Response to Reviews

May 23, 2017

Referee #3:

Manuscript summary: The authors combine recent direct atmospheric observations and available records from several ice cores to produce smoothed splines of CO_2, CH_4 and N_2O back to 156 kyr BP. They also calculate changes in radiative forcing due to variation in each of these gases, for future use in paleoclimate modeling.

Overall assessment: It is unclear to me whether this is a contribution that merits publication on its own. There are no original data presented, and the scope of the work seems limited. This work may be better suited for a supplementary section to a future paleoclimate modeling study that the authors would conduct. However, my experience with ESSD is limited and the editor would be the better judge of this. If it was clear that the results would definitely be used by multiple groups/multiple paleoclimate modeling studies, the case for independent publication would be stronger. Below I provide some suggestions on how this work could be improved / expanded to a point where it would more likely merit independent publication.

Our reply: The data set of continuous greenhouse gas splines of CO_2, CH_4 and N_2O since the penultimate glacial maximum, which have been produced for this draft, will be used by modelling groups within the German project PALMOD. PALMOD is a national integrated paleo-modelling project, consisting of $>$ 50 sub-projects from around 20 research institutes, whose long-term (10 years) overall aim is the transient simulation of a full glacial cycle. Within PALMOD transient simulations with full GCMs are envisaged from groups affiliated at the Max-Planck Institute for Meteorology in Hamburg, the University of Bremen, the University of Kiel, and the Alfred-Wegener-Institute, Helmholtz Center for Polar and Marine Research in Bremerhaven. Additionally, supporting simulations using EMICs from groups situated at the GEOMAR—Helmholtz Center for Marine Science, Kiel, and the Potsdam Institute for Climate Impact Research (PIK) are planed. Various individual projects within PALMOD at other research institutes or universities contribute to these larger efforts. Altogether, already within Germany at least 6 research groups will use this data set in the near future. Furthermore, within the next phase of PMIP (PMIP4, simulating the last deglaciation, Ivanovic et al., 2016), alternative GHG forcing data sets are welcome, if well-motivated. The PALMOD output will contribute to PMIP4 and we hope that our data product, which we like to publish here, in the end will become the standard to be used for transient simulations in the near future from as many international groups as possible. We therefore believe, our aim and the envisaged user groups warrant this draft to become an independent paper.
It is true, no new raw data points have been generated for this study. However, we generated a continuous spline for each of the 3 GHGs, that is well documented here and will be of use for these modelling group. It was suggested by the reviewer, that this data set might also be part of a supplement of any future publication study, and not an independent publication. We disagree with this suggestions, since we believe this preparation of the GHG data to a form which can be used by others, is not trivial and merits publication of its own, and needs expert knowledge from the data-producing side (ice core gas community = coauthors from the University of Bern), that is missing in the simulation-centred project PALMOD. Furthermore, none of the authors of this study will be directly involved in the planed future transient simulations within PALMOD. Only one author (PK) is part of PALMOD, and there (besides GHG data compilation) only interested in a side product of transient climate simulations related to carbon cycle changes.

Major comments:

- Stopping the smoothed record at 156 kyr seems somewhat arbitrary and strongly limits the usefulness of the work, in my opinion. A quick look at the EDC ice core CO_2 data reveals that average Δt is actually lower (≈630 yr) in the 700–800 kyr interval than in the 140–160 kyr interval (≈1500 yr). I would recommend extending the spline for the entire duration of the EDC record for all 3 gases, even if the spline has to be discontinuous for a gas like N_2O. This would add a lot of value to the splines, as it would allow them to be used for comparison of multiple glacial terminations as well as peak interglacials that may be analogues for near-term future climate (e.g., MIS 11).

  Our reply: Our main motivation for this study comes from the needs of the planed transient simulations within the PALMOD project. Since PALMOD plans to simulate one full glacial cycle, but also wants to cover Termination II to avoid any potential bias due to (wrong) initial conditions or spin-up effects, the start of the time series around the penultimate glacial maximum has been chosen, and in detail was then determined, where the EDC CO_2 time series started (Schneider et al 2013).

  Furthermore, all modelling intercomparisons within PMIP4 are so far restricted to the time windows of the last 156 kyr, so well covered by our approach.

  We agree, that an extension over the available full 800 kyr might be of interest for readers. However, the dominant part of the necessary work is included in what we have covered here (from instrumental records into the ice core regime, well-based motivation on core selection or averaging schemes). Further back in time, raw GHG data were mainly obtained from the EDC ice core (with some contribution from Vostok until 400 kyr BP).

  Additionally, there is one technical challenge, which we have not yet overcome: So far, the spline can be calculated with our routines (with one intermediate step) in one go for the wanted temporal resolution of 1 years. When going to the full 800 kyr, the necessary internal data storage is too small to calculate one spline with 1 year resolution. The spline has then either to be split (and merged in post-processing) in at least 2 parts, or the temporal resolution has to be decreased (e.g. to 2 years). Discontinuous splines for N_2O are also difficult to generate and probably of limited use.

  Therefore, we decided for the time being to restrict our spline to the last 156 kyr as done so far. However, we keep the extension of the spline to older times in mind and anticipate, that this might be a useful extension, if a revision of the spline might be compiled in the future, (concept of ESSD Living Data, also suggested to be followed on by reviewer #1). Please also note, that CO_2 measurements from the EDC ice core of the time window, which is still only covered by data from the Vostok ice core (156-393 kyr BP) are in preparation at the University of Bern. Ideally, an extension of the CO_2 spline to older times would also then include these new, to be published data points.

- Considering that it is very well established that there is a substantial inter-polar CH_4 gradient (IPG), the authors should either present an additional northern hemisphere CH_4 spline or present a global average estimate instead of a southern-only spline. Although the difference in radiative forcing would be relatively small, a global average would still be more useful for models. The authors could consider using the available information about the IPG from the last glacial cycle, and extrapolating this further back in time while accounting for additional uncertainties.

  Our reply: New measurements have shown that the dust-rich sections in Greenland ice cores are affected by CH_4 a small artefact production during the melt-extraction process with the amount of CH4 produced scaling with the dust concentration (unpublished results). Based on these recent experiments we will use only Antarctic ice core data for CH_4 throughout the glacial and refrain from constructing a northern hemisphere CH_4

time series. Since a revised inter-polar CH_4 gradient (IPG) and thus the difference in the CH_4 forcing between the hemispheres will be lower than previous estimates (e.g. Baumgartner et al., 2012), using only the Antarctic CH_4 time series is currently the best option that is available to us.
CH_4 values in low dust Holocene or interstadial ice seems not significantly affected by this process. The relative IPG during the Holocene is around 6% of the Southern Hemisphere value, however, the relative IPG during peak glacial and stadial times was significantly smaller (<3%). We estimate that a Southern Hemisphere CH_4 value underestimates the global mean in the glacial by less than 1.5%. Accordingly, the change in the radiative forcing relative to preindustial values is overestimated in glacial times by using a significantly lower southern hemisphere value by typically less than 2.5%. As CH_4 is only of secondary importance in terms of radiative forcing compared to CO_2, this systematic error is of little relevance in transient climate simulations. Current ice core activities are under way to improve our knowledge on the northern hemisphere CH_4 value also for glacial times.
This will be briefly discussed in a revised version.

- I was surprised that continuous CH_4 data from WDC (Rhodes et al., 2015) were not used in this compilation. Surely, these data would provide the best temporal resolution for a paleoclimate model run? I would recommend the authors include these data, accounting for any offsets from discrete CH_4 data sets and associated uncertainties.
  Our reply: We will now include the continuous CH_4 data from WDC as suggested. This comment was also brought up by reviewer #1.

- Comparing tables 3, 6 and 8 to associated text, it seems that CO_2, CH_4 and N_2O uncertainties associated with offsets between different ice core records (and in the case of N_2O, possible in situ production) were not included in the uncertainties for the splines. As these are all components of the true overall uncertainties in absolute CO_2, CH_4 and N_2O atmospheric histories, they need to be included. Such a more thorough treatment of uncertainties would also make the compilations more useful for comparison with future ice core measurements.
  Our reply: Indeed, so far only the stated measurement uncertainty of individual data points (or in case of averaging 2 data points, the error from this averaging) has been included in the uncertainties, which are used in the spline calculations. Offsets between different ice cores have only been taken into consideration for CO_2 between WDC and other ice cores (adjusted WDC CO_2 data, SI Figs 1, 2). In CH_4 we had in the revised version corrected for inter-lab offsets in WDC between Oregon State University and Penn State University (see reply to reviewer #1 for details). N_2O data have never been corrected for offsets. Possible N_2O artefacts due to in situ productions have also been avoided by not choosing the relevant data points to be included in the spline.
  If we would now include the calculated offsets in CO_2 from WDC to EDC to the uncertainties of the relevant WDC CO_2 data points, we would have uncertainties on the order of 7 or 4 ppm. This would clearly make the WDC CO_2 data highly unattractive, and in case of the Termination I data even of less usable than the EDC CO_2 data, which can be used without any offsets and therefore with a lot smaller uncertainties on the order of 1-2 ppm. To our understanding the WDC data show real temporally high variability in CO_2, but on a background CO_2 values that contains this still unexplained offset. We will not recalculate the uncertainty of the data, but will include a sentence on this issue in a revision.

Minor comments:

- While the writing overall is quite clear, there are multiple small mistakes in the English. This manuscript would benefit from careful editing from a native English speaker.
  Our reply: We implemented various improvements of the text based on the detailed comments given by reviewer 1, whose is a native English speaker. Furthermore, we will make efforts to give the final version of the paper to a native speaker for further refinements.

- The title is somewhat misleading. Given the title, I was expecting to see new measurements of the 3 gases in ice cores done via a continuous technique. I would recommend revising the title to something like: "A smoothed atmospheric history of CO_2, CH_4 and N_2O compiled from available ice core data to 156 kyr BP"
  Our reply: We can agree with this comment and will revise the title towards something around "A smoothed history of atmospheric greenhouse gases CO_2, CH_4 and N_2O and their radiative forcing compiled from available data since 156 kyr BP".

- I found the discussion on page 4 that involves equations 1 and 2 somewhat confusing and circular. First, Pcutoff is defined in terms of lambda, and then lambda is defined in terms of Pcutoff. Which is prescribed first? Later in the manuscript, it becomes clear that Pcutoff is prescribed and to a large degree determines the smoothing, but perhaps it would be best to explain this more clearly on page 4.
  Our reply: The description around Eq 1 and 2 was done more generally without choosing already if lambda or Pcutoff are prescribed. It is clearly stated that Eq 2 follows out of Eq 1. However, we agree, that some revision might improve the understanding here. We will do so, also by directly stating that Pcutoff is the prescribed parameter from which via these equations the values of other variable lambda is determined.

- On a related note, it would be useful to explain the choices of Pcutoff better they seem generally reasonable in the tables given the Δt values for different intervals, but what is the process for assigning the Pcutoff values?
  Our reply: A similar comment was given by reviewer #1 and we have largely expanded on this, also by including Pcutoff in a revised version of Figs 1, 3, 5. Please see our reply there.

- Do EDML CH_4 data have better or comparable resolution to EDC for some of the time intervals considered? If so, they should be included. It may be useful to include these regardless to help in estimating uncertainties arising from offsets between different data sets / cores.
  Our reply: The layer thickness of EDML is larger than that of EDC only for times younger than 80 kyr (Fig 3 in Ruth et al 2007, Clim. Past, 3, 475484). This implies that from the boundary conditions of the ice cores CH_4 from EDML might potentially be of interest here with higher resolved data in the short time window between 67 kyr BP (oldest data point of the WDC ice core) and 80 kyr BP. However, EDML CH_4 data are not well documented in the scientific data bases. We found (beside the EDML CH_4 data of the last 50 kyr contained in the EPICA 2006 Nature paper) non of them in NOAA and only one combined, but not well documented, EDML CH_4 data set in PANGAEA, connected with the new AICC2012 age model. These data indeed might contain some parts which are temporally higher resolved than EDC. The given data citation in the PANGAEA data sets is the EPICA 2006 Nature paper only, which covers only the last 50 kyr. From going through the literature again, it is clear, that some new EDML CH_4 data points have been included in Schilt et al., 2010, and a whole section between 80-123 ka in Capron et al (2010, QSR). All-together, we feel not confident in using these EDML CH_4 data from PANGAEA, since it is not even clear which data points was measured

in which lab and therefore it will be difficult to assign any data specific uncertainty to them. We therefore refrain from using the EDML CH_4 data here.