Global and Planetary Change 165 (2018) 128–136

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Research article

Long-term cyclicities in Phanerozoic sea-level sedimentary record and their potential drivers

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ARTICLE INFO

Keywords:
~9.3
~36
~91 and ~250 Myr sea-level periodicities
Tectonics
Milankovitch
Solar System periodicities
Vertical and radial motions
Earth's climate

ABSTRACT

Cyclic sedimentation has varied at several timescales and this variability has been geologically well documented at Milankovitch timescales, controlled in part by climatically (insolation) driven sea-level changes.

At the longer (tens of Myr) timescales connection between astronomical parameters and sedimentation via cyclic solar-system motions within the Milky Way has also been proposed, but this hypothesis remains controversial because of the lack of long geological records. In addition, the absence of a meaningful physical mechanism that could explain the connection between climate and astronomy at these longer timescales led to the more plausible explanation of plate motions as the main driver of climate and sedimentation through changes in ocean and continent mass distribution on Earth.

Here we statistically show a prominent and persistent ~36 Myr sedimentary cyclicity superimposed on two megacycles (~250 Myr) in a relatively well-constrained sea-level (SL) record of the past 542 Myr (Phanerozoic eon). We also show two other significant ~9.3 and ~91 Myr periodicities, but with lower amplitudes. The ~9.3 Myr cyclicity was previously attributed to long-period Milankovitch band based on the Cenozoic record. However, the ~91 Myr cyclicity has never been observed before in the geologic record. The ~250 Myr cyclicity was attributed to the Wilson tectonic (supercontinent) cycle. The ~36 Myr periodicity, also detected for the first time in SL record, has previously been ascribed either to tectonics or to astronomical cyclicity.

Given the possible link between amplitudes of the ~36 and ~250 Myr cyclicities in SL record and the potential that these periodicities fall into the frequency band of solar system motions, we suggest an astronomical origin, and model these periodicities as originating from the path of the solar system in the Milky Way as vertical and radial periods that modulate the flux of cosmic rays on Earth. Our finding of the ~36 Myr SL cyclicity lends credibility to the existing hypothesis about the imprint of solar-system vertical period on the geological record. The ~250 Myr megacycles are tentatively attributed to a radial period. However, tectonic causal mechanisms remain equally plausible.

The potential existence of a correlation between the modeled astronomical signal and the geological record may offer an indirect proxy to understand the structure and history of the Milky Way by providing a 542 Myr long record of the path of the Sun in our Galaxy.

1. Introduction

Increasing evidence from high-resolution sediment records from ocean drilling programs (Zachos et al., 2001; Cramer et al., 2009; Friedrich et al., 2012) and a parallel development of well-constrained astronomical models (Laskar et al., 2004, 2011) suggests that significant astro-climatic (Milankovitch, 1941) variability is present at million year (Myr) to multi-Myr timescales (e.g., Pälike et al., 2006; Boulila et al., 2011, 2012). The study of the influence of Myr to multi-Myr Milankovitch cycles to climate change and sedimentation is of considerable value in deciphering biological turnover (e.g., van Dam et al., 2006), carbon-cycle variations (Pälike et al., 2006; Boulila et al., 2012), ice-sheet events (Zachos et al., 2001; Pälike et al., 2006), sea-level fluctuations (Boulila et al., 2011), etc. Cyclicities of tens of Myr to few hundreds of Myr have also been detected in the geological records (e.g., Raup and Sepkoski, 1984; Rohde and Muller, 2005; Svensmark, 2006; Meyers and Peters, 2011), but the causes of these cyclicities are not well understood. Two potential drivers have been proposed for these very long geological periodicities: 1) major plate tectonic motions (e.g., Cogné et al., 2006; DeCelles et al., 2009; Meyers and Peters,

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https://doi.org/10.1016/j.gloplacha.2018.03.004
Received 4 August 2017; Received in revised form 5 March 2018; Accepted 9 March 2018
Available online 26 March 2018
0921-8181/

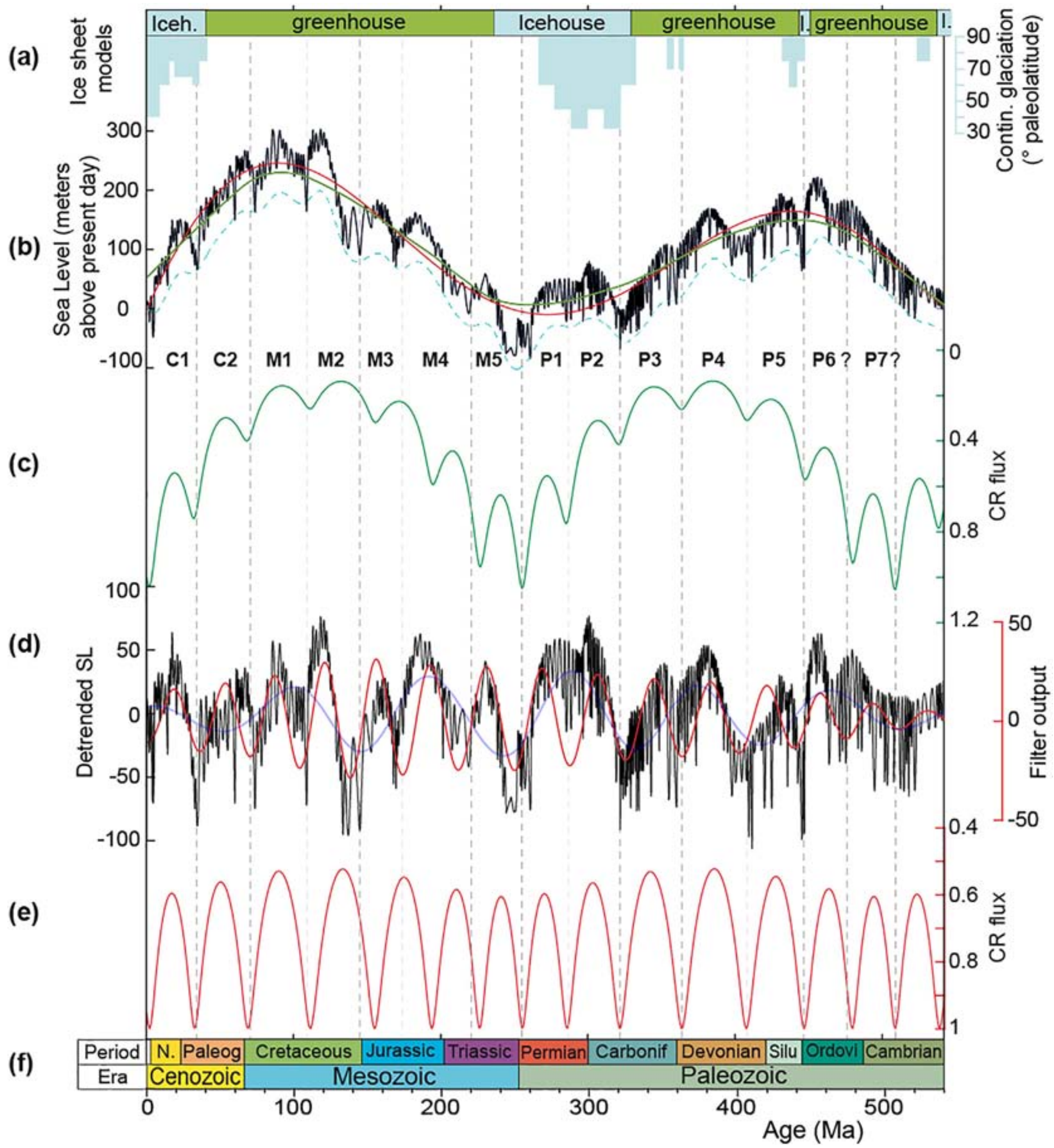

Fig. 1. Comparison of Phanerozoic eustatic curve, ice sheet models, and solar-system motion induced cosmic-ray (CR) models. (a) Ice sheet models, upper model (greenhouse in white boxes, and icehouse in grey boxes) from (Zachos et al., 2008; Frakes et al., 1992), lower model (in vertical grey bars for icehouse intervals) from (Ridgwell, 2005). (b) Original Phanerozoic eustatic curve (after Haq et al., 1987, Haq and Al-Qahtani, 2005, and Haq and Schutter, 2008). Roughly Meso-Cenozoic and Paleozoic megacycles are fitted by 25% weighted average (dashed curve) and six-order polynomial (solid curve) methods (see Fig. 3). Gaussian lowpass filter output (0 to 0.05 Myr^{-1} frequency cutoff) performed to uncover both ~36 and ~250 Myr cycles is also shown (dashed curve); C1, C2, M1-M5, and P1-P7 are the visually inspected ~36 Myr cycles (roughly 'C' for Cenozoic, 'M' for Mesozoic, and 'P' for Paleozoic), question marks indicate that ~36 Myr cycle boundaries are uncertain. (c) CR astronomical modeling (inverted axis) showing the ~36 and ~250 Myr vertical and radial motions of the solar system in the Milky Way (with a decay in $1/d^2$, see Supplementary material SM-2); times of midplane crossings and galactic center nearing correspond to periods of higher CR, climatic cooling, ice-sheet formation and glacioeustatic sea-level falls (see text for discussion). (d) Detrended eustatic curve (residuals of the 25% weighted average shown in "b") and Gaussian bandpass filter outputs: $0.028 \pm 0.012\ Myr^{-1}$ frequency cutoff to recover the ~36 Myr cyclicity (red curve), and $0.0103 \pm 0.005\ Myr^{-1}$ frequency cutoff to recover the ~91 Myr cyclicity (blue curve). (e) CR astronomical modeling (inverted axis) showing the ~36 Myr vertical motion of the solar system in the galaxy (with a decay in $1/d^2$, see Supplementary material SM-2). (f) Geologic Time Scale (after Ogg et al., 2016).

2011), and 2) the motions of the Solar System in the Milky Way (e.g., Svensmark, 2006; Medvedev and Melott, 2007).

The effect of tectonics on climate and sedimentation has been hypothesized through changing ocean volume as well as the geographic re-arrangement of continental and ocean mass distribution (e.g., Vail et al., 1977; Haq et al., 1987; Lagabrielle et al., 2009; Meyers and Peters, 2011; Cloetingh and Haq, 2015; Zaffos et al., 2017). Changes in galactic cosmic-ray (GCR) flux induced by periodic motions of the Solar System in the Galaxy have been also been proposed to explain the link between climate and astronomy at tens to hundreds of Myr (e.g., Shaviv, 2002).

Since 1980's several researchers have focused on the imprint of Solar System motions in the Millky Way in the geological record, because of the potential implications for Earth's climate change (Shaviv and Veizer, 2003) and biotic mass extinctions (Raup and Sepkoski, 1984; Medvedev and Melott, 2007; Svensmark, 2012). However, previous studies were hampered by the low resolution of geological records, or by the lack of understanding of the significance of the geological variations in terms of climate or environmental factors. For instance, biodiversity variations were used to relate environmentally-driven cyclic extinctions to cometary impacts on Earth (Raup and Sepkoski, 1984) or to Earth's climate change induced by the galactic cosmic ray (GCR) flux (Medvedev and Melott, 2007; Svensmark, 2012), both in response to Solar System motions in the Milky Way.

The hypothesis of the influence of GCR on climate is being debated because of the absence of an arguable physical mechanism that can explain the connection between GCR and temperature. The most popular suggested mechanism is the formation of cloud layer that modifies Earth's albedo (Shaviv, 2002; Shaviv and Veizer, 2003; Svensmark, 2006, 2007). Although it has not been suggested to be the only effective parameter, GCR surprisingly seem to have a significant impact on Earth's climate, evidenced through the remarkable correlation between cosmic ray and climate variations (Svensmark, 2007).

Despite these constraints, there is some consensus that the Solar System vertically oscillates across the Galactic midplane, with a half-period ranging from 26 to 41 Myr (Bahcall and Bahcall, 1985; Stothers, 1998; Randal and Reece, 2014). In addition, it has been proposed that the Solar System moves around the galactic center with an orbital period of ~240 Myr (Svensmark, 2006), with a radial period of 180 Myr (Bailer-Jones, 2009). But given our limited knowledge of gravitational potential of the Galaxy, these two periods can in fact range over a large set of values, with the only observational constraint being the measured present velocity of the Sun, with respect to an inertial frame, as proposed by Schönrich et al. (2010) (Supplementary material SM-2).

Here we statistically quantify long-term cyclic sea-level (SL) variations from a Phanerozoic SL data that provide a rare longer-term and continuous record of geological parameters. We show that some detected SL periodicities are of the same order as those predicted for the Solar System motions in the Galaxy. Then, we astronomically model these dominant geological periodicities by fitting them to galactic parameters, with the aim to provide constraints on the gravitational potential within the Milky Way. Finally, we discuss other possible causal mechanisms of SL change at these timescales.

2. Data and methods

The eustatic sea level curve for the Phanerozoic is constructed based on sequence-stratigraphic studies of the marine sedimentary sections around the world. The details of these methodologies are described in Haq et al. (1987) for the Meso-Cenozoic and in Haq and Schutter (2008) for the Paleozoic. Sections for such studies mostly come from the ancient continental margins or interior basins where base-level fluctuations of the ocean (advance and retreat of shoreline) are best preserved. Where possible, margins with tectonic quiescence (or where tectonic influences can be corrected for) are chosen (such as peri-cr areas), to be able to isolate the eustatic signal from the tectonic (local subsidence or uplift) one. Correlations are based on the available marine biostratigraphic markers, and if an event can be demonstrated to be present in a number of non-contiguous sections, they are considered wide-spread and therefore eustatic.

We have compiled the Ceno-Mesozoic eustatic curve (Haq et al., 1987), revised through a comparison with the Arabian Platform records (Haq and Al-Qahtani, 2005), and the most recent Paleozoic eustatic curve (Haq and Schutter, 2008). This unified Phanerozoic (0 to 542 Ma) sea level curve (Fig. 1) allows a regular temporal resolution of 0.1 Myr and has been recalibrated to recently updated geological timescale (Ogg et al., 2016).

To quantify the long and short-term cyclicities, we performed spectral analysis using the multitaper method (MTM) associated with the robust noise modeling (Ghil et al., 2002) as implemented in the "astrochron" freeware (Meyers, 2014) (Fig. 2). For false "significant" spectral peaks of multiple null-hypothesis testing, especially for statistical significance of the dominant 36 Myr period, we have used the Bonferroni correction (Fig. 2). The megacycles were measured using both weighted average and polynomial methods, then subtracted to highlight the shorter-term cycles (Figs. 1 and 2). The effect of detrending on the spectral quantification of shorter periods has been extensively tested. Here we automatically compared a pure period

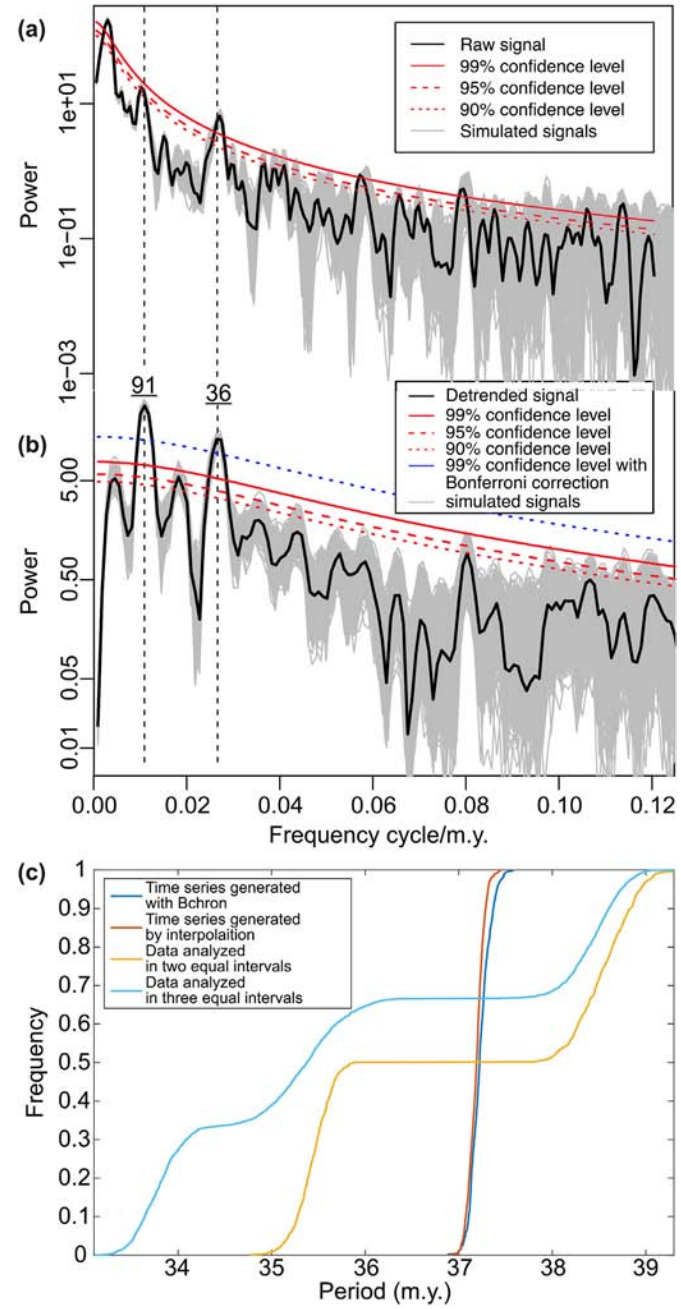

Fig. 2. Spectral analysis of the Phanerozoic SL data. (a) 2π-MTM power spectrum of the raw Phanerozoic SL data (the data were 2×-padded prior spectral analysis, see Supplementary material SM-1 for details of spectral analysis), results of robust red noise modeling were estimated using linear fitting and median filtering over 20% of the Nyquist frequency. Grey-colored spectra are 1000 Markov Chain Monte Carlo (MCMC) simulations. (b) as in "a" where spectral analysis was applied to the detrended data (6th-order polynomial fit removed, see Fig. 1b). We also added Bonferroni correction for the 99% confidence level. (c) Experimental cumulative distribution function of the 36 Myr period of SL data over three time intervals: the entire SL data, SL data split into two equal time intervals, SL data split into three equal time intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

retrieved from the undetrended original SL data using the Generalized Lomb-Scargle (GLS) periodogram (Zechmeister and Kürster, 2009) with periods estimated (with the same GLS method) after successive polynomial-order detrends (Fig. 3).

To study the continuity of cycles throughout the Phanerozoic, we

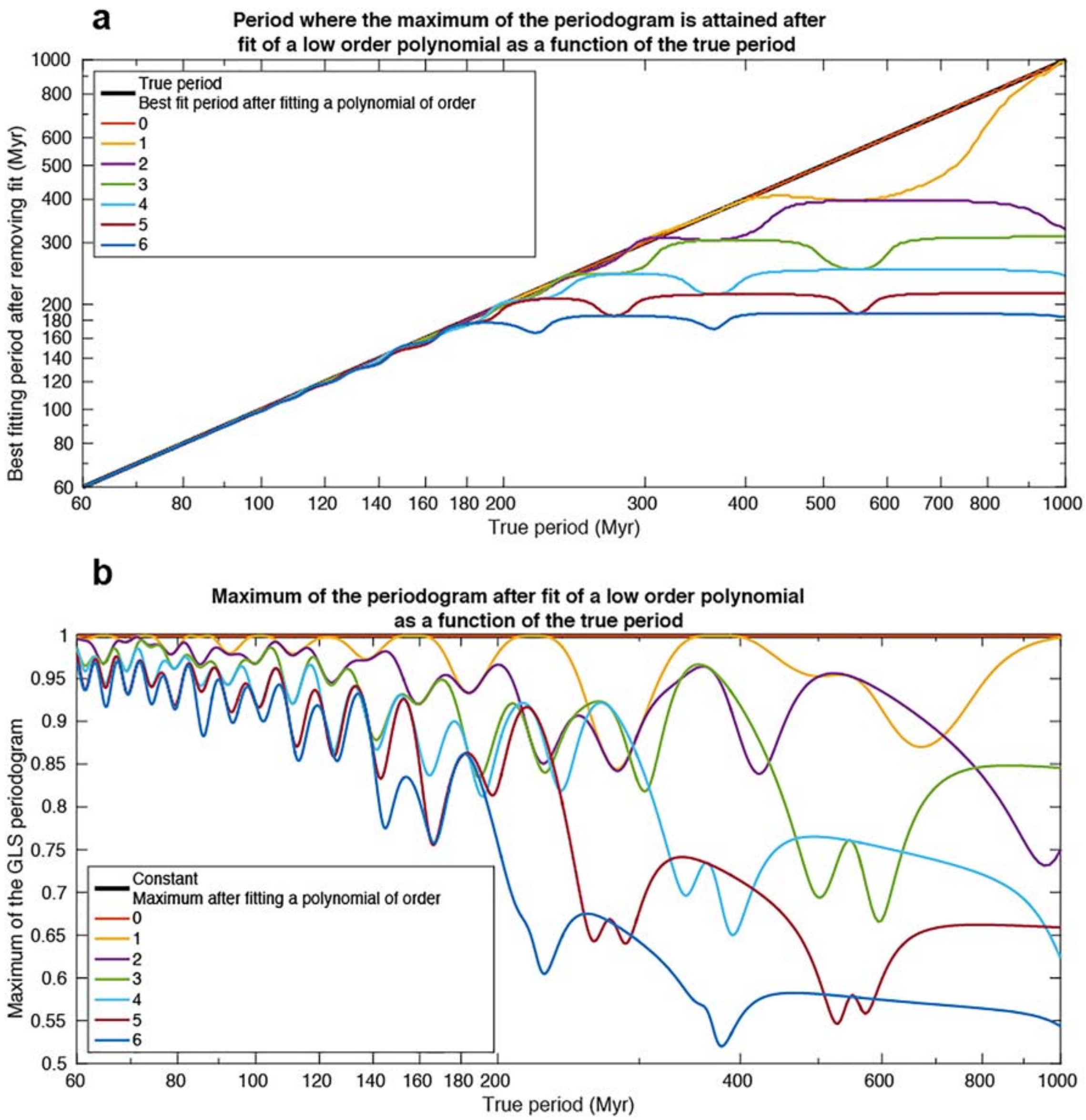

Fig. 3. The effect of long-term detrend on spectral period estimates. (a) Change in spectral period estimates after successive polynomial fits. (b) Ratio of amplitude maxima of Generalized Lomb-Scargle (GLS) periodogram before and after polynomial fits. Note that spectral outputs of periods shorter than 180 Myr are not affected by the detrend process.

used evolutive harmonic analysis based on the MTM spectral method (Meyers, 2014) (Fig. 4). To extract cycles we performed filtering using the Gaussian filter in the freeware *Analyseries* (Paillard et al., 1996).

The effect of geologic timescales on the estimated periods was tested in two manners. First, we calibrated SL record to different geologic timescales (e.g., GTS2004, GTS2008, GTS2012 and GTS2016). GTS2008 is a slightly modified version of GTS2004, and GTS2016 is a slightly modified version of GTS2012. We then performed spectral analysis on the calibrated SL records to look for the persistence (or not) of the interpreted periods (Supplementary material SM-1). Second, in a more statistical way, we tested the impact of GTS2016 timescale uncertainties on spectral estimates using Monte-Carlo age-random simulations based on Bayesian Markov Chain Monte Carlo (MCMC) simulations (Fig. 2) via "Bchron" program (Haslett and Parnell, 2008).

We have adapted "Bchron" program in order to satisfy the required conditions: (1) Continuity and monotony of the age scale, and (2) age variance increases away from anchor age points. Ages and uncertainties of Stage boundaries are from the International Commission on Stratigraphy website.

To test the significance of long-term SL change in terms of climate forcing, we used stable oxygen isotopes ($\delta^{18}O$) data (Supplementary material SM-1), which were correlated to SL using cross-MTM spectral analysis (Huybers and Denton, 2008). We used the cross-MTM spectral analysis to study the coherency and phase relationship between $\delta^{18}O$ and SL signals at the 36 Myr cycle band.

Based on the classical model of Paczynski (1990), we have built a parametrized model for the Milky Way with several free parameters that have then been adjusted in order to fit the observed periodicities of 72 and 254 Myr (Supplementary material SM-2). Additionally, we have modeled the GCR flux using the sources distribution of Lorimer (2004). The numerical integration of the orbit of the Sun then provides the variation of GCR flux on Earth in the past. This target curve closely matches the SL curve.

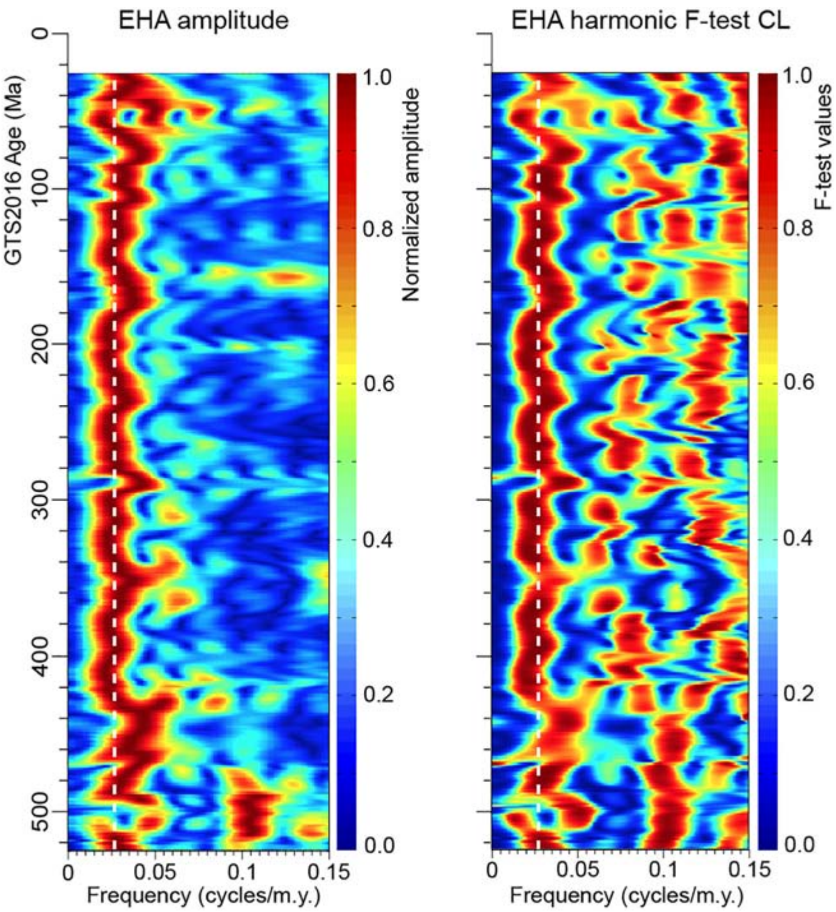

Fig. 4. Evolutive harmonic analysis (EHA) using 2π-MTM spectral analysis (Meyers, 2014) of the raw Phanerozoic eustatic data. Left panel: amplitude spectrogram (window = 50 Myr, step = 1 Myr). Right panel: the F-test confidence levels. Note the prominent, significant cyclicity at the mean period of ~36 Myr (vertical dashed white line) throughout the Phanerozoic Eon.

3. Results

3.1. Time-series analysis of the Phanerozoic sea-level data

The Phanerozoic eustatic curve shows two strong megacycles (Fig. 1): roughly spanning the Ceno-Mesozoic (0–251 Ma) and the Paleozoic (251–542 Ma), with superimposed shorter prominent oscillations. Thus, the Ceno-Mesozoic megacycle contains 7 shorter oscillations of ~36 Myr mean duration (C1-C2 and M1 to M5 cycles).

Spectral analysis of the Phanerozoic SL data shows three significant peaks of ~9.3–36 and ~91 Myr periods (Figs. 2, SM-1-1, SM-1-2). The ~9.3 Myr peak corresponds to the shorter 2nd order eustatic sequences of Haq et al. (1987) (i.e., their "*supersequences*"), which were shown to be quasi-periodic for, e.g., the past ~70 Myr. A cyclicity of ~9.3 Myr period was first highlighted in the Cenozoic carbon-isotopic data (Boulila et al., 2012).

The ~36 Myr peak represents a prominent and continuous cyclicity throughout the Phanerozoic. Although this periodicity was not interpreted as continuous in previous studies (Haq et al., 1987), it sometimes matches the longer 2nd order eustatic sequence boundaries (i.e., "*supersequence sets*", i.e., Tejas-A, Tejas-B, Zuni-A, Zuni-B, etc., Fig. SM-1-3), but at other times shows correspondance to doublets of these (for example Zuni-C and lower Absaroka, Fig. SM-1-3) (Haq et al., 1987). The doublets are likely harmonics of the main ~36 Myr cycle. The ~91 Myr peak corresponds to the average of harmonics (two or three) of the ~36 Myr cycles (SM-1). This period may have a galactic (climatic) and/or a tectonic origin given its important amplitude in the SL record. We, however, explore the relatively well recognized ~36 Myr cyclicity in terms of solar-system vertical period. Evolutive Harmonic Analysis (EHA) shows evidence for the continuity of the ~36 Myr cyclicity throughout the Phanerozoic (Fig. 4). Thus, our time-series analysis of the Phanerozoic eustatic curve shows a strong continuous ~36 Myr cyclicity superimposed on the Ceno-Mesozoic and Paleozoic megacycles. The ~9.3 and ~91 Myr cyclicities are not continuously recorded within the SL signal compared to the exceptionally continuous ~36 Myr cyclicity (Fig. 4). It is likely that the unstationarity of the ~91 Myr cycle could also be related to the length of the time series, which is too short to precisely detect such cyclicity.

3.2. Astronomical modeling: solar system motions and galactic cosmic rays

We utilize a quantitative approach: starting from a well-known model of galactic potential (Paczynski, 1990), we have modified the free parameters of the model in order to fit the observed geological periodicities to the orbital motion. We demonstrate that both periods of 72 and 254 Myr can be interpreted as the vertical and radial periods in a galactic model that fulfill the other observational constraints (Fig. 1c,e and SM-1). The ~36 Myr SL cycles are then interpreted to represent the half-period of the 72 Myr vertical oscillations of the solar system moving in and out of the galactic plane.

In addition, we have modeled the distribution of GCR and demonstrated that the variation of incidental GCR on Earth is well correlated with the inferred climate changes from the geological record (Fig. 1).

This correlation is in accord with the notion that increased clouds and planetary albedo from GCR enhancement during times of galactic midplane crossings and galactic-center nearing lead to climatic coolings (Shaviv and Veizer, 2003; Gies and Helsel, 2005), thereby inducing large amplitude glacio-eustatic SL minima. The highest amplitudes of the eustatic megacycles related in the model to the radial motion goes with the idea that extended exposure to the higher GCR flux associated with the nucleus can lead to increased and extensive cloud cover and long ice-age epochs on Earth (Fig. 1a–c).

4. Discussion

4.1. A proposed new hierarchy of long-term SL change and potential drivers

The seminal studies showing the hierarchy of global sea-level (eustatic) sequences from seismic data and well-log stratigraphy, and their impact on sedimentary deposition were undertaken by researchers at Exxon Production Research Company (Vail et al., 1977; Haq et al., 1987 and Haq et al., 1988). In particular, Vail et al. (1977) divided these depositional sequences temporally into six orders ranging from tens-hundreds of millions years (first- and second-order) to tens of thousands years (sixth order). First- and second-order SL sequences were ascribed to tectono-eustatic changes in the global ocean volume, while fourth-, through sixth-order SL sequences were attributed to climate change within the Milankovitch (insolation) band. However, third-order SL sequences were interpreted as the result of climate or tectonic forcing (Vail et al., 1991; Cloetingh, 1988; Strasser et al., 2000), while more recent studies have argued long-period (1.2 and 2.4 Myr) Milankovitch forcing for the Cenozoic and Mesozoic third-order SL cycles (Boulila et al., 2011).

In addition, Haq et al. (1987) proposed a detailed subdivision at the first- and second-order sequences as follows. They subdivided the second-order into two suborders, longer (or *megacycle set*) and shorter (*megacycle*), and similarly the first-order into two suborders, longer (*supercycle set*) and shorter (*supercycle set*). Although durations of each suborder could vary considerably (Section 3.1), possibly because such subdivision would require statistical treatment which takes into accound both the amplitude and the period of the signal, we should note that Haq et al. (1987) manually arrived at the same number of (sub) orders detected today by spectral analysis.

Indeed, time-series analysis of long-term Phanerozoic SL data indicates mainly four frequency bands (Section 3.1, Table 1): ~9.3 Myr, ~36 Myr, ~91 Myr and ~250 Myr. Therefore, we suggest that the ~9.3 and ~36 Myr periodicities correspond respectively to shorter and longer second suborders. The ~250 Myr period correspond to the longer first suborder. The ~91 Myr mean period, which is temporally not well constrained in previous studies, could correspond to the shorter first suborder (Table 1).

These very long-term SL variations have been generally attributed to tectonic changes through geodynamically induced changes in the volume of the ocean basins (Vail et al., 1977). The attribution of these SL changes to tectonics rather than climate (or to both) is dictated by the lack of long time series of climatic proxies useful for comparison with eustasy, even though some researchers have pointed out the correspondence between very long-term climatic and eustatic trends (Kaiho and Saito, 1994; Abreu et al., 1998; Haq and Schutter, 2008). Tectonic forcing as the cause for long-term SL change has been generally accepted because major plate tectonic motions occur at a very slow pace, and also because no other explanation has been offered for the high-amplitude eustatic variations, especially during the so-called greenhouse periods when there were extensively no ice sheets. Other researches have postulated that icehouse conditions may have existed throughout the Earth's history and suggest that SL oscillations were largely glacio-eustatically driven (Matthews and Al-Husseini, 2010; Boulila et al., 2011). Unlike the well known climatically-driven higher-frequency SL fluctuations, those related to Milankovitch (insolation) orbital forcing, the mechanisms of low-frequency SL changes still remain controversial (Table 1).

Indeed, very long-term climatic variations (on the time scales of 10s to few 100 s of Myr) are thought to be controlled by galactic cosmic ray (GCR) changes via solar-system motions in the galaxy (Shaviv and Veizer, 2003; Gies and Helsel, 2005; Svensmark, 2006). In particular, the prominent ~36 Myr cyclicity that we have continuously detected throughout the Phanerozoic SL record has received increasing attention since 1980's from multiple disciplines: astronomy (e.g., Svensmark, 2006; Bailer-Jones, 2009), cosmoclimatology (e.g., Svensmark, 2007), geology (Kaiho and Saito, 1994), and astrobiology (Raup and Sepkoski, 1984; Medvedev and Melott, 2007).

Equivalent periodicity has been predicted in the motion of the solar system when it moves down- and upwards the galactic midplane. This would induce significant change in GCR and the resulting climate change (e.g., Svensmark, 2006). In addition, the ~250 Myr megacycles seem to modulate the ~36 Myr cyclicity. In this context, we are tempted to interpret the ~36 and ~250 SL cyclicities as astronomical in origin (Section 3.2) and investigate their possible climatic significance (Section 4.1), but without excluding the obvious potential tectonic drivers of climatic and SL changes (Section 4.2). Finally, a possible coupling between tectonics and astronomy on Earth's climate change as feedbacks is quite likely (e.g., Huybers and Langmuir, 2009; Kutterolf et al., 2012; Crowley et al., 2015).

4.2. Climate significance of the 36 and 250 Myr SL periodicities

Ice-volume proxies provide rough estimates of ice sheets formation through the Phanerozoic (Fig. 1a). Although a good correspondence can be observed between the eustatic minima of the megacycles and larger glacial episodes, no correlation is discernable at the scale of ~36 Myr cycles. Nevertheless, a deep-sea composite $\delta^{18}O$ curve over the past 115 Ma (Zachos et al., 2001, 2008; Cramer et al., 2009; Friedrich et al., 2012) extended to ~200 Ma (Veizer and Prokoph, 2015) shows evidence of a ~33 Myr cycle correlated to its equivalent in the SL record (Figs. 5, SM-1-6, SM-1-7). A ~31 Myr $\delta^{18}O$ cycle over the past 200 Ma was first demonstrated by Svensmark (2006) using a previous $\delta^{18}O$ compilation (Veizer et al., 1999). The $\delta^{18}O$ record over a large part of the Cenozoic indicates both temperature and ice-sheet variations (Zachos et al., 2001). Thus, the ~33 Myr $\delta^{18}O$ cycle may reflect a glacio-eustatically driven SL cyclicity. More recently, Shaviv et al. (2014) postulated the presence of the 32 Myr $\delta^{18}O$ cyclicity throughout the Phanerozoic, although data scatter and gaps exist in their original, master ML200, $\delta^{18}O$ signal for the past 490 Ma (Fig. SM-1-5a). In particular, the temporally most constrained 0–65 Ma interval does not show an obvious 32 Myr cyclicity either in their ML200 $\delta^{18}O$ record or in their ML175 record (Fig. SM-1-5b), in contrast to the deep-sea record (Zachos et al., 2001, 2008) that shows evidence of the ~33 Myr cyclicity (Fig. SM-1-6). This again may be an impediment of the data resolution for the very long geological signals, unlike the constrained SL record used here.

Table 1
Sea-level (SL) hierarchical orders inferred from time-series analysis of the Phanerozoic SL record. Note that Milankovitch and Galactic forcings act on SL via climatically (insolation and galactic cosmic rays respectively) driven glacio-eustasy and/or thermo-eustasy, while tectonic forcing acts on the changes in ocean basin volume. The proposed third- to sixth orders are from Boulila et al. (2011), while the first and second orders are an update from the present study (see Section 4.1).
The 0.17 Myr Milankovitch (obliquity modulation) cyclicity is recently recorded over nearly ten million years in the middle Eocene (Boulila et al., 2018).

Order	Suborder	Mean period (Myr)	Causal mechanism	Astronomy
First	Longer	250–300[a]	Tectonic, galactic	Radial motion?
	Shorter	91[a]	Tectonic, galactic?	
Second	Longer	36[a]	Tectonic, galactic	Vertical motion
	Shorter	9.3	Milankovitch?	Eccentricity?
Third	Longer	2.4	Milankovitch	Eccentricity
	Shorter	1.2	Milankovitch	Obliquity
Fourth		0.405	Milankovitch	Eccentricity
Fifth	Longer	0.17	Milankovitch	Obliquity
	Shorter	0.10	Milankovitch	Eccentricity
Sixth	Longer	0.04	Milankovitch	Obliquity
	Shorter	0.02	Milankovitch	Precession

[a] Phanerozoic mean periodicity.

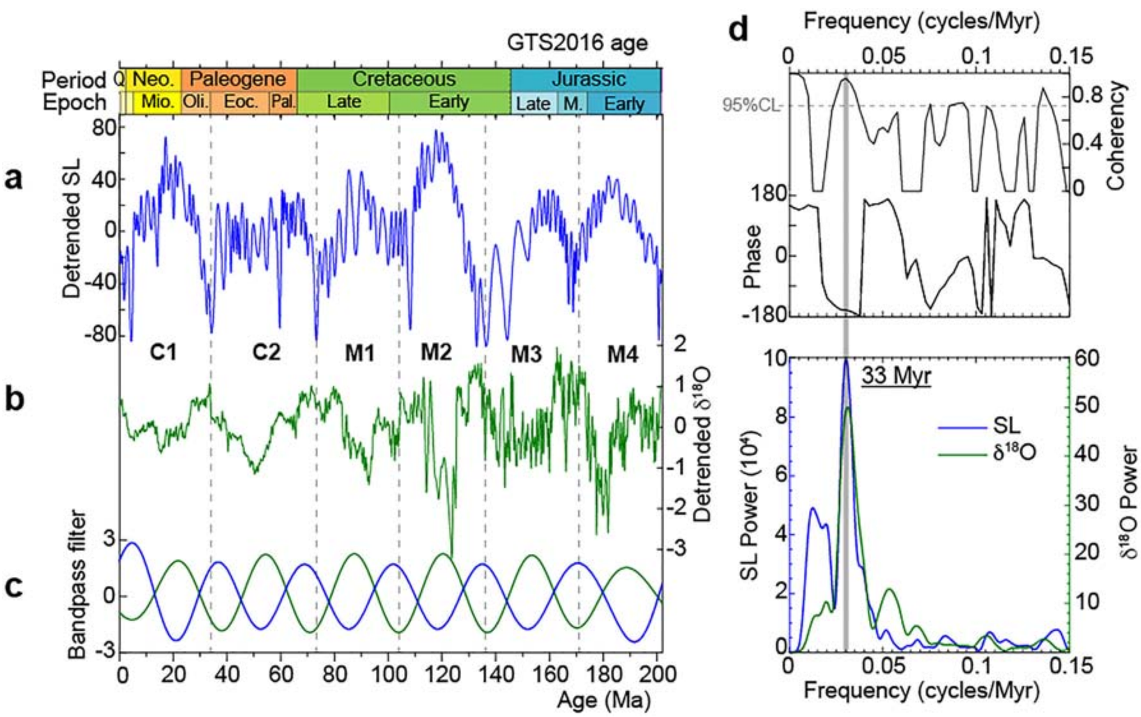

Fig. 5. Correlation of long-period geological cycles over the past 202 Ma (the mean period is 33 Myr over this time interval, see Fig. 2c). (a) Detrended SL (6th-order polynomial fit removed, see Fig. 1b for the raw SL). (b) Smoothed (least-square) and detrended stable oxygen isotopes, $\delta^{18}O$ (6th-order polynomial fit removed, see SM-1 for the raw $\delta^{18}O$ data and compilation). (c) Bandpass filtered SL (blue) and $\delta^{18}O$ (green) (0.03 ± 0.01 cycles/Myr). (d) 2π cross-MTM spectral analysis of detrended SL and $\delta^{18}O$ (both data were 1×-padded prior spectral analysis). Note that both signals are highly coherent (0.96) at the 33 Myr cycle band and nearly anti-phased (−170°), which is the expected phase relationship: heavier $\delta^{18}O$ values (cooler climate) correlate to lower sea levels. Except for "M2" $\delta^{18}O$ equivalent cycle, which exhibits lower $\delta^{18}O$ data (Fig. SM-1-7) the other 33 Myr $\delta^{18}O$ related cycles are defined with higher resolution. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.3. Origin of the 36 and 250 Myr SL periodicities: Astronomy or tectonics?

The similarities of the multi-Myr cyclicities in the geological record and the astronomical model indicates that vertical and radial solar-system motions could induce long-term climatic variations through the modulation (waxing and waning) of ice sheets and the consequent eustatic fluctuations. In particular, vertical and radial motions would modify the proximity of the solar system to density sources, and thus could have induced significant changes in the incidental GCR flux. Enhanced GCR would increase clouds and planetary albedo, climatic cooling (Shaviv and Veizer, 2003), ice age epochs (Gies and Helsel, 2005), and glacio-eustatic SL falls.

Nevertheless, the potential tectonic drivers for the ~36 and ~250 Myr cannot be ignored (Vail et al., 1977; Haq et al., 1987; Kaiho and Saito, 1994; Cloetingh and Haq, 2015), which leads us to reassess the importance of a coupled climate and tectonics effect (Lagabrielle et al., 2009) that could play a role in very long-term SL changes. It is very likely that several drivers (e.g., solar-system cycles, Milankovitch forcing, non-astronomical climatic processes, tectonics), and their combined effects control the eustatic variations at the multi-Myr time scales.

Currently, problems remain in accurate paleo-tectonic reconstructions that hinder the unambiguous determination of the duration and nature of tectonic variations that can produce global effects, except at the large scale of megacycles where good correlations have been inferred between eustasy and well-constrained tectonic processes, e.g., mean age of the oceanic crust and mid-ocean ridge volumes (Cogné et al., 2006).

Our most intriguing result is the detection of significant ~36 Myr cyclicity throughout the Phanerozoic, superimposed on the two ~250 Myr megacycles. These periodicities have been extracted from the most continuous and longest geological (SL) record, compared to those previously used for the detection of similar cyclicities ascribed to the Solar System motions. Moreover, the ~36 Myr cyclicity also emerges in the most constrained Cenozoic time series with a high-resolution ice-volume and temperature proxy data (Fig. 5). Furthermore, the ~250 Myr megacycle minima match the modeled and geologically documented major icehouse windows of the Phanerozoic (Fig. 1). The above close links provide compelling evidence for climatically driven SL at the longer timescales of ~36 and ~250 Myr. Interestingly, the modeled astronomically driven GCR flux is consistent with long-term cooling towards present day, as inferred from multiple paleoclimatic proxies (e.g., Lisiecki and Raymo, 2005). Our present-day proximity to the galactic mid-plane would favor great exposure of the Earth to cosmic rays, inducing a long-term cooling and lower SL. In short, while the ~36 Myr cyclicity could be astro-climatically driven, the megacycles could be astro-climatically and/or geodynamically driven.

Although we draw attention to this potential linkage between astronomy and climate, we must caution that several aspects in this correlation remain conjectural but at the same time present challenging questions that should be investigated in the future. One is the improvement of knowledge of the GCR impact on Earth's climate at these longer timescales (Kirby et al., 2011). The GAIA astrometric mission (Binney, 2002) will soon release new data on galactic parameters that could reduce uncertainties of solar-system periodicities. The resulting improvement of our knowledge of the galactic structure and the vicinity of the Sun in the Milky Way could constrain the ~36 Myr vertical periodicity, which seems robust compared to previous estimates, and condones (or rejects) the ~254 Myr radial periodicity, which is different from previous estimates, but fits the present available galactic parameters.

In this vain, we would like to point out that if the potential correlation presented here between geological and astronomical periodicities would be confirmed, this could provide an exceptional, independent constraint on the history and structure of the Milky Way by providing a record of the past evolution of the orbit of the Sun within the Galaxy over the past 542 Ma.

Finally, the icehouse phases observed throughout the Phanerozoic that more of less match the 250 Myr megacycle (see Fig. 1a) and also the changes in the ocean crustal production rates (Fig. SM1-4) favor tectonically-driven mechanisms through megacyclicity (i.e., the Wilson cycles) embodied in the coalescence-breakup of supercontinents (e.g., Zaffos et al., 2017). Similarly, the observed 36 Myr periodicity in the $d^{18}O$ record could also be plausibly due to tectonically-driven opening and closing of oceanic gateways and changes in circulation patterns that in turn modulate climates (Zachos et al., 2001; Lagabrielle et al., 2009).

5. Conclusions

We used a relatively well-constrained Phanerozoic (0–542 Ma) sea level (SL) record to statistically demonstrate a series of frequency bands providing constraints on the eustatic SL hierarchy. The first-order SL cycles are on the order of ~250 Myr although the analysed 542 Myr interval of the past is not enough long to precisely assess its mean periodicity. The second-order SL cycles could be subdivided into two suborders: a longer suborder of ~36 Myr period and a shorter suborder of ~9.3 Myr. A potential periodicity of ~91 Myr does not correspond to any previously defined order, thus we infer it as a shorter suborder of the first-order sequences, and the ~250 Myr being a longer suborder of the same order. While the ~9.3 Myr pseudo-periodicity was previously attributed to long-period Milankovitch modulation cycle, the other orders were generally attributed to major plate tectonic motions, generating changes of ocean volume.

Of particular interest is a prominent and continuous ~36 Myr cyclicity superimposed on the two ~250 Myr megacycles, which are of the same order as those predicted by the Solar System's motions within the Milky Way. The ~36 Myr SL cyclicity has also been detected in the climate proxy of the $\delta^{18}O$ data. Thus, we are tempted to propose a potential connection between climate and SL changes via galactic cosmic rays (GCR) flux for this periodicity. We have constructed a coherent model for the galactic potential and GCR flux that can be correlated to the geological record. At the same time, we do not rule out a possible coupled climate-tectonics effect that could play a role in very long-term SL changes. Currently, problems remain in accurate paleotectonic reconstructions that hinder the unambiguous determination of the duration and nature of tectonic periodicities useful for comparison with long-term SL cycles.

Acknowledgments

This work was supported by French ANR Grant ASTS-CM, and INSU-SYSTER Grant. S.B. thanks very much O. Friedrich (Heidelberg University), who kindly provided the compiled deep-sea stable isotope data. This study benefitted from discussions and exchanges with J. Binney, W. Dehnen, T. Delahaye, T. Montmerle, B. Famaey K. Kotera, and M. Haywood. We also thank the two anonymous reviewers, who significantly improved the quality of the manuscript. The paper also benefitted from reviews of three experts in time-series analysis (Graham Weedon and two anonymous reviewers) and three experts in astronomy (Henrik Svensmark and two anonymous reviewers).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloplacha.2018.03.004.

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