Stockholm, January 25, 2016

We thank the editor and the two reviewers for their comments and suggestions on our manuscript. We have carefully revised the manuscript accordingly and believe it is now much improved. Both the editor and the two reviewers agreed that discussions related to the relative timing of changes in CO_2 versus temperature should be removed or toned down given the time resolution of our study, a recommendation we have followed. Below is a full list of revisions made, as well as replies/rebuttals addressed to reviewers where appropriate.

Reply to 1st review

We thank Dana Royer for his constructive review, which has helped significantly improve our manuscript. Three major and several minor concerns are identified, summarized and replied to below:

Major concerns

1. More space should be devoted to discuss the paleo-CO_2 work of Roth-Nebelsick and colleagues, due to overlap in space and time, and in one case taxon, with our work. According to the reviewer, this only gets mentioned in passing on page 17 of the original manuscript. The fact they use the gas exchange model on the same species we used, and that we don't, should be discussed.

We want to first briefly point out that we did list the work of Roth-Nebelsick's group already on the 4th page of the original paper (p. 4988), as a part of the very first section of the introduction: 1.1 'The role of pCO_2 in Cenozoic climate', including Grein et al., 2011, 2013; Roth-Nebelsick et al., 2004, 2014. We concede however, that this should be expanded, and have now added a column to Table 2 that reviews and consolidates pCO_2 estimates based on Konrad's optimization model (2008) from Roth-Nebelsick et al. (2012) and Grein et al. (2013). It also demonstrates where direct comparisons between our pCO_2 estimates and those of Roth-Nebelsick's group is or is not possible.

We have also added the following text to the manuscript that explicitly compares our study with those of Roth-Nebelsick's group (section 4.3: Comparison with other pCO_2 records):

"*The results reported here are the highest stratigraphic resolution pCO_2 estimates for the late Eocene to early Miocene Basins in Saxony (Table 2, Figure 3). Previous studies have tended to only report temporal trends on stomatal parameters (Roth-Nebelsick et al 2004) or to lump pCO_2 estimates from single Saxony localities into coarse temporal bins making cross comparison difficult (Roth-Nebelsick et al., 2012). However, where individual site pCO_2 data are reported (Grein et al., 2013) our estimates are in very good agreement with previous studies despite differences in species and calibration approach (Table 2). For example, Grein et al (2013) report pCO_2 estimates of ~400 ppm and between ~430 to ~530 ppm respectively for the sites Kleinsaubernitz and Witznitz (Figure 3) using the Konrad et al. (2008) stomatal optimization model in a consensus approach on multiple species (3 – 4) including E. furcinervis (Table 2). The optimization model produces a very large range of pCO_2 estimates however (~270 to 710 ppm) when applied to E. furcinervis alone from stratigraphically lumped samples from Haselbach and Profen (Table 2) (Roth-Nebelsick et al., 2012). In compsarison with the study of Roth-Nebelsick et al (2012) we report seven stratigraphically well resolved pCO_2 estimates spanning the same interval for which they report a single lumped average (~470 ppm) for 2 sites (Table 2). This is the first study therefore to resolve a significant drop in palaeo-pCO_2 in the late Eocene, prior to the E-O boundary from a stratigraphically well constrained and relatively high resolution record.* "

The following text is has been added (section 1.2: the stomatal proxy method of paleo-pCO_2 reconstruction) explaining our rationale for CO_2 calibration choise and why specifically we have not applied stomatal mechanistic models to our CO_2 calibration . Three references supporting this are also added (see below).

"*We have chosen not to apply the mechanistic optimization model of Konrad (2008) to our study because it has been shown in a modern test of the model to produces the most accurate pCO_2 estimates when used on multiple species to produce a consensus pCO_2 estimate from their area of overlapping pCO_2 values (Grein et al., 2013). The optimization model produces very large and species dependent uncertainty in pCO_2 estimates when applied to single fossil species (Konrad, 2008; Roth-Nebelsick et al., 2012) and even modern species (Grein et al., 2013) for which all the biochemical, environmental and anatomical parameters required to* *initialize the model are known (Konrad, 2008; Grein et al. 2013; Roth-Nebelsick et al., 2012). We have also not applied the mechanistic stomatal model of Franks et al. (2014) because it is shown to be highly sensitive to initial parameterization of assimilation rate resulting in +/- 500 ppm error in paleo-pCO_2 estimates (McElwain et al., 2015) . Future work on* Eotriginobalanaus furcinervis *will aim to constrain likely palaeo-assimilation rate for this extinct taxon by applying available paleo-assimilation proxies (McElwain et al. 2015a; 2015b; Wilson et al., 2015) and undertaking elevated pCO_2 experiments on appropriately selected NLEs*."

References added:

McElwain, J. C., I. Montañez, J. D. White, J. P. Wilson, and C. Yiotis. "Was atmospheric CO 2 capped at 1000 ppm over the past 300 million years?."*Palaeogeography, Palaeoclimatology, Palaeoecology* (2015). doi:10.1016/j.palaeo.2015.10.017

McElwain, Jennifer C., Charilaos Yiotis, and Tracy Lawson. "Using modern plant trait relationships between observed and theoretical maximum stomatal conductance and vein density to examine patterns of plant macroevolution."*New Phytologist* (2015). doi:10.1111/nph.13579

Wilson, J.P., White, J.D., DiMichele, W.A., Hren, M.T., Poulsen, C.J., McElwain, J. C., Montañez, I.P., 2015. Reconstructing extinct plant water use for understanding vegetation-climate feedbacks: Methods, synthesis and a case study using the Paleozoic era medullosan seed ferns. The Palaeontological Society Papers 21, 167 - 195.

2 a) The decline in pCO_2 was not more dramatic than decrease in temperatures (based on d^{18}O). Estimates of global mean surface temperatures by Hansen et al. (2013) should allow quantification of the Earth system sensitivity within the 40-34 Ma interval.

This is a very good point. We have now re-evaluated our approach to this and removed any reference of the comparative size of pCO_2 relative to temperature change throughout the manuscript. We think it is premature to calculate Earth System sensitivity based on the results presented here, due in part to the dating and stomatal calibration uncertainties detailed in the paper, but principally because of the still large uncertainties regarding how such calibration should be undertaken. We have however added a new section at the end of the discussion: "4.4. Implications for Cenozoic climate sensitivity", where we briefly discuss the progress and remaining difficulties in evaluating Cenozoic Earth system sensitivity and place our results in this context. Several new references have been added.

2 b) The reviewer states that dating constraints on the earliest Oligocene sites are poor and the authors should pull back on suggesting that there's little change in pCO_2 across the E-O interval.

At the resolution of our sampling we do not detect a major change in pCO_2 across the E-O boundary, however that does not preclude the detection of pCO_2 shifts in the future if stratigraphic sample resolution can be increased. There is presently no evidence that we should place our "probably youngest Oligocene" elsewhere in the stratigraphy. We present the possibility that no significant change happens at the E-O proper, but rather has taken place before, and carefully lay out the caveats in the article. We acknowledge the reviewer concerns however by adding the sentences: *"The possibility remains that future terrestrial proxy reconstructions of pCO_2 will record a transient major drawdown of pCO_2 at the Eocene-Oligocene boundary. In order to resolve this, more proxy records from well-constrained Early Oligocene sites must be added."* (section 4.2: Comparison with vegetation and proxy continental climate records) and *"The substantial late Eocene decrease in pCO_2 reported here is consistent with terrestrial records of vegetation change (e.g. Teodoridis and Kvaček 2015) and reconstructions of coldest month mean temperatures, as well as with marine isotope records of global sea surface temperatures. The substantial drop in temperatures and/or ice sheet growth that defines the Eocene-Oligocene boundary in the marine record is not recorded here. This may be caused by the possibility that the Saxony record does not possess the stratigraphic resolution to record such a change, or indicate that decrease in pCO_2 took place before the recorded decrease in global sea surface temperatures*" (section 5: Conclusions).

3) The reviewer observes that there are statements in the manuscript claiming that the stomatal proxy often produces lower pCO_2 values than other proxies, and that this is not true in a consistent way. The reviewer points to figure 1 of Beerling and Royer (2011).

On deliberation, we agree with the reviewer on this point – that the stomatal proxy shows a high correlation to other pCO_2 proxies, as detailed in the Beerling and Royer (2011) paper – and have thus removed the following sentences from section 4.3: "*The seemingly more* *pronounced underestimation for pCO_2 values from Paleogene material is also found in the present study, where late middle to latest Eocene and possible earliest Oligocene samples yield pCO_2 values at the very low end, or lower than, previously published stomatal estimates. By contrast, values from the end Oligocene and early Miocene are in broad agreement with previous estimates (see Fig. 4A)*" and "*An important advance was made when it was demonstrated that Cenozoic pCO_2 estimates based on stomata should be adjusted upwards by 150-250 ppm to closely match the estimates based on separate (marine) pCO_2 proxies (Kürschner et al., 2008; Beerling et al., 2009). However, the fact remains that the now numerous Cenozoic pCO_2 records based on stomatal parameters from a range of woody plant species all indicate considerably lower pCO_2*" as well as minor corrections regards to this to improve the flow of the text.

The fact remains however that in previously published papers (pre the 2011 Beerling and Royer paper reporting the convergence of Cenozoic pCO_2 reconstructed by various proxies), both Kürschner et al. (2008) and Beerling et al. (2009), conclude that Cenozoic concentrations of CO_2 were, at least partially, underestimated based on the stomatal proxy. We therefore leave the brief mention of the above two paper, but have added the sentence: *"Recently discrepancies between the various pCO_2 proxies have narrowed significantly however, and a coherent pattern of long-term Cenozoic pCO_2 has emerged, indicating pCO_2 mostly in the hundreds rather than thousands of ppm, although shorter-term inter-proxy discrepancies remain (see Beerling and Royer, 2011, Fig. 1). It has thus become evident that pCO_2 values reconstructed using the stomatal proxy do not require a correction factor".*

Minor concerns:

p. 2, line 12: "hysteresis effect" – the reviewer comments that the correct term to use is "tipping point"

We agree and have amended the text and removed reference to 'hysteresis' in the abstract and conclusions, we use 'threshold' or 'tipping point' instead:

Abstract sentence changes: "*These results suggest that a decrease in pCO_2 preceded the large shift in marine oxygen isotope records that characterizes the Eocene-Oliogocene transition and that when a certain threshold of pCO_2 change was crossed, the cumulative effects of this and other factors resulted in rapid temperature decline, ice build up on Antarctica and hence a change of climate mode*".

Conclusion sentence changed: "*The results reported here lend strong support to the theory that pCO_2 drawdown, rather than continental reorganization, was the main forcer of the Eocene-Oligocene climate change, when a 'tipping point' was reached in the latest Eocene, triggering the plunge of the Earth System into icehouse conditions*."

p. 3, line 29: add "on" between "based climate"

Done

p. 4, lines 3-4: Comment: Papers cited (Goldner; Inglis) are the wrong papers to cite for the statement being made – on recent re-evaluation of timing of the E-O.

We fully agree with the reviewer and think that this sentence must be a mistake – a remnant of some previous writings – as well as being irrelevant, and we have removed it along with the references.

p. 4, lines 5-18: The E-O pCO_2 records from Pagani (alkenones) and Pearson (boron) should be discussed in this section.

In the section identified by the reviewer, we are introducing the stomatal proxy and briefly outlining results obtained using it for the Cenozoic. We think that the starting sentence of the paragraph "*Four proxies have been identified as particularly useful for Cenozoic pCO_2 reconstruction by*.." is confusing, and may imply that we will discuss all four proxies or at least the most important ones. The sentence in question has therefore been changed to start with "*One of four proxies identified as particularly useful…*", to clarify that we are only introducing stomatal pCO2 proxy records in this paragraph.

Note that we have also added the results of Liu et al. from this issue, with the sentence: *"late Eocene" pCO_2 from a single stratigraphical level of ca. 390 ppm. However, the chronological range they supply for their pCO_2 estimate (42.0-38.5 Ma) falls within the late Lutetian to Bartonian in the Middle Eocene, thus recording an unusually low pCO_2 estimate for this time-interval characterized by high temperatures (Liu et al., 2015)".*

We had already briefly introduced the pCO_2 work of Pagani and Pearson earlier in the introduction of the original manuscript (p. 4986, line 25 – p. 4987, l. 2, and also discuss it at some length in the discussion). However, we agree with the reviewer that these two high-resolution records should be introduced in more detail, and have added the following text immediately above lines 5-18 in the original paper, in direct continuation of the introduction of modelled thresholds for the growth of a permanent Antarctic ice shield (Introduction, section 1.1.): "*Modeling studies thus indicate that lowering of* pCO_2 *may have been the primary forcer of this cooling transition (DeConto and Pollard, 2003; DeConto et al., 2008). However, detailed estimates for* pCO_2 *for the Eocene and the Oligocene are highly variable and sometimes contradictory or showing unexpected relationships with paleo-temperature proxy records (see Pagani et al., (2005)). For example, comparing the* pCO_2 *record of Pearson et al., (2009: Fig. 1), which is based on measurements of Boron isotopes in planktonic foraminifera, and the benthic foraminifera oxygen isotope (*$d^{18}O$*) compilations of Zachos et al., (2008), it is evident that in the late Eocene* $d^{18}O$*-inferred deep ocean cooling coincided with decreasing* pCO_2*. In contrast, there is little evidence of warming in the early Oligocene, despite a surprising initial large increase in* pCO_2*. Overall, the* pCO_2 *and O isotope-based temperature records seem to be (largely) coupled in the Eocene, but decoupled in the Oligocene. Pagani et al. on the other hand recently published compiled alkenone-based* pCO_2 *records and found declining* pCO_2 *before and during the Antarctic glaciation (EOT and earliest Oligocene) (Pagani et al., 2011: Fig. 4), supporting the role of* pCO_2 *as the primary forcing agent of Antarctic glaciation, consistent with model derived thresholds. A compounding factor of these discrepancies is that the influence of temperature on ice sheet volume is unconstrained and the influence of temperature versus ice volume the* $d^{18}O$ *record is unresolved, with no proxy identified to isolate ice sheet volume changes, complicating further the interpretation of the climate proxy datasets. Independent proxy records of E-O* pCO_2 *are therefore desirable and may support one or the other of the major prevailing scenarios outlined above, or provide alternative information on Cenozoic climate change*".

We have also added the following text to the discussion section 4.3 "Comparison with other pCO_2 records": "*Pearson et al. (2009) reconstructed* pCO_2 *for the late Eocene to early Oligocene using the planktonic foraminifera boron isotope pH proxy and found that the main reduction in* pCO_2 *took place before the main phase of EOT ice growth (ca. 33.6 Ma: DeConto et al., 2008), followed by a sharp recovery to pre-transition levels and then a more gradual decline. Their results thus support the central role of declining* pCO_2 *in Antarctic ice sheet initiation and development and agree broadly with carbon cycle modelling (e.g. Merico et al., 2008). The quantitative estimates of* pCO_2 *varied greatly however, according to which* $d^{11}B$ *value was used to derive pH, with geochemical models of the boron cycle suggesting a range of 37-39 ‰ for sea water (sw)* $d^{11}B$ *during this time (Simon et al., 2006). The range of*

pCO_2 values spanned from ca. 2000-1500 ppm at the upper end and ca. 620-450 ppm at the lower end (Pearson et al., 2009). Recently published alkenone-based pCO_2 records found significantly declining pCO_2 before, as well as during, the Antarctic glaciation (EOT and earliest Oligocene), supporting the pCO_2 pattern of Pearson et al. (2009) and the role of pCO_2 as the primary forcing agent of Antarctic glaciation, consistent with model derived thresholds (Pagani et al. 2011; Zhang et al., 2013). The alkenone-derived dataset values are overall higher than those derived by stomatal densities, with late Eocene values of ca. 1000 ppm, minimum value of ca. 670 at 33.57 Ma and then gradual decline to ca. 350 ppm at the Oligocene-Miocene boundary".

p. 12, line 14: add "the" before "NLE"

Done

p.14, line 23: Comment: Royer (2003) shows this for *Ginkgo* as well

Yes, thank you, reference now added.

Fig. 4: Add error bars for temporal uncertainty.

We discuss the uncertainties regarding the stratigraphy and dating in detail in the paper (section 2.2. Stratigraphy and dating) and feel that this suffices. The size of any error bars added would be guesswork and thus would not in our opinion improve the paper.

Reply to 2nd review

We thank the anonymous reviewer for their positive review, which has helped further improve our manuscript. A few concerns are identified, summarized and replied to below:

Over-reaching in discussion and conclusion regarding the relationship between timing and magnitude of pCO_2 versus global sea surface temperatures.

Both reviewers and the editor pointed this out and we agree with their assessment. We have now changed the manuscript significantly to reflect this, including removing estimations of timing-discrepancies between pCO_2 and temperatures in the late Eocene, as well as adding substantial amount of discussion regarding the relationship between pCO_2 and temperatures as recorded by proxies. We have also added a new section that tackles Earth Sensitivity and place our results in the ongoing effort to understand it to the discussion (section 4.3.). Please see reply to reviewer 1 above for more detail.

Figure 4 layout could be improved.

We prefer to keep the figure the way it is at present, since we find it easy to read and its components are true to their origin.

Section 1.2. is too long

We have now slightly shortened the section by removing a sentence from the first paragraph, and shortening and consolidating two others. However, from our experience we find it highly useful to include a proper introduction to the stomatal proxy method, which is still not well understood or well known to many paleo-climate scientists. In this study in particular, it is also necessary to introduce the methods used by researchers that have published on stomatal pCO_2 reconstructions from the same time period, area and in one case fossil plant species, in order to justify our decision to employ a separate approach.

Delete last sentence in section 1.1.

We agree that this sentence is superfluous and have deleted it.