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On the Milankovitch sensitivity of the Quaternary deep-sea record

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Abstract

The response of the climate system to external forcing has become an item of prime interest in the context of global warming, especially with respect to the rate of melting land-based ice masses. The deep-sea record of ice-age climate change has been useful in assessing the sensitivity of the climate system to such forcing, notably to orbital forcing, which is well-known for the last several million years. When comparing response and forcing, one finds that sensitivity varies greatly through time, apparently in dependence on the state of the system. The changing stability of ice masses presumably is the underlying cause for the changing state of the system. A buildup of vulnerable ice masses within the latest Tertiary, when going into the ice ages, is conjectured to cause a stepwise increase of climate variability since the early Pliocene.

1 Introduction

The ice-age record of deep-sea sediments demonstrates sensitivity of the climate of the last two million years to Milankovitch forcing ("MF" in what follows). This is hardly in doubt any more. The pioneer studies of Hays et al. (1976) and the milestone articles in A. Berger et al. (1984) established that MF Is present in the record, and can be used for tuning (i.e., for detailed dating). Also, by the mid-eighties it was shown that MF history can drive geophysical models able to generate an ice-mass history that closely mimics the real world (Pollard, 1984). These findings also opened the possibility of assessing the stability of the planetary orbits in the solar system, which are ultimately responsible for MF history through geologic time (A. Berger et al., 1992). Thus, Milankovitch theory has become central to all discussion of the long-term climate history of the ice ages and beyond, and not only for the deep-sea record (e.g., A. Berger et al., 1989; Einsele et al., 1991; Schwarzacher, 1993; EPICA Community Members, 2004).

Nevertheless, what may be called the "Milankovitch sensitivity" of the climate system ("MS" in what follows) remains poorly defined, even in the Quaternary, with its strong Milankovitch affiliations. Superficially, within the late Quaternary, the main reason for the difficulty of relating MF to the climate response (a relationship that reflects MS) is the problem of the 100-kyr cycle (Imbrie and Imbrie, 1980; Imbrie et al., 1984, 1992, 1993). The "100-kyr problem" reflects the fact that the dominant climate cycle of the time-span studied by Milankovitch (the last 650 000 yr, the "Milankovitch Chron" of W. Berger and Wefer, 1992) has a period near 100 000 yr. There is, however, no readily identifiable MF that could drive climate variation on this cycle. There are two possible solutions to the conundrum; both imply that linear MF is not the whole story behind the ice-age cycles. The most radical solution is to look for outside forcing elsewhere, such as in the cyclic variation of the inclination of the average orbital plane of the planets and the dust within that plane (Muller and Mcdonald, 2000). The other approach is to postulate long-term internal oscillation that is captured by eccentricity-related MF, notably varying precession, presumably with the help of stochastic forcing (W. Berger, 1999, and references therein).

Even if the 100-kyr problem were solved, however, the difficulty of defining MS would remain. It certainly exists for the time before the "Milankovitch Chron", a time when there were no 100-kyr cycles. The MS changes considerably both within the 100-kyr cycles (as exemplified by the presence of terminations) and it changes noticeably on longer time scales as well, being strongly linked to the size of the ice mass present on the Northern Hemisphere, and its state with regard to stability (Dolan et al., 2011), and being strongly influenced, presumably, by tectonic processes and associated erosion rates (Roe and Baker, 2007; Tomkin and Roe, 2007; A. Berger et al., 2008; Brocklehurst, 2008; Champagnac et al., 2012).

While the attempt to obtain a quantitative measure of Milankovitch sensitivity may fail, there are ways to track this elusive parameter semi-quantitatively. MS did change greatly through geologic time, presumably initially because of the buildup of northern ice (identified by Milankovitch as the crucial element in the ice-age climate system; Milankovitch, 1930), and at a later stage in consequence of the increasing vulnerability of ice masses to a rise in sea level. This particular element of instability presumably was caused by the erosion of fjords and basins that allowed deep penetration of seawater to below existing ice masses. The implication of a changing MS for using the ice ages as a source of lessons for recent and present climate change is to greatly increase uncertainty. Presumably, the best analog periods would be those for which the MS pattern is similar to the present one. If the MS cannot be measured, however, its patterns cannot be compared in detail from one period to another. Substitution of MF for MS (for example, by taking Stage 11 as a good analog for the Holocene; A. Berger and Loutre, 2003) may work, but moves the argument into the realm of geologic time, outside of societal concerns.

2 System response to Milankovitch forcing

Clearly, it is the response of the climate system to forcing that we are interested in when discussing sensitivity within the framework of ice-age history. The fundamental insight of Milankovitch (1930) was the realization that the response of the system originates in high latitudes on the Northern Hemisphere, and that the ice masses there are particularly vulnerable to melting within warm northern summers (Fig. 1), forcing being documented in seasonal values of high-latitude insolation.

Although aware of positive feedback from albedo (hence the choice of a crucial latitude in the far north, where snow can persist through the summer), Milankovitch assumed that the response to forcing would be predictable, and he used MF as a template for conditions in the ice ages (prominently in his graph published by Köppen and Wegener, 1924). The proposition can be tested. It fails the test. The test consists in finding the correlation of two series, MF and the oxygen isotope record in deep-sea sediments, after precise matching of MF with the record. The matching (or "Milankovitch tuning") is best done between MF and the derivative of the proxy record; that is, the oxygen isotope stratigraphy of benthic or planktonic foraminifers. After all, Milankovitch theory refers to *change*. A match to *conditions*, while generally assumed, should not be expected.

The most widely used proxy record, already tuned to Milankovitch, and available for decades, is the stacked record published by Imbrie et al. (1984) and commonly referred to as the "SPECMAP" template (here: "Imb84"). Its derivative is readily made in a spreadsheet, numerically. Comparison with MF shows the good fit expected from tuning (Fig. 2). MF is here taken as the series calculated by A. Berger and Loutre (1991), who give the insolation for July at 65° N. The precise phase between MF and response is unknown, as is the variability of that phase. The good fit between MF and proxy seen represents an assumption of zero phase shift and zero variability of phase, a conjecture that simplifies the issue but has no inherent heuristic value.

It is immediately obvious from inspecting Fig. 2 that the fit is in the timing, but that the magnitude of the response is not closely linked to the magnitude of the MF (the mean is set to unity, and one standard deviation to 0.25). This implies that the sensitivity of the system to forcing changes through time. That this is the case has been well known for several decades. A major change in sensitivity during the Pleistocene manifests itself, for example, in the Mid-Pleistocene Climate Shift, when the system started to strongly respond to precession (and hence eccentricity) in addition to the changing tilt of Earth's axis (Pisias and Moore, 1981; Ruddiman et al., 1989). The appearance of a strong 100-kyr cycle some 650 000 yr ago (W. Berger and Wefer, 1992; Mudelsee and Stattegger, 1997) is another major change in climate response (Fig. 3). In fact, the striking sensitivity of the climate system to forcing associated with the ca-100-kyr cycle has provided a rich field for investigation and conjecture since the 1990s (Imbrie et al., 1992, 1993; W. Berger, 1999; A. Berger et al., 2005; Ganopolski and Calov, 2011; Nie, 2011).

2.1 Deaf zones

The assessment of MS proceeds from proxy records thought to be Milankovitch-driven, commonly the oxygen isotope record of either benthic or planktonic foraminifers. Remarkably, the difference between the two types of records is not important in the context (Fig. 4). This suggest that both proxy records reflect the dominant parameter of climate change (ice mass) or else that other parameters that matter (such a temperature) are highly correlated to the primary one. Given the observed similarities, I shall analyze the compilations of benthic proxy records in what follows, confident that they represent global signals. The compilations are based on tuned records. Thus, a good fit to Milankovitch forcing can be taken to be built in. Nevertheless, a combination of the compilations of Zachos et al. (2001) and of Lisiecki and Raymo (2005) was re-tuned to Milankovitch forcing using the derivative of the stacked record (Table A1 in W. Berger, 2011). The series comprises the last million years in 1-kyr intervals. It should yield maximum values for MS when analyzed, since Milankovitch theory underlies all age dating in this case. To get an assessment of MS; that is, the climate response to Milankovitch forcing, windowed correlation is useful. It answers the question of how well proxy series and MF are correlated along a sliding window. To establish the effects of window size on the resulting correlation, I chose 12 000 yr, 25 000 yr, 50 000 yr (Fig. 5) and 100 000 yr (not shown). The larger windows, not surprisingly, represent summations of the shorter ones.

Whatever the window size, there are some striking stretches of very low correlation, suggesting zero influence of MF on the climate record. I have referred to such time spans as “deaf zones” elsewhere (W. Berger, 2011). However, the term “deaf,” while describing the situation correctly, may be misleading. Some of the “deafness” may result from a lack of input; that is, from insufficient power of MF to move the system, and not because of an inherent lack of sensitivity of the system to outside influence (Fig. 5, bottom panel). If true, a difficult question arises: to what degree does “sufficiency” in the MF depend on the state of the system, and does “sufficiency” change through time, therefore? Changes in sufficiency presumably may affect the practice of Milankovitch tuning through geologic time. Such tuning is now widely applied, following the success of Shackleton et al. (1990) in correctly dating sediments of Pleistocene age and of various authors in finding verifiable ages for sediments considerably older than that (e.g., Hilgen et al., 1995; Shackleton et al., 1995; Liebrand et al., 2011).

2.2 Terminations

The response of the climate system to Milankovitch forcing is at maximum strength at the beginning of deglaciation events; that is, the relatively brief periods when large ice masses on the Northern Hemisphere disappear entirely, and sea level rises accordingly. The periodic switch within the system from buildup of ice to its rapid demise gives rise to asymmetric cycles, as noted first by Broecker and van Donk (1970), who also coined the label "termination" for the large-scale melting of glacial ice-masses. That the rapid decay of ice indicates instability within the system was emphasized by Hughes (1987), among others. Questions surrounding the stability of ice masses both in Greenland and in Antarctica have become of urgent importance in recent years, given that global warming is inexorably proceeding (e.g., Jansen et al., 2007). It seems obvious, from comparing MF with the timing of the onset of terminations (Fig. 6) that MF acts as a trigger in these circumstances rather than as a driver.

The implication for the present predicament (stability of ice masses in the face of global warming) is that large ice masses can be stable or unstable, presumably dependent on their internal temperature and on the presence of back-stops such as shelf ice. Also, history suggests that once large ice masses start deteriorating they will continue to do so for more than a thousand years, presumably largely reflecting internal system feedback rather than external forcing. If so, this would imply that a disintegration of large ice masses, once started, is irreversible. To what degree such disintegration reflects the participation of the ocean in climate system processes (e.g., Broecker and Denton, 1989) is an interesting question that remains to be investigated. Simple physical principles suggest that disintegrating ice heats up from fast motion, and breaks up, thus admitting lubricating water to the base. Furthermore, ice masses that terminate within the sea are vulnerable to a rise in sea level, as well as to tsunamis and to tides.

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3 Agitation

A highly variable climate system may be said to have a high level of "agitation"; that is, its various elements change rather rapidly. A system can enter high agitation in response to unchanged forcing because of a high content of instability, which implies increased sensitivity to outside disturbance. A typical response of a high-agitation system to external forcing is a switch to another mode of operation; that is, external forcing acts as a "trigger" rather than a "driver", and the system moves around a set of quite different states. Any effects of a "trigger," of course, are inherently less predictable than those of a "driver". In this sense, it seems, the Quaternary, and especially the late Quaternary, is a less predictable environment than, say, the early Pliocene (Fig. 7). The change from predictable to unpredictable is of considerable interest in the context of evolution in the last 5 million years, which presumably includes the invasion of the increasingly variable northern realm by migrating birds and various types of arctic mammals.

The overall trend toward increased agitation in the global climate system is not subtle at all, but is very evident (Fig. 7). The trend is a result of stepwise increase in variability, presumably linked to the buildup of large ice masses in northern land areas. A step near 3 million years ago supports the concept (based on the discovery of glacial debris by drilling in the North Atlantic) that glacial ice masses date from that time (Berggren, 1972, and many authors since). The moderately high agitation level at the end of the Miocene may owe to an earlier northern ice buildup (Jansen and Sjøholm, 1991; Larsen et al., 1994). If so, a decrease in agitation would be expected from northern warming (as observed for the early Pliocene).

I suspect that increased heat transport by the Gulf Stream system is an important factor in northern warming, in consequence of closing the connection between Caribbean and Pacific (W. Berger and Wefer, 1996). Presumably, the northern ice buildup was not prevented, but it started with some delay, as the planet continued to cool. The increased supply of Gulf Stream heat, in the geologic time that followed, then helped make the

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northern ice masses unstable and vulnerable to sporadic removal. In this sense, the Quaternary may indeed owe its main features to the emergence of the Panama Isthmus, although hardly in the way envisaged by those who call on the additional heat to make vapor and snow.

It seems clear from inspection of Fig. 7 that the currently accepted boundaries between Miocene and Pliocene, and between Pliocene and Pleistocene, are readily reconciled with the evidence for climate variability. In addition, it is of interest that the general increase in climate variability parallels increasing participation of the carbon cycle in the climate narrative. The latter expresses itself as an increased negative correlation between oxygen and carbon isotopes in the benthic deep-sea foraminifers, with a maximum near 1.3 M years ago. The cause for the correlation is not known; it may reflect climate control on the buildup and destruction of forests on land, or high-latitude control on carbon content in the deep sea, or a combination of these processes, or other factors. There is no evidence, in these records, of a quiet time in the middle of the Pliocene. This relatively warm period (3 Myr to 3.3 Myr) has been studied for sensitivity to Milankovitch forcing (by climate modeling), and was found to likely have had substantial sea-level fluctuations around a mean that was substantially higher than today (Dolan et al., 2011).

4 Conclusions

The use of Milankovitch theory for the purpose of dating deep-sea sediments is an important and widespread practical application to deep-sea stratigraphy. However, it is clear that the depth of understanding of how “Milankovitch forcing” is translated into changes in the climate system is not commensurate to the task. Likewise, the use of ice-age history in drawing lessons for the climate problems of the present suffers from a greatly changing sensitivity of the system to MF. The chief problem appears to be that the system responds as much to triggers as to drivers. Whenever MF provides the trigger it is not clear why the trigger was effective exactly at the time observed.

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Presumably the system is in a crucial state at that time; a state that is difficult or perhaps impossible to define using available proxies. As concerns the response of the climate system to drivers, it appears that this response is subject to unknown factors causing reluctance and even “deafness” on occasion.

While the main patterns of forcing and response are readily established using data from the last million years, there are insights to be gained from studying the trends that led into the Quaternary, at the end of the late Tertiary.

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Fig. 1. Melting tidewater ice in the Svalbard archipelago, Arctic Ocean, summer 2007.

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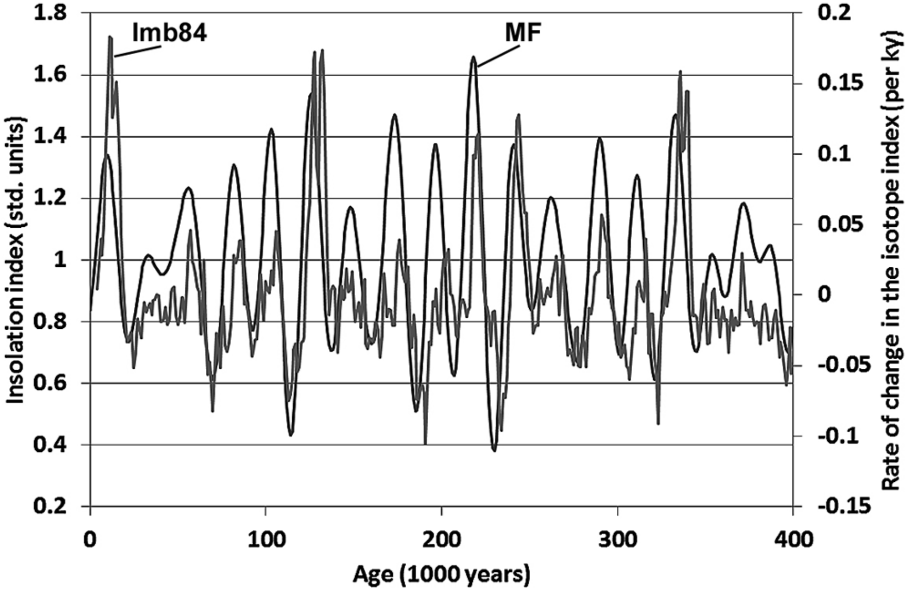

Fig. 2. Comparison of the derivative of the SPECMAP template (Imb84; Imbrie et al., 1984) with Milankovitch Forcing (MF) as given in Berger and Loutre (1991). All values are standardized (by linear transform). The rate of change in the oxygen isotope record (secondary y-axis) can be read as meters of sea-level change per decade, approximately.

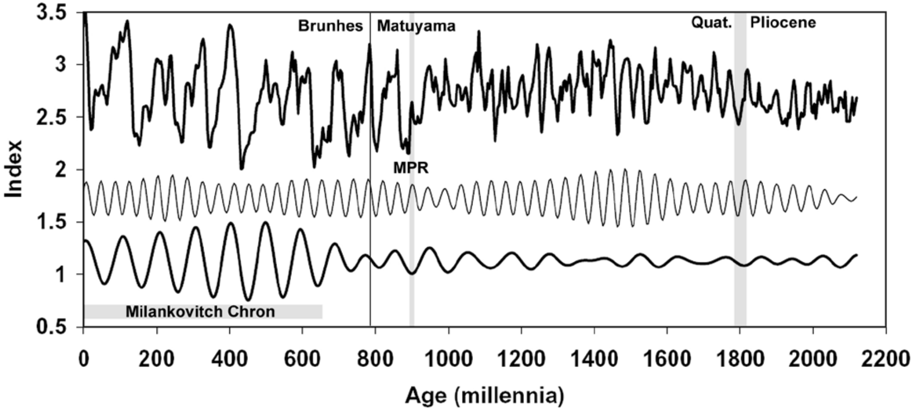

Fig. 3. Oxygen isotope record of ODP Site 806: extraction of ca. 40 000-yr and ca. 100 000-yr cycles by Fourier analysis. Adapted from Berger and Wefer (1992).

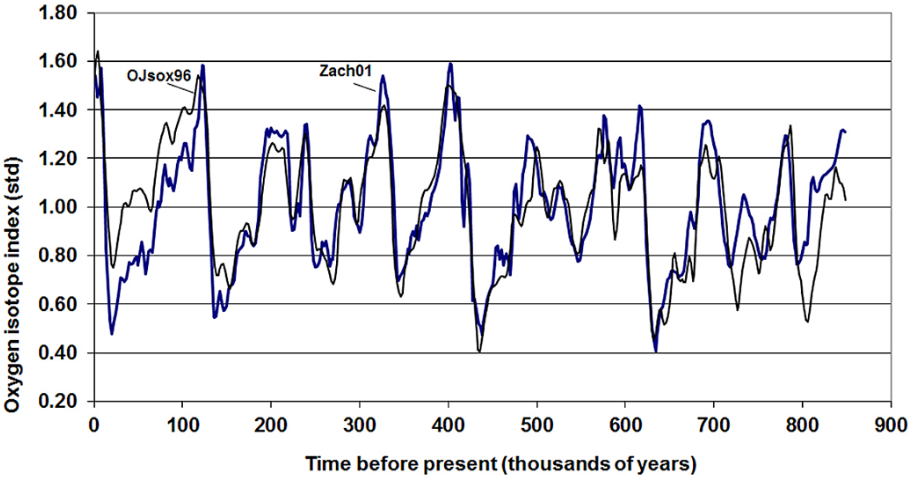

Fig. 4. Comparison of standardized oxygen isotope series from deep-sea sediments, one based on planktonic foraminifers (*G. sacculifer*), ODP Site 806, Ontong Java Plateau (Berger et al., 1993); the other based on 1-kyr interpolation of a compilation of benthic values by Zachos et al. (2001), on a global scale.

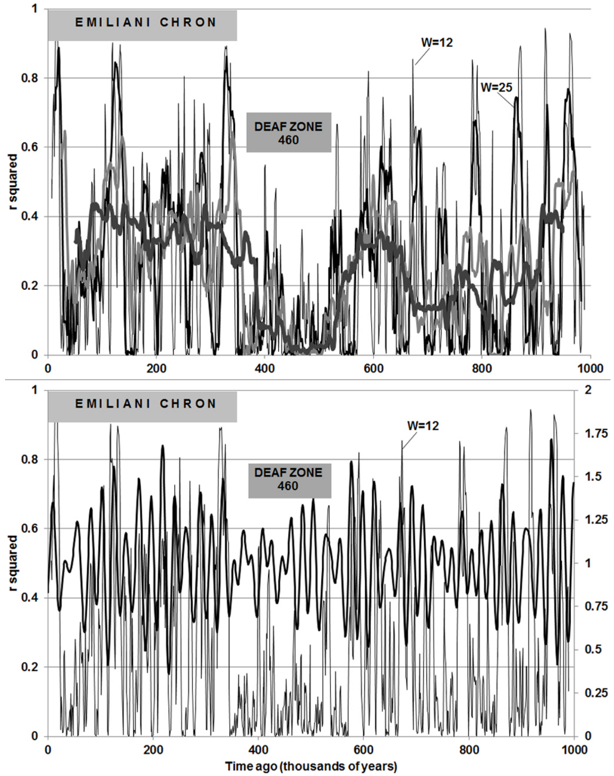

Fig. 5. Evidence for a lack of MS in climate change ("deaf zone") centered on 460 000 yr, in windowed correlation of MF and a proxy series based on compilations of Zachos et al. (2001) and Lisiecki and Raymo (2005), combined, interpolated, and re-tuned to Milankovitch forcing (Berger, 2011). The "deaf zone" includes Stage 12. Its end defines the beginning of the "Emiliani Chron," the time span studied by Emiliani (1955) and recognized as rich in climate cycles. $W = 12$, window width is 12 kyr. Heavy gray line (top graph), window width is 50 kyr. Black line (bottom graph): MF (from Berger and Loutre, 1991).

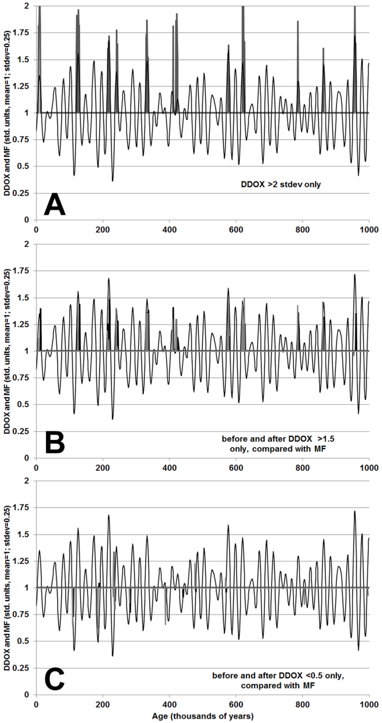

Fig. 6. Unusually large rates of change compared with MF. **(A)** derivative of δ^{18}O record (Table A1 in Berger, 2011) larger than 2 standard deviations above the mean, placed along the MF series (calculated by Berger and Loutre, 1991). These are the “terminations”. **(B)** rates of change before and after events for which positive δ^{18}O’ values exceed 2 standard deviations (search for persistence of fast positive rates). **(C)** rates of change before and after events for which negative δ^{18}O’ values exceed 2 standard deviations (search for persistence). (Mean of the series set to one, standard deviation to 0.25.)

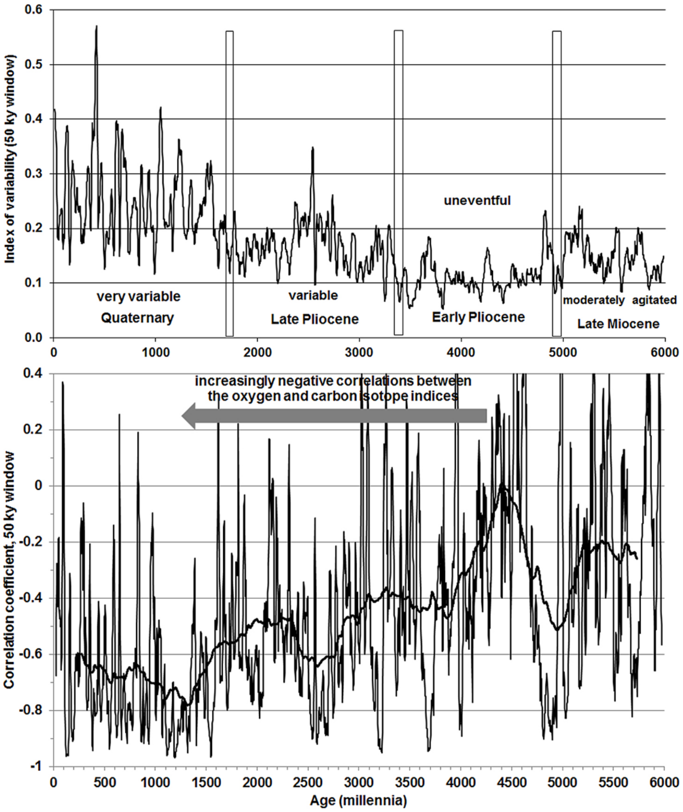

Fig. 7. The late Tertiary-to-Quaternary trend of increased variability (as seen in the oxygen isotopes) and the increased constraints on the carbon system (as seen in the evolution of correlation coefficients between oxygen and carbon isotopes). Data are from the compilation of Zachos et al. (2001), interpolated for 2 kyr intervals. The correlation in the lower graph is based on a moving 50-kyr window, with the solid line showing average conditions for 500 kyr.

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