Spectral Features of 250 kyr Long Lake Van Sediments: Milankovitch Cycles and Their Harmonics

250 Bin Yıl Uzunluğundaki Van Gölü Çökelleri'nin Spektral Özellikleri: Milankoviç Döngüleri ve Onların Harmonikleri

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ABSTRACT

Lake Van, which is the largest soda lake of the earth, lies in the Eastern Anatolian High Plateau. Two different composite cores, that span the last 250 kyr and 90 kyr, were drilled in Lake Van within the framework of PALEOVAN project (ICDP). In order to test the theories of quasi-periodic behavior of climate, generated by astronomical and solar forces, this study investigates the cycles in Lake Van sediment geochemistry data by the Lomb-Scargle Periodogram (LSP) spectral method. The results are correlated with the Eastern Mediterranean LC21 sediment core, Soreq and Sofular Cave speleothem stable isotope data LSP results. The analyses show the presence of the Milankovitch cycles, harmonics of the Milankovitch cycles, Holocene Bond cycles and the Hallstadtzeit solar cycle. However, the results do not give a 1500 year cycle for 11.5-75 kyr BP interval.

Keywords: Eastern Mediterranean, Holocene Bond cycle, Lomb-Scargle periodogram, paleoclimate, solar cycles

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ÖZ

Dünya'nın en büyük sodalı gölü olan Van Gölü, Doğu Anadolu Yüksek Platosu'nda yer almaktadır. ICDP projesi olan PALEOVAN kapsamında, Van Gölü'nden son 250 bin yılı ve 90 bin yılı temsil eden iki karot alınmıştır. Bu çalışmada, astronomik ve solar döngülerin etkileri ile oluştuğu düşünülen, iklimin yarı periyodik davranışını sınamak amacıyla Van Gölü çökelleri jeokimya verileri Lomb-Scargle Periodogramı (LSP) spektral yöntemi ile analiz edilmiştir. Elde edilen sonuçlar, Doğu Akdeniz LC21 çökel karotu ve Soreq ile Sofular Mağaraları speleotem duraylı izotop verileri LSP sonuçlarıyla karışılaştırılmıştır. Analizler

Milankoviç döngülerini, harmoniklerini, Holosen Bond döngülerini ve Hallstadtzeit güneş döngüsünü vermiştir. Ancak, GÖ 11,5-75 bin yılları arasında 1500 yıllık bir döngü gözlenmemiştir.
Anahtar Kelimeler: *Doğu Akdeniz, Holosen Bond döngüleri, Lomb-Scargle periyodogramı, paleoiklim, güneş döngüleri*

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INTRODUCTION

Climate is a dynamical phenomenon and possibly involves many nonlinear components. Therefore, even for a short period in geological sense, forecasting has many pitfalls and forecasts' statistical significance boundaries are loose. On the other hand, it was claimed that climate must have behaved in a periodic manner due to the changes in insolation in geological timescales (Croll, 1875; Milankovitch, 1941; Sonett et al., 1991; Hoyt and Schatten, 1997).

Search for the periodicity of climate has been a matter of interest since the 19th century (e.g. Lockyer, 1874). The theory of astronomical forces acting on the climate system (Croll, 1875; Milankovitch, 1941) are now well-established (Hays et al., 1976; Imbrie et al., 1984; Elkibbi and Rial, 2001), still with explanatory issues, though (Muller and MacDonald, 2000; Paillard, 2015). Also, some shorter cycles that govern the dynamics of the climate system have been theoretically hypothesized (e.g. Ghil and Le Treut, 1981; Le Treut et al., 1988; Hagelberg, 1994; Rial and Anaclerio 2000) or observed through geological data (e.g. Dansgaard et al., 1984; Bond et al., 1997; Mayewski et al., 1997; Sonett et al., 1997). Furthermore, within instrumental records some shorter solar cycles have also been observed (Lean, 2010). The periodical behavior of the climate system is important in understanding the past, and essential to make better projections into the future. There are still ongoing debates about the behavior of some of these phenomena, such as the Dansgaard-Oeschger events (DO) of the Late Pleistocene or Bond cycles of the Holocene. The discussions are mainly centered on the origin of periodic behavior of the cycles (Bond et al., 2001; Schulz, 2002; Debret et al., 2007; Braun and Kurths, 2010) or their global characteristics (Clark et al., 1999) or dynamics that govern these events (Grootes and Stuiver, 1997; Sakai and Peltier, 1999; Bond et al. 2001; Turney et al., 2005; Braun et al., 2005).

Long and highly-resolved geological data are scarce in Eastern Mediterranean. The LC21 core of Mediterranean (Grant et al., 2012), Soreq and Peqiin Cave isotope records (Bar-

Matthews et al., 2003) and Sofular Cave isotope record (Fleitmann et al., 2009; Badertscher et al., 2011) are almost continuous and the longest (spanning the last 150 kyr, 185kyr, 250 kyr and 670 kyr, respectively) records in the region up to now. In Lake Van, a drilling campaign has been carried out in 2010, within the framework of International Continental Scientific Drilling Program (ICDP), in order to investigate past climate changes as recorded in the sediments of the lake (Litt and Anselmetti, 2014). Two sites, namely, Ahlat Ridge (AR) and Northern Basin (NB) were drilled. The former has been drilled at 360 m below present day lake level which is 219 m long, and the latter at 245 m below present day lake level which is 145 m long. The AR core spans the last 600 kyr with some discontinuities. The NB core spans the last 90 kyr. In this study we have searched for the potential periodicities in geochemical data of Lake Van sediment cores which were previously published in Çağatay et al. (2014), Kwiecen et al. (2014) and Stockhecke et al. (2014). By doing so, we will test current theories of climate periodicities, which have been mentioned in the previous paragraph. To find the representative chemical proxies, we first applied principal component factor analysis to the data and then looked for the periodicities by Lomb-Scargle Periodogram and tested the hypotheses about quasi-periodic behavior of climate in the Pleistocene.

Regional Setting

Lake Van lies in the heart of the Eastern Anatolian High Plateau. It is surrounded by semi active volcanoes to the west and north, and by Eastern Taurides to the south (Figure 1). The lake level is 1650 m above sea level. It has approximately 3600 km^2 surface area which makes it the fourth largest closed lake on Earth and it is highly alkaline (Wong and Degens, 1978; Degens et al., 1984). The lake is a volcanic dammed lake (Şaroğlu and Güner, 1981), which formed, according to Çukur et al., (2014), at least 600 kyr ago, and was originally a part of the Zilan, Bendimahi and Murat river system. Lake Van-Muş Basin was separated into two sub-basins as a consequence of eruption of Nemrut Volcano.

While evaluating the climate of the region, one should keep in mind the topographic and geographic complexity of the whole Anatolian Peninsula. It is surrounded by three major seas, the Eastern Mediterranean Sea to the south, the Aegean Sea to the west and the Black Sea to the north. Anatolia is like an inclined plane, the altitude gently increases through the east. Summer climate of the peninsula is mainly under the influence of two macro scale

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atmospheric phenomena. The first one is the subtropical high pressure system, which migrates to the north in summer and the second one is the low pressure system settled on Persian Gulf that carries a continental dry system over Eastern Anatolia (Rohling and Hilgen, 1991). This dry system changes its character over the Black Sea by getting saturated with the warm Black Sea waters, which makes Black Sea summer and fall precipitation sum more than winter and spring precipitation sum (Bozkurt and Şen, 2011; Göktürk et al., 2011). On the other hand, even though the low pressure system cools over Black Sea and passes over the warm Aegean Sea, Western Anatolia and Eastern Mediterranean is almost dry during summer, due to its complex interactions with the subtropical high pressure cell on Atlantic Ocean. Goldreich (2003) calls this condition as "summer paradox" and discusses in detail. In winter, the Eastern Mediterranean region is mainly affected by the maritime low pressure system to the west and the high pressure system to the north (Bozkurt et al., 2012). The precipitation and lake levels in the peninsula are mainly affected by the North Atlantic Oscillation (NAO) winter index (Türkeş and Erlat, 2003; Krichak and Alpert, 2005; Küçük et al, 2009). Cullen and deMenocal (2000) and Cullen et al. (2002) reported that NAO enters the function of the Middle Eastern rivers' streamflow amount, which are mainly fed by the precipitation through Eastern Anatolian High Plateau, as a variable. These atmospheric systems shapes the Anatolian Climate, but distinctive topography and orography renders the system too complex to be characterized by these large-scale atmospheric features. Lake Van, most probably because of the orographic sharpness of the Eastern Taurides at the south of the lake, forms the climatologic border of Continental Mediterranean and Continental Eastern Anatolia (Türkeş, 1996; Ünal et al., 2003). Precipitation mainly occurs as snow in winter and as rain in late fall and late spring (Stockhecke et al., 2012). Annually, the lake loses 4.2 km^3 of water by evaporation and this loss is balanced by 1.7 km^3 river discharge, and by 2.5 km^3 precipitation in volume.

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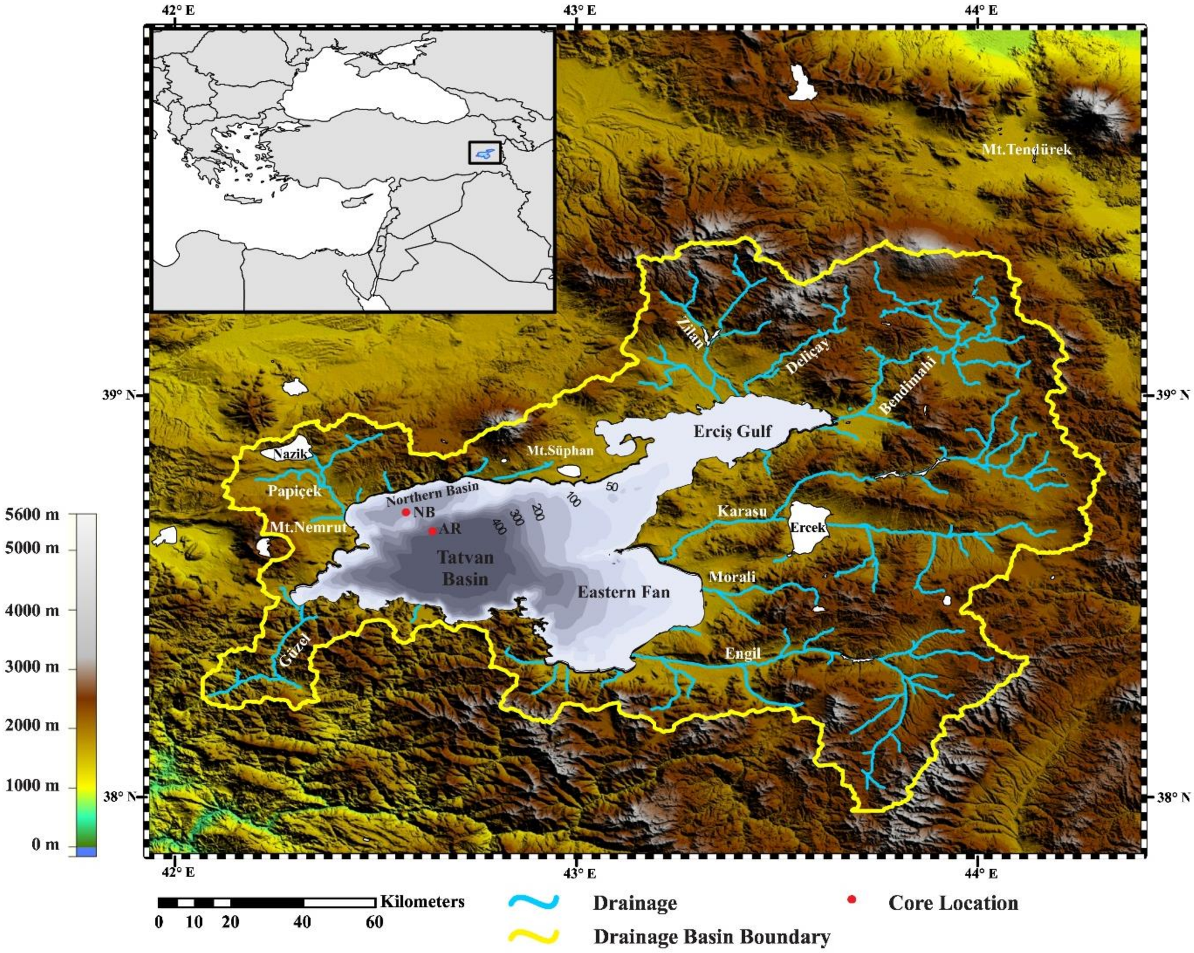

Figure 1. Lake Van location and drainage basin map. The red dots show the AR and NB core locations. The digital elevation is constructed via from SRTM 90 m data (Jarvis et al., 2008).
Şekil 1. *Van Gölü lokasyon ve akaçlama havzası haritası. Gölün içindeki kırmızı noktalar AR ve NB karot lokasyonlarını göstermektedir. Dijital Yükseklik SRTM 90 m verisi kullanılarak oluşturulmuştur (Jarvis vd., 2008).*

MATERIALS AND METHODS

Lake Van Ahlat Ridge and Northern Basin Geochemistry Records

Sediment samples of the AR core were subjected to stable oxygen isotope analyses from bulk carbonate and micro-X-ray fluorescence (μ-XRF) analysis by Kwiecien et al. (2014). Furthermore, for the same core, total organic carbon (TOC) and total inorganic carbon analyses were conducted by Stockhecke et al. (2014). Similarly, the samples of the NB core were subjected to stable oxygen and carbon analyses of the bulk carbonate, μ-XRF elemental analysis and TOC analyses by Çağatay et al. (2014). Because the machines and tubes used during the μ-XRF analyses of the AR and NB cores are different, elemental intensities of the analyses differ. For this study we have used Si, K, Ca, Fe and Mn ratios of the AR core and Ti, Fe, Ni, Mn, Ca and Sr ratios of the NB core, along with TOC, $\delta^{18}O_{bulk}$ of AR and NB and $\delta^{13}C_{bulk}$ of NB.

According to the published age models, AR and NB cores span the last 600 kyr and 90 kyr, respectively. The dating methods and the errors are explained in detail in Stockhecke et al. (2014), Kwiecen et al. (2014) and Çağatay et al. (2014). In this study we used the 0-250 kyr interval of the AR record, since discontinuities exists before 250 kyr. The mean uncertainty in the age model of the AR core for the 0-250 kyr period is ~908 years and in the NB core for the 0-90 kyr period is ~232 years. The mean temporal resolutions of the AR core μ-XRF, $\delta^{18}O_{bulk}$ and TOC data on average are 57.35, 787 and 153 years, respectively. The mean temporal resolutions of the NB core μ-XRF, $\delta^{18}O_{bulk}$/ $\delta^{13}C_{bulk}$ and TOC data on average are 2.12, 314 and 315 years, respectively (Table 1). The mean temporal resolutions of the AR core μ-XRF data and the NB core μ-XRF data in Holocene 57.21 and 0.79 years respectively.

Factor Analysis

Principle component factor analysis (PCFA) is a simple and an effective method to explore the linear relations between variables and is an effective way of dimension reduction in multivariate data sets. In PCFA, it is assumed that linear relations between the variables exist and these hypothetical relations are revealed by a predefined model.

The general model for the PCFA is as follows;

$$X_{d\times n} - \bar{X}_{d\times n} = A_{d\times k}F_{k\times n} + E_{d\times n}, \qquad (1)$$

where $X_{d\times n}$ is the data matrix with d observations of n variables. $\bar{X}$ represents the mean of X. $F_{k\times n}$ is the factor scores matrix with k hypothetical or statistically determined factors. $A_{d\times k}$ is the factor loading matrix and $E_{d\times n}$ is the specific factor matrix. The factor loading and factor scores matrix of PCFA are determined, according to the spectral decomposition of the covariance matrix of $X_{d\times n}$, by;

$$A_{d\times k} = \Gamma_{d\times k}\Lambda_{k\times k}^{1/2}, \qquad (2)$$

$$F_{k\times n} = \Lambda_{k\times k}^{-1/2}\Gamma_{d\times k}^{T}(X_{d\times n} - \bar{X}_{d\times n}), \qquad (3)$$

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where $\Lambda_{k\times k}$ is the diagonal matrix with the first k selected eigenvalues with decreasing order lying on the diagonal and $\Gamma_{d\times k}$ is the matrix of the corresponding eigenvectors as columns of the first k eigenvalues (Koch, 2014).

Since factor analysis methods depend on the correlation of the data, outlier values within the data should be eliminated before factor analysis. Multivariate outlier analysis methods do exist but we have chosen the Wilk's method and the Yang and Lee (1987) significance test, which uses the F-test (Rencher and Christensen, 2012). The significance level has been chosen to be 0.05 for all the outlier analyses. In order to determine the number of factors for each analysis, we chose the number of the factors according to the corresponding principle components which are greater than 1.

Detrending and Filtering

Natural time series are generally considered as a combination of the signal and noise, plus a trend (Mudelsee, 2014). Long-term climate time series may show long-term trends and these trends can cause small pseudo-frequencies which should be removed before spectral analyses (Muller and MacDonald, 2000). In this study, in order to detrend a single time series, we have subtracted the best fit line of the data, obtained by the least squares method, from the data vector. Furthermore, to remove the high frequency noise, which is most of the time a result of measurement errors, we have preferred the Savitzky-Golay smoothing filter, since it allows filtering unevenly spaced time series. The Savitzky-Golay method fits a polynomial on the window chosen and then picks up the value for the mid element for the chosen window vector (Press et al., 2007). We believe that, in order to get rid of the noise one should not manipulate the data excessively. Therefore, we have chosen first order polynomials while using Savitzky-Golay filters.

For the $\delta^{18}O_{bulk}$ record of the AR, and $\delta^{18}O_{bulk}$, $\delta^{13}C_{bulk}$ and TOC record of NB record, we have applied the 3-point frame size Savitzky-Golay filter. For the TOC record of AR, we have applied a 7-point frame size filter and then resampled 1 point from each consecutive 7-points. Similarly, for K and Ca/K record, we have applied a 15 point frame size filter and resampled 1 from each 15-points.

Before applying the spectral analyses for the Holocene μ-XRF record of NB, we have applied a 50-point frame size Savitzky-Golay filter and then resampled 1 point from each consecutive 50 points.

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Lomb-Scargle Periodogram

There exist several methods to pick up the frequencies in a given time series (for a detailed discussion see Muller and MacDonald, 2000). For unevenly spaced data it is possible to transform the data into an evenly spaced one by interpolation. But the LSP, which fits the data to sinusoidals by the method of least squares, allows applying spectral analysis on unevenly spaced data without suffering loss of information obtained by interpolation. (Lomb, 1976; Scargle, 1982; Press et al., 2007). The final formula of the method is follows:

$$P(2\pi f) = \frac{1}{2\sigma^2}\left\{\frac{\left[\sum_{k=0}^{N-1}\left(h_k - \bar{h}\right)cos(2\pi f(t_k - \tau))\right]^2}{\left[\sum_{k=0}^{N-1} cos^2(2\pi f(t_k - \tau))\right]} + \frac{\left[\sum_{k=0}^{N-1}\left(h_k - \bar{h}\right)sin(2\pi f(t_k - \tau))\right]^2}{\left[\sum_{k=0}^{N-1} sin^2(2\pi f(t_k - \tau))\right]}\right\}, \quad (4)$$

where, h_ks are unevenly spaced time series of t_k for k=1,…,N and $\acute{h}$ and σ^2 are the mean and variance of the data respectively. $P(2\pi f)$ is the power spectrum as a function of each frequency f. Here τ is defined as:

$$tan(4\pi f\tau) = \frac{\sum_{k=0}^{N-1} sin4\pi f t_k}{\sum_{k=0}^{N-1} cos4\pi f t_k}. \quad (5)$$

In order to distinguish the significant frequencies from the insignificant ones, Scargle (1982) stated that the normalized LSP obeys the exponential distribution, and Horne and Baliunas (1986) showed that, for a chosen M value, the statistical significance level of the peaks can be calculated for the chosen level z as:

$$P(Z > z) = 1 - (1 - e^{-z})^M. \quad (6)$$

Horne and Baliunas (1986) empirically showed that, unless the data is clumped, the value of M can be chosen as equal to the length of the dataset N. Since our data is more or less evenly sampled, we preferred M to be equal to the length of the data sets.

The results of the periodogram of different proxy records may slightly differ due to noise within the data, errors in age models, the resolution of the data, and different laboratory analyses which introduce different instrumental noise. Therefore, in order to test the hypotheses of the periods found, we applied the t-test (since the cardinalities of the resultant sets are relatively small) for the consistency of the numbers declared under each band (see Results and Discussion), within the 0.05 significance level.

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RESULTS AND DISCUSSIONS

In paleolimnology studies TOC records are representatives of lake productivity and can be used as proxies for the analysis of long term climate cycles (Cohen, 2003). $\delta^{18}O_{bulk}$ and $\delta^{13}C_{bulk}$ are considered as reliable isotope records, if the source of the bulk is known. $\delta^{18}O_{bulk}$ may represent the changes in both temperature and hydrology (Cohen, 2003). For Lake Van, since it is a terminal lake, $\delta^{18}O_{bulk}$ record is considered as representative for water balance, precipitation/evaporation ratio and lake level, i.e. it is mainly affected by climate variability. $\delta^{13}C_{bulk}$ depends on the photosynthetic activity which is affected by the organic productivity and climatic conditions in and around the lakes. For closed large lakes, like Lake Van, $\delta^{13}C_{bulk}$ and $\delta^{18}O_{bulk}$ data show covarying behavior and $\delta^{13}C_{bulk}$ can also be used as a climatic indicator (Stuiver, 1970; Kelts and Talbot, 1980; Leng and Marshall, 2004)

While μ-XRF elemental data of lake sediments have traditional interpretations, there may be different views (cf. Davies et al., 2015). After removing the outliers, we applied principal component factor analysis on the μ-XRF elemental profiles, in order to group the profiles and test the traditional approaches adapted by Çağatay et al. (2014) and Kwiecien et al. (2014). The results of the analysis of AR core give a single factor which is led by two opposite elemental profiles (Table 2). The first group is defined by Fe and K and the contrasting element is Ca. The factor analysis of the NB core gives two main factors (Table 3). The first factor is characterized by Fe, Ti and K, the second factor is characterized by Ca and Sr. For both cores, even the highest communality of the first factor is Fe, which may have two meanings, either reflecting redox conditions or the detrital flux. On the other hand, except for highly saline lakes, K resembles erosional features. (Cohen, 2003). Therefore, we preferred to use K as the proxy for detrital input in the AR data. Since, through the elemental profiles analyzed in NB, Ti is the most immobile element, it is chosen as a proxy for detrital flux. Ca, which is the other main elemental profile, may precipitate authigenically or result from detrital input. Therefore, we used here the Ca/K ratio for the NB core and Ca/Ti ratio for the AR core as proxy for the relative concentration of detrital versus authigenic material (Çağatay et al., 2014).

The LSP applied to the geochemical data picks the sinusoidal frequencies, which lie in the data, and the frequencies found in this study are interpreted as paleoclimate cycle signals.

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There exist almost infinitely many choices of intervals to check for periodicities, but we have chosen four main intervals, which are:

i. The last 0-250 kyr BP,
ii. The Late Pleistocene (0-90 kyr BP, for the whole NB record)
iii. 11.5-75 kyr BP, to test the periodic behavior of Dansgaard/Oeschger events, and
iv. The Holocene Period (0-11.5 kyr BP)

Table 1. Temporal resolution of the data in years, used in this study.
***Çizelge 1**. Bu çalışmada kullanılan verilerin zamansal çözünürlüğü*

Region	µ-XRF	Stable isotopes	TOC
AR	57.35	787	153
NB	2.12	314	315

Table 2. Factor loading matrix of AR µ-XRF data. Fe, K and Ca represent the same factor, however Ca is negatively correlated with Fe and K.
***Çizelge 2.** AR µ-XRF verisi faktör yükleme matrisi. Bu matrise göre, Fe ve K aynı faktörü temsil ederken, Ca ise bu element profilleri ile ters davranış göstermektedir.*

µ-XRF_{AR}	Component 1
Ca	1.00
Fe	-0.97
K	-0.93
Si	-0.75
Mn	-0.59

Table 3. Factor loading matrix of NB µ-XRF data.
***Çizelge 3.** NB µ-XRF verisi faktör yükleme matrisi. Bu matrise göre, Fe, Ti ve K aynı faktörü temsil ederken, Ca ve Sr diğer faktörü temsil etmektedir.*

µ-XRF_{NB}	Component 1	Component 2
Ca	-0.099	-0.99
Sr	-0.44	-0.81
Fe	0.94	0.33
Ti	0.90	0.34
K	0.88	0.06
Mn	0.72	0.24
Ni	0.63	0.15

The power spectrum results, which exceed 95% significance level, of the last 250 kyr period of AR and the last 90 kyr period of NB are listed in Table 4.

The first observation on the results (Figure 2) of 250 kyr of the AR core and of 90 kyr of the NB core gives the Milankovitch bands, i.e. the obliquity (~41 kyr) and the precession of

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the equinoxes (~21.7 kyr). In order to test the consistency of the periods under the 21.7 kyr band, we used the t-test with the null hypothesis that the mean of the numbers under the band is 21.7 kyr. According to result, it is 95% statistically significant that the mean of the band is 21.7 kyr. On the other hand, the resultant periodicities under the 41 kyr band, cannot succeed to pass the t-test. It must be because of the relatively low number of results, but we believe that the cycles under the 41 kyr band reflect the obliquity cycle. It is surprising not to see the 41 kyr cycle at $\delta^{18}O_{250kyrAR}$. However, it is possible that the relatively low resolution may hide the cycle. And the reason for the lack of 41 kyr cycle at NB dataset is the shortness of time span of the dataset. To detect a cycle through spectral analysis methods, the timespan of the data should be at least 2.5 times of the temporal length of the queried cycle.

Table 4. Spectral analysis results of the AR, NB, LC21 and Soreq Cave records, which exceed the statistical significance.
Çizelge 4. *AR, NB, LC21 ve Soreq Mağarası verilerinin istatistiki anlamlılık eşiğini aşan spektral analiz sonuçları.*

Region	**AR (0-250 kyr BP)**			**NB (0-90 kyr BP)**			**LC21 (0-156 kyr BP)**	**Soreq (0-184 kyr BP)**
Data	$\delta^{18}O$	TOC	Ca/K	$\delta^{18}O$	$\delta^{13}C$	TOC	$\delta^{18}O$	$\delta^{18}O$
62 kyr band	62.4	62.3	66.5				62.7	60.7
	47.6							
41 kyr band		39.9	39.9				39.2	38.3
30 kyr band	33.3	29.3	28.5	32.9	32.9	36.2	29.8	29.1
	24.4	25.6					24.1	24.3
21.7 kyr band	21.7	23.7	22.7	21.3	21.3	22.6	20.2	20.2
16.2 kyr band	15.4			15.7	16.4	17.2	16.9	18.2
12.3 kyr band	11.4			12	12.5	12.5		12.3
10 kyr band	9.4				10.3	10.95		
				6.7				
5.8 kyr band				5.8	5.8	5.8		5.4
				4.2				
3.5 kyr band				3.65	3.65	3.4		3.6
						2.6		

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Other results of LSP through 250 kyr and 90 kyr intervals of AR and NB records reveal the ~62 kyr, ~30 kyr, ~16.2 kyr, ~12 kyr, ~10kyr, ~5.8 kyr and ~3.5 kyr bands. Similar to 21.7 kyr band, according to t-test within %95 significance level, means of each band satisfy the band average indicated in Table 4. An explanation to these cycles is given by Le Treut and Ghil (1983). According to their model, the interactions between the ice sheet, the crust beneath and the ocean produce a dynamical behavior, which give rise to the harmonics, subharmonics, i.e. linear combinations of the Milankovitch cycles. The main idea beneath the model is that the long term change in insolation is reflected in the ice sheets with a lag, because of the visco-elastic behavior of the underlying crust. The resulting lagged behavior of the visco-elastic crust affect the equilibrium line altitude. Therefore, the ice sheet and the crust beneath oscillate not on the exact periodic timescales of insolation and the model gives a nonlinear climatic oscillator (Ghil and Le Treut, 1981; Le Treut and Ghil, 1983; Le Treut et al., 1988). The evidences of this theory have been mentioned in some studies (Pestiaux et al., 1988; Yiou et al., 1991; Nobes et al., 1991; Yiou et al., 1994; Mommersteeg et al., 1995; Mayewski et al., 1997; Ortiz et al., 1999; Wara et al. 2000). Therefore, we believe that, changes in insolation and their effects on the behavior of the ice sheet is a global climate driver in the long term. On the other hand, there exist some other explanations brought to the 30 kyr, 12 kyr and 10 kyr cycles found through this study. Beaufort et al. (2001) reports the 30 kyr cycle in various records of Indo-Pacific Ocean and also in Antarctica CO_2 records. According to Beaufort et al. (2001), 30 kyr cycle is a consequence of the boreal summer monsoon's effect on the thermocline. Short et al. (1991) argue that, a ~10 ka and a ~12 ka climatic cycle must persist on equatorial and subtropical regions according to their energy balance climate model. However, they add that tropical convective processes may export these oscillations to higher latitudes. Our tests are not meant to find an explanation to the physical mechanisms of the aforementioned cycles. The existence of most of the cycles mentioned by Le Treut et al. (1988) support their hypothesis; though, we cannot neglect the latter mentioned ones.

The other interesting consequence of the analyses is the absence of the periodic behavior of the DO events (~1500 years) which is especially reported in the previous studies through North Atlantic and Greenland data of Late Pleistocene (Mayewski et al., 1997; Yiou et al., 1997; Bond et al., 1999; Alley et al., 2001; Schulz, 2002) and also in the uranium data

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of AR core for the 13-75 kyr BP interval (Baumgarten and Wonik, 2014). The test on NB and AR proxies, for the 11.5-75 kyr BP time interval, failed to show a significant cycle in the 1500 year band. In order to test the lack of 1500 years cycle, we have applied similar analyses on the available Eastern Mediterranean data, namely $\delta^{18}O_{rub}$ records of the LC21 core drilled in the Eastern Mediterranean (Grant et al., 2012) and the Soreq Cave $\delta^{18}O$ record (Bar-Matthews et al., 2003). The LC21 record spans the last 156 kyrs with 260 years of resolution and the Soreq record the last 184 kyrs with a resolution of approximately 468 years. The results of the spectral analyses of whole LC21 and Soreq record (Table 4) almost coincide with Lake Van results, which support the Milankovitch theory and the harmonics/subharmonics theory of Le Treut et al. (1988). On the other hand, the spectral analyses of the 11.5-75 kyr interval of the LC21 and Soreq data show no evidence of 1500 years of periodicity.

The results on the 11.5-75 kyr interval reveal the possibilities that, the DO events may not be really periodic. On the other hand, high latitude studies (Dansgaard et al., 1984; Grootes and Stuiver, 1997; Mayewski et al., 1997; van Kreveld et al., 2000) and Western Mediterranean studies (Moreno et al., 2005) show that the DO events may be periodic. It is claimed that the physics behind the DO events is similar to the physical setting of the NAO (Sánchez Goñi et al., 2002; Moreno et al., 2005). If the DO events are really periodic, then we can claim that, within the longer timescales the climate of the Eastern Mediterranean, which is thought to be at the border of NAO's influence (Cullen and deMenocal, 2000), is not directly connected to North Atlantic or the signal is being disturbed by some other mechanisms. Second alternative to the previous assertion is, since the region is at the border of NAO's influence, the DO periodicity may be masked and the power of the periodic events is lessened. According to this power diminish, the spectral analyses may not detect the periodic behavior. Furthermore, it is reported that the absence of ~1500 year periodicity for the Sofular stalagmite record of 15-50 kyr interval (Fleitmann et al., 2009) supports our results.

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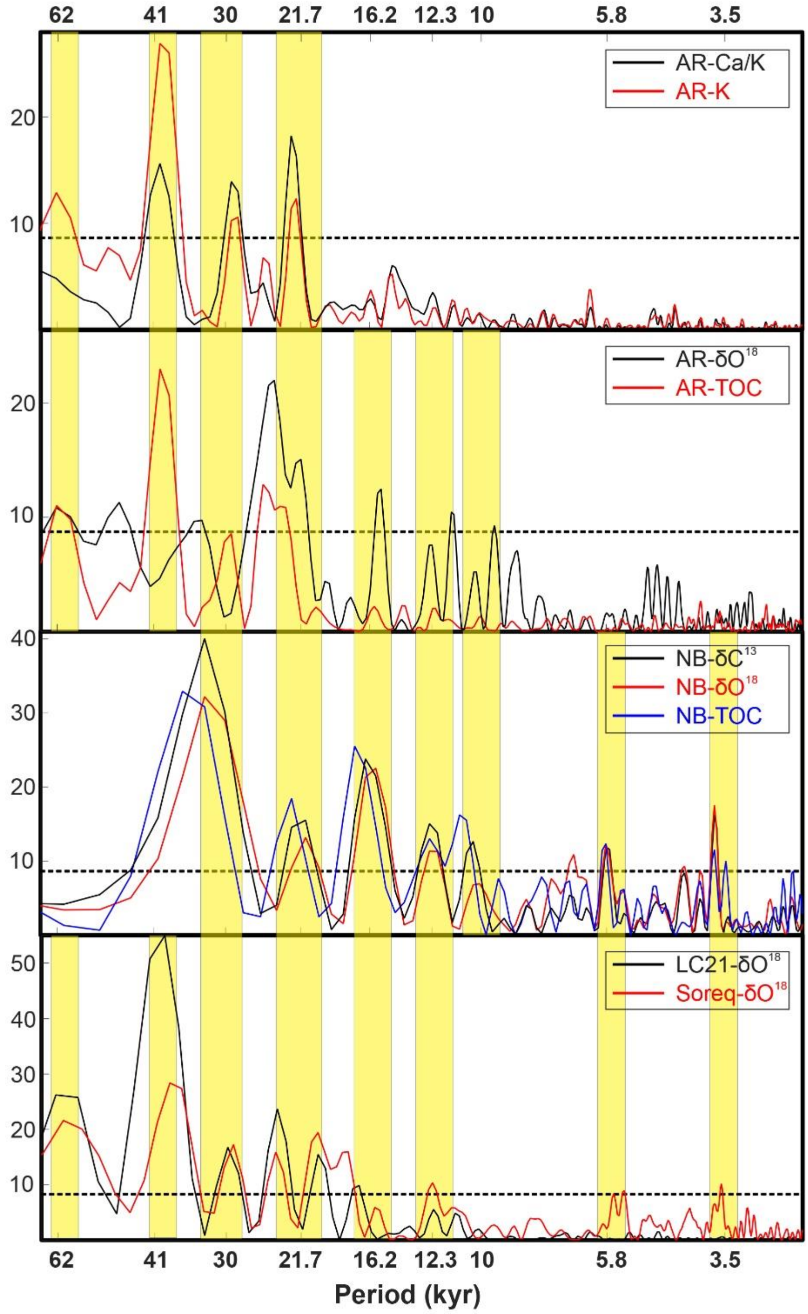

Figure 2. Spectral analysis results of Lake Van AR core (top two plots), NB core (third plot), LC21 and Soreq Cave stable oxygen data (bottom plot). The yellow bands show the statistical significant periods of each group. The y axes show the spectral power of each analysis and they are unitless.

Şekil 2. *Üstteki iki grafik Van Gölü AR, üstten üçüncü grafik NB, alttaki grafik ise LC21 ve Soreq mağarası verilerinin spektral analiz sonuçlarıdır. Sarı bantlar ise her grafiktki gruplar için istatistiki anlamlılık eşiğini aşan değerleri göstermek için kullanılmıştır. Grafiklerde y eksenleri her analizin spektral gücünü göstermektedir ve birimsizdir.*

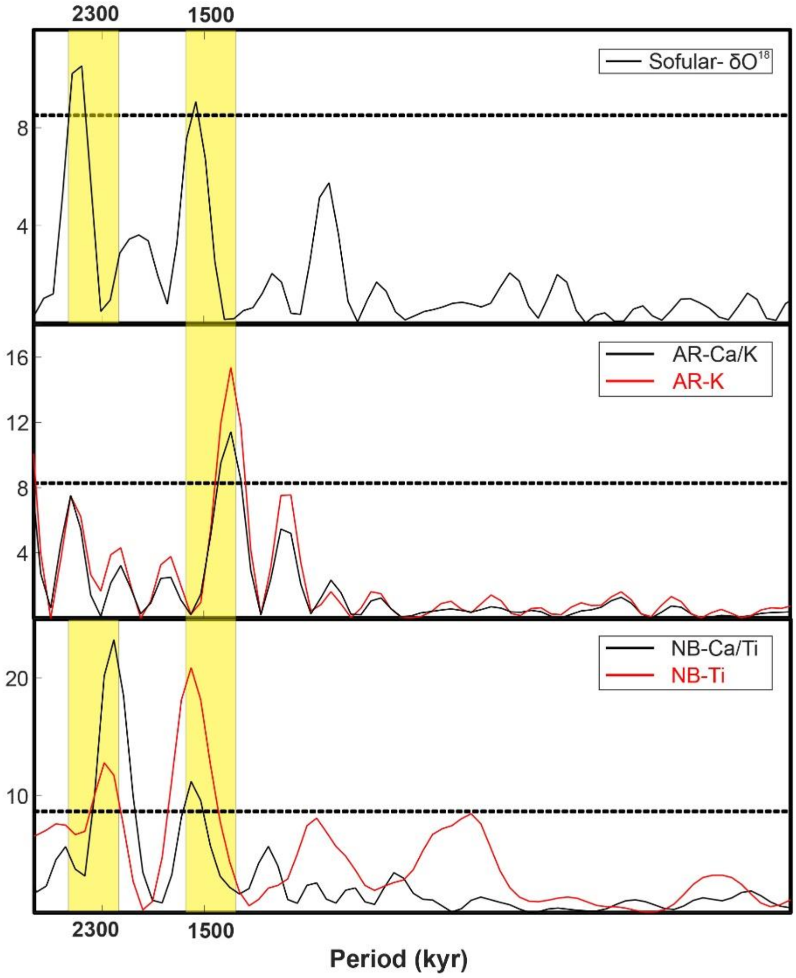

Figure 3. Spectral analysis results of Sofular Cave δ^{18}O data (uppermost plot), AR and NB cores µ-XRF data (second and third plot respectively) for the Holocene period. The yellow bands show the statistical significant periods of each group. The y axes show the spectral power of each analysis and they are unitless.

Şekil 3. *Üstteki grafik Sofular mağarası δ^{18}O verisinin, ikinci ve üçüncü grafikler sırasıyla AR ve NB µ-XRF verisinin spektral analiz sonuçlarıdır. Sarı bantlar ise her grafikteki gruplar için istatistiki anlamlılık eşiğini aşan değerleri göstermek için kullanılmıştır. Grafiklerde y eksenleri her analizin spektral gücünü göstermektedir ve birimsizdir.*

Table 5. Spectral Analysis results of the AR, NB, and Sofular records for the Holocene (0-11.5 kyr BP).

Çizelge 5. *AR, NB ve Soreq Mağarası verilerininHolosen için (GÖ 0-11.5 binyıl) istatistiki anlamlılık eşiğini aşan spektral analiz sonuçları.*

Region	**AR**	**NB**	**Sofular**
Data	Ca/K	Ca/K	δ^{18}O
2300 yr band		2155	2570
1500 yr band	1373	1560	1540

The power spectrum results (Figure 3) for the Holocene, i.e. for the last 11500 years, are listed at Table 5. According to the results of the Holocene, the most prominent value is the ~1500 year band. This value is accepted to be the Bond cycles of Holocene. It is thought that the cause of the Bond cycles may be solar forcing (Bond et al., 2001) or an internal oscillation of the oceanic thermohaline circulation (Bianchi and McCave, 1999), which are accepted to be one of the driving mechanism of the climate in millennial timescales (Broecker et al., 1990). Contrary to our results, Rohling et al. (2002) reports that, for the Aegean Sea record they have, there is no evidence for a ~1500 year cycle. On the other hand, analysis on $\delta^{18}O$ of Sofular in Holocene gives almost similar results to Lake Van data.

The other prominent result, which is missing in the AR record, is the ~2300 year band of periodicity. It is almost accepted that, the 2300 years of periodicity represents the solar variation, namely Hallstadtzeit (or Charvátová) cycle, and its effect on climate is extensively discussed (Charvátová, 2000 and references therein). For the Holocene period, this cycle was also reported in the Aegean Sea records (Rohling et al., 2002).

One question arises after the Holocene results. If the Holocene Bond events are solar originated, then why is this effect not seen in the Late Pleistocene records of Eastern Mediterranean? We think that, if there are solar originated changes in the oceanic circulation (Braun et al., 2005; Braun and Kurths, 2011), the influences of these changes may not reach up to Eastern Mediterranean because of the distance. But the changes in solar output would surely affect the climate of the region. Therefore, the solar cycle which is observed through the Holocene must have existed through the Late Pleistocene as well. But the effects of the changes in the solar output are limited relative to large climatic oscillations of glacial times, which are masked in the analyses.

CONCLUSIONS

The aim of this study is to test the debated long term climate cycles by using Lake Van sediment geochemistry data. The results of the spectral analyses of Lake Van sediment cores imply

1. The Milankovitch cycles, namely the obliquity cycle (41 kyr) and the precession of the equinoxes cycle (21.7 kyr), pass the test through Lake Van data. In order to support the

results, we also applied the same analyses on the LC21 and Soreq data. Their results also support the Milankovitch theory.

2. We also observe the harmonics and subharmonics of the Milankovitch theory. Among the theories on these shorter cycles, the theory of Le Treut et al. (1988) almost fit to our results, which are 62, 30, 16.2, 12.3, 10, 5.8 and 3.5 kyrs of cycles.

3. For the 11.5-75 kyr interval there is no evidence of a 1500 year cycle neither in Lake Van data nor in LC21 and Soreq data.

4. The Holocene interval shows two prominent cycles which are 1500 year of Bond cycle and 2300 year of Hallstadtzeit solar cycle.

According to the third and the fourth conclusions, the straightforward climatic connection of Eastern Anatolia and Eastern Mediterranean in the geological timescale needs a more complex reasoning, which goes beyond this study and should be further investigated.

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GENİŞLETİLMİŞ ÖZET

Avrupa'nın bir zamanlar buzullarla kaplı olması gerektiği fikri ortaya atıldıktan sonra buzullaşmaların birden fazla kez ve periyodik olabileceği ilk kez Esmark (1827) tarafından dile getirilmiştir. Esmark'a göre buzullaşmalar Yer'in ilk zamanlarından kalma olgulardır ve periyodik olarak oluşmuşlardı. Esmark'a göre, Dünya oluştuğu ilk zamanlarda, bir kuyrukluyıldız gibi yörünge eliptikliği çok büyüktü. Eliptik yörüngede Güneş etrafında dönerken, Güneş'ten uzak dönemlerde bir buzullaşma yaşanırken, yaklaştığında ise buzullar eriyordu. Ancak Esmark'ın bu fikirleri üzerine dayandırdığı astronomik teoriler yanlıştı. Çünkü, Esmark'ın iddia ettiği gibi Dünya oluşumunun ilk zamanlarında, bir kuyrukluyıldız gibi, eksantrisitesi çok büyük olan bir eliptik yörüngeye sahip değildi.

Esmark'tan sonra Adhémar (1842), buzullaşmaların ekinoksların presesyonu ile yaklaşık 22.000 yıllık periyotlarla güney ve kuzey yarımkürelerde salınım yapması gerektiğini söylemiştir. Bugün kabul gören iklimlerin astronomik döngülerle şekillendiğine dair hipotezlerin temelini Adhémar atmıştır denebilir. Ekinoksların presesyonu, Dünya'nın dönme ekseninin, bir topaç gibi, yalpalamasına ve aynı zamanda dünyanın güneş etrafında dönme ekseninin de rotasyonu ile oluşan duruma verilen isimdir. Presesyon, etimolojik olarak Latince geriye gitmek demektir. Bu astronomik harekete bu ismin verilmesinin sebebi kuzey kutbundan kuşbakışı bakan bir gözlemcinin ekinoksların eliptik düzlemde meydana geldikleri noktaların zaman içinde saat yönünde döndüklerini görecek olmasıdır. Buna göre ekinokslar ve gündönümleri eliptik düzlemde farklı zamanlarda başka noktalarda bulunmaktadır. Örneğin, bugün kuzey yarımkürede kış gündönümü neredeyse Dünya Güneş'e en yakın noktadayken gerçekleşirken, yaklaşık 11.000 yıl önce güneşe en uzak noktada gözlemlenmekteydi.

Adhémar'ın çalışmalarından haberdar olan Croll (1875), ekinoksların presesyonunun Dünya'nın iklimine olan etkisi fikrini genişletmiştir. Croll'a göre Dünya'nın eliptik ekseninin eksantrisitesinin (eksenin daha dairesel ve daha eliptik durumları arasında hareketi, yani elipsin odaklarının birbirlerine olan uzaklıklarının değişmesi) yaklaşık 100.000 yıllık döngülerle değişmekte olması ekinoksların presesyonunun iklime olan etkisinde temel olan kavramdır. Bunun dışında, Dünya'nın dönme ekseninin eğimi (bugün yaklaşık 23.5^o'lik bir eğime sahiptir) yaklaşık 41.000 yıllık salınımlarla yaklaşık 21.5^o ila 24.5^o eğimlere ulaşmaktadır ki bu da Dünya iklimini, özellikle yüksek enlemlerde, etkilemektedir. Croll, yarımkürelerin en az güneşlenen kışlarda buzul çağlarına gireceğini düşünmekteydi. Buna göre, yörüngenin eksantrisitesinin fazla, Dünya 21 Aralık günü güneşe en uzak olduğunda, eğim açısı da fazla ise kuzey yarımküre kendini bir buzullaşmanın içinde bulacaktı. Croll'un iklim bilimine yaptığı katkılar sadece bunlarla sınırlı değildir. Hipotezini, hem buzun albedosunun yüksekliğinden kaynaklanan geri besleme kavramıyla hem de okyanus akıntılarının geri beslemesi kavramıyla genişletmiştir.

Croll'un hipotezi jeomorfolojik gözlemlerle örtüşmediği için 20. yüzyılın başında popülerliğini kaybetmeye başlar. Ancak, Milutin Milankoviç (1941) Croll'un fikirlerini kaldığı yerden alıp geliştirecektir. Milankoviç, Croll'dan farklı olarak buzullaşmanın olabilmesi için kuzey yarımküre yazlarının kışlarından daha soğuk olması gerektiği fikrini

(Murphy, 1869) benimsemiştir. Bunun dışında, yıl içinde güneşlenmenin en fazla olduğu yarıyıl için kullanılan bir tabir olan kalorik mevsimlerin güneşlenme değerinin gereken bütün matematiksel hesaplarını son 600.000 yıl için elliptik integraller yardımıyla yapmıştır ve bunların grafiklerini çizmiştir.

Milankoviç çizdiği eğrideki tepe noktalarını sayarak güneşlenmenin 20.700 (ekinoksların presesyonu), 40.040 (eksen salınımı) ve 91.800 (elliptpik yörüngenin eksantrisitesindeki değişim) yıllık periyotlar belirlemiştir. Ancak daha kesin sonuçlar Berger'in (1973, 1977) çalışmalarından sonra, spektral analiz sonuçlarıyla ortaya çıkmıştır. Buna göre ortalaması 21.700 yıl olan ekinoksların presesyonu, en güçlü bileşeni 41.000 yıl olan eksenin salınımı ve en güçlü 2 bileşeni 412.000 yıl ve ortalamada 100.000 yıl olan yörüngenin eksantrisitesindeki değişimler, yerin iklimi üzerinde etkili en önemli astronomik parametrelerdir. Hays vd. (1976) yılında, Hint Okyanusu'ndan alınmış karotta, planktonik foraminifer kavkılarından elde edilmiş duraylı oksijen izotopu eğrilerine uyguladıkları spektral analiz yöntemi ile elde ettikleri sonuçlar, Milankoviç teorisinin en önemli teyidi kabul edilmektedir. O günden beri yapılan küresel ölçekteki çalışmaların büyük çoğunluğu Hays vd. (1976)'nin sonuçlarını desteklemektedir.

Teori bazı sorunlara çözüm getirdiği gibi, birçok problemi de beraberinde getirmiştir. Bunlardan en önemlisi, son bir milyon yıldaki en güçlü periyodik bileşen olan 100.000 yıllık döngünün gücü Milankoviç'in teorisinde yok denecek kadar azdır. Bir diğer büyük sorun da güneşlenmedeki salınım en düşükken (MIS-12, MIS-11 geçişinde olduğu gibi) iklim sistemi çok güçlü salınımlar yapmakta ve bunun tersi güneşlenmedeki salınım en güçlüyken ise (MIS-7 gibi) sistem düşük salınımlar yapmaktadır. Teorinin sorunları hakkında daha fazla bilgi için okuyucu Muller ve MacDonanld (2000), Paillard (2015) gibi kaynaklara danışabilir. Tarihsel perspektif için Imbrie ve Imbrie (1979), Bard (2004) ve Berger (2012), içindeki referanslarla beraber uygun kaynak görevi görmektedirler.

Biz bu çalışmada, Doğu Anadolu'da bulunan Van Gölü'nden alınmış, son 250 bin yılı ve son 90 bin yılı temsil eden iki karotun jeokimyasal verilerinde (μ-XRF, TOC ve duraylı oksijen/karbon izotopu) Lomb-Scargle perioyodogramı yöntemi ile bölgenin iklim döngülerini araştırdık. Sonuçların tutarlılığını desteklemek için Doğu Akdeniz'den alınmış LC21 karotu duraylı oksijen izotopu verisi, Soreq ve Sofular mağaraları duraylı izotop verilerine de aynı analizi uyguladık. Verilere spektral analiz uygulamadan önce Savitzky-Golay filtresinden *geçirildi ve verilerin üzerindeki lineer trend kaldırıldı. Sonuçlar Doğu Akdeniz verilerinde Milankoviç döngüleri, Milankoviç döngülerinin harmoniklerini, Holosen Bond döngülerini ve bir solar döngü olduğu düşünülern Hallstadtzeit döngüsünü vermiştir. Ancak, 11.5-75 bin yıl önce aralığında başka çalışmalarda var olan 1500 yıllık döngü ile bu çalışmada karşılaşılmamıştır.*

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