The study by Lenz and colleagues provides a high-resolution terrestrial organic carbon isotope curve covering the Late Paleocene – Early Eocene. The new d^{13}Corg curve is embedded into a detailed stratigraphic framework based on new dinoflagellate biostratigraphy coupled with sequence-stratigraphic considerations. The new age constraints enable comparison (and tentative correlation) of pronounced carbon isotope anomalies (CIE 1 to 6) observed in the lignite-bearing record with marine carbon isotope trends and associated hyperthermals including the PETM, ETM2 (questionable) and EECO. The core of the study is a high-resolution $\delta^{13}C_{org}$ curve based on >320 measurements, part of which (~120 data points) has already been published by Methner et al. (2019) in Climate of the Past.

The manuscript represents a well written scientific study of very good quality, presenting new and important findings. The data-set is well presented in a number of high-quality figures and diagrams. Stratigraphically well constrained land-sea correlations during times of exceptional global warmth are of paramount importance to better understand the coupled response of the marine and continental biosphere during such hyperthermal events. In this respect, the study is clearly well suited for publication in Climate of the Past. However, some aspects remain critical and need revision, as outlined below.

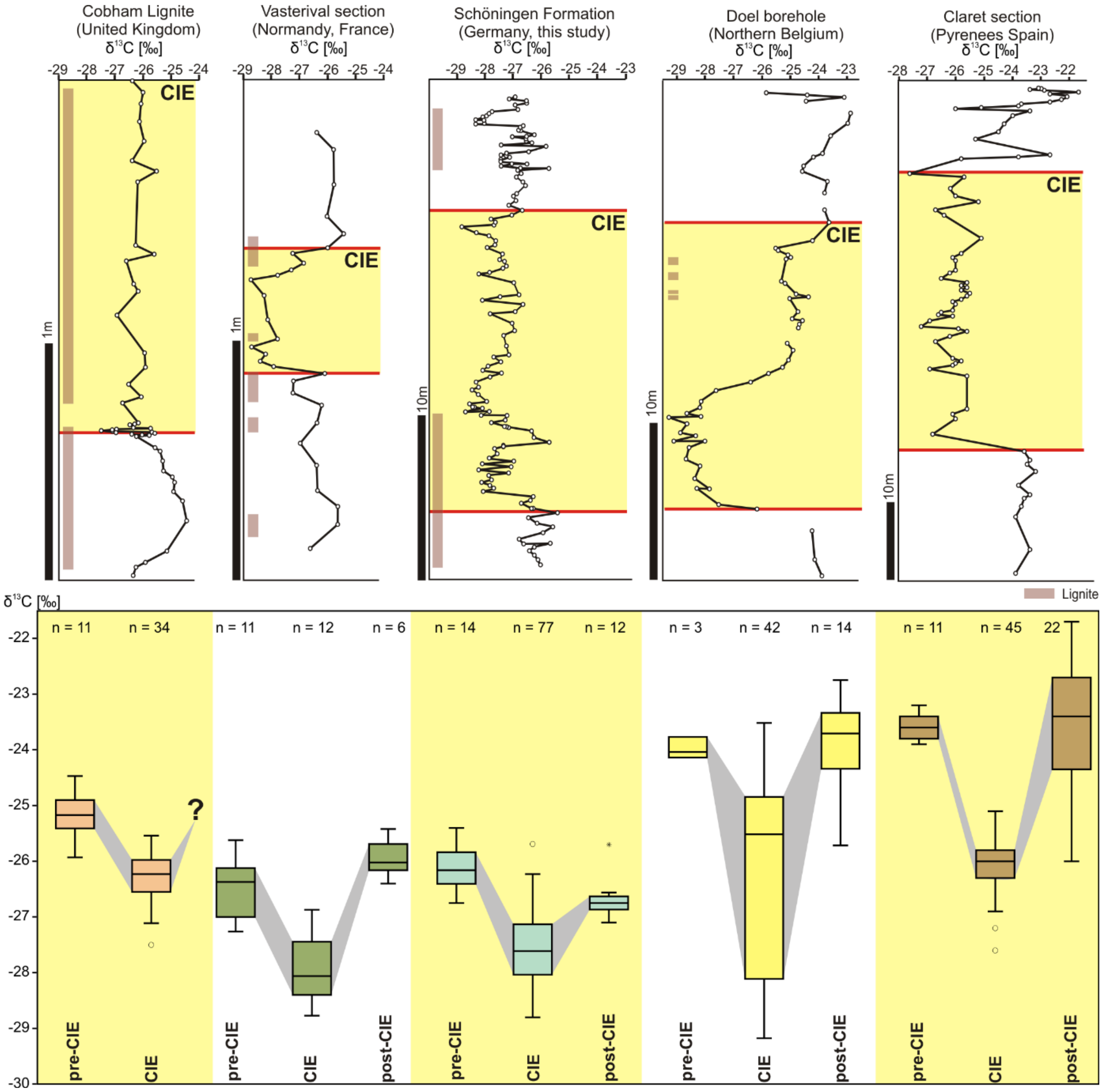
We thank the reviewer for the careful and constructive comments and suggestions to improve the paper. In the following each of the comments are specifically addressed.

Major points

Reviewer comment 1: *My main criticism is the absence of an in-depth discussion on the controls of the carbon isotopic composition of the mire-derived OM, which is interpreted here to record a global atmospheric carbon isotope signal. In my view, several aspects should be considered in order to better distinguish between potential global and local carbon isotope signatures. Firstly, the overall composition of the predominantly land plant-derived OM is rather negative (-25.5 to -28.5 ‰) which deserves some discussion. Gröcke (2002) gives an average of -23 to -27 for C3 land plant-derived OM. Comparison with time-equivalent plant derived carbon isotope values would help to get an idea of the background level expected during the Late Paleocene – Early Eocene. In addition, data from other nearshore mire deposits would provide a range for the carbon isotope composition variability in such environments.*
Our response: We will extend the discussion in paragraph 4.4.1 and will add a new figure providing a comparison to other PETM-CIEs from lignite-bearing deposits at the southern margin of the paleo-North Sea such as Cobham, Vasterival and Northern Belgium. In addition, a continental isotope curve from the Pyrenees (Claret section) is also shown for comparison. The $\delta^{13}C$ values from this section, which does not contain any lignites, are clearly higher than those from the wetlands of the North Sea. Only the $\delta^{13}C$ values from the Doel borehole in Belgium are comparable to those from the Pyrenees. However, the section from Belgium includes only few terrestrial sediments, is mainly lagoonal to marine influenced and therefore not fully comparable to the sections from Cobham, Vasterival and Schöningen. Especially in comparison with Vasterival, the variability of the $\delta^{13}C$ values in the pre-, peak and post-CIE intervals is almost identical.
We pointed to the similarities between the lignite deposits at Cobham, Vasterival and Schöningen (CIE 2 in our manuscript) already in Methner et al. (2019):

1. Absolute $\delta^{13}C_{TOC}$ values and the range in $\delta^{13}C_{TOC}$ values (-3:2 ‰) are very similar.
2. All three records attain similar minimum $\delta^{13}C_{TOC}$ values during the CIE (-27.5‰ to -28.8‰), averaging 28.05$\pm$0.5‰.
3. At the onset of the CIE the magnitude of changes in $\delta^{13}C_{TOC}$ (calculated as the difference between the last pre-CIE value and the first CIE value) ranges only between -1.4‰ and -1.8‰.
4. Magnitudes of the CIE in bulk organic matter calculated as the difference between the mean pre-CIE and the mean CIE values range from -0.9‰ to -1.6‰. CIEs calculated as the difference between the mean pre- CIE values and the most negative value during the CIE yield magnitudes of -1.1‰ to -2.6‰.

These characteristics now also apply to CIE 1, which we correlate to the PETM in the present study. In summary, the very similar data from the lignite records show that the wetlands at the southern edge of the paleo-North Sea had a uniform behavior during latest Paleocene-early Eocene thermal events. The CIE magnitudes are damped compared to purely continental terrestrial archives such as the Claret section in the Pyrenees but yield a very consistent and robust signal. In Methner et al. (2019) we discussed different possibilities for the dampened magnitude of the CIE in the lignite records such as mixing and dilution of the input signal, occurrence of local signal perturbation (e.g., due to vegetation changes), or the differential degradation and/or reservation of organic matter during the climatic perturbation.



New figure: Comparison of mid-latitudinal $\delta^{13}C_{TOC}$ records surrounding the paleo-North Sea: Cobham, UK (Collinson et al., 2003), Vasterival, France (Storme et al., 2012), Schöningen, Germany (this study), Doel borehole, Northern Belgium (Steurbaut et al. 2003). A terrestrial $\delta^{13}C_{TOC}$ record from the Pyrenees (Claret section, Domingo et al. 2009) is given in addition that highlights the isotopic differences to the lignite records. Note the different stratigraphic thicknesses due to different sediment accumulation and preservation conditions in the individual depositional environments.

Reviewer comment 2: *In chapter 4.3, the authors refer to the general difference in the $\delta^{13}C$ composition of land- and marine-derived OM. In consequence, mixing of marine and terrestrial organic* *carbon is used to explain certain variations in the Schöningen stratigraphic record (line 321 ff.). However, when comparing the $\delta^{13}C$ signature of isolated marine particles (dinoflagellate cysts) analyzed from before and throughout the PETM (Sluijs et al. 2017, Geology), it becomes clear that the dinoflagellate-derived $\delta^{13}C$ composition covers a similar range compared to the OM from the Schöningen record. During the Early Paleogene, the $\delta^{13}C_{org}$ composition of marine OM is not depleted compared to the values obtained from Schöningen, which hampers any source assignment of the OM based on the $\delta^{13}C$ signature. To better distinguish between different sources, RockEval pyrolysis and/or palynofacies data would certainly help.*

Our response: It is correct that the $\delta^{13}C$ signature of isolated dinoflagellate cysts as reported by Sluijs et al. (2018) covers a similar range compared to the Schöningen record, but our bulk organic matter may include other marine organic matter. For example, Sluijs et al. (2018) present data of marine amorphous organic matter that is very depleted in ^{13}C. We will therefore extend the respective paragraph and write:

"Since marine organic matter is depleted in ^{13}C (Sluijs and Dickens, 2012) mixing of ^{13}C from marine and terrestrial sources will influence $\delta^{13}C_{TOC}$ values. By comparing the $\delta^{13}C$ signature of isolated dinoflagellate cysts analyzed from before and throughout the PETM (Sluijs et al. 2018) with $\delta^{13}C_{TOC}$ values from the Schöningen Formation, it becomes clear that the $\delta^{13}C$ composition of dinocysts covers a similar range. However, the marine bulk organic matter that has been analyzed here, also contains organic compounds that may have been strongly depleted in ^{13}C such as amorphous organic matter shifting the $\delta^{13}C_{TOC}$ record to lower values (see Sluijs et al. 2018)."

RockEval pyrolysis and/or palynofacies data are indeed possibilities to distinguish between different sources of organic matter but beyond the scope of the present paper. However, a detailed palynofacies study is ongoing and preliminary results already exist for minor parts of the record (e.g., Seam 1, Lenz et al. 2021). However, the data are far from having been completed yet for the lower part of the Schöningen Formation.

Reviewer comment 3: *At the beginning of chapter 4.3 (line 309-310), the authors state that when comparing the new CIEs with known CIEs, a differentiation between shifts at lithological boundaries and shifts occurring within the same lithology is necessary. This statement seems to indicate that CIEs associated with lithological boundaries are more prone to be caused by local changes (e.g. OM composition) compared to within-facies shifts, which are – in consequence - interpreted as super-regional (global) phenomena. The authors do not refer to potential processes, which may cause the high-amplitude shifts in $\delta^{13}C_{org}$ within individual coal seams. Their data shows that pronounced changes do occur within many of the studied coal seams, which may be controlled by various environmental processes and not necessarily reflect changes in the global $\delta^{13}C$ signature. Mires do evolve with time and mire-producing plant successions change with mire growth, which is expected to cause stratigraphic changes in the bulk $\delta^{13}C$ signature of the peat/lignite. Interestingly, the detailed pollen record from the main seam (Fig. 7) does show pronounced changes in the pollen assemblage, which does occur time-equivalent to a major shift in the $\delta^{13}C$ record (e.g. pronounced increase of Myricaceae associated with a strong negative CIE). This negative CIE is considered to represent the onset of the PETM negative CIE and therefore, the co-occurrence of negative CIE and vegetation shift needs to be explained in more detail. In lines 411 ff. the authors refer to this coincidence as intra-PETM fluctuations, but a more in-depth discussion is lacking. The authors need to explain, on which basis local environmental drivers (incl. vegetation and/or humidity changes) can be excluded to explain the onset of the negative CIE 1. In general, potential environmental processes affecting the $\delta^{13}C$ composition of the OM need to be considered in more depth and need to be included in the interpretation of the stratigraphic trend obtained from Schöningen.*

Our response:

We absolutely agree with the reviewer's note that mires evolve with time and mire-producing plant communities change with mire growth. The peat forming plant communities of the lower Schöningen Formation are a perfect example for this. So far, high-resolution palynological studies are available for Seam 1 (Lenz et al. 2021) and Seam 2 (Methner et al. 2019) and expanded here to the Main Seam. All three seams are characterized by highly variable pollen assemblages.

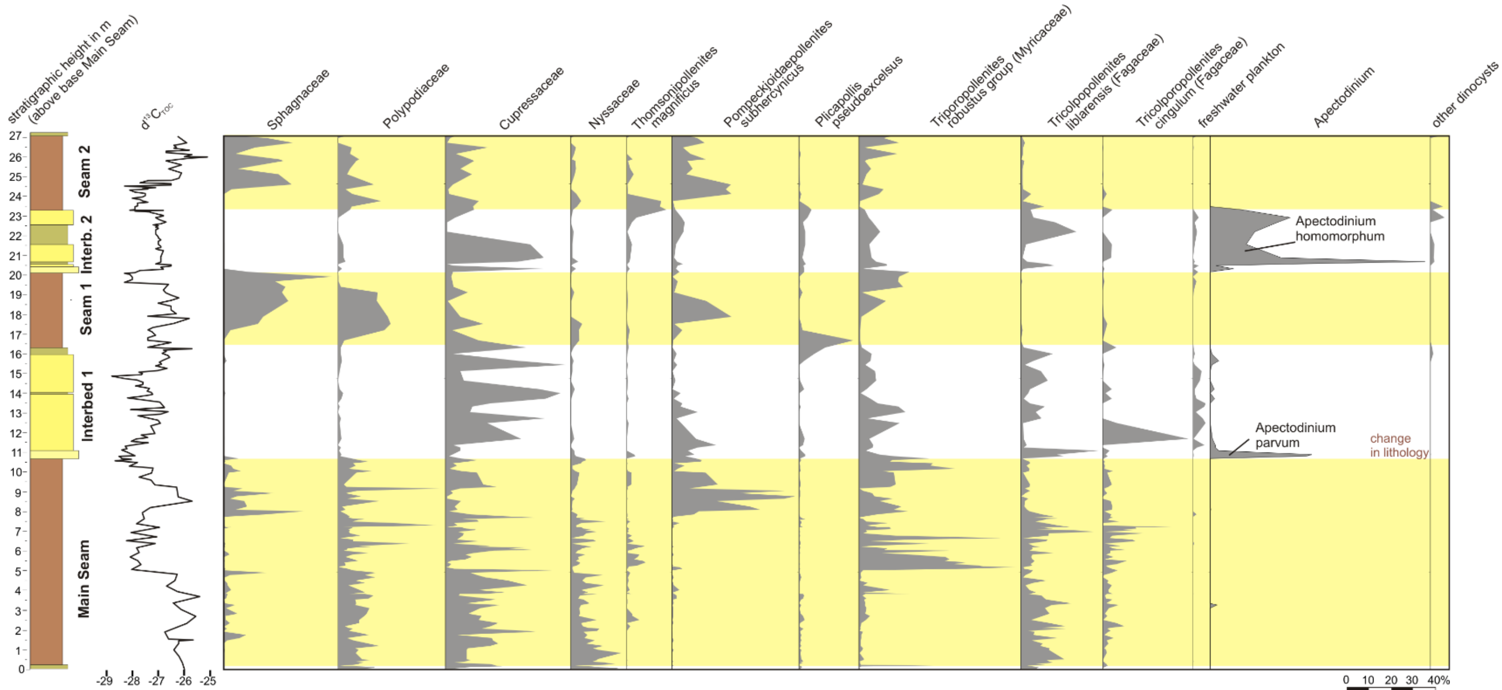
We also agree with the reviewer that it is of crucial importance to prove whether vegetation changes and related $\delta^{13}C$ variations in the record of the Schöningen Formation are caused by changes of the Paleogene climate (global signal) or induced by other probably regional factors. However, a climatic influence and the corresponding response of the ecosystems cannot simply be revealed from the microflora as documented in our studied successions. Multiple alternations of lignites with marginal marine and fluvial interbeds in the section indicate significant facies changes which should have been coupled with changes in vegetation. When studying climate changes and perturbations in the palynomorph record it is therefore necessary to distinguish between changes in vegetation that were controlled by climate or other factors such as natural succession due to peat aggradation.
The isotope analyses from the lower part of the Schöningen Formation revealed an excursion ranging from the top of Seam 1 to the middle of Seam 2 (Methner et al. 2019, CIE 2 in the present manuscript). However, carbon isotope values do not indicate a CIE for Seam 1 except for the uppermost samples. Therefore, Seam 1 has been deposited almost completely during a period without strong climate perturbations and changes in the vegetation were only controlled by factors other than climate. Therefore, Seam 1 was selected in a recent study (Lenz et al. 2021) to study the composition and variability of the regional flora beyond warming events. In spite of low variability in isotope values considerable changes of the vegetation have been observed here:
Seam 1 (Lenz et al. 2021) shows a distinctive threefold succession of the vegetation during formation of the seam: an initial, a transitional and a terminal stage. The seam is sandwiched between marginal marine Interbeds 1 and 2. Therefore, in total four different types of peat depositional environments and vegetation have been distinguished for Seam 1 representing the natural succession of plants in the early Eocene coastal wetland: (1) a coastal vegetation, (2) an initial mire, (3) a transitional mire and (4) a terminal mire.
The same natural succession is observed for Seam 2 (Methner et al. 2019) and now for the Main Seam (this study), revealing that the natural succession as seen in Seam 1 is typical for the evolution of the peat forming mire forest at the edge of the southern proto-North Sea during this time and reflects vegetation responses to changes in environment and facies that took place during an early Paleogene regression/transgression cycle including the formation of peat. Noteworthy is a pronounced change in the palynomorph assemblage composition that occurs in the upper part of the three seams, which represents a terminal mire at the end of peat accumulation. This is mainly due to the rise to dominance of *Sphagnum*-type spores. Furthermore, a great increase in pollen of the Myricaceae can be recognized. Together with *Sphagnum* they clearly signal that peatbeds in the terminal mire phase were decoupled from groundwater and their hydrology was increasingly controlled by precipitation. This shows that regional factors play a major role for the composition of the vegetation.
As the reviewer noted, in the Main Seam (this study), the occurrences of myricaceous pollen and *Sphagnum* spores clearly correlate with the $\delta^{13}C$ values. The strong increase of myricaceous pollen with a simultaneous decrease of *Sphagnum* spores is associated with a strong decrease of $\delta^{13}C$ values, while at the top of the seam the increase of $\delta^{13}C$ values is associated with a strong increase of *Sphagnum* spores and *Pompeckjoidaepollenites subhercynicus*. If the $\delta^{13}C$ signal is a purely regional signal that reflects environmental processes in the mire forest, the isotope values in Seams 1 and 2 should behave similarly. In Seam 1, however, the $\delta^{13}C$ signal remained constant during the increase of *Sphagnum* spores and *P. subhercynicus* during the terminal phase, and the strong decrease in the $\delta^{13}C$ values at the top of the seam was only evident after the increase of myricaceous pollen started (see Methner et al. 2019). Also in Seam 2 the values of myricaceous pollen and *P. subhercynicus* are not correlated with the isotope values. Only the increase in *Sphagnum* spores is associated with an increase in $\delta^{13}C$ values, which according to Methner et al. (2019) coincides with the end of a CIE. Therefore, main changes in the peat-forming vegetation only correlate to the isotope signal in the Main Seam, but not in Seam 1 and Seam 2. Local processes therefore have no strong influence on the isotope signal in Seam 1 and 2. Although the vegetational changes are fundamentally controlled by regional environmental changes, the pattern of $\delta^{13}C$ values in the Main Seam, which differs significantly from that in the other two seams, indicates that global processes such as climate change during the PETM also have played an additional role during deposition of the Main Seam. Accordingly, the extreme increase of myricaceous pollen in the Main Seam, which is much stronger compared to

their increase in Seams 1 and 2, may indicate that climatic changes have enhanced environmental changes within the peat-forming vegetation.

A detailed discussion of potential environmental processes affecting the $\delta^{13}C$ composition has already been given by Methner et al. (2019). However, we will extend the discussion by the above described comparison of palynological and carbon isotope changes within the Main Seam and Seams 1 and 2. Furthermore, we will change the last paragraph of chapter 4.4.1. and write:

"A comparable shift from a mixed angiosperm-conifer flora in the Paleocene to an angiosperm flora at the onset of the PETM-related CIE was already reported for the Bighorn Basin in Wyoming (Smith et al., 2007, Diefendorf et al., 2010). Diefendorf et al. (2010) thereby suggested that a 4.6 ‰ decline in $\delta^{13}C$ values of atmospheric CO_2 at the onset of the PETM can be attributed to the different carbon isotope budget of gymnosperm and angiosperm leaves. Conifers and angiosperms reacted differently in isotopic fractionation during the PETM-CIE resulting in different isotopic excursions of ca. 3‰ for conifers and 6‰ for angiosperms (Schouten et al. 2007). Therefore, the strong decline of $\delta^{13}C_{TOC}$ values at 5.20 m in the Main Seam may also be attributed to the strong increase of Myricaceae in the wetland vegetation. However, at around 8.20 m a further increase in angiosperm pollen (*P. subhercynicus*) and the simultaneous decrease in pollen from the Cupressaceae is not associated with a decrease in $\delta^{13}C_{TOC}$ values but with a shift to less negative values. Therefore, a local change in the vegetation that altered the carbon isotope signal is unlikely to account solely for the CIE in the Main Seam."

Additionally, we will add a respective figure (see below) in the supplementary material that summarises isotope data and palynological data between the base of the Main Seam and the top of Seam 2.



New supplementary figure: Simplified pollen diagram of the base of the Main Seam up to the top of Seam 2, showing palynological abundance changes of dominant taxa. Due to the different thicknesses of interbed sections that were studied for palynology and carbon isotopes, $\delta^{13}C_{TOC}$ values of the interbeds have been tied to the top of the Main Seam and the base of Seam 1 as well as the top of Seam 1 and the base of Seam 2. Data for the part between the top of the Main Seam and the top of Seam 2 are taken from Methner et al. (2019).

<u>**Reviewer comment 4:**</u> *Chapter 4.4.1 deals with the CIE associated with the PETM. The authors provide compelling evidence for a correlation of the Schöningen CIE1 with the globally recognized PETM CIE. What is less clear is the basis for the base and top boundaries show in Fig. 6, which constrain the PETM CIE. Why is the basal boundary placed at the data point showing the least*

negative value in this part of the curve (and not slightly higher at the data point just before the negative shift)? This has implications for the total amplitude of the anomaly (see table 2). Similarly, the positioning of the upper limit (red line in Fig. 6) of the CIE is hard to follow given that another interval with comparatively negative values is following above. A more plausible termination of the CIE would be at the transition towards less negative values (~23 m height). Are there any stratigraphic constraints for the positioning of those boundaries?

Our response: The PETM reflects injections of large amounts of carbon into the atmosphere-ocean system, but, whether single or multiple episodes of carbon release caused this event is uncertain. We think that we have a robust example, which shows that the beginning of the PETM consists of more than one discrete interval of decreasing carbon isotope values as shown by Bowen et al. (2015) and Tremblin et al. (2022). Zhang et al. (2017) present an example that shows that the PETM is associated with a stepped CIE curve indicating complex processes of carbon injection into the atmosphere. As discussed in Zhang et al. (2017) in detail there are several possible reasons that sometimes the PETM-related CIE is triangular with a single large decrease in $\delta^{13}C$ values, followed by an exponential recovery as seen in several marine isotope curves such as those presented in our Figure 6 and sometimes a curve, where $\delta^{13}C$ values decrease in several steps. These steps can be interpreted as a result of multiple phases of carbon release. Therefore, we think that our isotope curve reflect a stepwise injection of carbon into the atmosphere comparable to the situations shown by Bowen et al. (2015) and Zhang et al. (2017). We have therefore placed the basal boundary of the CIE in our record at the least negative $\delta^{13}C$ value at 3.53 m with -25.4‰, which is followed by a strong decrease to -28.1‰ at 5.37 m, only interrupted by a short but small increase of 0.4‰ at 4.57 m, which may be interpreted as carbon injection in two steps.

The position of the upper boundary of the CIE is indeed not correct in Fig. 6. Originally it should be at 16.46 m, after which a general decrease in $\delta^{13}C$ values occurs. However, this decrease in $\delta^{13}C$ values may have had sedimentological reasons, because the increasing $\delta^{13}C$ values in the lower part of Interbed 1, which are interpreted as the recovery phase of the PETM-CIE, have been measured in light-colored silts and sands, with low content of organic material. In contrast, the sediments in the upper part of Interbed 1 from 16.46 m upwards are clayey silts with increasingly higher TOC contents (see supplementary data). A higher terrestrial organic content can be assumed here. Therefore, it is possible that the decreasing $\delta^{13}C$ values are due to the stronger influence of the terrestrial carbon source. We therefore follow the reviewer's suggestion and move the upper boundary of the CIE to a depth of 22.39 m at the transition towards less negative values. According to our comment, we will discuss the upper and lower limits of the CIE in more detail in the text.

Reviewer comment 5: *Line 351 – here, the authors refer to the previous study by Methner et al. (2019, CP), which – according to the authors - already did suggest a position of both, the PETM and the P/E boundary below seam 1. However, when reading the study by Methner et al. (2019), one does get another impression. In this previous work, a pronounced negative anomaly (the interval entitled CIE2 in the submitted paper) is suggested to tentatively correspond to the PETM negative anomaly and comparison and correlation with PETM equivalent anomalies (Cobham lignite, Vasterival) is given. This view is now significantly revised and the part considered to correspond to the PETM by Methner et al. (2019) is now placed in the post-PETM part of the Schöningen record. This is not in itself problematic since new stratigraphic data does results in a re-interpretation of the previous data set. But this re-interpretation needs to be made clear and the statement above (line 351) should be rephrased to better represent the suggestions of Methner et al. (2019).*

Our response: We will rephrase the statement in line 351. Instead of "Methner et al. (2019) already suggested that both the PETM and the associated Paleocene/Eocene boundary should be placed below Seam 1." we will write:

"Methner et al. (2019) could not clearly assign the CIE between the top of Seam 1 and the lower part of Seam 2 (CIE 2 in this paper) to the PETM and already assumed that the CIE pointed to a later early Eocene thermal event. Due to a cooler mesothermal climate that is indicated by the palynoflora with mass occurrences of pollen of *Alnus*, Lenz et al. (2021) concluded that Seam 1 has been deposited during a strong temperature decline that followed the PETM in the first million years of the Eocene

(Wing et al. 2000) and suggested that both the PETM and the associated Paleocene/Eocene boundary should be placed below Seam 1."

Minor points

Reviewer comment 6: *Line 22: The abbreviation EECO is not explained in the abstract.*
Our response: We will add "Early Eocene Climatic Optimum" to explain the abbreviation.

Reviewer comment 7: *Line 40: Please include "to 27 to 35°C in the earliest Eocene (Inglis et al. 2020)"*
Our response: We will add "in the earliest Eocene".

Reviewer comment 8: *Line 49: The author refers to "kilo year to millennial scale". To me (and maybe to other readers) the difference between the 2 time intervals is not clear? Please explain or rephrase.*
Our response: We will delete "kiloyear to" in the sentence.

Reviewer comment 9: *Line 76 ff. There is a new published terrestrial $\delta^{13}C_{Org}$ record and associated palynology across the PETM published by Xie et al. (2022, Paleo3) entitled "Abrupt collapse of a swamp ecosystem in northeast China during the Paleocene–Eocene Thermal Maximum" which should be referred to.*
Our response: This is correct. Our sentence "…there are only few records providing insight into the response of terrestrial ecosystems" should include some references that use a combination of $\delta^{13}C$ data and associated palynology. Therefore, we will add Jaramillo et al. (2010) and Xie et al. (2022) as references.

Reviewer comment 10: *Line 272: The heading refers to the "basal Schöningen Formation" but the interval studied does represent more than half of the Schöningen Formation. Hence, the phrase "lower" might be better suited here…*
Our response: We will change "basal Schöningen Formation" in "lower Schöningen Formation"

Reviewer comment 11: *Line 421: Change to "observed in the terrestrial records".*
Our response: We will change this part of the sentence as suggested.

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