

The temperature–CO₂ climate connection: an epistemological reappraisal of ice-core messages

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Abstract. As simply based on fundamental logic and on the concepts of *cause* and *effect*, an epistemological examination of the geochemical analyses performed on the Vostok ice cores invalidates the marked greenhouse effect on past climate usually assigned to CO₂ and CH₄. In agreement with the determining role assigned to Milankovitch cycles, temperature has, instead, constantly remained the long-term controlling parameter during the past 423 kyr, which, in turn, determined both CO₂ and CH₄ concentrations, whose variations exerted, at most, a minor feedback on temperature itself. If not refuted, the demonstration indicates that the greenhouse effect of CO₂ on 20th century and today's climate remains to be documented, as already concluded from other evidence. The epistemological weakness of current simulations originates from the fact that they do not rely on any independent evidence for the influence of greenhouse gases on climate over long enough periods of time. The validity of models will, in particular, not be demonstrated as long as at least the most important features of climate changes, namely the glacial–interglacial transitions and the differing durations of interglacial periods, remain unaccounted for. Similarly, the constant 7 kyr time lag between temperature and CO₂ decreases following deglaciation is another important feature that needs to be understood. Considered in this light, the current climate debate should be considered as being the latest of the great controversies that have punctuated the march of the Earth sciences, although its markedly differs from the preceding ones by its most varied social, environmental, economical and political ramifications.

1 Introduction

Perhaps the most important feature evidenced by the history of science is how ideas that were unanimously accepted for very long periods of time have eventually been firmly rejected. Among innumerable examples, two of the most famous are the central position of the Earth in the universe and the theory of the four elements (fire, air, water and earth) mutually transforming through exchange of their four qualities (hot, cold, dry and wet). Both theories remained uncontested for 2 millennia in spite of shortcomings that were pointed out early on. For geocentrism, the 24 h rotation of the most distant fixed stars around the pole, for instance, flatly contradicted the firm rule that, from the 27.3 days of the moon to the 29.4 years of Saturn, sidereal periods of revolution markedly increase with the distances of celestial bodies from the Earth. Similarly, the four-element theory was already criticized by Theophrastus (4th–3rd c. BCE), who pointed out

that fire is “unable to persist without fuel. Hence, it seems foolish to speak of fire as a first substance and original element.”

As robust and convincing as they may appear, theories are rarely immune to various kinds of flaws that appear more or less rapidly and serve as seeds for either major reformulation or for complete rejection, as exemplified by geocentrism and the four-element theory. With the reasonable premise that we are not any smarter than our predecessors, an intriguing problem is to identify which of the currently accepted theories might fall into oblivion in the future and make historians study why their demise did not take place earlier. The goal, then, consists of spotting practical or theoretical weaknesses and assessing whether they are actually significant or not. For this purpose, epistemological approaches are most valuable because they focus on fundamental principles without the need for delving into technical details.

A thesis for which such an approach can be followed is that anthropogenic emissions of CO₂ and other greenhouse gases, such as methane, have dire warming effects on the Earth's climate. Because CO₂ emissions are considered to be the single most important factor currently affecting climate, unprecedented efforts are being formulated to achieve carbon-free societies within a few decades. In view of the major social, environmental, political and economic issues raised by such a transition, two points deserve special attention. The first concerns geochemical evidence available for the greenhouse effects of CO₂ (and of CH₄ as well) over periods of time long enough to encompass great climate cycles. The second deals with the actual heuristic value of climate simulations, which appears to be generally acknowledged without having undergone real in-depth analyses. Both points will, thus, be reviewed critically from an epistemological standpoint in the present study. In fact, the approach followed will be justified by serious weaknesses pointed out on both counts, which will, in particular, illustrate once more why models that are now so extensively relied on in many fields of science and in public policies can lack any real demonstrative value.

2 Background

Real attention to the greenhouse effect of atmospheric carbon dioxide is not at all recent, since it had already been drawn by Fourier (1827), Tyndall (1861) and especially Arrhenius (1896). The effects of ever-increasing anthropogenic CO₂ emissions became a real concern only in the 1970s, however, because anthropogenic and natural gases cannot be distinguished in the complex exchanges that are continuously taking place between the atmosphere, hydrosphere and biosphere. At that time, Broecker (1975) coined the term global warming and stated, from a review of the literature data, that a doubling of the CO₂ concentration with respect to preindustrial levels would result in a global temperature increase of 2.4 °C (the so-called climate sensitivity).

The global warming thesis apparently received strong geochemical support when investigations of ancient ice cores revealed that past temperature increases were accompanied by marked increases in atmospheric CO₂ concentrations (Lorius et al., 1990). In this respect, the extensive geochemical analyses of ice cores in Antarctica (Petit et al., 1999; Lüthi et al., 2008) remain what seem to be the most compelling direct evidence for the climate effects of greenhouse gases over a large time interval of 800 000 years (800 kyr). In addition to local temperature and atmospheric CO₂ concentrations at the time of snow deposition, CH₄ concentrations or sodium and dust contents have also been measured accurately. These geochemical results, thus, represent a Rosetta stone of climatology through the continuous record of this set of key parameters that they provide.

The existence of past glaciations remained controversial for several decades after it was discovered by geologists early in the 19th century (see Hallam, 1989). After another long debate that lasted until the 1970s, the control of ice ages exerted by variations in the Earth's insolation was, in the end, firmly established from determinations of climate-sensitive parameters in deep cores of the southern Indian Ocean, namely the oxygen isotopic compositions of the tests of planktonic foraminifera and the summer sea-surface temperatures estimated from radiolarian populations (Hays et al., 1976). During the cycles identified by Milankovitch (1913), the insolation varies with time as a result of complex gravitational interactions that cause periodic changes in the parameters of the Earth's motion around the Sun, namely the eccentricity of the orbit (main period of 100 kyr), the angle of the tilt axis (the obliquity of the ecliptic) from 22.1 to 24.5° (main period of 41 kyr) and the top-like precession of this axis relative to the fixed stars (main period of 26 kyr).

Within the framework of Milankovitch cycles, the relationships between past temperatures and CO₂ concentrations are generally interpreted in terms of an initial orbital forcing of temperature that is then amplified by CO₂ forcing, which is, in turn, amplified itself by fast atmospheric feedbacks that are and will continue to act on present and future climate (e.g., Petit et al., 1999). It is in this way that the modern anthropogenic increases in atmospheric CO₂ concentrations are thought to be the main cause of global warming, a conclusion that numerical simulations of the Earth's atmosphere aim to support in a quantitative manner (IPCC, 2013).

Curiously, however, so much attention is now given to simulation models that the fundamental sources of information provided by the ice-core records have only been partially exploited. Although inferences on deglaciation processes have, for example, been drawn from the marked time lags observed between temperature and CO₂ variations (e.g., Hertzberg and Schreuder, 2016; Broecker, 2018), such analyses have not been pursued in any detail. For example, Broecker simply noted that “the interglacial CO₂ peaks are wider than those for the air temperature.” Hence, the first goal of this study is to analyze the nature of these relationships to ascertain whether or not CO₂ is the real climate driver of the Earth.

In view of the claimed global nature of climate change, the essentially homogeneous concentrations of atmospheric CO₂ (and CH₄) make it sufficient to consider a single but accurate and comprehensive record of past temperatures and CO₂ contents to determine the mutual relationship between these two parameters. For this purpose, the Vostok record is ideally suited because it adequately samples the fundamental features of glaciation–deglaciation cycles, which have represented, ever since the early 19th century, the most conspicuous evidence of climate change. Over the long enough time intervals considered, one can then neglect climate variations caused such by factors such as changes in solar activity and, even on timescales of thousands of years, differences

between the freezing and melting dynamics of ice sheets and their dependences on local factors.

Thanks to this specific focus, a rigorous assessment of the ice-core data can rely on pure logic and, thus, on the fundamentals of scientific reasoning as early laid down by Aristotle in the 4th century BCE (Before Common Era). The conclusions derived should, thus, be particularly robust because they are directly drawn from the ice record itself. As such, they are not restricted to a specific geographical setting, and they depend neither on any physical mechanisms assumed to be at work in the complex Sun–Earth system nor on any particular climate models and values of their respective input parameters. As surprising as it might appear, the assumed forcing of climate by CO₂ is inconsistent with both the major and minor features of the source data. Unless its fallacy can be proven or the ice records were shown to be fundamentally misleading, the present demonstration points instead to, at most, a minor greenhouse effect of atmospheric CO₂ (and CH₄) compared with that of water vapor throughout the last 423 kyr.

Consistent with inferences recently drawn from other evidence, this conclusion contradicts models that consider the CO₂ concentration in the atmosphere as being the major driver of an ongoing climate change. In this light, the current debate appears to be a new episode in a series of protracted geological controversies entertained by the bewildering complexity of the Earth as a subject of physical enquiry. In addition, the present analysis points to well-defined 7 kyr time lags between temperature and CO₂ decreases at the end of the warmest episodes to which little attention seems to have been paid. It also revives the issue of a predicted new ice age in a not-too-distant future, as discussed in the 1970s when the validity of Milankovitch theory became accepted.

3 The temperature–CO₂ relationship

3.1 The ice-core analyses

The ice cores drilled down to a depth of 3310 m at the Russian Vostok station have yielded the first comprehensive climate record spanning the last 423 kyr (Petit et al., 1999). Including the current one, five great cycles of glaciation–deglaciation have been revealed. The four most ancient cycles lasted from 87 to 123 kyr each, during which Antarctic temperatures changed by about 10 °C and atmospheric CO₂ concentrations varied between 180 and 300 ppmv (parts per million by volume; Fig. 1), with the lowest values having slowed down but not impeded photosynthetic activity (Gerhart and Ward, 2010). Another record extending back to 800 kyr was subsequently obtained at the Dome C site of the European Project for Ice Coring in Antarctica (EPICA), 560 km south of Vostok (Lüthi et al., 2008). The two series of analyses are very similar for their period of overlap. Between 400 and 800 kyr, the Dome C record reveals four more glacial cycles over a 200 m depth. Possibly because of per-

turbations and rearrangements of the accumulated ice, however, the older material exhibits warming–cooling episodes in the form of broader features. Although these additional cycles are valuable for studying transitions between glacial and interglacial conditions, they will not be considered here because their lower resolution prevents further information from being drawn on the temperature–CO₂ relationship.

It has been stated that the Vostok series of analyses “has become a compelling target against which other records and modeling efforts are tested” (EPICA, 2004). This is the reason why the present analysis is restricted to these results. With regard to the parameters investigated, this record may be considered as spectra composed of peaks of temperature, gas concentrations and other environmental variables whose magnitudes, shapes and widths carry important information. It is, thus, useful to give a short overview of these geochemical analyses here so that the relevant technical aspects will not complicate the discussion.

The temperatures of the initial snow deposition are expressed as differences, ΔT , with respect to the present Antarctic temperature at atmospheric level. They have been determined from the D/H and ¹⁸O / ¹⁶O compositions of the ice fragments investigated through a calibration that relies on the surface temperature of the precipitation site and on the temperature above the inversion level where precipitation forms (Jouzel et al., 1997). What matters primarily in this respect is consistency, such that any minor calibration error should be immaterial because the other measurements made on the same ice fragments are referring to the same temperature scale. The sample ages were deduced from the depths of the fragments analyzed and a model of ice accumulation and flow. With uncertainties estimated to be generally as low as 5 kyr (Petit et al., 1999), the original chronology has been kept, especially as it is consistent with both the astronomical data and a revised timescale established from four different ice cores of Antarctica and Greenland (Lemieux-Dudon et al., 2010).

The reported gas concentrations are those of the air bubbles that were trapped upon compaction of the snow into the pores of the solid ice. Because of the prevailing homogeneity of the atmosphere with respect to CO₂ and CH₄, the concentrations measured in ice pores should reflect those of the atmosphere itself at the time of pore closure. The finite time needed for the ice pores to become closed microsystems represents a source of uncertainties, but their estimated values of a few hundred years determined from volcanic event matching between four ice cores (Gest et al., 2017) are inconsequential for the present analysis.

For either gases or both hydrogen and oxygen isotopes, the ice record may have been perturbed by physical and chemical processes such as physisorption and chemisorption, separation by gravity, formation of hydrates or reaction with ice or even cracks forming upon drilling (Raynaud et al., 1993). Vertical diffusion of isotopes and entrapped gases from regions of higher to lower concentrations in the ice column

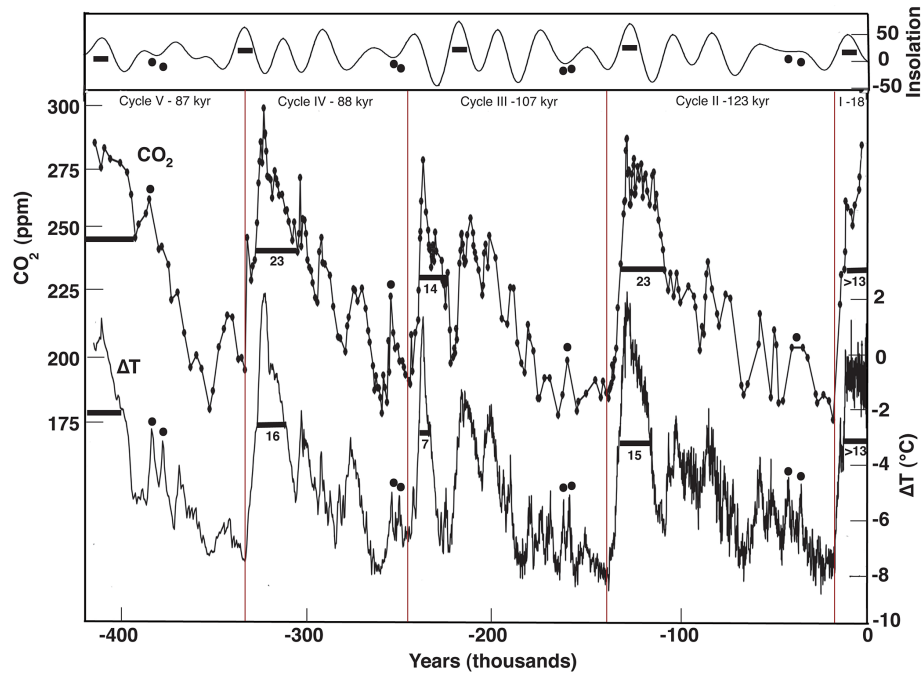


Figure 1. Temperature variations (ΔT) as the cause of the changes in atmospheric CO₂ concentrations throughout the last 423 kyr of the Vostok record and their control by Milankovitch insolation cycles. All data from Petit et al. (1999) are replotted in chronological order from left to right, including the insolation variations in watts per square meter (W m^{-2}) shown at the top and reported for a reference value in mid-June at 65° N. The thin vertical bars emphasize the steepness of the temperature and CO₂ rises at the beginning of the cycles, for which the durations are indicated (cycle V excluded because of its missing beginning). The systematically narrower peaks for temperatures compared to CO₂ concentrations are particularly well exemplified at the beginning of the cycles (where related temperature, CO₂ and insolation peaks are indicated by thick horizontal bars) and by the temperature and CO₂ peaks (signaled by solid dots) associated with the reduced insolation changes of characteristic recurring Milankovitch configurations (dots in insolation plots placed at the precise positions of the temperature doublets).

would have caused broadening on both sides of the temperature and concentration peaks, respectively. Diffusion kinetics depend on concentration gradients through gradients of chemical potentials. For CH₄, the observed narrow peaks probably resulted from very slow diffusion rates ensured by a big molecular size, very low concentrations and a low chemical affinity with H₂O. Even for CO₂, however, diffusion appears to have been generally unproblematic in the main peaks because the increases at the beginning of the cycles are as sharp for CO₂ concentrations as they are for temperatures. But the steepest chemical potential gradients should have prevailed for hydrogen and oxygen isotopes, whose sharp relative variations resulted in the apparent noise and numerous temperature spikes apparent in the most recent data. Inter-diffusion of hydrogen and oxygen isotopes could, thus, have been the reason why the noise and spikes are averaged out back in time in the record without having affected the overall patterns (Fig. 1). If differences in either CO₂ contents and temperatures are found for the same period at different sites, the highest (and lowest) values should, thus, be considered to be closest to the original parameters since all subsequent perturbations of ice columns could have caused only some smoothing out of CO₂ and isotopic gradients. In this respect,

the great sharpness of the 300 ppm (parts per million) CO₂ maximum of Fig. 1 makes this peak a case in point.

3.2 Geochemical inferences

With the obvious exception of the ongoing cycle I, which began 18 kyr ago, all others follow a common pattern whereby a sharp glacial–interglacial transition is followed by a series of warming–cooling episodes of smaller magnitudes (Fig. 1). Even without ever having heard of Milankovitch cycles, one would readily draw firm conclusions from the quasi-periodicity of these cycles and their common patterns. In logical order, these inferences are as follows:

- i. The major peaks were necessarily under astronomical control because no natural phenomena on Earth exhibit anything approaching, even very distantly, such observed regularities with periods of tens of thousands of years.
- ii. This astronomical control of glacial cycles was necessarily exerted through variations in the energy received by the Earth. This energy could have been emitted only

by the Sun. At constant Sun power, its amount itself depends, in a complex manner, on a great many local and seasonal parameters, such as the extent of ice sheets.

- iii. In the absence of photochemical production of CO₂ in the atmosphere, increases in the amount of heat transferred by solar radiations necessarily translate directly into either temperature increases or endothermic phase changes (e.g., ice melting) at the Earth's surface.
- iv. Acting also first on temperature and ice volume, the opposite changes take place when the Earth's net radiation energy budget becomes negative.
- v. The temperature variations themselves induce concentration changes of chemical species in the atmosphere; for example, CO₂, through variations of its overall solubility in seawater and the temperature dependence of the concentrations of carbonate species, or CH₄, through adjustment of biological activity.
- vi. Barring any exceptional event, such as the impact of a giant meteorite or a mega-volcanic eruption, whose occurrences are not apparent in the Vostok record, temperature changes were, thus, necessarily the triggering causes of all episodes. In accordance with geological evidence (Lane et al., 2013), the signature of even the most explosive volcanic event of the Quaternary, the Toba super-eruption 75 kyr ago, could not be found in the record.
- vii. As indicated by the jagged nature of the record, temperature and CO₂ fluctuations constantly took place with a variety of intensities and timescales, with the shortest ones appearing as numerous spikes superimposed on the most recent temperature peaks.
- viii. Since there is no reason why temperature spikes would have been less frequent or less intense in the most ancient than in the most recent part of the temperature record, the contrast between the jagged temperature and smoother CO₂ records was unlikely restricted to the most recent cycle. Instead, it existed in all cycles before the temperature record was progressively smoothed out back in time as noted above.

In terms of Milankovitch cycles, the particular latitude and time of the year most relevant for calculating insolation changes in the past have long been extensively debated (e.g., Imbrie and Palmer Imbrie, 1979). Much work has been done to determine, with spectral analysis, how the complex interplay of astronomical periodicities determines climate changes (e.g., Crucifix et al., 2006). The critical effect of the instantaneous solar radiation power during summer solstices has, in particular, been stressed as it correlates with the derivative of the ice volume (Edvardsson et al., 2002). But these features do not need to be reviewed here; to interpret

the message carried by the ice record on the temperature–CO₂ relationship over long timescales, to which this study is devoted, it will suffice to state that, for obvious consistency reasons, the insolation calculations reported by Petit et al. (1999) for mid-June and 65° N have been used (Fig. 1). Although obviously not perfect, the strikingly good match of the major temperature and CO₂ peaks with the insolation maxima noted by Petit et al. (1999) in particular confirms the good accuracy of the ice-core dating.

4 Epistemological analysis

4.1 The atmospheric CO₂ concentration: a plain temperature effect?

Despite the aforementioned inference (iii), the remarkable proportionality between the amplitudes of the increases in temperatures and CO₂ concentrations at the beginnings of the glacial–interglacial transitions has led to ascertain which of these two parameters controlled the other (Petit et al., 1999). For the sharp initial rises, determining a time difference between the two series of observations is problematic, particularly because of the time needed to achieve ice pore closure. Further analyses and interpretations have indicated that CO₂ increases lagged by less than 1 kyr behind the initial temperature increases (Fisher et al., 1999; Caillon et al., 2003; Vakulenko et al., 2004). Further work has pointed to still shorter time lags (Pedro et al., 2012) or even to a practical synchronicity (Parrenin et al., 2013). This close coupling is in agreement with the fast rates at which atmospheric CO₂ adjusts itself to changes in the ocean surface temperature as observed in a study covering the 1980–2011 period (Humlum et al., 2013).

To investigate the temperature–CO₂ relationships more closely, it is useful to adopt, from the spectroscopic literature, the concept of full width at half maximum of a given peak to quantify the time intervals of the glacial–interglacial transitions. For this purpose, the thin vertical bars marking in Fig. 1 the beginning of each cycle have been used to determine the minima of the CO₂ and temperature peaks in an objective and consistent way. As indicated by the thick horizontal bars in Fig. 1, these full widths range from about 7 to 16 kyr for temperature and from 14 to 23 kyr for CO₂. Regardless of the particular Milankovitch configuration to which they are associated, all other peaks are also narrower for temperature than for CO₂, with the latter lagging behind the former by 1.3 ± 1.0 kyr (Mudelsee, 2001). In all instances, identifying the cause and the effect is, in principle, straightforward because an effect cannot last for a shorter period of time than its cause, whereas the converse can obviously hold true. If one assumes that CO₂ increases were causing temperature rises, then the width differences in their respective signals would make one wonder why, after some time intervals, high CO₂ levels or even further steps of CO₂ increases (e.g., cycle II) would result instead in temperature decreases.

Very long ago, Aristotle (4th c. BCE) discussed such situations in his celebrated *Metaphysics*. As he pointed out, believing “the same thing to be and not to be” implies having “contrary opinions at the same time.” With his *Principle of Non-Contradiction*, Aristotle further stated that “the same attribute cannot at the same time belong to and not belong to the same subject in the same respect.” As he also explained, without having ever been contradicted since then in scientific studies, “it is for this reason that all who are carrying out a demonstration refer it to this as an ultimate belief; for this is naturally the starting point even for all the other axioms.”

The fact that the peak widths are systematically larger for CO₂ than for temperature thus implies that the variations in CO₂ concentrations were driven by temperature changes throughout all cycles and not only at their onsets. Of particular interest in this respect are the peaks signaled by one or two solid dots in Fig. 1. Because, in each instance, a single CO₂ peak correlates with a temperature doublet, such features would again plainly violate the non-contradiction principle if variations in CO₂ concentrations were considered as causes and temperature changes as effects.

Making physical sense of this conclusion is straightforward. The total amount of CO₂ in the atmosphere is only a tiny fraction of that present in the ocean (Lee et al., 2019). Even though the acid base properties of CO₂-bearing aqueous solutions and the biological role of carbonate and bicarbonate ions make the picture difficult to unravel quantitatively (see Michard, 2008), temperature rises cause an overall decrease in the CO₂ solubility in the ocean and, correlatively, an increasing concentration of atmospheric CO₂.

In this respect, the differences observed in the peak widths of Fig. 1 reveal an important timescale contrast in each cycle between the very strong initial glacial–interglacial transition and the subsequent episodes. With their relatively small temperature and CO₂ variations, these episodes display reduced time lags of the order of 1 kyr only between these two parameters, which are similar to the timescales usually assigned to the global homogenization of the ocean. In these cases, exchange with the atmosphere thus appears to proceed nearly as swiftly as during the warming period, which is consistent with the rapid atmosphere–hydrosphere equilibration (Hummel et al., 2013). For the strong glacial–interglacial transitions, the widths of the temperature peaks widely vary from 7 to 16 kyr (Fig. 1), but their differences with the widths of the CO₂ peaks nonetheless have the same large value of 7 kyr. If not coincidental, this common time lag suggests much longer timescales than usually assumed for thorough homogenization of the ocean after large temperature decreases. Such timescales have been related to changes in the land ice coverage and buildup of the terrestrial biosphere (Fisher et al., 1999). Contrary to the suggestion made by these authors, however, these modifications would not depend on the duration of the preceding warm period.

4.2 The CO₂ feedback

The simple temperature–CO₂ relationship described in the previous section is not commonly considered, however, because it ignores greenhouse effects. To conform to the Arrhenian paradigm, Petit et al. (1999) took over the idea that the initial rise in the atmospheric CO₂ concentration (induced by temperature increases at the onset of a Milankovitch cycle) in turn amplifies the initial orbital forcing and is itself amplified by atmospheric feedbacks. Epistemologically, such a four-step process must be examined in the light of the principle of parsimony, which was also first stated by Aristotle in his *Topics*. “It is also a fault in deduction when a man proves something through a long chain of steps, when he might employ fewer steps.” To be justified, therefore, such additional steps require unquestionable evidence.

Feedbacks are indeed possible, where a cause alternatively becomes an effect and an effect a cause. By definition, however, such a mechanism implies the synchronicity of causes and effects to within the timescales of their mutual interactions. In the Vostok case, the CO₂ feedback would reinforce temperature increases during the warming periods but also, reciprocally, temperature decreases during the cooling stages of the Milankovitch cycles. From the dual way in which the feedback would work, temperature decreases and increases should thus be similar for the same concentrations of greenhouse gases regardless of the residence times of these gases in the atmosphere.

Now, the synchronicity of causes and effects is well respected only during the warming periods, where the time lag between the temperature and CO₂ increases is very small. As already emphasized, in contrast, synchronicity clearly breaks down during the cooling periods, and this is most clearly so when temperatures sharply decrease while CO₂ concentrations remain high (Fig. 1). This feature is most obvious in the glacial–interglacial transition of cycle III, where the temperature peak is narrow and symmetrical whereas the CO₂ peak exhibits the large shoulder representing the aforementioned 7 kyr time lag. The feature is also clearly seen in cycle II, where the large jagged CO₂ peak contrasts with the rapidly decreasing magnitude of the temperature peak. Hence, the fact that temperature decreases do not depend in any noticeable way on CO₂ concentrations in all cycles clearly demonstrates that the synchronicity required by the feedback mechanism is lacking.

The CO₂ feedback mechanism is, in addition, contradicted by the marked contrasts between the broad maxima in CO₂ concentrations and doublets of sharp temperature peaks signaled by solid dots in Fig. 1. As indicated by the data for cycle IV, these contrasts are unlikely due to a resolution difference between the two parameters. That they are not coincidental is revealed by their systematic observation only in those parts of Milankovitch cycles where insolation changes are the smallest (Fig. 1). Also striking is the fact that, as shown by the dots included in the insolation plots at the top

of Fig. 1, the temperature doublets are found, each time, at similar places within insolation cycles. Put differently, the dotted peaks of Fig. 1 again demonstrate that temperature is sensitive to insolation changes but not to CO₂ concentration, a conclusion also consistent with the contrasting the jagged–smooth contrast of temperature and CO₂ records.

Regarding CO₂ feedback, the CH₄ concentrations raise yet another difficulty that may be even more fundamental. Like those of CO₂, their variations could not be directly caused by changes in the solar energy transferred to the Earth's atmosphere. They necessarily resulted from temperature changes. If CO₂ contents had exerted a noticeable feedback on temperatures, then the peak widths of the reported CO₂ and CH₄ concentrations should be highly correlated. Such a causal correlation is actually nonexistent because, in marked contrast with the CO₂ contents, the CH₄ concentrations show no time lags whatsoever with respect to temperatures. Instead, these CH₄ concentrations correlate remarkably well with temperatures, as made clear by the fact that these two parameters have nearly the same peak widths (Fig. 2). More recent data have even revealed closer still correlations (e.g., Buizert et al., 2015). Ironically, this clear synchronicity might make CH₄, and not CO₂, a potential match for a feedback mechanism. But CH₄ concentrations ranged from only 0.4 to 0.7 ppmv, which were about 500 times smaller than those of CO₂ (Fig. 1) and from 3 to 4 times lower than the current values. If really significant in the past, a methane feedback would then cause today's temperatures to be considerably higher than observed. Therefore, the ice-core data conversely also rule out any noticeable influence of methane.

5 Implications

5.1 The CO₂ conundrum

As a rule, correlation does not necessarily imply causality. In marked contrast, a lack of correlation resolutely rules out any causality. Reconciling the driving role of CO₂ assigned by climate models with the opposite conclusions drawn from the ice-core record thus seems fraught with considerable difficulties. Hence, the ice-core results shift the burden of proof of any CO₂ influence on temperature to the proponents of the feedback mechanism and make, in addition, any climate sensitivity determinations problematic.

Current climate models are, in practice, not open to falsifiability in Popper's (1959) sense because they are so complex, involve so many physical parameters, rely on so much data for their design and assessment, lack proper error propagation estimations and suffer from the fact that the observations they aim at reproducing cannot be changed at will to check their responses under widely different conditions. Instead, models are claimed to be reliable thanks to their sound physical basis, which is not supported by the present analysis, whereas recourse is also made to the subjective notion of consensus to assert their validity. Whether or not such

a consensus prevails here does not need to be discussed at length because this notion is epistemologically irrelevant. As already alluded to, the history of science is nothing more than a long stroll through the cemetery where ideas that were overwhelmingly accepted are now resting in peace.

For the present issue, the point has been remarkably well exemplified in the late 19th century and then again in mid-20th century by the consensus successively reached *for*, then *against* and, finally, *for* the astronomical control of ice ages. As stated for the latter period by Imbrie and Palmer Imbrie (1979), “during the 1930s and 1940s, most European geologists were won over by the Milankovitch theory” and “the majority of scientists continued to favor the astronomical theory as late as 1950. But the early 1950s saw a dramatic about-face since, by 1955, the astronomical theory was rejected by most geologists.” The case *against* became particularly strong when the new technique of ¹⁴C dating “revealed a pattern of climatic change that was at variance at almost every point with the astronomical theory.” Shortly before Hays, Imbrie and Shackleton published their landmark study (Hays et al., 1976), it followed that, according to Imbrie and Palmer Imbrie, “by 1969, the majority of scientists were sufficiently impressed with the radiocarbon evidence against the Milankovitch theory to eliminate the idea as a serious contender in the ice age sweepstakes.”

In contrast to climate simulations, the present analysis is open to falsifiability since its fallacy, if any, could be pointed out without ambiguity. In this respect, one may stress that the approach followed here directly integrates, with the appropriate weights, all factors relevant to the problem and that it is totally independent of any assumed physical mechanisms, interactions surmised between climate variables, considerations on the CO₂ cycle, statistical analyses of selected sets of data assumed to be representative of the problem and any other simulation features.

A cardinal rule in science is to reject a hypothesis that clearly contradicts the experimental findings it is supposed to account for, especially if it also contradicts the most fundamental tenet of science, the principle of non-contradiction, which is “the most certain of all” in Aristotle's words. If the present analysis cannot be refuted, one should then reject the Arrhenian paradigm and conclude (i) that changes in the concentration of atmospheric CO₂ up to 300 ppm had minor effects at most on temperatures during the past 423 kyr, (ii) that, as described in Sect. 4.1, the concentration of atmospheric CO₂ simply adjusted during this period to the prevailing temperature conditions at the Earth's surface, whose variations were mainly determined by insolation changes during Milankovitch cycles, and (iii) that significant contributions of CO₂ and CH₄ to temperature changes at the Earth's surface remain unsubstantiated by direct, independent evidence.

Entertaining the possibility that temperature rises along Milankovitch cycles could have been triggered by increasing CO₂ concentrations is in fact surprising as it would violate fundamental thermodynamics. As known since Planck's

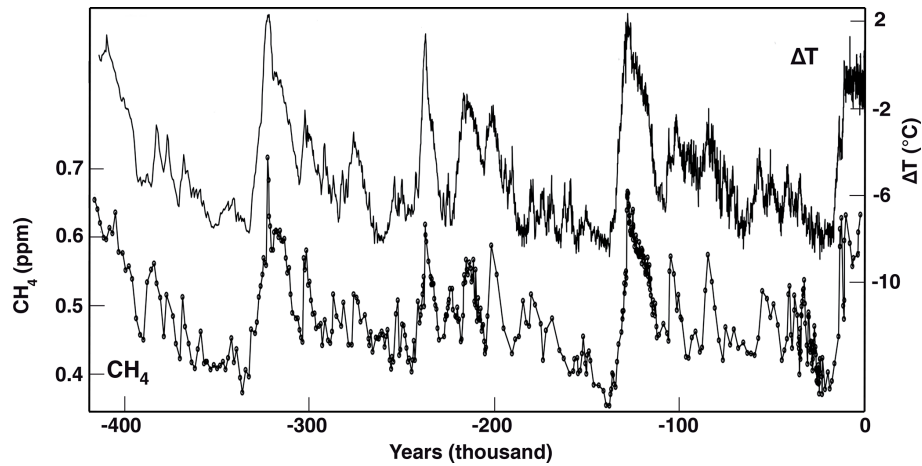


Figure 2. The remarkable correlation between the variations in temperatures and atmospheric methane concentrations in the Vostok record. Data from Petit et al. (1999) are replotted in chronological order from left to right.

work, radiation represents not only energy but also entropy. Regardless of the particular ways in which radiation entropy is transferred to the Earth's surface and atmosphere, or lost from them, the basic fact is that temperature and entropy are the intensive and extensive conjugate variables of thermal energy, respectively. Under all circumstances, any temperature (or, more generally, enthalpy) changes of a system are thus necessarily driven by an entropy change (see Richet, 2001). This is another way of stating that greenhouse gases can affect climate only via thermal changes. As such, their effects would manifest themselves in any temperature record, which must be considered in this respect as thermograms in thermal analyses.

Obviously, one could alternatively claim that other factors than CO₂–temperature interactions are involved in the very complex climate problem; if so, however, an important aspect would be that changes in atmospheric CO₂ contents of tens or even hundreds of parts per million certainly could not directly affect ice volume or tipping points related to patterns of oceanic circulation, to name a single important feature, but could act only through thermal changes as described above. The conclusion, thus, remains that it would not make sense to place so much emphasis on the effects of CO₂ in either climate models or on emission reductions in environmental policies.

For ice cores, a first key factor that ensures reliable assessments of temperatures with respect to CO₂ and CH₄ concentrations is the determinations of the three parameters for the same ice fragments of known ages. A second factor is the fact that the temperature variations of up to 12 °C during climate cycles observed in polar regions are much greater than the 2–3 °C that affected the entire Earth, which accounts for the much higher resolution of the polar records. And a third factor is the large timescales of these observations, which are more than 1000 times longer than those of climate simulations and of available measurements of atmospheric tempera-

tures and gas concentrations. Of particular importance is also that the 423 kyr considered here are long enough to encompass four complete glacial cycles, for which short-term fluctuations can be neglected, but short enough to not be affected by other factors, such as changes in continent positions, that play an important role over very long timescales. In addition, the lack of correlations that support CO₂ forcing is immune from the inevitable biases that arise when unrelated sets of data are used for different parameters, especially when some are derived indirectly from proxy studies or when investigations deal with short periods of time.

In the atmosphere, the maximum CO₂ concentration of 300 ppm found in the Vostok record was reached again in the 1910s. The main effect of such high concentrations was simply to increase considerably the subsequent CO₂ time lag behind the temperature leads, without significant effects on past climate. Hence, it is doubtful that any significant global warming could have been caused by human emissions during most of the 20th century as a result of the additional 50 ppm CO₂ increase observed until the 1980s. Given the lack of evidence for feedback mechanisms particularly well demonstrated by the CH₄ record, it in fact remains to be determined from which level, if any, CO₂ concentrations would begin to become relevant and to ascertain the dire consequences of current CO₂ levels. The principle of parsimony thus points to any current warming as being just one of the recurrent fluctuations clearly recorded as spikes in the last two climate cycles, which have not yet been averaged out in the Vostok record (Fig. 1) and, surprisingly, seem to be overlooked in discussions of short-term temperature variations. As often noted, it would in fact be an arbitrary assumption to posit that a system as chaotic and as highly heterogeneous as the Earth, which must be described in terms of complex sets of coupled nonlinear equations, would always evolve in a smooth manner over long periods of time.

Probably the most in-depth geochemical discussion of glacial cycles and climate effects of CO₂ has been published by Broecker (2018), who pointed out that some important features of past climate could not be accounted for in terms of CO₂ variations. Broecker nonetheless stated that “the geologic record makes a strong case that CO₂ has been instrumental in driving past climate changes”, adding that “as made clear by the record for the last 150 kyr”, CO₂ “has not acted alone” because insolation cycles, ocean circulation or reorganization and latitudinal temperature gradients also contributed. Although less important than insolation cycles, the other factors mentioned by Broecker certainly have to be taken into account in more detailed pictures of climate change. Overall, however, the fundamental importance of the Antarctica records rests on the fact that glaciation–deglaciation cycles are the most conspicuous features of climate changes and that the ensuing sea level variations necessarily affect the whole planet. Of particular interest in this respect is the synchronicity of the episodes of warming and cooling found over long timescales between Greenland and Antarctica (Pedro et al., 2011). In addition, the remarkable synchronicity of temperature and methane variations points to a lack of major latitudinal time lags, since the methane budget appears largely controlled by tropical sources and sinks (Loulergue et al., 2008) and not by interactions with seawater (Reeburgh, 2007).

5.2 The threat of circular reasoning

Petit (2013) asserted that the amplifying role of CO₂ on climate change was first demonstrated by the Vostok analyses and added that these results were then “very rapidly taken into account by IPCC, which recently concluded that human activities are responsible for the current climate warming.” The importance of the Vostok results has, thus, been central in the current debate, even though it is now commonly emphasized that global warming is demonstrated instead from a quantitative understanding of the physical mechanisms through which temperatures and CO₂ concentrations are related in advanced climate models.

Regarding their Vostok analyses, Petit et al. (1999) stated that “results from various climate simulations make it reasonable to assume that greenhouse gases have, at a global scale, contributed significantly (possibly about half, that is 2–3 °C) to the globally averaged glacial–interglacial temperature change.” That this statement is clearly contradicted by the present analysis in turn invalidates those climate simulations from which it derived. The CO₂ feedback supposedly shown by the ice-core results thus appears to exemplify a rather common situation whereby a preconceived notion of causality has led to the misinterpretation of the data – perhaps also because these results were not plotted as a function of time but of depth, which may carry the illusion that CO₂ peaks systematically precede temperature peaks. This situation illustrates the peril of transposing theoretical concepts

to a very complex system when the observational support is incomplete or when an independent, rigorous assessment of the validity of the procedure is lacking. In other words, interpreting the CO₂ and temperature records of ice cores in the light of climate models has represented an incorrect methodological leap. Ironically, any claim that models accurately reproduce the reported climate evolution since the late 20th century would rather illustrate their spurious nature, and not prove their validity, if the temperature rises of this period are not caused by increases in CO₂ concentrations.

There is, additionally, a great epistemological weakness in climate models because the timescales of 150 years at most they consider with direct or indirect observations are tremendously short with respect to those of even the shortest fluctuations exhibited by the climate record (Fig. 1). The situation is analogous to that one would face in attempts made at understanding the basic physics of tides through focusing on a single ripple at the water surface and not on entire ebbing and waning cycles of variable amplitudes. The reliability of climate models should thus be ascertained on the basis of their ability to match at least the main features of the latest glacial cycles, beginning with the sharp glacial–interglacial transitions. Given the fundamental role assigned to greenhouse gases, any specific model cannot be considered valid as long as the width differences between temperature and CO₂ peaks are not accounted for quantitatively.

As a matter of fact, current models suffer from the circular nature of the reasoning behind their assumed feedback mechanism whereby, in the last analysis, the predicted influence of CO₂ simply conforms to the posited effects in a situation where the anthropogenic increases in CO₂ concentrations happen to accompany those of temperatures. In a kind of *reductio ad absurdum*, a similar situation would be encountered if the quantitative correlation observed between the recent increases in atmospheric CO₂ contents and the geographic displacement of the magnetic north pole (Fig. 3) were interpreted as a causality relationship – which could of course not be considered seriously in view of a complete physical implausibility!

In a well-known statement, the Latin writer Macrobius (fl. early 5th c. BCE) long ago illustrated such a circularity when he explained why the place of the Earth was at the center of the world. As he asserted, in a way reminiscent of complex feedbacks, “those reasons are truly incontrovertible which are mutually confirmed, the one substantiating the other and each arising from the other, never abandoning each other’s support.” Then, Macrobius concluded that “with such bonds nature has held the Earth fast: all things tend toward it since, being the middle, it does not move; again, it does not move because it is at the bottom; finally, it must be at the bottom since all things tend towards it.”

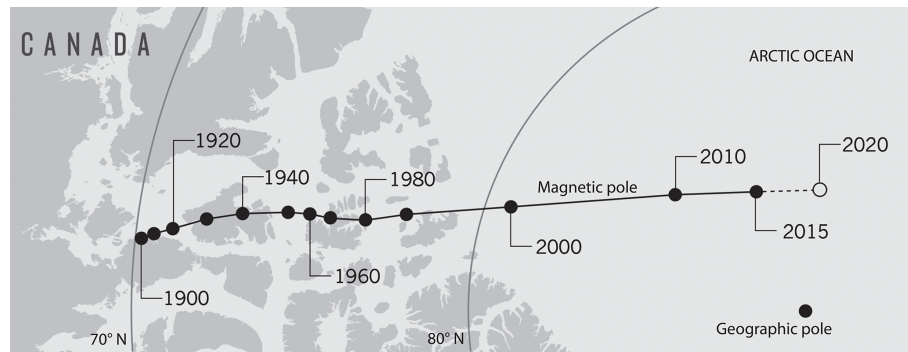


Figure 3. The strongly accelerating displacement of the magnetic north pole (after Witze, 2019). Similar distances were traveled from 1900 to 1980 and from 2000 to 2020, correlating quantitatively (but of course coincidentally), during both periods with a ~ 40 ppm increase in atmospheric CO₂ concentration (Hawaii Observatory, 2019).

5.3 Earth sciences – a pitfall factory

To an Earth scientist, the ongoing climate debate is a reminder of the long series of controversies to which geology has been especially prone (see Hallam, 1989). The huge size, very long timescales, complexity and large number of parameters that need to be considered for the Earth system as a whole have more than once clearly misled eminent scientists too committed to their own physics. The claim repeatedly heard that science has settled, for good, the climate problem particularly reminds the observer of two famous debates. Regarding continent motion, the greatly influential mathematician and theoretical geophysicist Jeffreys (1929) was right when he claimed that, in a rigid Earth, “secular drift of continents relative to the rest of the crust, such as have been maintained by Wegener and others, are out of the question.” But he was nonetheless quite wrong because he did not envision convection in a highly viscous mantle, which was proposed at the same time as a viable mechanism by Holmes (1928).

Also relevant is the climax of the long controversy on the antiquity of the Earth at the end of the 19th century. At that time, an age lower than 100 million years was apparently demonstrated with the utmost rigor, i.e., without any fit parameters, in four completely independent ways, namely from the cooling history of the Earth from an initially molten state, from the age of the Sun, as constrained by the first law of thermodynamics, from the time needed by the world ocean to acquire its saltiness and from the time at which the Moon separated from the Earth, as calculated from astronomical considerations (see Richet, 2007). Tait (1885), a well-known physicist and close friend of Kelvin, then exemplified the theoretician’s self-confidence by claiming, “We say – So much the worse for geology as at present understood by its chief authorities, for, as you will presently see, physical considerations from various independent points of view render it utterly impossible that more than ten or fifteen millions of years can be granted.”

Perhaps even more relevant was the clear consensus that was reached in the 1890s when geologists evaluating the age of the Earth found ways to comply, at least partially, with the physicists’ requirements; by adjusting their estimated thicknesses of the stratigraphic column and average rates of sedimentation, they did arrive at ages ranging from 26 to 100 million years. Hence, the great irony of the situation was that this consensus, spontaneously reached – i.e., without any funding, social or political pressures – to conform to the newly prevailing physical paradigm, was shattered into pieces not even 2 decades after Tait’s utterance when radioactive dating began to point to an age of billion years instead (see Richet, 2007).

In contrast to the context of previous debates, new fundamental principles unlikely need to be discovered to improve climate understanding. As indicated by the limitations of current climate models pointed out over the years (e.g., Lindzen, 1997; Christy et al., 2018; Lewis and Curry, 2018; McKittrick and Christy, 2020; Mitchell et al., 2020), the issue at hand is rather to determine which of the basic assumptions made and calculation procedures used are either too approximate or even incorrect and what factors and interactions have been omitted or not been properly taken into account in simulations.

The question is in no way new, since various suggestions have already been made in this respect. Without needing to discuss here the validity of such approaches, it will suffice to state (i) that the constantly lagging effects of CO₂ concentrations with respect to the rate of change of the global ice have already been pointed out (e.g., Roe, 2006); (ii) that the radiative forcing of CO₂ and CH₄ has been found to be several times smaller than changes in solar insolation at climatically sensitive zones and latitudes (Soon, 2007); (iii) that doubling the current concentrations of CO₂ and CH₄ would increase their forcings by a few percent, according to recent calculations made for the five most abundant greenhouse gases from a comprehensive set of over 333 000 rovibrational bands (Van Wijngaarden and Happer, 2020); (iv) that

the greenhouse mechanisms usually assumed have indeed been strongly called into question (e.g., Chilingar et al., 2008; Allmendinger, 2017; Hertzberg et al., 2017; Nikolov and Zeller, 2017); (v) that climate change has been little investigated from the fundamental thermodynamic standpoint of entropy production in the atmosphere (Delgado-Bonal, 2017); (vi) and that the overall picture has also been disputed on a broader perspective (e.g., Hertzberg and Schreuder, 2016; Fleming, 2018; Frank, 2019). Following, for example, Blaauw (2017), it would be particularly interesting to ascertain whether simpler models free from greenhouse gas effects would yield more reliable results for time spans longer than those currently considered.

5.4 Toward a new ice age?

As noted above, an important feature that must be accounted for in terms of dynamical responses is the constant 7 kyr time lag between the temperature and CO₂ peaks at the interglacial–glacial transitions (Fig. 1). It is much longer than the equilibration times for CO₂ intake by the world ocean, but its constant value points to processes of an overall reproducibility that could have not been expected.

In terms of Milankovitch cycles, another problem of special importance is to find a quantitative explanation for the observed 1 : 2 ratios of the temperature peak widths between cycle III and cycles II and IV. The current transition I in Fig. 1 made the invention of agriculture possible and led to the beginnings and expansion of civilization. At 13 kyr, however, the full width at half maximum of its temperature peak is already much greater than the 7 kyr of cycle III and is approaching the 15–16 kyr of cycles II and IV, which seriously raises the issue of the next ice age.

When the validity of Milankovitch cycles was beginning to be acknowledged, it was commonly assumed that temperatures had been decreasing since the late 1930s (see Imbrie and Palmer Imbrie, 1979). That cooling lasted much longer than warming in great climate cycles was ascertained from his loess studies by Kukla (1970), an author who was also a proponent of the cooling thesis. Hence, Kukla and Matthews (1972) suggested, from expanding snowbanks around Baffin Island, peak ice hindering navigation around Iceland or warmth-loving animals retreating southward, that “the natural end of our warm epoch is undoubtedly near when considering a geological timescale.”

In the current context of global warming, such fears of a new ice age are retrospectively taken very lightly. According to a model based on a relationship between boreal summer insolation and CO₂ air concentration, the current interglacial period would probably last for 50 000–100 000 more years, depending on the amount of anthropogenic CO₂ emissions (Ganopolski et al., 2016). Even if CO₂ forcing is assumed, however, then the reliability of such a model should first be established from its ability to reproduce quantitatively the respective durations of past ice ages.

As long as such an assessment is lacking, one can assume, instead, that the high sensitivity of climate to minor features of Milankovitch cycles (Fig. 1) makes it a priori unlikely that the present warm period should last considerably longer than the former ones. In this respect, the important difference between now and the situation in the 1970s is that the succession of eight major glacial cycles during the last 800 kyr is so well established that the precise chronology yielded by the ice-core records (Fig. 1) suggests that an onset of global cooling might be observed within less than a couple of millennia from now. By then climate models may be expected to have reached the level of confidence needed to make accurate predictions. It, nonetheless, remains that the threat to be faced with a new incoming ice age would be of the extraordinary magnitude already envisioned in the 1970s and would make current fears of global warming look quite insignificant.

6 Postface

Regardless of any particular interpretation of the climate record, it seems appropriate to give the last word to the famous naturalist Georges-Louis Leclerc, Earl of Buffon (1749). Himself a mathematician by training, Buffon (1749) voiced a strong warning very early on about the misuses of what are now called *models* by expounding in the *Initial Discourse* of his monumental *Natural History* the “difficulties one finds when attempting to apply geometry or calculations to physical subjects that are too complicated.” As he noted, one has “to strip the subject from the majority of these qualities, to produce an abstract being that no longer resembles the actual being” and, after much reasoning and calculation, one projects an “ideal result onto the real subject, and this is what produces countless falsehoods and errors.” Hence, Buffon concluded, “the most delicate and most important point in scientific studies” is “to distinguish well between what there is of the real in a subject from that which we add to it arbitrarily as we consider it: to recognize clearly which properties belong to the subject and which properties we only imagine it to have.”

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Competing interests. The author declares that there is no conflict of interest.

Disclaimer. The author has never had any professional relationship with oil, gas or coal companies, nor has he had any private interest in them, and he has never requested or received funding from any environmentally related agency or organization. The present study simply represents the outcome of an old-fashioned search for truth – something that “is sunk in the depths”, as aptly understood

2.5 millennia ago by Democritus (5th–4th c. BCE), the celebrated Greek atomist.

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