A novel carbon cycle turbulence index identifies environmental and ecological perturbations

Z.-H. Li\textsuperscript{1}, Z. Guo\textsuperscript{2}, Z.-Q. Chen\textsuperscript{2}, S.W. Poulton\textsuperscript{1,3}, Y. Bao\textsuperscript{4}, L. Zhao\textsuperscript{1*}, F.-F. Zhang\textsuperscript{5}

Abstract

Earth’s history has been characterised by complex interactions between life and the environment, which are often difficult to resolve. Here, we propose a new carbon cycle turbulence index (CTindex), based on the carbonate-carbon isotope (\(\delta^{13}C_{\text{carb}}\)) record, to measure the extent of environmental perturbation over the last billion years. The CTindex trend is closely linked to Phanerozoic biotic extinction rates (ERs), as calculated from a palaeobiology database, supporting a strong environmental control on biotic ERs. We use the empirical CTindex—ER relationship to compare the extent of environmental perturbation due to greenhouse gas emissions with that during the Permian-Triassic (PTr) transition (~252 Ma), representing the most severe mass extinction of the Phanerozoic. At the current peak of fossil fuel emissions, the pronounced CTindex peak greater than that which occurred during the PTr transition is indicated, which suggests the potential for a severe “sixth mass extinction” in the future.

Introduction

The evolution of life on Earth has been punctuated by extreme environmental/climatic events, often leading to mass extinctions (Chen and Benton, 2012; Rothman, 2017). Carbon cycle perturbations, global warming or cooling, and widespread anoxia have all played major roles in shaping the course of biotic macroevolution (Payne \textit{et al.}, 2020). However, there is no general model that encompasses the range of scenarios documented by the geological record. For example, in terms of global \(\delta^{13}C\) records, negative (\textit{e.g.}, end Permian) and positive (\textit{e.g.}, end Ordovician) excursions have both been linked to biotic extinctions (Fan \textit{et al.}, 2020). Thus, while major biotic events were linked to intervals of environmental perturbation and ecologic disturbance, they were not universally driven by one particular environmental process. However, there are no reliable proxies for measuring the extent of carbon cycle instability and associated environmental stress through Earth history.

Here, we develop a carbon cycle turbulence index (CTindex) to measure perturbations in the \(\delta^{13}C_{\text{carb}}\) record (Cramer and Jarvis, 2020) over the last 1,000 Myr. The CTindex emphasises perturbations to the carbon cycle as a metric for ecosystem instability. The rationale for using \(\delta^{13}C_{\text{carb}}\) perturbation is because the \(\delta^{13}C_{\text{carb}}\) Record is robust and at high resolution, and short term (0.5–10 Myr) \(\delta^{13}C_{\text{carb}}\) variability over the past 1,000 Myr has been suggested to record ocean-atmosphere system instability (Rothman, 2017). The CTindex is calculated according to Equation 1:

\[
\text{CTindex}(t) = \left( \frac{1}{N} \sum_{i=1}^{N} [F(i) - \mu(t)]^2 \right)^{1/2}
\]  

(Eq. 1)

To measure the degree of carbon cycle turbulence at each point (CTindex \((t)\)), over a pre-determined duration (\textit{e.g.}, \(\tau_{\text{span}} = 0.05\) Myr), we compiled all the datum points within the \(\tau_{\text{span}}\) (centred on the calculating point, \(t\)) in array F. In this case, N and \(\mu(t)\) represent the number and average isotopic value of the array F, respectively, where \(n\) is a statistical control to avoid a situation where the sum of the mean deviations is zero. When \(n = 2\), the output of the calculation, CTindex, \((t)\), is equal to the standard deviation of the array F (see sensitivity tests for parameters \(\tau_{\text{span}}\) and \(n\) in Supplementary Information). Thus, major positive and negative excursions will both result in a CTindex peak.

Phanerozoic biotic extinction rates (ERs) at the generic level were derived from a palaeobiology database (PalaoDB), and are applied to represent biodiversity changes and ecologic disturbance for comparison with CTindex values (Fig. 1). The fossil


1. State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan 430074, China
2. State Key Laboratory of Biogeology and Environmental Geology, School of Earth Sciences, China University of Geosciences, Wuhan 430074, China
3. School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK
4. Institute of Remote Sensing and Geographical Information Systems, School of Earth and Space Sciences, Peking University, Beijing, China
5. State Key Laboratory for Mineral Deposit Research, School of Earth Sciences and Engineering Frontiers Science Center for Critical Earth Material Cycling, Nanjing University, Nanjing 210023, China

* Corresponding author (email: zhong.qiang.chen@cug.edu.cn; lszhao@cug.edu.cn)
record often documents a direct link between enhanced ERs and dramatic reductions in biodiversity, or major ecologic disturbance, during mass extinctions (Alroy et al., 2008). Hence, relationships between CTindex peaks and higher ER values can be employed to investigate coincidence between catastrophic environmental stress and biotic crises through Earth history. Moreover, increasing evidence suggests that we are in the midst of a “sixth mass extinction” (Barnosky et al., 2011; Ceballos et al., 2015), and a pronounced negative excursion in δ13CO2 caused by greenhouse gas emissions has been recorded since the onset of the industrial revolution (Graven et al., 2020). In order to investigate the current and potential future significance of rising greenhouse gas emissions on biotic ERs, we compare the present day CTindex value to that observed during the Permian/Triassic (PTr) transition, representing the most severe mass extinction of the Phanerozoic.

Results and Discussion

CTindex vs. environmental perturbations. Our reconstruction of the CTindex through time (Fig. 1; analytical methods and database details are given in the Supplementary Information) highlights that it is both the magnitude and duration of the carbon cycle perturbation that exhibits a major link to the extent of environmental and biotic change. The CTindex offers a unique measure of the intensity of δ13C fluctuations, which reflect carbon cycle perturbation and the dynamic balance between the input of carbon and its burial as carbonate and organic matter (Kump and Arthur, 1999). As such, the CTindex peaks during the late Tonian, through the Cryogenian and Ediacaran glaciations, and into the Cambrian (Fig. 1), broadly correlate with periods of environmental oxygenation (Canfield et al., 2007; Lyons et al., 2021). The major variability evident in CTindex values (in both magnitude and frequency) reflects well documented instability in the extent of Earth surface oxygenation over this interval (Canfield et al., 2008; Sahoo et al., 2016; He et al., 2019; Li et al., 2020).

As the Earth progressed to near modern levels of oxygenation in the Palaeozoic (Krause et al., 2018) and life continued to evolve and diversify (Lenton et al., 2016), the ensuing environmental stability generally resulted in lower peaks in CTindex values, with the exception of the major peak across the PTr boundary (Fig. 1). However, despite the general decrease, the CTindex trend is of sufficient resolution (see Fig. S-4) to distinguish nearly all of the major individual carbon cycle perturbations during the Phanerozoic (Fig. 1). Thus, although there are many potential controls on the δ13C databased record (Lenton et al., 2018), the CTindex provides an integrated and robust assessment of the overall extent of environmental perturbation.

Deciphering extinction rates and environmental perturbations. The CTindex trends correlate with biodiversity fluctuations, ERs and ecologic disturbance through the Neoproterozoic and Phanerozoic (Fig. 1). Several important intervals of biodiversification, including the initial evolution of the Ediacaran biota, the Cambrian explosion, the Great Ordovician Biodiversification, the Carboniferous-Permian, and the mid-Triassic and Jurassic-Cretaceous radiations (Sepkoski, 1981; Alroy et al., 2008; Erwin et al., 2011; Darroch et al., 2018; Fan et al., 2020), all coincide with low CTindex values. By contrast, pronounced CTindex peaks correspond to higher ERs, as evident during mass extinctions (Fig. 1b).

However, since the datum sampling densities of δ13C database and PaleoDB are clearly different, it is difficult to directly calculate the regression relationship between the CTindex and ERs. To address this, we begin by identifying significant global perturbation events during the Phanerozoic (Fig. S-4, Table S-2). These 41 events comprise the major δ13Cperturbations (Rothman, 2017), mass extinctions (Bambach, 2006), and biodiversifications (Fan et al., 2020). While the CTindex trend reflects the degree of environmental perturbation on the time-scale of individual events (Fig. S-3), consideration needs to be
PaleoDB itself. For each stage, we use the maximum, minimum which also consider the potential errors caused by the explored 12 different metrics to calculate ER values (Fig. 1b), the Cambrian to the first stage of the Ordovician), and (2) events ER and low CTindex values, occurring from 541 to 480 Ma (from ing ER perturbation.

Nevertheless, the CTindex suggests that environmental turbu-

lation, but when the degree of volatility increases to a certain threshold, the biotic ER rapidly increases (e.g., the PTr and TJ mass extinctions).

In addition to distinguishing these well studied events, the logistic curve also provides new insight into broader trends through time. Here we study a major δ13CO2 events suggests that the thresholds of catastrophe in the Earth system have not changed systematically over time (Rothman, 2017). Building on this, our data implicitly suggest that, although life has evolved into more complex forms, ecosystem tolerance to environmental turbulence has not significantly improved through time (discounting the Cambrian and Silurian; Fig. S-5c). This observation naturally leads to consideration of whether the CTindex may be used to evaluate the possible nature of Earth’s “sixth mass extinction” in the modern and future environment.

Contrasting the CTindex during the PT Tr and from 1700 to 2100 A.D. Current high extinction rates of some taxonomic groups suggest that the Earth may be entering a “sixth mass extinction”, which may have a causal relationship with increasing greenhouse gases in the atmosphere (Barnosky et al., 2011; Ceballos et al., 2015). However, there is still a widely recognised “last kilometre gap” between the fossil record and the modern bio-record and their extinction rates, for the following reasons: (1) most modern data focus on terrestrial vertebrates (e.g., mammals and birds), whereas the fossil record dominantly reflects marine invertebrates (e.g., brachiopods, gastropods and bivalves) (Kocsis et al., 2019), and (2) there are different time spans when considering a particular extinction. Specifically, the “Big Five” Phanerozoic mass extinctions are only constrained across a broad time resolution of millions of years, so a comparison with modern events occurring on a timescale of a hundred to a thousand years is not straightforward, and (3) there is uncertainty in the near future. For example, calculation of ERs for modern species is hampered since it remains unknown whether “critically endangered species” will actually go extinct (Barnosky et al., 2011). (4) Other unknowns, including continental configuration, pre-existing climate state, and the extant biota at the time of CTindex perturbation might also affect how the ER responds.

To address these issues, we note that if the core hypothesis of the CTindex stands, then the sixth mass extinction should be accompanied by a distinct CTindex peak. We thus reconstruct CTindex values from 1700 to 2100 A.D., representing the time period prior to, and after, the industrial revolution, and we contrast this with the PTr transition at ∼252 Ma, representing the most severe mass extinction of the Phanerozoic. We used δ13CO2 curves from ice core to reconstruct the modern CTindex trend due to its complete and robust record over the last several centuries, in addition to the availability of modelled near future values (Rubino et al., 2013; Graven et al., 2020). However, we note that other carbon hosts, including surface ocean dissolved inorganic carbon, coral samples, and CH4 in Antarctica ice core also sensitively record significant CTindex peaks (Fig. S-7). This approach is reinforced by an observed strong similarity in the modern and future environment.

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transition, between Bed 24e to Bed 25 in the Meishan GSSP section, which documents the extinction level itself (Burgess et al., 2014). This interval has 11 original δ¹³C_carb datum points across an estimated interval of ∼3,000 years. Hence, we calculate the CT_index for both the PTr and the industrial revolution period using the same parameters (n = 1; τ_span = 100 years), and the datasets were pre-normalised to a datum density of one point per year.

The relative size of the CT_index peaks calculated under the same conditions for the two time intervals is of practical comparative significance (Fig. 3). The CT_index peak during the PTr ranges from 0.47 to 0.78, whilst the CT_index peak of the industrial revolution period ranges from 0.61 to 1.61, with the latter reflecting the predicted range for the δ¹³CO₂ trend into the near future. If fossil fuel emissions peak at the present level and are at a low level through the next century, it has been suggested (Graven et al., 2020) that δ¹³CO₂ may recover from −8.8‰ to 7.0‰, which leads to a moderate CT_index peak (line SSP1-1.9; Fig. 3). However, in other scenarios without such effective limits on fossil fuel emissions, δ¹³CO₂ will likely continue to decrease through the next century (line SSP8.5), causing a dramatic peak in the CT_index that may be even greater than the PTr CT_index peak (Fig. 3). While the current extinction of species is driven by biodiversity loss that is only partly associated with fossil fuel driven climate change, the empirical relationship between ecosystem stability and biotic ERs implies that, if fossil fuel emissions are not significantly decreased, Earth’s “sixth mass extinction” has the potential to be severe.

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Additional Information

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References

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Supplementary Information

The Supplementary Information includes:

➢ The Geochemical and Paleobiology Databases
➢ Analytical Approaches and Statistical Analysis
➢ Datum Density vs. Bias
➢ Comparison of Carbon Cycle Perturbations and CTIndex Values between the Permian-Triassic Mass Extinction and the Industrial Revolution Period of the Anthropocene
➢ Tables S-1 and S-2
➢ Figures S-1 to S-8
➢ Supplementary Information References

The Geochemical and Paleobiology Databases

The carbon isotope ($\delta^{13}$C$_{\text{carb}}$) dataset through the last one billion years is adapted from Cramer and Jarvis (2020) and collected from other key studies (Xiao et al., 2014; Zhu et al., 2019; Rooney et al., 2020; Westerhold et al., 2020). We note that $\delta^{13}$C$_{\text{carb}}$ data before and after ~650 Ma have markedly different data density (Fig. S-1), with the ~1000 to 650 Ma period having lower density and intervals with no data. However, this feature does not affect the analyses focused on the Phanerozoic.
The Sepkoski database (Sepkoski, 1996) and Paleobiology database (PaleoDB, http://www.paleobiodb.org/, http://fossilworks.org) are employed to calculate biotic extinction rates at the genus level through the Phanerozoic. The former was only used as a comparison in Figure S-2, while the latter was used to run the CT_{index} curves. It should be noted that the raw dataset (PaleoDB) that was used in this study follows Kocsis et al. (2019), which was downloaded on May 31, 2019 (https://github.com/divDyn/ddPhanero/raw/master/data/PaleoDB/2019-05-31_paleoDB.RData). Time series were drafted based on the resolution of Stages (Ages), which is the highest resolution of the PaleoDB. Twelve different metrics (Fig. 1b) were set to calculate ER based on three different data treatments, including: raw data, Classical Rarefaction (cr), and Shareholder Quroum Subsampling (sqs). In addition, four different rate calculation methods were employed, including: per capita rates, corrected three-timer rates, gap-filler equations, and second-for-third substitution rates. Kocsis et al. (2019) suggested metric, with sqs data treatment and second-for-third substitution rates (‘sqs2f3’), should be used as the standard extinction rate trend in this study. The other metrics were used as a necessary contrast to form the error bars in Figure 2.

Analytical Approaches and Statistical Analysis

All mathematical approaches were performed in R (for the PaleoDB) and Matlab (other processes). The original δ^{13}C_{carb} database has an uneven sample resolution across different intervals. We used an interpolation method to average all densities to 0.02 Ma per point (Fig. S-1), which is employed in Matlab by using the function ‘interp1’ with method ‘Linear’. In particular, the original δ^{13}C_{carb} database (Westerhold et al., 2020) has a much higher resolution from 0 to 0.5 Ma (~0.005 Ma per point), whilst the resolution from 750 to 2100 A.D. is ~1 year per point. For these higher resolution intervals, we did not lower the resolution to be consistent with more ancient intervals. The CT_{index} value therefore reflects δ^{13}C_{carb} variability not only on a long-timescale (>10 Ma), but also within a short-timescale (>0.02 Ma). Multiple studies have suggested that δ^{13}C_{carb} may dominantly reflect the original ocean-atmosphere carbon isotope composition and can sensitively record oscillations across this short-timescale (Bachan et al., 2017), although local restriction, water-mass ageing and authigenic carbonate formation may also affect the isotopic record (Swart, 2008). The CT_{index}, however, weakens the direction or simple magnitude of δ^{13}C_{carb} excursions and emphasises the possibility of isotopic instability over a predetermined timespan (see sensitivity test in Fig. S-3 for further detail).

The post-interpolation δ^{13}C_{carb} dataset was used to calculate the CT_{index} according to Equation 1. And the number of datum points within a predetermined τ_{span} should be kept the same to ensure that the calculation of
CT\textsuperscript{index} is not affected by different datum densities across different time periods. Given the fact that differentiation between the parameters \(\tau_{\text{span}}\) and \(n\) will significantly shift the output of the calculation, we employed sensitivity analyses of \(\tau_{\text{span}}\) and \(n\) to the CT\textsuperscript{index} (Fig. 1), indicating that as both \(\tau_{\text{span}}\) and \(n\) increase, the output of the CT\textsuperscript{index} also increases synchronously. However, when the datum density is high (e.g., PTr interval and Cenozoic), there is little deviation when these parameters change (differentiation <10 %). We note here that the parameter \(\tau_{\text{span}}\) plays a more important role in running CT\textsuperscript{index}, and thus dependent on the \(\tau_{\text{span}}\) used, a very different CT\textsuperscript{index} value may be obtained. As shown in Figure S-3, we used some simple ‘witches hat’ pulses (linear increase followed by linear decline at the same rate), and the time-dependent forcing pulses for \(\delta^{13}\text{C}_{\text{carb}}\) variations are given in Equations S-1-3:

\[
Pulse_1 = [0:0.1:1.2], [0 0 5 0 0 -5 0 0 5 0 5 0] \quad \text{(Eq. S-1)}
\]

\[
Pulse_2 = [0 0.4 0.5 0.6 1.2], [0 0 5 0 0] \quad \text{(Eq. S-2)}
\]

\[
Pulse_3 = [0 0.4 0.6 0.7 0.9 1.2], [0 0 7 7 0 0] \quad \text{(Eq. S-3)}
\]

where the first vectors are time (in Myrs) and the second vectors are the \(\delta^{13}\text{C}_{\text{carb}}\) values (in ‰). Different \(\tau_{\text{span}}\) values were used for a sensitivity test. Rothman (2017) observed that the duration of the major carbon isotope events through the entire Phanerozoic is approximately limited between \(10^4\) to \(10^6\) years. This means that if we employ a longer (larger) \(\tau_{\text{span}}\) (e.g., \(\tau_{\text{span}} \geq 1\) Ma), the CT\textsuperscript{index} is unable to distinguish individual events, and the CT\textsuperscript{index} curve would represent a mixed signal of adjacent events (Fig. S-3a). This feature is directly evidenced by Pulse_1, which also shows that the CT\textsuperscript{index} is not sensitive to the direction of the carbon isotope excursion. In addition, multiple carbon isotope events have different degrees of offset and duration (simplified as Pulse_2 and Pulse_3). When \(\tau_{\text{span}}\) is greater than the event duration, calculated CT\textsuperscript{index} values and the timing of the CT\textsuperscript{index} perturbation are not accurate (Fig. S-3b). When \(\tau_{\text{span}}\) greatly exceeds the event duration, CT\textsuperscript{index} values approach a straight line with artificially high values (Fig. S-3b). Hence, the \(\tau_{\text{span}}\) value may be greater than the events of relatively small duration (e.g., PTr) and lower than the events of relatively large duration (e.g., SPICE). In this case, we suggest to employ a relatively low \(\tau_{\text{span}}\), which should be similar to the minimum duration of the events in question (e.g., the duration of the PTr = \(~0.06\) Ma, and the duration of the PETM = \(~0.08\) Ma). In this case, a \(\tau_{\text{span}}\) of 0.05 Ma is our recommended standard value, which is greater than the average density (= 0.02 Ma per point) of the \(\delta^{13}\text{C}_{\text{carb}}\) database, but less than the more short-lived intervals of interest. The parameter \(\tau_{\text{span}}\) may still be accurate (but smaller) if the resolution of carbon isotopes is further
improved. For instance, we employ a $\tau_{\text{span}}$ of 0.0001 Ma (100 years) for our subsequent evaluation of the interval from 700-2100 A.D.

In order to reveal the relationship between $\text{CT}_{\text{index}}$ and ER, we employed a logistic function to test the data of 41 events (Eq. S-4):

$$P(x) = \frac{K + P_0 e^{rx}}{K + P_0 (e^{rx} - 1)}$$  \hspace{1cm} (Eq. S-4)

which calculates the logistic curve (sigmoid curve) and is used to run the logistic regression, where $x$ denotes the $\text{CT}_{\text{index}}$, and $P(x)$ denotes the calculated ER. $P_0$ and $K$ represent background ER and maximum ER values, respectively, and $r$ is a free parameter measuring how fast the curve varies. When the $\text{CT}_{\text{index}}$ is infinite, ER is equal to $K = 1$, indicating that all organisms became extinct. A logistic function was fitted to the data (Fig. 2). All the datum points contributing to Figure 3 are listed in Table S-2. When $\text{CT}_{\text{index}}$ approaches zero indefinitely, the ER = ~0.086.

In order to reveal the similar statistical distribution of the $\text{CT}_{\text{index}}$ and biotic extinction rates, we employed a log-normal distribution function to test the original databases (Eq. S-5):

$$\varphi \ln (x) = \frac{1}{\sqrt{2\pi}\sigma x} \exp \left(-\frac{(\ln x - \mu)^2}{2\sigma^2}\right)$$  \hspace{1cm} (Eq. S-5)

$$E(X) = e^{\mu + \sigma^2/2}$$  \hspace{1cm} (Eq. S-6)

$$\text{var}(X) = (e^{\sigma^2} - 1) \times e^{2\mu + \sigma^2}$$  \hspace{1cm} (Eq. S-7)

where $x$ denotes that the $\text{CT}_{\text{index}}$ and generic ER are a random variable. Both $\mu$ and $\sigma$ are free parameters in this distribution function, which are the mean and standard deviation of logarithms of variables, respectively. The mathematic expectation ($E(X)$) and variance ($\text{var}(X)$) were calculated by Equations S-6 and S-7, respectively. The histograms of the $\delta^{13}C_{\text{carb}}$ and ER values fit with log-normal distribution functions (Fig. S-2, Table S-1). The $\text{CT}_{\text{index}}$ values since the mid-Tonian are divided into two parts: 870-520 Ma and 520-0 Ma. The log-normal best fit curves of the histogram show that the $\text{CT}_{\text{index}}$ values prior to 520 Ma ($E(X) = 0.246$) are relatively higher than afterwards ($E(X) = 0.168$), implying more volatility in the carbon cycle from 860 to 520 Ma. However, we note that there are some $\delta^{13}C_{\text{carb}}$ data gaps and this reduces the accuracy of $\text{CT}_{\text{index}}$ output during the Precambrian period.
Datum Density vs. Bias

The δ¹³C_carb database and PaleoDB covering the entire Phanerozoic were used to calculate the CT_index and ER values, respectively. The uneven density distribution in the datasets is a major potential source of the error when calculating both the CT_index and the ER. As shown in Fig. S-1b, the density of the δ¹³C_carb database is lower than 0.05 Ma per point, except for some intervals of high density. Therefore, we have uniformly pre-normalised the density of the δ¹³C_carb database to 0.02 Ma per point.

The PaleoDB has a different and more complex sampling density to the δ¹³C_carb database. The density of Stage (or substage) time-bin is lower than that of the δ¹³C_carb database. Following the Sepkoski (1996) scheme, each stage has three statistical points corresponding to the start, middle and end ages. The calculated ER has the age point set to the middle age of each stage/substage. For instance, the Induan (early Triassic) contains three statistical age points calibrated to 251.9, 251.6 and 251.2 Ma. The ER of the Induan was calculated based on extinction rate data from the middle age point (251.6 Ma), and its value is 0.5, then the ER and its age for the Induan are expressed as [0.5, 251.6]. This differentiation of density causes potential error when calculating the correlation between CT_index and ERs (Fig. S-4), because the resolution of this three-statistical-points scheme is much lower than that of the CT_index curve, and the major CT_index peaks in each stage may not exactly emerge at the three-statistical-points of this stage. For instance, the onset timing of the PTr carbon isotope excursion is ~251.94 Ma, which is apparently not at the three-statistical-points of the Changhsingian. To minimise this bias, we assume that the onset timing of the major extinction events is equal to the onset timing of the major carbon isotope excursion in each stage. In other words, the ER curves have a normalised new timing abscissa, as listed in Table S-2.

In terms of the taxonomic data of the PaleoDB, the uneven collections and/or occurrences will lead to different degrees of data quality between different stages. Specifically, the periods including the early Cambrian, Silurian, and Stages Bashkirian, Kasimovian and Thanetian, are characterised by extremely low collections (red boxes, Fig. S-4a). This will likely make the calculated ERs less reliable, and for these five low-quality data intervals special attention was paid in the following CT_index and ER correlation processes.

The PTr and TJ intervals have nearly an order of magnitude higher CT_index and ERs than other events, and this can cause the correlation between them to be artificially high. Hence, the CT_index and ER values are logarithmic normalised to eliminate the effect of order of magnitude differences in correlation. As shown in Fig. S-5b,
after the logarithmic normalisation, the relationship between the CT$_{\text{index}}$ and ER remains highly relevant ($R^2 = 0.697$, $p$ values $= 5.21 \times 10^{-9}$).

Furthermore, positive correlations are also observed between the ER of various clades (phylum or class) and CT$_{\text{index}}$ values during these events (Fig. S-5d), where the slopes of the ER-CT$_{\text{index}}$ represent the tolerance of animal genera to environmental perturbation, indicating that the precise behavior of each clade is different when the CT$_{\text{index}}$ value increases. Specifically, the Cnidaria, Brachiopoda and Cephalopoda suffered more severe extinctions (higher ER-CT$_{\text{index}}$ slopes) relative to the Arthropoda, Bivalvia and Gastropoda. This indicates that the Cnidaria were physiologically fragile and more unbuffered, and the other clades were less affected and more physiologically buffered, strengthening observations on the decrease in physiologically unbuffered taxa and increase in physiologically buffered taxa after the PT$_{\text{r}}$ extinction (Knoll et al., 2007; Payne et al., 2020).

**Comparison of Carbon Cycle Perturbations and CT$_{\text{index}}$ Values between the Permian-Triassic Mass Extinction and the Industrial Revolution Period of the Anthropocene**

We highlight carbon perturbations and CT$_{\text{index}}$ values across two critical periods, represented by the most severe mass extinction of the Phanerozoic, and the last ~300 years before and after the Industrial Revolution (Suess effect). Both periods record high greenhouse gas emissions and pronounced negative excursions in $\delta^{13}$C$_{\text{carb}}$.

In the original $\delta^{13}$C$_{\text{carb}}$ database, data for the PT$_{\text{r}}$ period is proxied by the GSSP Meishan section (Burgess et al., 2014). To provide a more detailed case study, we compiled C isotope data for another three well-studied sections around the palaeo-Tethys realm, including: Zal (Iran, Zhang et al., 2018), Bálvány North (Hungary, Schobben et al., 2017), and Wadi Shahha (Arabian, Clarkson et al., 2013). During the PT$_{\text{r}}$, data density is higher than in other geologic intervals, reaching $\sim 10^{-4}$ Ma per point. Hence, we employed $\tau_{\text{span}} = 0.05$ and 0.01 to run the CT$_{\text{index}}$. Fig. S-6 shows that due to the $\delta^{13}$C$_{\text{carb}}$ excursion, the CT$_{\text{index}}$ abruptly reaches 1.2 to 1.6 in Meishan, with relatively high values in the other sections, indicating that the huge carbon cycle perturbation was clearly recorded around the entire palaeo-Tethys. With an ER of $\sim 0.81$ (Fan et al., 2020), the PT$_{\text{r}}$ is distinguished from the other events on a cross plot of ER vs CT$_{\text{index}}$ (Fig. 2). However, the datum resolution of the PT$_{\text{r}}$ event still has an unbridgeable gap relative to the modern carbon isotope record. Hence, we focus
on an extremely short period containing 11 data points from bed 24e to bed 25 of the Meishan section. This period represents a duration of ~3000 years (Burgess et al., 2014), and is characterised by a significant sharp δ¹³C_carb excursion, whilst the carbon isotope data were subjected to an Interpolation method to achieve one point per year data resolution (Fig. 3). Then a comparison can be employed between the PTr and the Industrial Revolution period across the same event duration and τ span.

In terms of the Industrial Revolution period, we compiled δ¹³CO₂ data from 700 to 2100 A.D. (Rubino et al., 2013; Bauska et al., 2015; Graven et al., 2020). For the geologic record we used carbonate carbon isotopes, but for the Industrial Revolution period we used atmospheric CO₂ carbon isotopes. While the carbon isotope signatures from these different sources have different triggering mechanisms and observations, they should result in only a minor difference in the final CT_index values. For example, for coral carbon isotope records around the world, the average declining rate = -0.022 ‰ per year from 1960 to 2000 A.D. (Liu et al., 2021); for the globally averaged δ¹³C-DIC (dissolved inorganic carbon) at the sea-surface, the declining rate = -0.013 ‰ per year from 1960 to 2000 A.D. (Kwon et al., 2021); for δ¹³CO₂ in ice core the declining rate = -0.025 ‰ per year from 1960 to 2000 A.D. (Rubino et al., 2013). These carbon carriers all record the ‘Suess effect’, which is a dilution effect whereby burning of fossil fuels increases ¹²CO₂ at a faster relative rate than ¹³CO₂ and ¹⁴CO₂ (Suess, 1955). For the δ¹³C composition of CH₄ in Antarctica ice core, the increasing rate = 0.024 ‰ per year from 1960 to 2000 A.D. (Mischler et al., 2009), which is caused by biomass burning being closely related to the agricultural source scales and population. The calculated CT_index curves for these four carbon carriers are plotted in Figure S-7. All four carriers show peaks of the same order of magnitude as during the PTr. It should be noted that the δ¹³C-coral records (orange lines) and δ¹³CO₂ (yellow lines) have totally different carbon isotopic values and shifts, but they show nearly the same CT_index curves, demonstrating that from the point of view of the CT_index, the δ¹³CO₂ record can be directly compared to the δ¹³C-coral record, and hence the palaeo-δ¹³C_carb record.

The near future data in Figure S-8 were predicted by using six scenarios based on the shared socioeconomic pathways (SSPs) from the 6th Coupled Model Intercomparing Project (CMIP6) (Graven et al., 2020), with each scenario having a profound influence on the determination of the CT_index. If δ¹³CO₂ peaks in the near future and falls back quickly, the CT_index will be limited to a much lower value, but if δ¹³CO₂ keeps falling, the ‘Suess effect’ may create a larger and sharper carbon isotope excursion than the PTr, resulting in a major CT_index peak. A τ span of 0.05 Ma was used to calculate the Industrial Revolution period CT_index data, in order to compare to the deep-time data resolution. However, as discussed in relation to the τ span sensitivity test (Fig.
S-3), when $\tau_{\text{span}}$ is a significantly larger than the duration of the event, the CT$_{\text{index}}$ approaches a straight line and represents a mixed signal within the time span. Hence, we keep all the variables (or parameters) at the same values to compare the PTr and Industrial Revolution periods. Since the time resolution of the Industrial Revolution is much higher than that of the PTr, we employed $\tau_{\text{span}} = 0.0001$ Ma (100 year) and $n = 1$ to run the CT$_{\text{index}}$ of both PTr (251.94 to 251.942 Ma) and Industrial Revolution (1700 to 2100 A.D.) periods, and the resolution of the datasets were set to equal to one point per one year by employing the function ‘interp1’ with method ‘Linear’ in Matlab.
Supplementary Tables

Table S-1 The best-fit parameters of the log-normal function fitted to the histograms.

<table>
<thead>
<tr>
<th></th>
<th>CT_index</th>
<th>Extinction rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu )</td>
<td>-3.563 -3.228</td>
<td>-1.906</td>
</tr>
<tr>
<td>( \delta )</td>
<td>1.887 1.912</td>
<td>0.837 1.013</td>
</tr>
<tr>
<td>( \mu )</td>
<td>0.168 0.246</td>
<td>0.211 0.226</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>0.964 2.284</td>
<td>0.045 0.092</td>
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</table>
Table S-2  Event names, event intervals (stages and ages) and data used to construct Figures 2 and S-5. B. = background, representing stabilised and diversification intervals with extremely low ER and CT\textsubscript{index} values. These events are timmed by biostratigraphy with reference to the Geologic Time Scale (Cramer and Jarvis 2020). The fourth column contains the average CT\textsubscript{index} values during the event intervals. Extinction rates after Kocsis et al. (2019) are proportionally normalised to a range of 0 to 1, the sixth column is derived from the method ‘sqs2f3’. ER\textsubscript{Diff}\_Min. and Max. represent the minimum and maximum values under all the ER calculation methods in Kocsis et al. (2019), respectively. ER\_error\_bar\_N. = (ER\_sqs2f3 - ER\_Diff\_Min.), ER\_error\_bar\_P. = (ER\_Diff\_Max - ER\_sqs2f3.) Neg. = negative, Pos. = positive. ER of different phylum is derived from the method ‘sqs2f3’.

<table>
<thead>
<tr>
<th>Events</th>
<th>Age (Ma)</th>
<th>Stages</th>
<th>CT\textsubscript{index} (%)</th>
<th>CT\textsubscript{error} bar</th>
<th>ER_sqs2f3 (normalised)</th>
<th>ER_Diff_Min.</th>
<th>ER_Diff_Max.</th>
<th>ER_error_bar_P.</th>
<th>Extinction rate_different_phylum</th>
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<td>1900 - 2100 A.D.</td>
<td>After Suess effect</td>
<td>0.4 - 1.5</td>
<td>0.06</td>
<td>0.10</td>
<td>0.32</td>
<td>0.14</td>
<td>0.16</td>
<td>0.06</td>
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<td>750 - 1900 A.D.</td>
<td>Before Suess effect</td>
<td>&lt; 0.1</td>
<td>0.06</td>
<td>0.10</td>
<td>0.32</td>
<td>0.14</td>
<td>0.16</td>
<td>0.06</td>
<td>0.19</td>
</tr>
<tr>
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<td>Holocene</td>
<td>0.23</td>
<td>0.06</td>
<td>0.10</td>
<td>0.32</td>
<td>0.14</td>
<td>0.16</td>
<td>0.06</td>
<td>0.19</td>
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<tr>
<td>Pli.</td>
<td>2.6 - 3.6</td>
<td>Late Pliocene</td>
<td>0.11</td>
<td>0.06</td>
<td>0.19</td>
<td>0.10</td>
<td>0.32</td>
<td>0.14</td>
<td>0.16</td>
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<tr>
<td>B. _Tor</td>
<td>9 - 10</td>
<td>Tortonian</td>
<td>0.04</td>
<td>0.06</td>
<td>0.02</td>
<td>0.02</td>
<td>0.13</td>
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<tr>
<td>B. _Cam</td>
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<td>Langhian</td>
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<td>0.05</td>
<td>0.12</td>
<td>0.03</td>
<td>0.07</td>
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<td>P_OM</td>
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<td>Priabonian</td>
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<td>Ypresian</td>
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<td>0.05</td>
<td>0.03</td>
<td>0.09</td>
<td>0.01</td>
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<td>KPg</td>
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<td>PFGBE &amp; TOAE</td>
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<td>201.25 - 201.3</td>
<td>Rhetic - Hettangian Tr.</td>
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<td>Nor</td>
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<td>Norian</td>
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<tr>
<td>251.42 - 251.52</td>
<td>251.941 - 251.88</td>
<td>280.5 - 281</td>
<td>293.1 - 293.5</td>
<td>300 - 301</td>
<td>335.5 - 335.7</td>
<td>359.2 - 359.7</td>
<td>375 - 372</td>
<td>379 - 380</td>
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<td>0.62</td>
<td>0.20</td>
<td>0.43</td>
<td>0.22</td>
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</tbody>
</table>
Supplementary Figures

**Figure S-1** (a) Variation in $\delta^{13}$C$_{\text{carb}}$ through the last 1 billion years. Data sources are indicated by lateral bars showing chronostratigraphic intervals. (b) Sample resolution over the one-billion-year interval. (c) The normalised $\delta^{13}$C$_{\text{carb}}$ dataset, where the function ‘interp1’ with method ‘Linear’ in Matlab was used to uniformly change the data density to 0.02 Ma.

**Figure S-2** Histograms and best fit curves of the log-normal function relative to: a. CT$_\text{index}$ values (0 to 1000 Ma); b. calculated extinction rates (Sepkoski, 1996; Kocsis et al., 2019). E(x) and var(x) represent the mathematical expectation and variation of the dataset x, respectively.
Figure S-3 Sensitivity test for parameter $\tau_{\text{span}}$. **(a1-2)** Pulse 1 with four different $\tau_{\text{span}}$ values (0.05, 0.2, 0.5, 1 Ma). The $CT_{\text{index}}$ is not sensitive to the direction of the carbon isotope excursions, and a longer $\tau_{\text{span}}$ obscures individual events and gives unrealistically high $CT_{\text{index}}$ values. **(b1-2)** Pulse 2 and 3, with three different $\tau_{\text{span}}$ values (0.05, 0.2, 0.5 Ma). The relationship between the duration of the events and the $\tau_{\text{span}}$ has a profound effect on calculated $CT_{\text{index}}$ values.
Figure S-4 (a) Occurrences and collections of the Paleobiology database through the Phanerozoic. The red boxes represent the period with extremely low collections including: Cambrian, the Silurian, and stages Bashkirian, Kasimovian and Thanetian. (b) CT_index peaks and their correspondent $\delta^{13}$C_carb events over the last 1,000 Myr. All CT_index peaks correspond to extreme $\delta^{13}$C_carb events, documenting either positive or negative excursions. See Table S-2 for event names. Black and red marks represent negative and positive $\delta^{13}$C_carb excursions, respectively.
Figure S-5 Cross-plots of the CT_index and ER, and their correlations (a1) with Cambrian and Silurian data, (a2) with Silurian and without Cambrian data, and (a3) without Cambrian and Silurian data. (b) The CT_index and ER values are logarithmic normalised to eliminate the effect of order of magnitude differences in correlation. This accounts for the effect of extremely high values during the PTr and TJ. (c1-2) Cross-plots of the CT_index and ER for different time intervals. Nearly all the data points fall within the purple zones, with the exception of the Cambrian, Silurian and Cenozoic. (d1-
2) Cross-plots of the $CT_{\text{index}}$ and ER for different phyla. The higher the ER/$CT_{\text{index}}$ slope, the more intolerant the phylum was during the extinction events.

Figure S-6 (a) $\delta^{13}C_{\text{carb}}$ data for the Permian-Triassic transition from 252.2 to 251.3 Ma. Data sources: Meishan (Burgess et al., 2014), Zal (Zhang et al., 2018), Bálvány North (Schobben et al., 2017), Wadi Shahha (Clarkson et al., 2013). (b1-2) $CT_{\text{index}}$ for the $\delta^{13}CO_2$ curves, where parameter $n = 1$, and $r$ was set equal to 0.05 (b1) and 0.01 (b2).
Figure S-7 (a) Carbon isotope trajectories for ocean surface dissolved inorganic carbon (DIC), coral from the northern South China sea, CO₂ from air bubbles trapped in continental ice, and CH₄ in Antarctica ice core. (b) Calculated CT index for these datasets. Data sources, the time interval of each dataset, and the CT index values are marked on the figure.
Figure S-8 (a) Observed $\delta^{13}$CO$_2$ for 750 to 2015 A.D., and simulated $\delta^{13}$CO$_2$ for 2015 to 2100 A.D. for the six SSP-based CMIP6 ScenarioMIP scenarios (after Graven et al., 2020). Data sources are indicated by lateral bars. (b1-2) CT$_{\text{index}}$ of the $\delta^{13}$CO$_2$ curves, where parameter $n = 1$, and $r$ was set equal to 0.05 (b1) and 0.0001 (b2), respectively. A.D. = Anno Domini.
Supplementary Information References


