Journal of Statistical Planning and Inference 170 (2016) 158–165

Contents lists available at ScienceDirect

Journal of Statistical Planning and Inference

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

Evaluating alternatives to the Milankovitch theory

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ARTICLE INFO

Article history:
Received 8 October 2014
Received in revised form 9 October 2015
Accepted 10 October 2015
Available online 19 October 2015

Keywords:
Analytical bias
Reporting bias
Orbital tuning
Milankovitch theory
Spectral analysis
Universal cycle

ABSTRACT

The physical process that causes cycles in Earth's precession, obliquity, and eccentricity is well established, and researchers have detected and modeled the orbital cycles for millions of years into the past. The Milankovitch theory postulates that Earth's orbital cycles contribute to similar periodicity in climatic variation — with the periods of the climatic cycles primarily ranging from 19,000 years to 1,200,000 years. Even while support for the Milankovitch Theory remains strong, opposition to the process of tuning sedimentary records to Milankovitch models has become increasingly vocal. Here, we discuss another negative aspect of orbital tuning that has been ignored to this point. Specifically, orbital tuning contributes to a type of negative analytical bias against research aimed at modifying the Milankovitch theory as well as bias against testing alternatives to the Milankovitch theory, such as the Universal cycle model, presented in this work.

1. Introduction

About a century ago, Milutin Milankovitch began developing a theory that orbitally driven variability in the insolation of the Earth over the ages serves as the dominant factor causing major climatic cycles such as ice ages (Milankovitch, 1941). Many initially reacted to Milankovitch's theory with skepticism. Other theories involving variation in solar intensity, fluctuation in the atmosphere's volcanic dust content, and changes in Earth's magnetic field were widely considered to be adequate explanations of climatic cycles.

Researchers generally ignored the Milankovitch Theory until improved climatic records extended further into the past. Methods such as those used by Shackleton and Opdyke (1973) paved the way for Hays et al. (1976) to revive the Milankovitch Theory. Their study of a 450 thousand year (kyr)[1] sequence of Southern Hemisphere ocean-floor sediments showed cycles of roughly 23, 42, and 100-kyr. These cycles corresponded reasonably well to the Milankovitch cycles associated with precession, obliquity, and eccentricity. Subsequent research showed similar cycles from a variety of geological data (Hilgen, 1991; Imbrie, 1982; Johnson, 1982; Shackleton et al., 1984).

Soon afterward, a type of analytical bias crept into chronostratigraphy through the practice of "orbitally tuning" stratigraphic time-series to the predictions of the Milankovitch Theory. The bias was dangerously prevalent around a decade ago, but has since been exposed in a critique by Proistosescu et al. (2012). Although practitioners are now aware of the

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[1] The time-related abbreviations kyr, myr, Ka, and Ma have distinctly different meanings. Ka (a thousand years ago) and Ma (a million years ago) always refer to a specific time in the past, whereas kyr (a thousand years) and myr (a million years) refer to an interval of time.

http://dx.doi.org/10.1016/j.jspi.2015.10.006
0378-3758/

problems associated with tuning induced Milankovitch spectra (Hilgen et al., 2015), some still prefer to work with tuned records by using Monte Carlo simulation to adjust for the effect of tuning on inferences from the null hypothetical random process (Proistosescu et al., 2012; Zeeden et al., 2015).

Currently, the Milankovitch Theory serves as the generally accepted explanation of the quasi-periodic oscillations in the relative disposition of Earth and Sun – especially precession, obliquity, and eccentricity – which are assumed to be the primary drivers of terrestrial climate. Milankovitch Theory now offers a seductively elegant solution to the problem of age-stratum mapping. The problem is, the depth–age relationship need not be piecewise linear with respect to depth, because of gaps in the records and variable deposition rates. At any rate, some type of age model for the strata is required.

Accurate celestial mechanical calculations have allowed extrapolation of the predicted insolation curves millions of years into the past. Supposing that the sedimentation of stratigraphic data was subject to Milankovitch insolation forcing (but also to jitters in the deposition rate), one might try to determine the depth–age mapping that makes the data cohere best with the insolation curve or some related target. One way to tune the depth–age mapping is to optimize, over a variety of jitters, the least squares fit of the target curve to the data. If the coherence of the tuned data and the target is very strong, it justifies the tuning *a posteriori*. This method of dating strata is known as cyclostratigraphy (Weedon, 2003).

With these methods currently entrenched in the planetary science culture, what can go wrong with orbital tuning? One obvious problem is that orbitally tuned chronologies will be biased to conform to Milankovitch theoretic predictions. In particular, astrochronological alignment of time-series records artificially forces outlying spectral power into frequencies corresponding to Milankovitch bands (Hinnov, 2000; Neeman, 1993; Shackleton et al., 1995). This issue is addressed head-on by Hilgen et al. (2015). Those authors acknowledge that the potential for Milankovitch frequencies to be introduced into records through astronomical tuning is well known and is a serious drawback. However, they advise that drawbacks resulting from tuning can be overcome by conducting time-series analysis in the stratigraphic domain, or in the time-domain with an independent age model, such as a magneto-biostratigraphic model. That is, the drawbacks can be overcome by using un-tuned data (Hilgen et al., 2015).

Hilgen et al. (2015) seem to condone the practice of astronomical tuning but warn that it must be applied with caution because it produces paleoclimatic time-series that are vulnerable to circular reasoning. Pälike et al. (2006) exemplified this kind of circular reasoning by reporting evidence of the long eccentricity cycle in a time-series that had been orbitally tuned using that cycle as part of the target. This mistake was pointed out by Proistosescu et al. (2012), who then proposed a way to adjust confidence levels for inferences about spectral peaks in the estimated spectra of tuned records.

The fact that orbital tuning produces a positive analytical bias in favor of Milankovitch theoretic predictions has been accepted by the interested research communities. However, a significant problem of equal concern is that orbital tuning induces a negative analytical bias against other hypotheses concerning cyclicity not predicted by Milankovitch theory. That is, orbital tuning inhibits the discovery of other possible periodic components of Earth's climate.

2. Universal cycle model

In particular, orbital tuning limits objective testing of an empirical hypothesis that major cycles, on global and astronomical scales, belong to a family of harmonically related oscillations (Prokoph and Puetz, 2015; Puetz et al., 2014)—referred to as Universal Wave Series (UWS) cycles. The periods of the UWS cycles are generated from a base-period by a sequence of period-tripling and period-halving operations, empirically estimated and simplified from previous versions as

$$P_{k,n} = \left(\frac{3^k}{2^n}\right) P_{0,0} \tag{1}$$

where k is a positive or negative integer corresponding to a cycle in the primary period-tripling sequence, n is a secondary harmonic where $n \in \{0, 1, 2, 3, 4, 5, 6, 7\}$, and $P_{0,0}$ is a base cycle with a period of 2.82894367327307 solar years. The primary UWS cycles in the kyr-range appear in the first four columns of Table 1 ($n = 0, 1, 2, 3$). The primary UWS cycles appear more often in the periodograms and normally show higher confidence levels than the secondary UWS cycles. The last four columns of Table 1 ($n = 4, 5, 6, 7$) contain the secondary UWS cycles. The UWS cycles form a set different from but not contrary to Milankovitch Theory. That is, the UWS cycles might occur independent of, and in addition to, Milankovitch cycles.

3. Testing cyclical climatic models

Several years ago, we began testing the occurrence and significance of UWS cycles in the power spectral densities of certain stratigraphic time-series. The tests included both tuned and un-tuned time-series. Shortly thereafter, it became apparent that astronomical tuning siphoned spectral power away from the UWS frequencies, while at the same time enhancing the Milankovitch frequencies, perhaps at the expense of the UWS cycles.

This awkward discovery put us in a position of having to explain why the original high-profile papers that analyzed the same data produced different results and different conclusions — which is the main purpose of this article. The results (Section 7) and discussion (Section 8) give examples of the opposing spectra often found between tuned and

Table 1
Theoretical $P_{k,n}$ cycles in the range from 1-kyr to 999-kyr.

k	n							
	0	1	2	3	4	5	6	7
6	2.062	1.031	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
7	6.187	3.093	1.547	N.A.	N.A.	N.A.	N.A.	N.A.
8	18.56	9.280	4.640	2.320	1.160	N.A.	N.A.	N.A.
9	55.68	27.84	13.92	6.960	3.480	1.740	N.A.	N.A.
10	167.0	83.52	41.76	20.88	10.44	5.220	2.610	1.305
11	501.1	250.6	125.3	62.64	31.32	15.66	7.830	3.915
12	N.A.	751.7	375.9	187.9	93.96	46.98	23.49	11.75
13	N.A.	N.A.	N.A.	563.8	281.9	140.9	70.47	35.24
14	N.A.	N.A.	N.A.	N.A.	845.7	422.8	211.4	105.7
15	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	634.2	317.1
16	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	951.4

un-tuned records — which illustrate points about two types of bias that are commonly found in research associated with the Milankovitch Theory: analytical bias and reporting bias.

Analytical bias develops from a fundamental assumption about a process that simplifies the understanding of complex phenomena (Kane, 1997; Kuhn, 1970). Analytical bias does not necessarily invalidate the correctness or objectivity associated with a particular method. It merely highlights the set of peer-defined rules for understanding the complexity of the process, as well as the rules for portraying phenomena in ways that reflect worldviews, including specific approximations and assumptions incorporated into a measurement procedure (Kane, 1997; Kuhn, 1970). As it pertains to the Milankovitch Theory, orbital tuning is the analytical bias of concern.

Reporting bias (McGauran et al., 2010) occurs from selective reporting of research results dependent on the outcome of the tests. Statistically significant positive results that support a desired outcome are more likely to be published in high-impact journals, and thus to be cited by others, than results that fail to show the expected outcome (McGauran et al., 2010). As it pertains to the Milankovitch Theory and as described in the discussion (Section 8), reporting bias occurs when articles mention favorable results from orbitally tuned records, which are supportive of the Milankovitch Theory, while failing to mention unfavorable results from un-tuned versions of the same records.

4. Geologic time scales and orbital tuning

Details about models used to aligning sedimentary records to various time-scales are important for understanding how human choices affect spectral analysis results. The acronyms described here are standards generally assigned by the original authors, and then commonly used in the literature thereafter. The acronyms might cause confusion because the year associated with a timescale or a model might differ from the year of publication — for example, the GTS2004 timescale (Gradstein et al., 2005) was written and submitted in 2004, but published in 2005. The La2010 astronomical model (Laskar et al., 2011) has a similar discrepancy between the model-year and the year of publication.

For the CK1995 timescale (Cande and Kent, 1995) and the GPTS1995 timescale (Berggren et al., 1995), ages younger than 5.23 Ma are orbitally tuned. Conversely, ages for these two timescales older than 5.23 Ma are estimated from a geomagnetic chronology, meaning these ages are not biased by the Milankovitch Theory. This neutrality for ages older than 5.23 Ma permitted objective evaluations for the Milankovitch model as well as the alternative Universal Cycle model. Most of the recent climatic data are assigned ages from either the GTS2004 timescale (Gradstein et al., 2005) or from the newer GTS2012 timescale (Gradstein et al., 2012). GTS2004 contains astrochronologically tuned ages for events younger than 23.03 Ma, while GTS2012 contains orbitally tuned ages for events younger than 252 Ma. Gradstein et al. (2012) incorporated astronomical ages into GTS2012 in three steps. First, they used a full model of Milankovitch cycles (precession, obliquity, and eccentricity) to extend orbital tuning to 33 Ma. Second, because the La2004 and La2010 models (described in the next paragraph) have difficulty predicting precession and obliquity cycles for ages older than 50 Ma, GTS2012 only uses the eccentricity cycles for estimating ages from 66 to 33 Ma. Third, for the 252–66 Ma interval, Gradstein et al. (2012) calibrate ages to 405-kyr cyclicity, but omit the 94.9-kyr eccentricity cycle from the model. GTS2012 still has five gaps in the eccentricity-based ages. Insufficient stratigraphic data prevents tuning for the intervals 83–76 Ma, 93–89 Ma, 171–161 Ma, 194–189 Ma, and 244–227 Ma.

The Milankovitch-related insolation model continues to evolve, with at least six major versions published over the past 73 years. After Milankovitch (1941) first devised the theory, Berger (1978) formulated the first modern version. Then a succession of versions by Jacques Laskar followed: La1990 (Laskar, 1990), La1993 (Laskar et al., 1993), La2004 (Laskar et al., 2004), and La2010 (Laskar et al., 2011). In the latest version, Laskar et al. (2011) were confident in their insolation computations for ages younger than 50 Ma. However, they recommended caution for the 65–50 Ma interval, and noted that they could not guarantee the solution for the 250–65 Ma interval. They mentioned difficulty in finding a precise solution for Earth's eccentricity beyond 65 Ma. This explains why they released four versions (La2010a–d), instead of a single version, for this final adaptation of the insolation forcing model. In a personal communication (Oct, 21 2014),

Table 2
Orbital forcing periods (kyr) from La2010d (eccentricity) and La2004 (precession and obliquity).

Age (Ma)	Ecc-1	Ecc-2	Ecc-3	Ecc-4	Ecc-5	Misc.	Misc.	Obliq	Pre-1	Misc.	Pre-2
250–200	2643	None	404.9	125.3	95.80	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
200–150	2284	951	404.9	125.9	96.24	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
150–100	2308	970	405.1	125.5	95.82	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
100–90	2329	941	404.7	125.4	96.01	55.96	49.35	37.59	22.56	21.38	18.33
90–80	2329	941	404.7	126.0	96.02	56.04	49.47	37.89	22.67	21.48	18.41
80–70	2329	941	404.7	126.6	96.12	56.15	49.38	38.24	22.79	21.59	18.47
70–60	2329	941	404.7	125.5	96.01	56.15	49.45	38.49	22.92	21.69	18.50
60–50	2329	941	404.7	125.5	96.09	56.43	49.79	38.75	23.03	21.80	18.60
50–40	2381	961	405.0	125.6	95.91	56.06	49.41	39.27	23.15	21.92	18.68
40–30	2381	961	405.0	126.1	96.04	56.11	49.49	39.59	23.27	22.01	18.75
30–20	2381	961	405.0	125.0	95.65	56.04	49.42	39.96	23.38	22.13	18.82
20–10	2381	961	405.0	125.1	95.58	56.19	49.45	40.31	23.50	22.23	18.89
10–0	2381	961	405.0	125.7	95.71	56.18	49.51	40.61	23.62	22.33	18.97

Laskar recommended using the La2010d insolation model for defining the periods of the eccentricity cycles and La2004 for defining the periods of the precession and obliquity cycles. Table 2 lists the important Milankovitch cycles that influence the insolation curve, segregated into 10-myr intervals. The tabulation illustrates that the average periods for some of the quasi-periodic Milankovitch cycles vary over time.

5. Data — tuned and un-tuned

This section contains short paragraphs that describe the datasets used in the present study — with links to the data repository sites to facilitate replication of the results stated within. All of the data were derived either from ocean drilling project cores or from continental strata cores. Records from these types of sedimentary cores often include simultaneous measurements, at incremental depths, of δ^{18}O, δ^{13}C, gamma ray attenuation, paleomagnetic intensity, sedimentary structures (depth ranks), and/or sedimentary colors.

5.1. —Newark basin depth ranks

The analyses include one dataset of continental strata, extracted from the Newark Basin (Olsen and Kent, 1999), which spanned the interval from 223.2 to 202 Ma. The download site http://www.ldeo.columbia.edu/~polsen/nbcp/data.html contains tuned and un-tuned versions of the stratigraphic time-series. Dataset 5.1a is the composite un-tuned depth rank curve (Nursery through Martinsville). Dataset 5.1b is the composite tuned depth rank curve (Nursery through Martinsville).

5.2. —Oligocene isotope records

Pälike et al. (2006) developed tuned and un-tuned versions of δ^{13}C records for the interval from 33.88 to 21.78 Ma. The core was extracted from Ocean Drilling Program (ODP) Leg 199, Site 1218, in the equatorial Pacific — available at repository http://doi.pangaea.de/10.1594/PANGAEA.547942. Dataset 5.2a contains un-tuned δ^{13}C records aligned to the CK1995 timescale. Dataset 5.2b contains orbitally tuned δ^{13}C records aligned to the La2004 model.

5.3. —66-myr Isotope records

This dataset of δ^{18}O records (Zachos et al., 2001) consists of a compilation of several ocean drilling cores merging into a single time-series from 66 Ma to present. The time-series is divided into two segments. Dataset 5.3a contains un-tuned records from the GPTS1995 timescale (ages older than 5.23 Ma). Dataset 5.3b contains orbitally tuned records from the GPTS1995 timescale (ages younger than 5.23 Ma), available at http://www.es.ucsc.edu/~silab/ZACPUBDATA/2001CompilationData.txt.

5.4. —Relative paleointensity

This is a compilation of relative paleointensity from 1500 to 0 Ka (Channell et al., 2009), derived from measurements from thirteen ocean drilling cores in the Atlantic, Pacific, and Indian oceans. They estimated ages with the δ^{18}O-based MATCH algorithm. Dataset 5.4 is available at http://dx.doi.org/10.1016/j.epsl.2009.03.012.

5.5. —Gamma ray attenuation

Westerhold et al. (2012) estimated gamma ray attenuation concentrations using the oceanic core from ODP Leg 199, Site 1218, available at http://doi.pangaea.de/10.1594/PANGAEA.757200. Ages were aligning to the depth records, using the

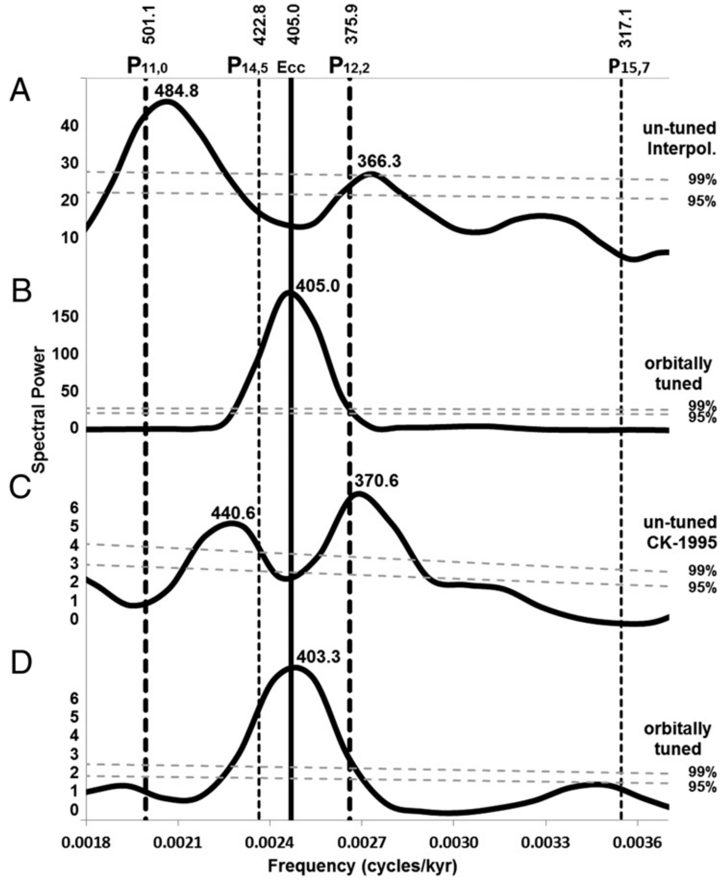

Fig. 1. Periodograms showing cycles in the 270-kyr to 550-kyr bands: (a) Dataset 5.1a, Newark Basin Depth Curves from 223.2 to 202 Ma, un-tuned, ages from interpolation between geomagnetic-chrons; (b) Dataset 5.1b, Newark Basin Depth Curves from 223.2 to 202 Ma, orbitally tuned to a 405-kyr eccentricity cycle; (c) Dataset 5.2a, δ^{13}C from 33.88 to 21.78 Ma, un-tuned, CK1995 timescale; (d) Dataset 5.2b, δ^{13}C from 33.88 to 21.78 Ma, orbitally tuned to the La2004 model.

CK1995 timescale, available at http://doi.pangaea.de/10.1594/PANGAEA.771930. For this study, dataset 5.5 consists of the time-series segment from 41 to 30 Ma.

6. Methods

REDFIT software version 3.5 (Schulz and Mudelsee, 2002) was used for spectral analysis to obtain modified periodograms by Welch's Overlapped Segment Averaging method. In addition to estimating spectral power, REDFIT also calculates 95% and 99% confidence bands from an AR(1) model. Vaughan et al. (2011) were concerned that the family of AR(1) nulls was not rich enough to model spectra from noise in sedimentary time-series. However, the REDFIT confidence bands illustrated in this work are not used with any type of hypothesis testing. The confidence bands only provide a rough guide for assessing spectral power in the periodograms. Rodionov (2006), Vaughan et al. (2011), and Meyers (2012) discuss the general problem of finding spectral signals against a red noise background.

7. Results

Figs. 1 and 2 contain the spectral analysis results (periodograms), formatted with four stacked periodograms in each. The x-axis designates frequency, and the y-axis designates spectral power (spectral density). Dashed horizontal lines represent the 95% and 99% confidence bands from REDFIT. Numbers across the top give theoretical periods of primary UWS cycles (heavy dashed vertical lines), secondary UWS cycles (light dashed vertical lines), and Milankovitch cycles (solid vertical lines). This assortment of vertical lines enables distinction between UWS cycles and Milankovitch cycles.

Fig. 1 displays results in the 270 to 550-kyr bands. The first time-series (dataset 5.1a) consists of un-tuned Newark Basin Depth Curves for the interval from 223.2 to 202 Ma, which uses linear interpolation to assign ages to the depths with uncertain ages, which are tied to the known ages of specific depths associated with geomagnetic-chrons (Olsen and Kent, 1999). The periodogram from this time-series (Fig. 1(a)) indicates periodicity of 484.8-kyr and 366.3-kyr — both roughly

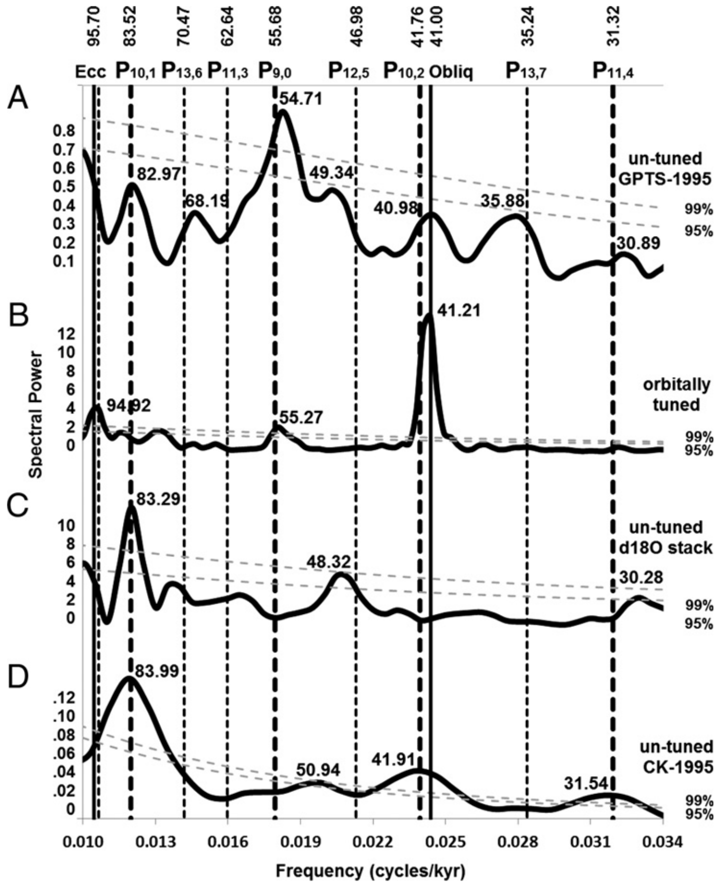

Fig. 2. Periodograms showing cycles in the 30-kyr to 100-kyr bands: (a) Dataset 5.3a, δ^{18}O from 17.80 to 5.23 Ma, un-tuned, GPTS1995 timescale; (b) Dataset 5.3b, δ^{18}O from 5.23 Ma to present, orbitally tuned to the GPTS1995 timescale; (c) Dataset 5.4, relative paleointensity from 1.5 Ma to present, ages from the δ^{18}O-based MATCH algorithm; (d) Dataset 5.5, gamma ray attenuation from 41 to 30 Ma, un-tuned, CK1995 timescale, from drilling site ODP 199-1218.

corresponding to UWS cycles. However, the periodogram from the orbitally tuned version of the same time-series (dataset 5.1b), shows a powerful 405-kyr eccentricity cycle (Fig. 1(b))—which, of course, is the objective of orbital tuning.

A more recent time-series of δ^{13}Crecords (dataset 5.2a) that spans the interval from 33.8 to 21.6 Ma (Pälike et al., 2006) also has tuned and un-tuned versions. The periodogram from the un-tuned version (Fig. 1(c)) shows periodicity of 370.6-kyr — again roughly corresponding to the 375.9-kyr UWS cycle already highlighted in Fig. 1(a). Conversely, the tuned version of the same records (dataset 5.2b) shows the expected eccentricity cycle, with no evidence of an ∼376-kyr cycle (Fig. 1(d)). Both pairs of periodograms clearly demonstrate how orbital tuning removes spectral power from surrounding frequencies and transfers the power to Milankovitch bands (Hinnov, 2000; Neeman, 1993; Shackleton et al., 1995).

Fig. 2 illustrates similar but slightly different variations of tuned and un-tuned records, for cycles in the 30–100-kyr bands. The periodogram from an un-tuned segment of δ^{18}O records (dataset 5.3a) for the interval from 17.8 to 5.23 Ma (Zachos et al., 2001) shows bumps in the spectrum near every theoretical UWS cycle in Fig. 2(a), except for the 62.64-kyr cycle. However, the 54.71-kyr cycle is the only spectral peak above the 95% confidence level. Conversely, Fig. 2(b) shows the tuned segment of the same δ^{18}O time-series (dataset 5.3b, from 5.23 Ma to present), and the periodogram contains two strong peaks near the theoretical eccentricity cycle (95.7-kyr) and theoretical obliquity cycle (41.0-kyr). As might be expected, two different segments of the same time-series, derived from two different age models, produce two significantly different results.

In addition to climatic data, cycles corresponding to the UWS frequencies often appear in non-climatic records. The periodogram from a time-series of relative paleointensity (dataset 5.4, Fig. 2(c)) shows a spectral peak near the 83.52-kyr UWS cycle. The periodogram from another non-climatic time-series (dataset 5.5), consisting of gamma ray attenuation measurements from 41 to 30 Ma (Fig. 2(d)), also exhibits spectral power near the 83.52-kyr UWS cycle — in addition to showing peaks near the 41.76-kyr and 31.32-kyr UWS cycles. The 41.91-kyr peak is notable because the theoretical obliquity cycle for this interval is 39.59-kyr (Table 2). The 5.5% difference between the 39.59-kyr obliquity cycle and the 41.76-kyr UWS cycle at ∼35 Ma might ultimately be enough to judge which of the two models best fit the climatic and non-climatic variation for that age.

8. Discussion

Since its inception, the Milankovitch Theory has evolved into an increasingly complex explanation of climatic variation. Some researchers now apply the theory to non-climatic events and look for Milankovitch cycles in natural gamma radiation and gamma ray attenuation (Cooper, 1995), paleointensity (Yamazaki and Oda, 2005), magnetic susceptibility (Clemens et al., 2008), and volcanic activity (Kutterolf et al., 2012).

Researchers still criticize some aspects of Milankovitch Theory (Berger, 2012; Coplen et al., 1994; Elkibbi and Rial, 2001; Hinnov, 2000; Maslin and Ridgewell, 2005; Neeman, 1993; Pelletier, 2003; Winograd et al., 1988; Wunsch, 2004). Yet critics generally stress that the deficiencies do not entirely invalidate the theory. For instance, Berger (2012) believes that future modifications to the theory will eventually resolve the discrepancies between the current theoretical models and the existing climatic records. However, orbital tuning inhibits rigorous testing of any type of alternative to the standard Milankovitch models, which could prevent such modification attempts.

The failure of Pälike et al. (2006) to report the negative results from the un-tuned records (Fig. 1(c)) causes another unrecognized problem. The article states that their tests (Fig. 1(d)) confirmed strong spectral power at the eccentricity period of 405-kyr. This type of selective commentary is a reporting bias (McGauran et al., 2010) that inaccurately portrays the conclusiveness of the tests. The selective reporting is inappropriate because it can overly influence readers who remain unaware that only some of the results were reported.

Furthermore, the tuning process itself is rather arbitrary. Researchers must subjectively choose targets for the alignment process. Factors influencing that decision include temporal resolution, the magnitude of age-errors, and the indicated periodicity from preliminary spectral analysis using an unbiased age model. For example, the resolution might be inadequate for tuning records to the precession cycles, but fine enough for tuning to obliquity and/or eccentricity. Or, for instance, if a pre-tuned version of the time-series indicates a cycle of ∼95 kyr, then the 95.7-kyr eccentricity cycle might be used as the primary target. Moreover, the targets themselves change with releases of new Milankovitch models. As an example, CK1995 used an eccentricity cycle of 412.9-kyr, which was the standard from Berger (1978), while Laskar et al. (2004) defined the eccentricity cycle as 405.1-kyr.

The work of Wu et al. (2012) highlights the subjective nature of orbital tuning with a demonstration of how various tuning scenarios affected the spectral results. They tuned two time-series (anhysteretic remanent magnetization and magnetic susceptibility) to 20, 100, and 405-kyr targets. Their spectral analysis results showed different spectral peaks for each of the six scenarios. Interestingly, the only versions that produced a 405-kyr cycle were the two specifically tuned to a 405-kyr target. The other four versions from Wu et al. (2012) indicated a cycle of ∼370-kyr, similar to the cycles in Fig. 1(a) and (c). Thus, spectral analyses of tuned records are highly dependent on the assumed age-model and the specific interests of each research team. This is yet another reason why performing spectral analysis on orbitally tuned records can give conflicted or unreliable results.

9. Conclusion

Spectral peaks near important Milankovitch frequencies generally appear to be *manufactured* by the tuning process. Orbital tuning hinders objective testing of the Milankovitch Theory — as well as hampering tests for modifications of the Milankovitch Theory and for alternatives to the theory. We suggest that researchers take care to publish the results of un-tuned data, and focus future research on un-tuned data. Such neutrality will enable their colleagues to independently appraise the cyclicity hypothesized by three types of theories: standard Milankovitch Theory, modifications to the Milankovitch Theory, and alternatives to the Milankovitch Theory.

Acknowledgments

We thank Alex Gottlieb for indispensable statistical consulting services. We also thank Daniel Karner, Wolf Berger, Jean Kane, Ed Mason, Bill Howell, and Rick Dutkiewicz for review and feedback of earlier versions of the manuscript.

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