because Milankovich did not take into consideration reasonable conclusion made by Herschel and Humboldt. To explain the global climate fluctuation he used calculations of semi-annual insolation under the individual latitude! Therefore in his research Milankovich was not in need of using theory and development of positive feedback mechanisms suggested by J. Croll. (He used it mostly for identification the result of climate variation obliquity impact, what have already been done by J. Croll before.)

Thus it's obvious that the famous publication by J. Hays, J. Imbrie, and N. Shackleton [1976] discovered significant contradictions between the Milankovich theory and empiric data [Imbrie et al., 1993; Bol'skakov, 2003 a, b]. Attempts made by followers of Milankovich to solve these contradictions have led only to the new problems [Bol'shakov, 2008]. The main disadvantage in their works [Berger, Loutre, 1991; Berger et al., 1998; Imbrie, Imbrie, 1980; Imbrie et al., 1993 and many others] is use of mean monthly or even daily insolation variation under the individual latitude for paleoclimate interpretation and simulation. Obviously, it's even worse case scenario than use of semi-annual insolation by Milankovich. We think that it could be one of the main causes for the theory of Milankovich and his followers problems, such as 100 thousand years period problem, problem of Middle Pleistocene Transition etc.

Hereby, fall into oblivion of the main points of J. Croll paleoclimatic theory prevented the progress of orbital theory of paleoclimate. We have no doubts that, if influence of the positive feedback on climate, discovered by Croll, would have been taken into consideration seriously, then modern paleoclimatology would be on the higher stage of development itself. And it would definitely have more concrete point of view towards greenhouse effect particularly, and on anthropogenic influence on climate in general. Unfortunately, it seems that an outstanding discovery made by J. Croll appeared far too early.

REFERENCES

1. Adhémar, J. A. (1842) Revolutions de la mer: Déluges Périodiques. Carilian-Goeury et V. Dalmont, Paris.

2. Berger, A.L., Loutre, M.F. (1991) Insolation values for the climate of the last 10 million years. Quat. Sci. Rev., 10, 297–317.

3. Berger, A.L., Loutre, M.F., Gallee, H. (1998) Sensitivity of the LLN climate model to the astronomical and CO_2 forcings over the last 200 ky. Clim. Dyn., 14, 615–629.

4. Bol'shakov, V. A. (2003a) Modern climatic data for the Pleistocene: Implications for a new concept of the orbital theory of paleoclimate. Russian Journal of Earth Sciences, 5 (2), 125–143 (online version: http://rjes.wdcb.ru/v05/TJE03116/TJE03116.htm).

5. Bol'shakov, V.A. (2003b) The new concept of the orbital theory of paleoclimate. Moscow State University, 256 pp. (In Russian).

6. Bol'shakov, V. A. (2008) How long will the "precession epoch" last in terms of Pleistocene glacial cycles? Russian Journal of Earth Sciences, V. 10, ES3004, doi: 10.2205/2008ES000299.

7. Croll, J. (1864) On the physical cause of the change of climate during geological epochs. Philosophical Magazine, V. 28. P. 121–137.

8. Croll, J. (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, V. 33, P. 426–445.

9. Croll, J. (1875) Climate and time in their geological relations: a theory of secular changes of the Earth's climate. Edward Stanford, London, 577 pp.

10. Hays, J. D., Imbrie, J. and Shackleton, N. (1976) Variation in the Earth's orbit: Pacemaker of the ice ages. Science, 194, 1121–1132.

11. Imbrie, J. (1982) Astronomical theory of the Pleistocene Ice Ages: a brief historical review. Icarus, 50, 408–422.

12. Imbrie, J., Imbrie, J.Z. (1980) Modelling the climatic response to orbital variations. Science, 207. 943–953.

13. Imbrie, J. and Imbrie, K.P. (1986) Ice Ages: Solving the Mystery. Harvard University Press. Cambridge, Massachusetts and London. 224 pp.

14. Imbrie, J., Berger, A., Boyle A. et al. (1993) On the structure and origin of major glaciation cycles. 2. The 100 000-year cycle. Paleoceanography, 8, 699–735.

15. Milankovitch. M. (1930) Mathematische Klimalehre und astronomische Theorie der Klimaschwankungen. Handbuch der Klimatologie, 1, A. Gebruder Borntraeger, Berlin, 176 pp.

Vladimir A. Bol'shakov, Andrey P. Kapitsa