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Dates of Holocene environmental changes in Lake Bafa: A hierarchical Bayesian analysis of change points

Holosen'de Bafa Gölü'ndeki ortamsal değişikliklerin tarihleri: Hiyerarşik Bayes değişim noktası analizi

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ABSTRACT / ÖZ

The timing of the separation of Lake Bafa from the Aegean Sea and its subsequent transition to a lake remains a topic of debate, with considerable uncertainties associated with the proposed dates for these transitions. This study introduces a novel approach, hierarchical Bayesian change point analysis (HBCPA), to identify tipping points in paleoenvironmental time series. The objective is to offer more precise and objectively selected results concerning the previously uncertain transition dates of Lake Bafa's geological evolution in the Holocene. The method presented in this study is applied to analyze stable oxygen and carbon isotope data from foraminifer and ostracod shells, as well as total organic carbon (TOC) data, obtained from the BAFA09P02 sediment core. Results indicate that the transition from a marine to an isolated lagoon environment occurred around 2060 years BP, with an 89% uncertainty interval ranging from 2250 to 1870 years BP. Additionally, the transition from an isolated lagoon to a brackish lake environment is estimated to have occurred around 595 years BP, with an 89% uncertainty interval ranging from 780 to 425 years BP. The results of this study illustrate that the suggested HBCPA approach holds the capability to identify tipping points in environmental data while quantifying their intrinsic uncertainties.

Bafa Gölü'nün Ege Denizi'nden ayrılmasının ve ardından tatlısu gölüne geçişinin zamanlaması tartışmalıdır ve bu değişimler için önerilmiş olan tarihlerin belirsizlik aralıkları oldukça geniştir. Bu çalışmada, paleoçevre verilerinin analizinde kullanılmak üzere yeni bir yaklaşım olarak "hiyerarşik Bayes değişim noktası analizi" (HBCPA) önerilmektedir ve sonuç olarak Bafa Gölü'nün Holosen'de ortamsal değişim tarihleri için önerilmiş geniş belirsizlik aralıklarını daraltma amacını taşımaktadır. Önerilen yöntem, BAFA09P02 çökel karotu foraminifer ve ostrakod kavkılarından elde edilen duraylı oksijen ve karbon izotop verileri ile toplam organik karbon (TOC) verileri üzerinde uygulanmıştır. Sonuçlar, denizel ortamdan kapalı lagünel ortama geçişin yaklaşık GÖ 2060 yıl civarında gerçekleştiğini ve %89 belirsizlik aralığının GÖ 2250 ila 1870 yılları aralığında olduğunu göstermektedir. Kapalı bir lagünden acısu göl ortamına geçişin ise yaklaşık GÖ 595 yıl civarında gerçekleştiği ve %89 belirsizlik aralığının GÖ 780 ila 425 yıllarını kapsadığı bulunmuştur. Bu çalışmanın sonuçları, önerilen HBCPA yönteminin jeolojik verilerde çevresel değişim noktalarını, sahip oldukları belirsizlikleri ile ölçme potansiyeline sahip olduğunu göstermektedir.

1. Introduction

Lake Bafa, located near notable ancient sites including Miletos, Priene, and Herakleia, is a remnant body formed by the separation of the Gulf of Latmos from the Aegean Sea. The separation took place as a result of the progradation of the delta mouth of the Büyük Menderes River (referred to as the Maiandros River in ancient times), which led to the formation of a barrier (see Figure 1). Despite its environmental, archaeological and geological significance, the timing of the lake's isolation from the Aegean Sea is still a matter of debate (cf. Akçer-Ön et al., 2020; Brückner et al., 2017; Müllenhoff et al., 2004; Salihoğlu & Akçer-Ön, 2020).

Previous studies have reported conflicting dates, with variations of more than three thousand years, regarding the period when the basin became isolated from the open sea (cf. Akçer-Ön et al., 2020; Knipping et al., 2008; Müllenhoff et al., 2004). However, Akçer-Ön et al. (2020) used up-to-date calibration curves and advanced Bayesian age-depth modeling techniques to demonstrate the potential compatibility between the contradictory hypotheses proposed by Akçer-Ön et al. (2020) and Knipping et al. (2008). Given that the temporal findings presented by Akçer-Ön et al. (2020) are in direct contradiction with all previously documented studies, the uncertainty intervals for the transition dates are approached with utmost caution, resulting in the broadest range of uncertainty being reported. They utilized a multiproxy approach that included faunal distribution, geochemical data, and physical properties of the core. The discussion focuses on different age-depth models based on diverse assumptions, leading to a high level of uncertainty. Their results highlighted the temporal uncertainties associated with the transition from a marine environment to an isolated lagoon, spanning up to two millennia. Similarly, the transition from an isolated lagoon to a brackish lake exhibited uncertainties covering approximately 600 years (see the upper panel of Table 1).

The present study reports the results of a hierarchical (multilevel) Bayesian change point analysis (HBCPA) to estimate transition dates with greater objectivity and precision than those reported by Akçer-Ön et al. (2020). TOC data from bulk sediment, stable carbon and oxygen isotope data from foraminifer and ostracod shells (Figure 2) in the BAFA09P02 core are analyzed using HBCPA. This statistical method detects credible shifts or changes in multiple time series data simultaneously, providing an overall average that captures any type of uncertainty. The approach employs piecewise linear regression to approximate the data and estimate parameters for each segment, identifying points in time where the data deviates from the prior segment. A hierarchical Bayesian approach is advantageous for incorporating all levels of uncertainties and prior information of the data, and expressing the uncertainty of the results in an intuitive way.

Several prior studies in the field of earth sciences have utilized Bayesian hierarchical models (Ön et al., 2023, and references therein), Bayesian solutions of Kalman filter to assess potential changes through regression models (Ön et al., 2021), or Bayesian change point analysis to identify trend shifts or level changes in time series (Cahill et al., 2015; Gallagher et al.,

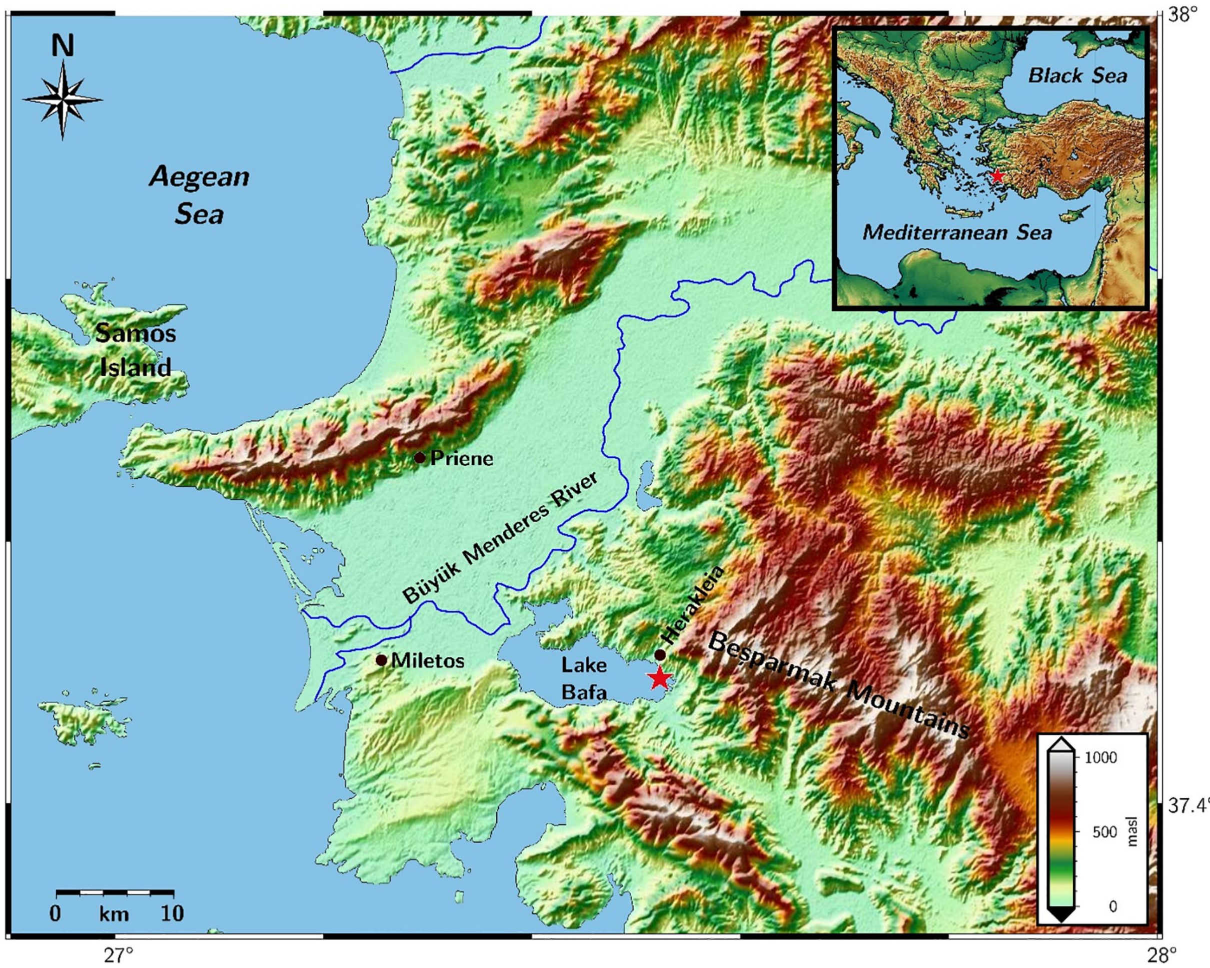

Figure 1. *Location map of Lake Bafa and the drilling site (red star) of BAFA09P02 core. Modified from Akçer-Ön et al. (2020).*

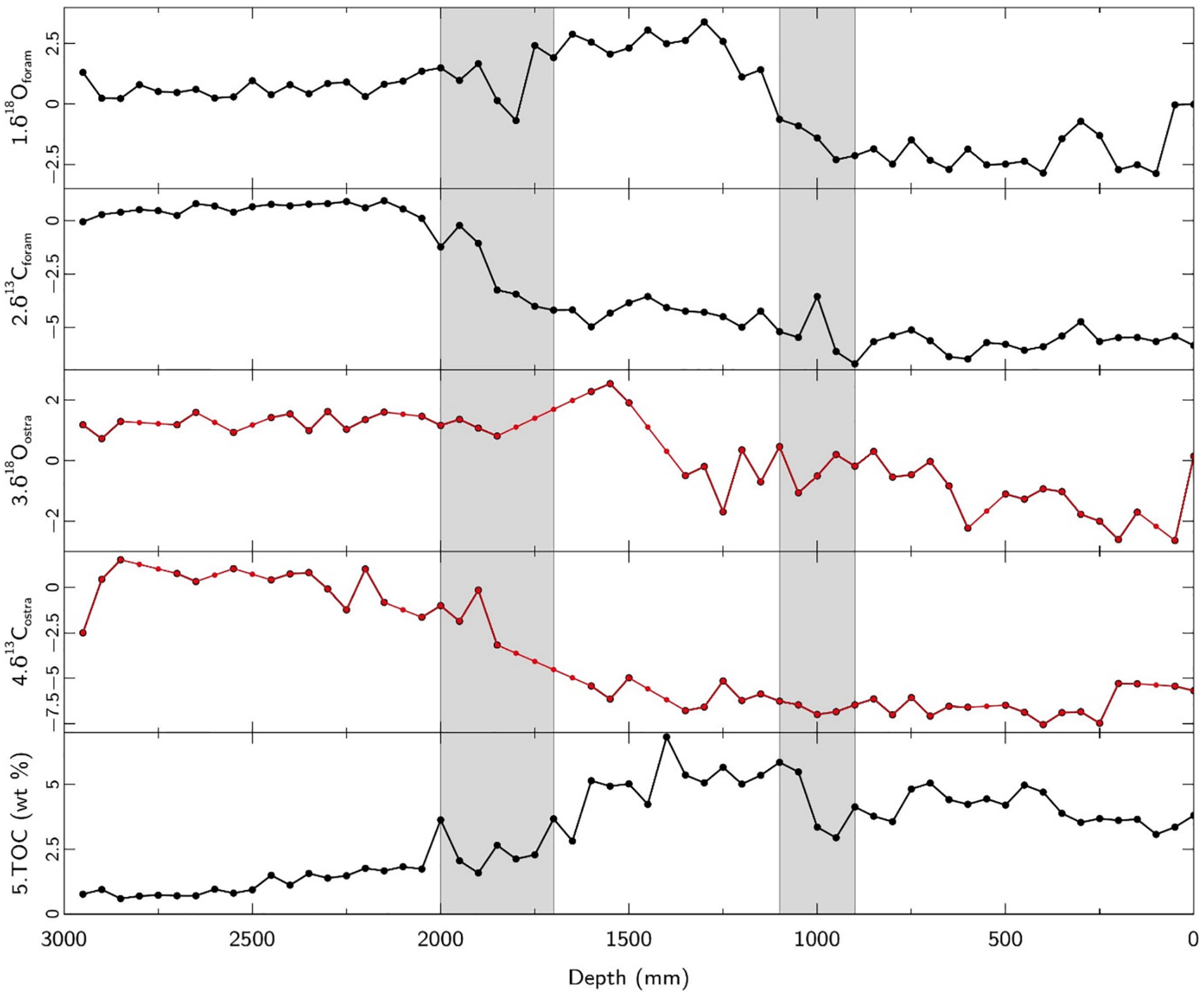

Figure 2. *The figure illustrates the core depth plotted against the proxy data obtained from Akçer-Ön et al. (2020) and employed in this study. The gray shaded areas indicate the intervals of environmental change as identified by Akçer-Ön et al. (2020). The red curves represent the missing datasets, with small red dots indicating the filled data.*

2011; Ön, in press). However, to the best of my knowledge, no previous studies have employed a hierarchical change point approach to analyze paleoenvironmental data. In the case of the Lake Bafa data, this approach is feasible since multiple proxy data indicate a discernible response to environmental changes. (Figure 2). Therefore, the findings of this study have the potential to offer insights into the disputed geographic history of the region in the archaeological timespan.

2. Regional Setting

Lake Bafa is a shallow freshwater lake located in southwestern Anatolia, Turkey, approximately 20 km inland from the Aegean Sea (Figure 1). The lake, covering an area of approximately 70 square kilometers, is a residual body of water that originated from the delta progradation of the Büyük Menderes River. The region is characterized by rugged terrain and is sparsely populated. The lake basin is situated within the Aegean extensional province, which is subject to active extensional faulting owing to significant tectonic activity (Mozafari et al., 2019). The area experiences the influence of a Mediterranean climate pattern, characterized by abundant rainfall during winter and scarce precipitation during summer. The lake is characterized as mesohaline with a salinity range of 8–13‰. Lake Bafa is fed by several small streams and is home to a diverse range of plant and animal species, including several endemic species (Akçer-Ön et al., 2020).

3. Materials and Methods

3.1. Data

This study examines a 298 cm long undisturbed sediment core (BAFA09P02) retrieved from the eastern part of Lake Bafa (Figure 1) in 2009 at a water depth of 4.9 m. According to the "preferred" age-depth model of Akçer-Ön et al. (2020), the core approximately spans the last 8700 years BP[1]. Akçer-Ön et al. (2020) provided a thorough analysis and description of the sediment core, including the TOC measurements, and also the $\delta^{18}O$ and $\delta^{13}C$ compositions of the shells from the most common and consistent benthic foraminifer species, *Ammonia tepida-Ammonia sp.*, as well as from ostracod species, *Cyprideis torosa* and *Xestoleberis sp.* To simplify notation, this study uses subscripts F and O to represent the isotope values of foraminifers and ostracods, respectively. These proxy data are suitable indicators of environmental changes, encompassing salinity, evaporation, and organic productivity. Their age-based profiles facilitate the exploration of the timing and associated uncertainties linked to the chemical and subsequent physical transitions of Lake Bafa, which was once connected to the Aegean Sea in the geological past.

[1] The term "years BP" is an abbreviation used to refer to years before the present, where the present is defined as 1950 CE, as established by Flint & Deevey (1962).

The data resolution for all presented data is 5 cm. However, at specific depths, as noted in the supporting information by Akçer-Ön et al. (2020), measurements of stable isotope data from ostracod species are missing. To address this, the original authors used linear regression approach, utilizing available data points from adjacent depths. Similarly, in this study, the same approach has been applied to estimate and complete the missing data points throughout the entire data matrix (Figure 2).

3.2. Hierarchical Bayesian Change Point Analysis

The time series of $\delta^{18}O_F$, $\delta^{13}C_F$, $\delta^{18}O_O$, and TOC in this study are assumed to have two change points, while $\delta^{13}C_O$, as described in Section 4, involves only one change point. All these data are assumed to be described as piecewise linear regressions between and beyond the change points. All these data are assumed to follow a piecewise linear regression model, both between and beyond the change points. In the equations below, the time axis for each series is defined by $\{x_1,\ldots,x_n\}$, where x_1 and x_n represent the first and last elements of the time vector. The piecewise regression models for each standardized (x_i, y_i^k) can be expressed as per the notation of Lindeløv (2020):

$$y_i^k \sim t_{(\nu^k)}\left(\mu_i^k, (\sigma^k)^2\right) \quad (1)$$

where μ_i^k is given by

$$\mu_i^k = [x_i \geq x_1][x_i < c_1^k]\left(\alpha_1^k + \beta_1^k x_i\right)$$
$$+[x_i \geq c_1^k][x_i < c_2^k]\left(\alpha_2^k + \beta_2^k x_i\right) \quad (2)$$
$$+[x_i \geq c_2^k][x_i \leq x_n]\left(\alpha_3^k + \beta_3^k x_i\right),$$

and

$$\sigma^k \sim \mathrm{N}^{(0,\infty)}(0,1), \quad (3)$$

$$\nu^k \sim \mathrm{Exp}(1/30). \quad (4)$$

In Equation 2, the mathematical statement $[a\hat{R}b]$ represents a binary indicator function that denotes the truth value of a relational statement $[a\hat{R}b]$ where $\hat{R}$ denotes any given relation. This relational statement evaluates to a logical variable that equals 1 if and only if the relation holds true, and 0 otherwise. The equation presented in Equation 1 above utilizes the notation t_ν to represent the t-distribution, where ν denotes the degrees of freedom or the normality parameter, as described by Kruschke (2015). In order to exercise greater caution with respect to the regression parameters, a robust t-distribution was selected to prevent any potential influence of outliers on the detection of change points in the data. Moreover, the parameter ν is assigned an exponential distribution with a mean value of 30 to create a prior that assigns equal probability to values of v less than or greater than 30, and thereby giving equal weight to an approximate normal distribution and a heavy-tailed distribution. ($\mathrm{N}^{(0,\infty)}$) denotes truncated normal distribution with truncation range $(0,\infty)$ and Exp denotes exponential distribution. The upper index k represents the index of the variable, running from 1 to 5. These index numbers, as also given in Figure 2, correspond to $\delta^{18}O_F$, $\delta^{13}C_F$, $\delta^{18}O_O$, $\delta^{13}C_O$, and TOC, respectively.

The uncertainty of the age model is implemented through:

$$x_i \sim \mathrm{N}(x_i^{\mathrm{am}}, (\sigma_i^{\mathrm{am}})^2), \quad (5)$$

where x_i^{am} and σ_i^{am} are the standardized mean and one sigma error of the age model presented as the "preferred age model" in Akçer-Ön et al. (2020).

For each variable, the change points c_1 and c_2 are described as:

$$c_1^k \sim t_4\left(c_1^{\mathrm{g}}, 200^2\right), \quad (6)$$

$$c_2^k \sim t_4\left(c_2^{\mathrm{g}}, 200^2\right), \quad (7)$$

where c_1^g and c_2^g are the comprehensive change points, which from now on I will call them as general change points, which are of primary interest and assumed as such:

$$c_1^g \sim t_{\{\nu^{\mathrm{cp1}}\}}(520, 200^2), \quad (8)$$

$$c_2^g \sim t_{\{\nu^{\mathrm{cp2}}\}}(2545, 200^2), \quad (9)$$

where

$$\nu^{\mathrm{cp1}} \sim \mathrm{Exp}(1/30), \quad (10)$$

and

$$\nu^{\mathrm{cp2}} \sim \mathrm{Exp}(1/30). \quad (11)$$

The mean and scale values of the t-distributions in Equations 6 to 9 were standardized with respect to the mean and standard deviation of the age model before conducting the analyses. The normality parameter in each t-distribution of the model is specified using an exponential distribution with a mean value of 30.

If not defined as zero, the parameters of each regression are defined as:

$$\alpha_j^k \sim t_{10}(0, 2^2), \quad (12)$$

$$\beta_j^k \sim t_{10}(0, 2^2). \quad (13)$$

However, according to our model assumptions $\beta_1^1, \beta_2^1, \beta_3^1, \beta_1^2, \beta_2^2, \beta_3^2, \beta_1^3, \beta_3^3, \alpha_3^4, \beta_3^4, c_1^4, \beta_1^5, \beta_2^5$ are assumed to be zero. For details, please refer to the JAGS model provided at https://github.com/zboraon/LakeBafeClosure_Bayesian_cps.

The posterior distributions of the model were obtained using Gibbs sampling through the JAGS program (Plummer, 2003) and the runjags interface (Denwood, 2016) in R (R Core Team, 2023). After discarding the initial 10,000 adaptation and burn-in steps, the Gibbs sampling process was performed for the standardized data model in JAGS. To ensure convergence, four separate Markov chain Monte Carlo (MCMC) chains with random initial points were ran, each consisting of 50,000 iterations for every dataset. The convergence of the Bayesian model was assessed by examining the trace plots, autocorrelation plots, effective sample size statistics, Gelman-Rubin statistics, and density plots, stacked for all four MCMC runs for all parameters (Figures S1–S6). The 89% highest density intervals (HDI), which provide uncertainty intervals for the outcomes, are presented following the methodology outlined by Kruschke (2015).

4. Results and Discussion

This study utilizes a HBCPA that assumes piecewise linear regressions before and after each change point, based on the two-step closure hypothesis of Lake Bafa described in Akçer-Ön et al. (2020). The assumptions for the model vary for each dataset, with three linear levels around two change points for $\delta^{18}O_F$ and $\delta^{13}C_F$, mixed levels and trends around two change points for $\delta^{18}O_O$ and TOC, and a single change point with trend lines on both sides for $\delta^{13}C_O$. Prior visual observations of the data were taken into account to establish these model settings and to determine which α and β values are zero, as explicitly given in Section 3.2 and in the JAGS model given in https://github.com/zboraon/LakeBafeClosure_Bayesian_cps.

Additionally, alternative approaches were explored for analyzing each dataset during the research process of this study. However, these alternative approaches were not included in the main analyses and are not presented in this paper. For example, trend lines spanning between and beyond change points were utilized when analyzing the $\delta^{18}O_O$ data (see the top plot in Figure 3). However, the MCMC runs did not converge for this approach, possibly due to model misspecification issues. Moreover, a single change point assumption was adopted for the $\delta^{13}C_O$ data, as alternative change point assumptions did not suggest a change at the isolated lagoon-to-lake transition. The results indicated a change occurring at a time point that is out of the context of this article. Therefore, the model specifications used in this study support the claims of a two-step transition and allow each model to converge to relatively meaningful dates.

The residual errors of the regression models in each segment are assumed to follow a *t*-distribution, as are the change point locations in each segment. The hyperparameters for the mean parameters of the *t*-distributions for the general change points (Equations 8 and 9) were selected based on the mean values reported in Akçer-Ön et al. (2020, p. 670), indicating that Lake Bafa started its transition to an isolated lagoon around 1180/1148 BCE (equivalent to 3130/3098 years BP), completed the transition by around 33/20 BCE (equivalent to 1983/1970 years BP), and fully transitioned to a closed brackish lake around 1397/1465 CE (equivalent to 553/485 years BP). The hyperparameters for the scale parameters of the *t*-distributions for the change points (Equations 6 to 9) were chosen with consideration given to its ability to span almost a millennium when multiplied by a factor of two. The limited

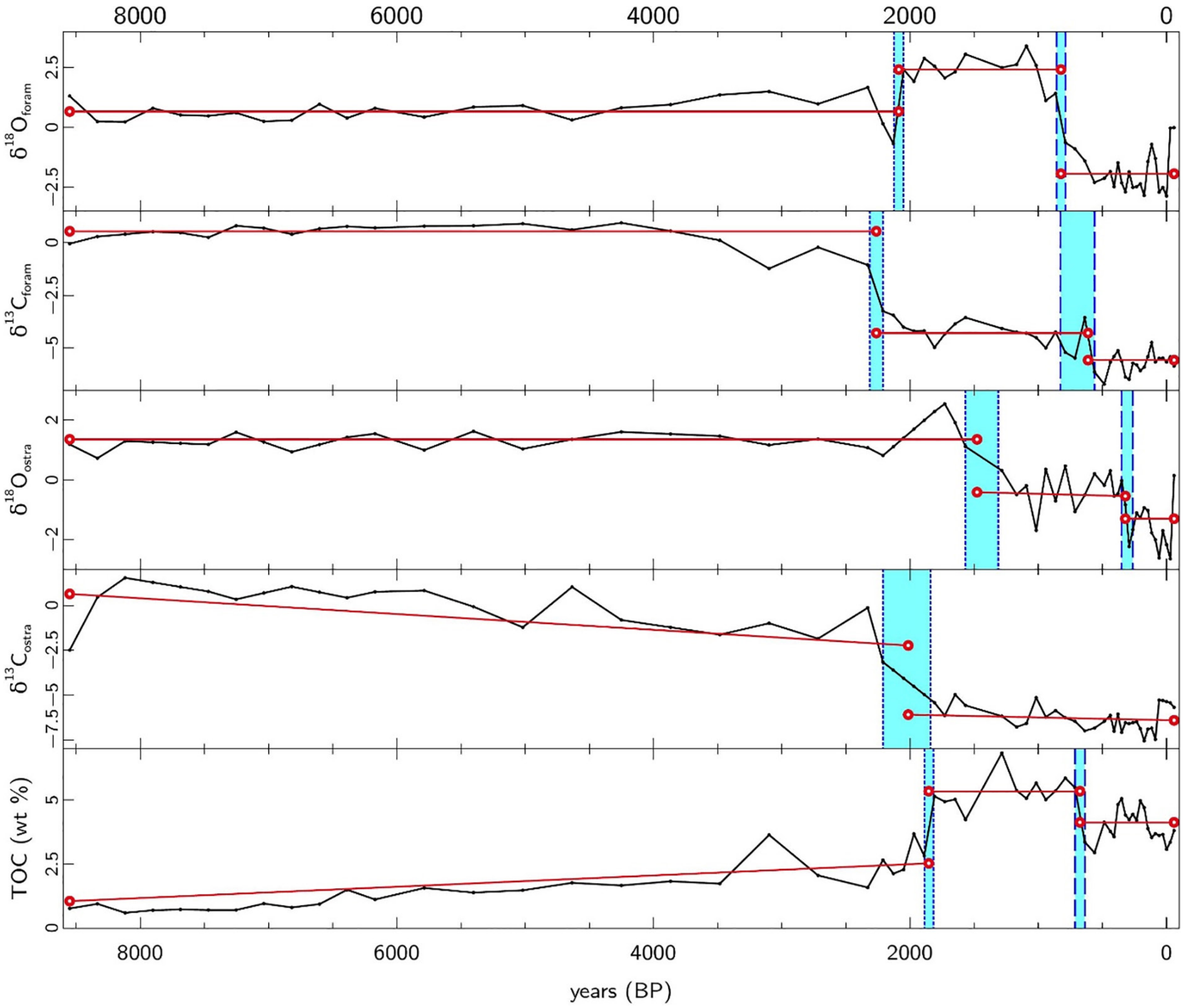

Figure 3. The figure displays the locations of the change points obtained from the change point analysis superimposed on the proxy time series. The cyan shaded regions represent the 89% highest density intervals (HDIs) of the posterior distributions of each change point. Within each segment, the red line segments show the piecewise linear regressions fitted to the median values of the posterior distributions of the regression parameters for each model.

Table 1. The top panel shows the uncertainty intervals of the start and end dates of environmental changes, obtained from the "preferred" age model proposed by Akçer-Ön et al. (2020, Table 3). The uncertainties have been expressed as 95.4% "credible interval". The lower panel of the table shows the results of the hierarchical change point analyses for each proxy data and the general change points obtained in this study. The columns display the median values of the posterior distributions for each change point and their uncertainties are represented as 89% HDIs.

	marine-to-isolated lagoon cp-2 (years BP)			isolated lagoon-to-lake cp-1 (years BP)		
Results from Akçer-Ön et al. (2020)		Start of the transition 3905–1509	End of the transition 2155–1774		Start of the transition 984–602	End of the transition 595–385
Proxy	Median	HDI high	HDI low	Median	HDI high	HDI low
$\delta^{18}O_F$	2085	2120	2050	820	855	790
$\delta^{13}C_F$	2260	2315	2210	610	825	560
$\delta^{18}O_O$	1480	1565	1310	320	350	260
$\delta^{13}C_O$	2010	2210	1840	—	—	—
TOC	1850	1890	1815	675	710	645
General cp's	2060	2250	1870	595	780	425

number of available datasets makes it challenging to obtain reliable estimates of parameters in statistical models. While using more informative priors than those specified in Equations 6 to 9 could potentially impact the results significantly, doing so would require disregarding the proxy data utilized in this study. However, if weaker priors are adopted, it would overlook the significant findings of Akçer-Ön et al. (2020), who utilized a valuable multiproxy approach with a primary focus on the faunal distribution within the core. To address this issue, the information from the faunal distribution data and other geochemistry data (specifically, μ-XRF elemental counts) are incorporated into the model through prior distributions and their hyperparameters (Equations 6 to 9).

The dates of the transitions obtained from the "preferred" age model are listed in Table 3 of Akçer-Ön et al. (2020) and sum-

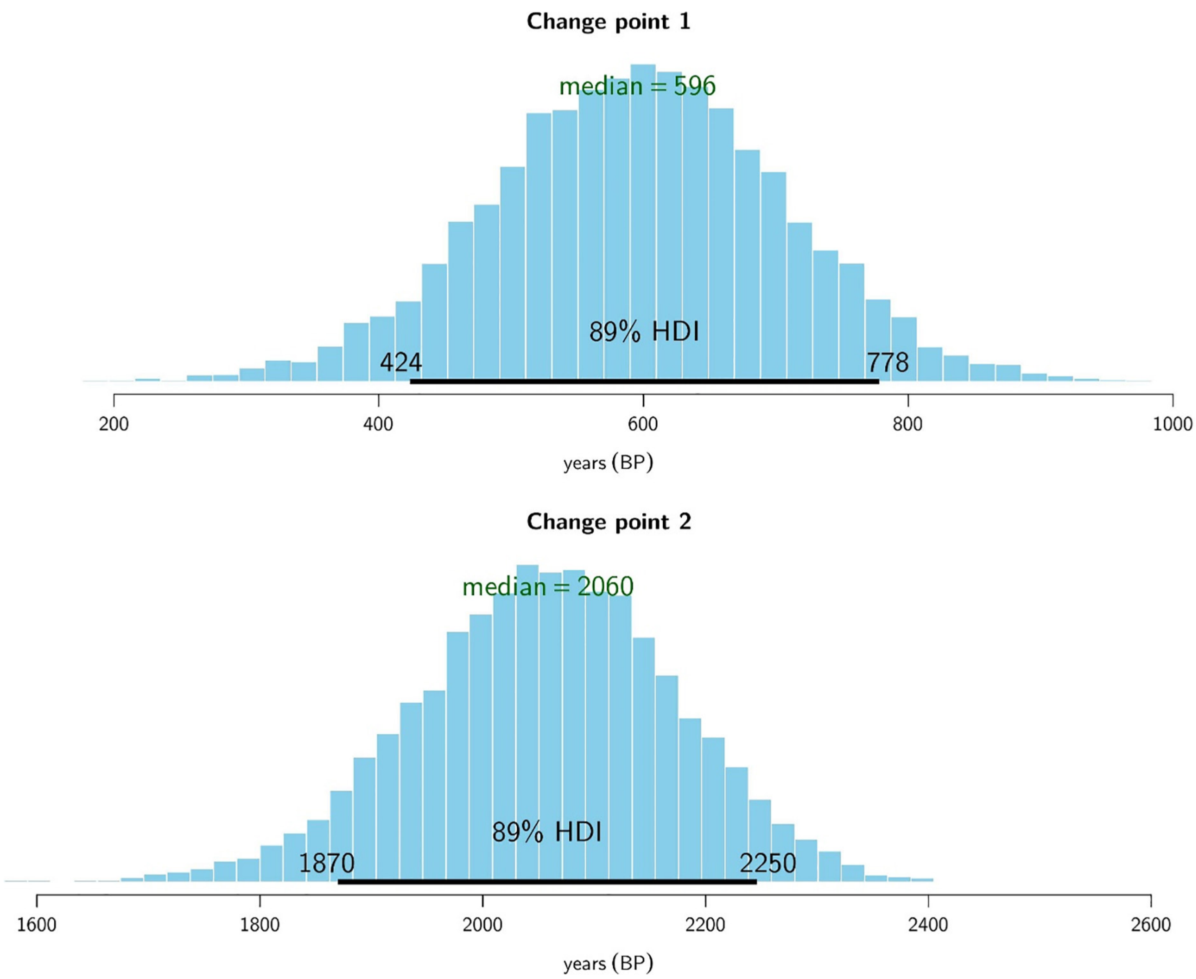

Figure 4. The figure exhibits the posterior distributions of the general change points, including their median values and 89% HDIs. The results of the transition from isolated lagoon-to-lake are displayed in the upper figure, while the results of the marine-to-isolated lagoon transition are shown in the lower figure.

marized in Table 1 of this study. These dates were determined based on the transition depths identified using multiproxy data, which included changes in faunal, lithostratigraphic, and geochemical characteristics along the core. The study aimed to demonstrate that the timing of the closure of Lake Bafa differed significantly from previous studies (Aksu et al., 1987; Knipping et al., 2008; Müllenhoff et al., 2004). Therefore, in order to be as cautious as they can, the presented dates include the widest possible uncertainties, taking into account different age-depth models.

The results of this study for each proxy data (Figure 3 and Table 1) show slightly different transition dates than those presented by Akçer-Ön et al. (2020), where each of the transitions of each proxy data are assumed to reflect phase transitions of environmental conditions. The dates and associated uncertainties of the general change points (Table 1 and Figure 4) obtained via the hierarchical model, which are 2060 (2250–1870) years BP and 595 (780–425) years BP, does not contradict with the proposed intervals by Akçer-Ön et al. (2020). The discrepancies in the transition dates between the results of each single proxy dataset, the multiproxy results of Akçer-Ön et al. (2020), and the general change points of this study are probably attributable to differences in sampling methods, sampling resolutions, bioturbation in the sediment column, and sensitivity of different proxies to transitions. Moreover, Salihoğlu & Akçer-Ön (2020), who conducted a recent study based on the cluster analysis of ostracod and foraminifer species counts, reported transition dates of 2200 ± 70 and 600 ± 80 years BP for marine-to-isolated lagoon and isolated lagoon-to-lake transitions, respectively. These dates are in close agreement with the results of our study.

5. Conclusions

The proposed method in this study employs a hierarchical Bayesian change point analysis to address the issues of "subjective" selection of transition points and large uncertainties of transition dates in a previous study on Lake Bafa. The proposed method is applied to the TOC data, and stable oxygen and carbon isotope data of foraminifers and ostracods from the BAFA09P02 core. The results suggests that, the transition from marine to isolated lagoon of Lake Bafa might have taken place within the period of 2250–1870 years BP (equivalent to 300 BCE–80 CE), with a median value of 2060 years BP (equivalent to 110 BCE), where the uncertainty is expressed as 89% HDI. And, the transition from isolated lagoon to lake is estimated to have occurred within the period of 780–425 years BP (equivalent to 1170 CE–1525 CE), with a median value of 595 years BP (equivalent to 1355 CE), where the uncertainty is expressed as 89% HDI. Furthermore, the study contributes to the field of earth sciences by utilizing a hierarchical change point approach for analyzing paleoenvironmental data.

Acknowledgements Figures 2-3 were produced utilizing Veusz 3.6.2, an open-source scientific plotting program, while Figure 4 was generated using the R software package. In addition, the language of this study was subject to editorial and refinement by OpenAI's ChatGPT, and then further reviewed by Dr. Sena Akçer-Ön and the author of this study.

Code and data availability All the data and codes used to generate the results can be found at https://github.com/zboraon/LakeBafeClosure_Bayesian_cps.

Appendix 1. Supplementary figures

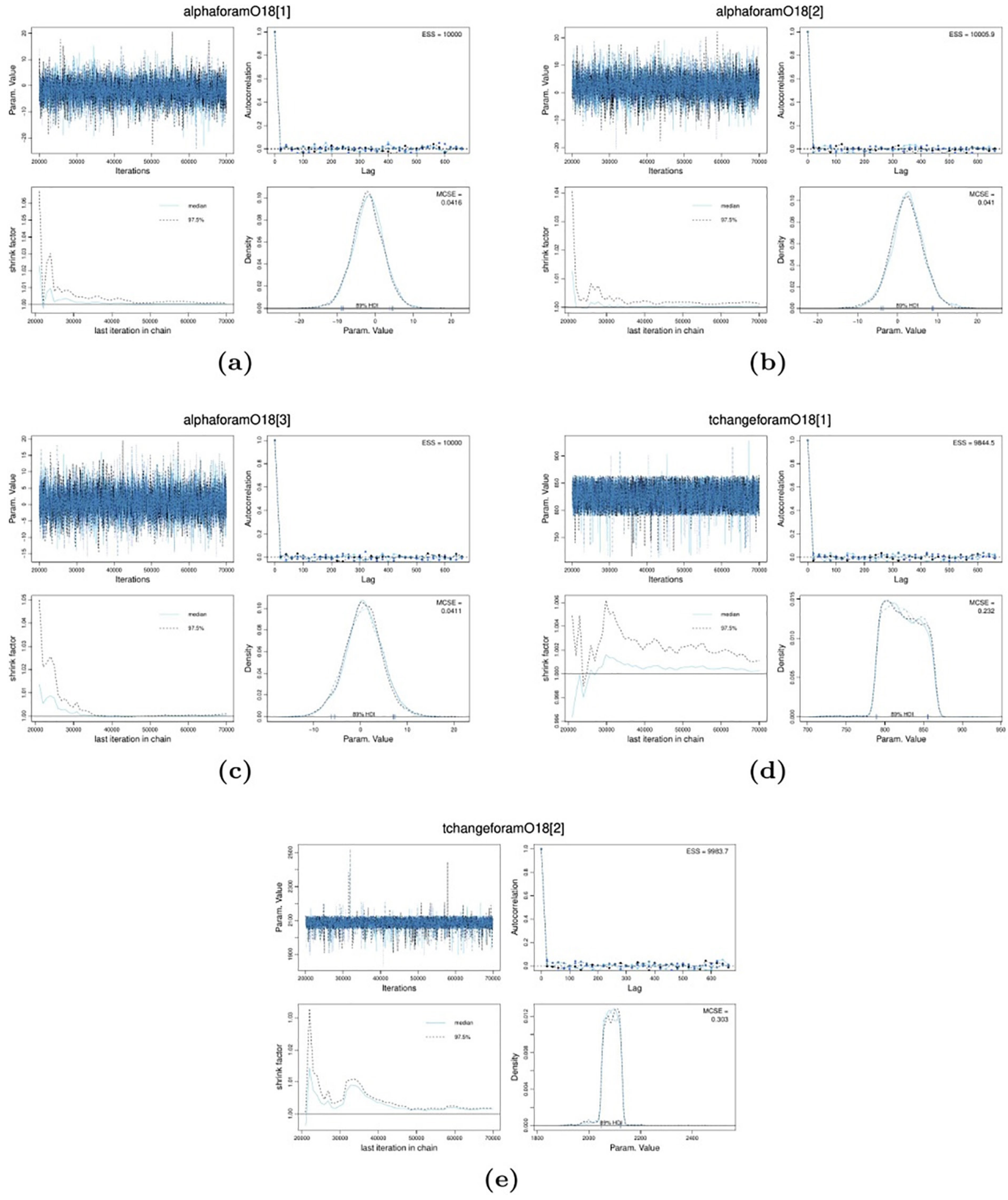

***Fig. S1**: Trace, autocorrelation, Gelman-Rubin statistic, and density plots are shown for all four runs of α_1, α_2, α_3, c_1, and c_2 pertaining to $\delta^{18}O_F$.*

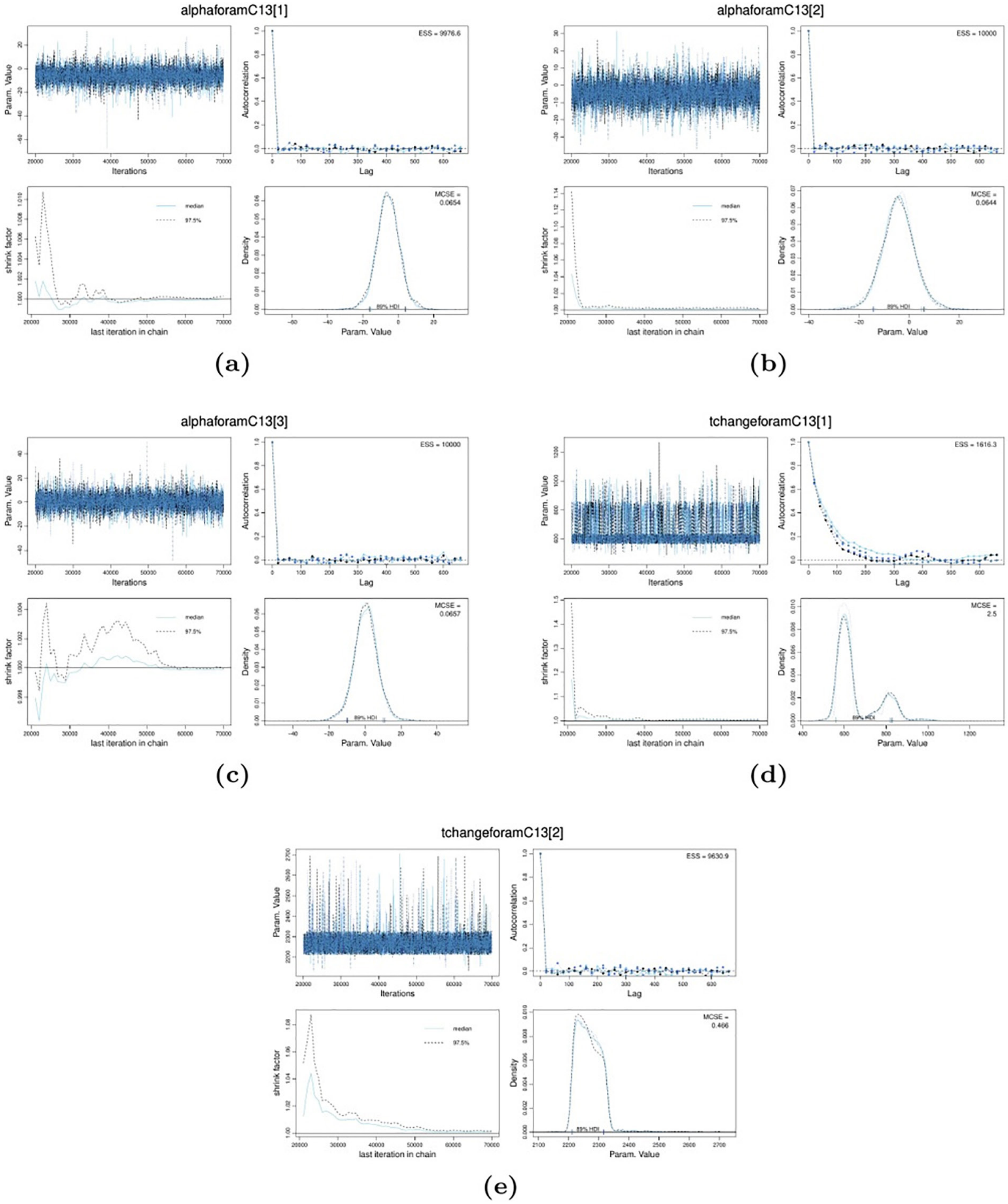

Fig. S2: *Trace, autocorrelation, Gelman-Rubin statistic, and density plots are shown for all four runs of* α_1, α_2, α_3, c_1, *and* c_2 *pertaining to* $\delta^{13}C_F$.

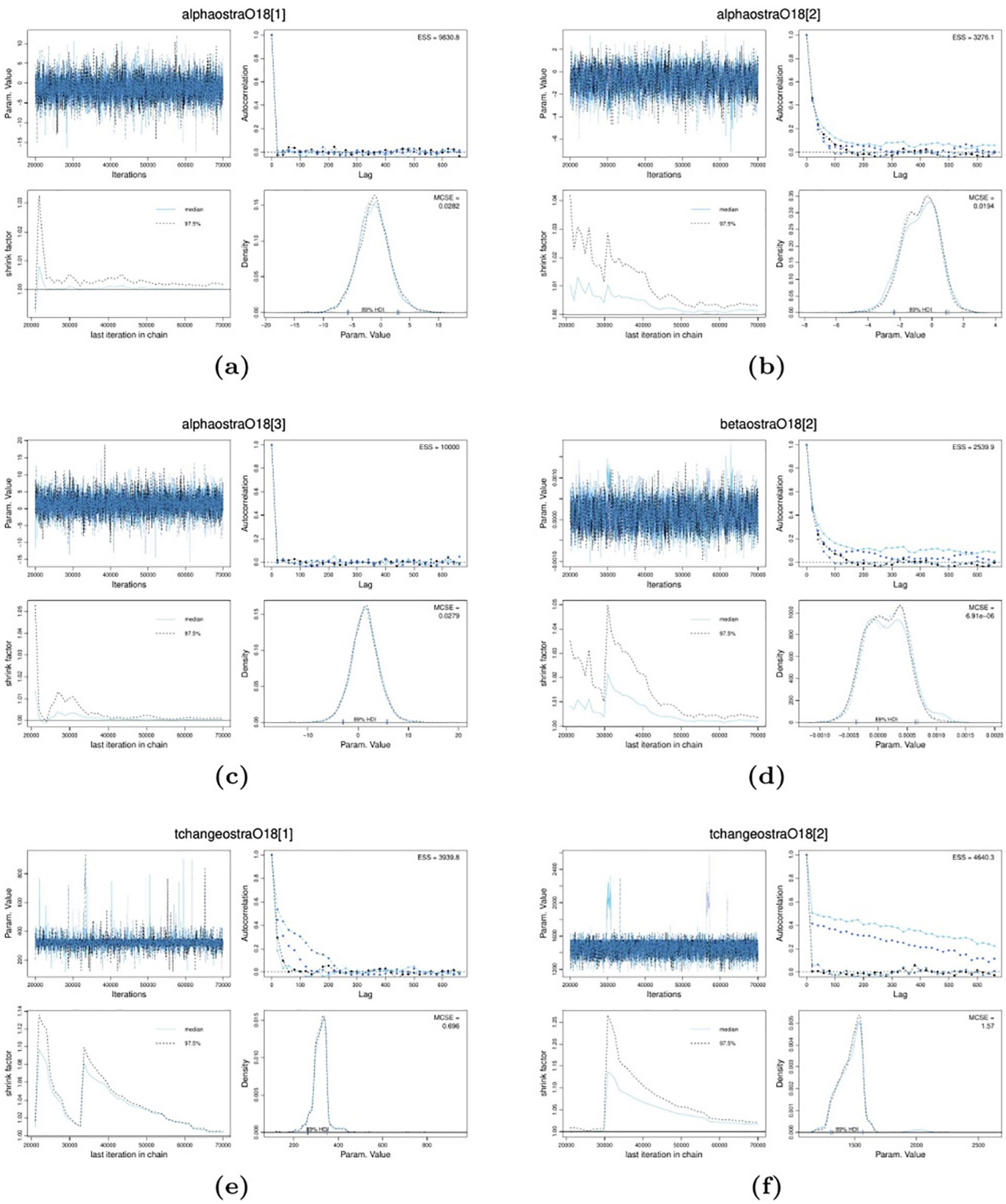

***Fig. S3**: Trace, autocorrelation, Gelman-Rubin statistic, and density plots are shown for all four runs of α_1, α_2, α_3, β_2, c_1, and c_2 pertaining to $\delta^{18}O_O$.*

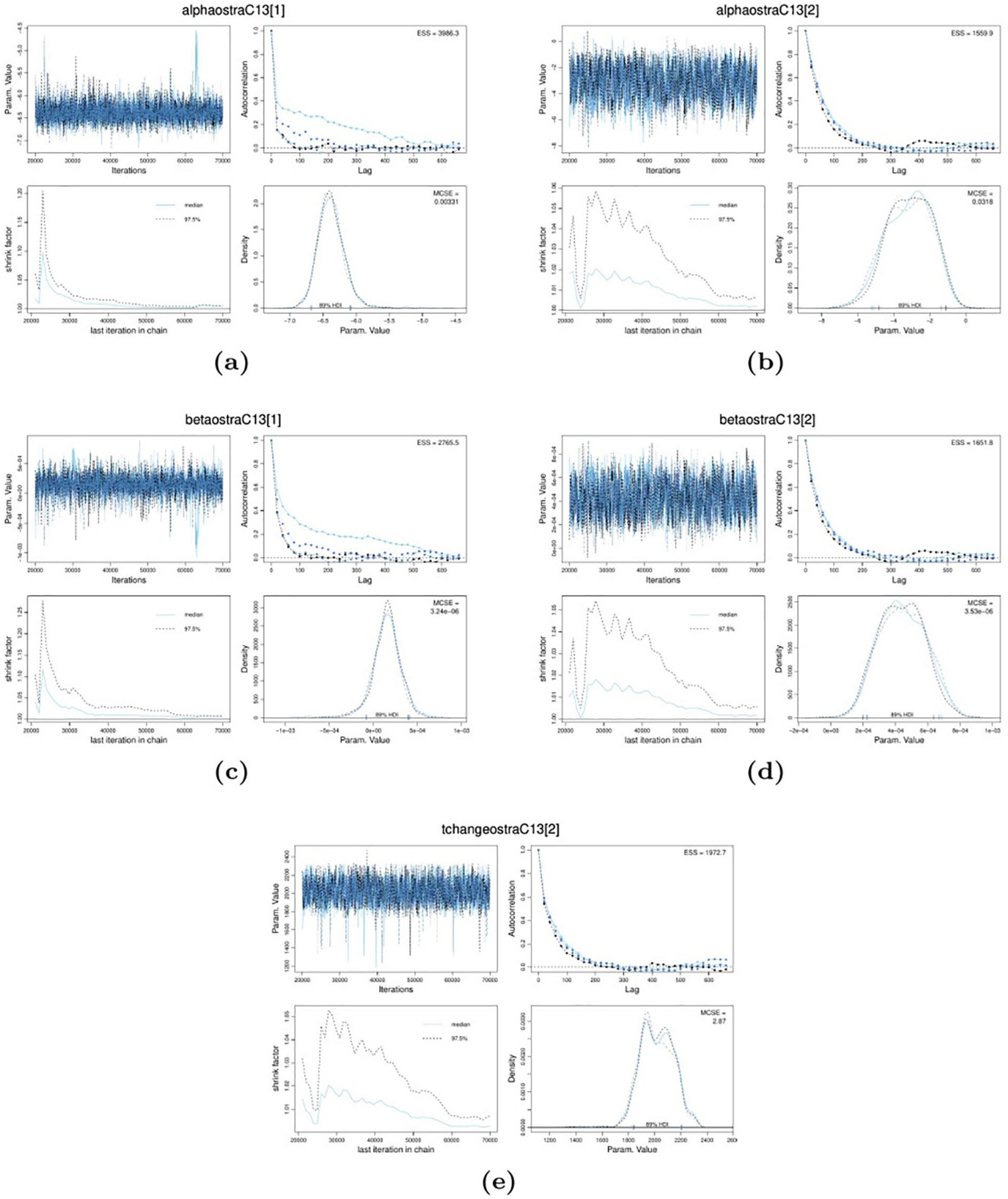

Fig. S4: *Trace, autocorrelation, Gelman-Rubin statistic, and density plots are shown for all four runs of* α_1, α_2, β_1, β_2, *and* c_2 *pertaining to* $\delta^{13}C_O$.

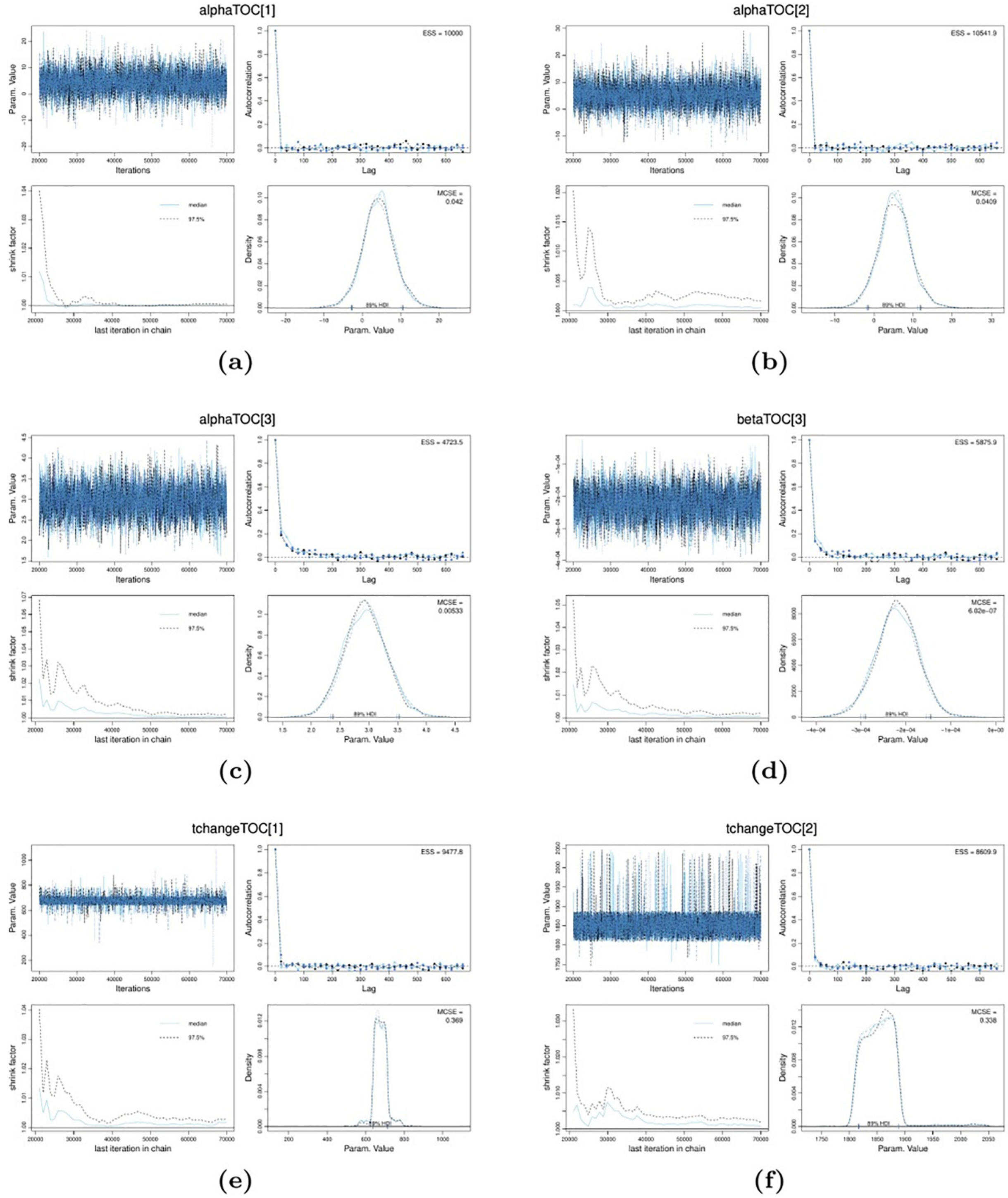

Fig. S5: *Trace, autocorrelation, Gelman-Rubin statistic, and density plots are shown for all four runs of α_1, α_2, α_3, β_3, c_1, and c_2 pertaining to TOC.*

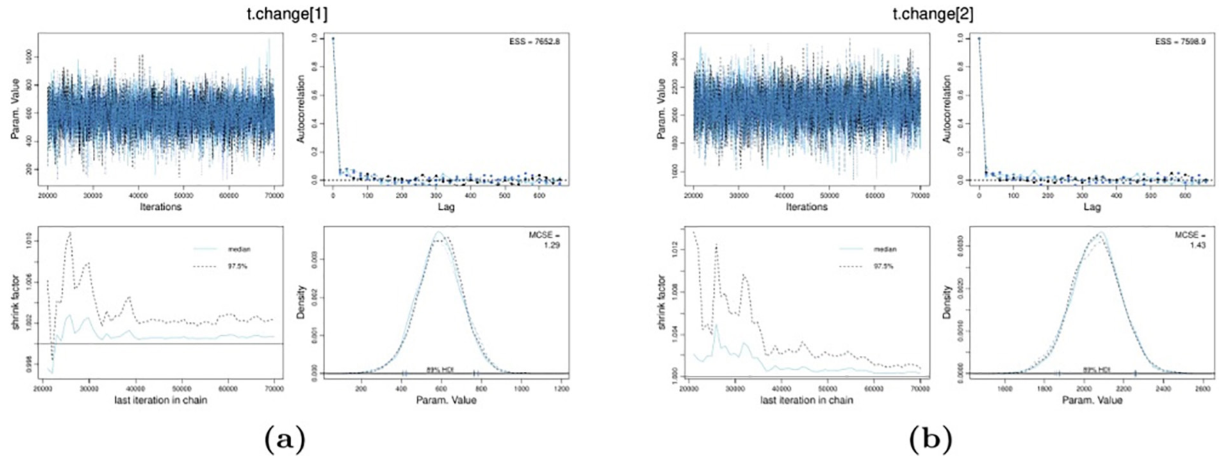

Fig. S6: Trace, autocorrelation, Gelman-Rubin statistic, and density plots are displayed for all four runs of the first and second general change points.

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