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Invited review

Quaternary glaciations: from observations to theories

Didier Paillard

Laboratoire des Sciences du Climat et de l'Environnement, IPSL, CEA-CNRS-UVSQ, Centre d'Etudes de Saclay, 91191 Gif-sur-Yvette, France

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ABSTRACT

Ice ages are known since the mid-nineteenth century. From the beginning, they have been at the center of theories of climate and climate change. Still, the mechanisms behind these large amplitude oscillations remain poorly understood. In order to position our current knowledge of glacial–interglacial cycles, it is useful to present how the notion of climate change appeared in the XIXth century with the discovery of glacial periods, and how the two main theories, the astronomical one and the geochemical one, emerged progressively both from sound physical principles but also from extravagant ideas. Major progresses in geochemistry in the XXth century led first to the firm evidence of an astronomical pacemaker of these cycles thanks to the accumulation of paleoceanographic data. Still, the Milankovitch's theory predicts an ice age cyclicity of about 41,000 years, while the major periodicity found in the records is 100,000 yr. Besides, ice cores from Antarctica proved unambiguously that the atmospheric carbon dioxide was lower during glacial periods. Even more importantly, during the last termination, the atmospheric pCO_2 increases significantly by about 50 ppm, several millenia before any important change in continental ice volume. This fact, together with many other pieces of information, strongly suggests an active role of greenhouse gases in the ice age problem, at least during deglaciations. Since terminations are precisely at the heart of the 100-ka problem, we need to formulate a new synthesis of the astronomical and geochemical theories in order to unravel this almost two-century-old question of ice ages. The foundations of such a theory have already been put forward, and its predictions appear in surprisingly good agreement with many recent observations.

1. Introduction

It is too often stated in textbooks but also in many scientific papers, that Quaternary glaciations are "caused" by the astronomical forcing, according to the Milankovitch theory. Consequently, there is sometimes a diffuse feeling, even within scientific communities working on climatic questions, that this problem was fully settled several decades ago. But if indeed ice ages are "paced" by the astronomy, the key physical mechanisms are far from being understood. On the other extreme, quite too often, some recent papers are discussing aspects of glacial cycles, like the role of the different orbital parameters on Earth's climate, without providing any clue towards the 150-year long historical context of theories and discoveries of Quaternary Sciences. But explaining that we are "standing on the shoulders of giants" is not only a question of acknowledgment: it is also a necessity to articulate our understanding of a scientific question. As a result, there is often some confusion among students and non-specialists, on what is the current knowledge on glacial cycles and what are the key questions. In the following, I will therefore try to provide a short historical account of the development of ideas on ice ages and how they relate to the building of climate sciences in general. In particular, I will present the birth and the development of the two major theories of ice ages, the astronomical one and the geochemical one, as well as the development of the major paleoclimatic reconstruction techniques, and how these new data have shifted the balance of evidence on one or the other side. Then, I will show why we currently need a synthesis of these two theories and finally I will provide a track towards this goal.

2. Historical background

Though it is probably difficult to pinpoint the emergence of the notion of Earth's climatic change in the history of Sciences, it is interesting to note that the evidence of a changing environment was described since the Antiquity. For instance, in the context of the astronomical theory of ice ages, Aristotle's writings (Meteorologica, Book 1, Chapter 14, translation by Lee, 1951) might seem quite prophetical:

"The same parts of the earth are not always moist or dry, but change their character according to the appearance or failure of

E-mail address: didier.paillard@lsce.ipsl.fr.

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rivers. ...sea replaces what was once dry land, and where there is now sea, is at another time land. This process must however be supposed to take place in an orderly cycle."

Then he speculates on the causes of such changes:

"we should suppose that the cause of all these changes is that, just as there is a winter among the yearly seasons, so at fixed intervals in some great period of time, there is a great winter and excess rain".

Quite clearly Aristotle was not talking of ice ages, which were not known at this time. He describes hydrological changes that were either observed historically, or inferred more indirectly, in Egypt or in Greece, and insists that the changes are mostly local or regional ones, with different regions experiencing sometimes opposite changes. This would be now called evidences of local or regional climatic changes. Still, Aristotle's writings were certainly very influencial in the construction of modern science in general, including geology. For instance, the above short sentence is cited by C. Lyell (1830) as a *"theory of periodical revolutions of the inorganic world*". The same word "*revolution*" is used by Cuvier in his book "Discours sur les révolutions de la surface du globe" (1825) (A Discourse on the Revolutions of the Surface of the Globe). The use of the word "*revolution*" is quite meaningful, and the same word is also used by Adhémar (1842) for the title of his book on the first astronomical theory of ice ages ("Révolutions de la mer, déluges périodiques"). It probably aims at reminding, in some way, Copernicus' book "*De revolutionibus orbium coelestium*" which is often presented as the foundation stone, on which Kepler and Newton developed modern physics. There was obviously among natural scientists a strong desire to build Geology on a similarly footing, ie. the occurrence of cyclic changes, whose unknown ultimate causes might possibly be related to some "cosmic" phenomena, either astronomical or divine depending on authors. Cuvier's book presents his theory of cataclysmic changes that paced the succession of fossils, which together with the work of William Smith, led to the foundation of stratigraphy. Since the Antiquity, geologists had found marine fossils over lands, even on top of mountains. This led to centuries of discussions on how these might have formed, and the dominant view at the beginning of the XIXth century was that recurrent floods or catastrophes occurred in the past, the last one being the "Great Flood" from the Bible. Looking for an explanation of these "revolutions" was a scientific challenge, as noted by the astronomer John Herschel (1830):

"Impressed with the magnificence of that view of geological revolutions which regards them rather as regular and necessary effects of great and general causes, than as resulting from a series of convulsions and catastrophes regulated by no laws and reducible to no fixed principles, the mind naturally turns to those immense periods with whose existence in the planetary system the astronomer is familiar".

Still, the notion that climate might change through time, in particular on a rather large or even a global scale, was controversial at the beginning of the XIXth century. Many fossils from former tropical environments were found in high northern latitude, but their interpretation was not necessarily straightforward. For instance, if mammoths, ie. "siberian elephants", were often cited as a proof of a former warm "african type" climate in arctic regions, such analogies were also strongly (and rightly) criticized by other scientists (eg. J. Fleming, 1829). The dominant view was, nevertheless, that the Earth probably experienced a gradual cooling, from a hot Paleozoic time period, with giant ferns growing even in arctic regions as evidenced in the coal mines, to a warm Eocene and then to the present-day temperate climate. This idea was also somewhat in accordance with the "plutonist" view that rocks formed in fire and that the Earth was initially molten: For instance, in *Les époques de la nature* (1778) Buffon computed an age of the Earth based on the cooling rate of iron, which led to an age of 75,000 years (though when accounting for the slow diffusion of heat, Lord Kelvin in 1897 obtained an age between 20 and 40 millions of years).

In this general context, the discovery of ice ages was a crucial step forward. Indeed, for the first time the evidences of climatic change were not based on paleontological interpretations, but on much less ambiguous, physically based observations, like moraines, erratic boulders, or glacial striations. It furthermore strongly suggested that climate evolution was not a simple long term cooling trend, as usually believed.

3. Discovery of ice ages and early theories of climate

3.1. The evidence of past glaciations

The erratic blocks found in lots of places in the Alps and in northern Europe had been subject to many speculations for a long time, often involving giants or trolls, while the usual scientific explanation involved again catastrophic floods or diluvium. But a new suggestion slowly emerged in the first half of the XIXth century: glaciers should be the cause. The morphology and geology of the Alps was indeed investigated by swiss scientists, in particular by Venetz (1833), de Charpentier (1836) and Agassiz (1840), who have carefully described and analyzed many morphological features in the Swiss Alps, with the unambiguous conclusion that the only valid explanation for moraines, erratic boulders, or glacial striations, involved episodes of significant glacial advances in the past. Similar observations and suggestions were also made in Scandinavia by Esmark (1827) (Andersen, 1992) or in Scotland by Jameson, who unfortunately did not publish his findings. A very nice and detailed account of the history of this discovery is given in Berger (1988, 2012) or in Bard (2004) or more recently in Krüger (2013) or Woodward (2014).

As noted by Lyell, geological theories were still too often associated with cosmogonies and philosophical preconceptions. In this respect, in contrast to the plutonists, the neptunists favored the idea that all rocks are sedimentary in origin and were formed in water. They were also more inclined to follow the idea of a cold origin for the Earth, like the famous poet, but also minister of mining, J. W von Goethe, a proponent of ice ages, who presents his doctor Faust in favor of neptunism, while Mephistopheles was, of course, a plutonist. Though necessarily very speculative, a possible scientific explanation for such glacial periods was put forward by J. Esmark. He notes that according to William Whiston's theory, Isaac Newton's successor at Cambridge University, the Earth was initially a "comet" on a very eccentric orbit. It was therefore in a frozen state when far away from the Sun. Accordingly, ice ages would occur when the Earth was very young, something which soon will be proved wrong. This was nevertheless probably the first suggestion of a possible link between the eccentricity of the Earth and ice ages. But it stoods somewhat in contradiction with astronomical knowledge at this time. J. Herschel (1830) states that *"Geometers have demonstrated the absolute invariability*" of the Earth's major axis, and therefore the length of the year: Increasing the eccentricity would only warm up the mean climate, since "the total quantity of heat received by the earth from the sun in one revolution is inversely proportional to the minor axis of the orbit". He further adds that for any significant mean annual change, the seasons would be so extreme that they would *"produce a climate perfectly intolerable*". He also considered that neither obliquity nor precessional changes (see below) could account for significant