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Biogeosciences
Discussions

Interactive comment on "Competing effects of nitrogen deposition and ozone exposure on Northern hemispheric terrestrial carbon uptake and storage, 1850–2099" *by* Martina Franz and Sönke Zaehle

Martina Franz and Sönke Zaehle

mfranz@bgc-jena.mpg.de

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Answers to Anonymous Referee #1

Q: The paper abstract mostly focuses on ozone effects alone. N deposition is discussed only briefly in last 3 lines. I realize that there are space limitations, but the abstract could be somewhat re-formatted to highlight these new findings. The Discussion section is much appreciated and needed by the community especially sections 4.2

and 4.4 to make clear the limitations of the current large-scale modelling approaches.

A: Abstract extended to take up more results regarding N deposition effects:

'Our simulations suggest that the stimulating effect of nitrogen deposition on regional mean GPP is lower in magnitude compared to the detrimental effect of O_3 during most of the simulation period for both RCPs. In the second half of the 21st century nitrogen deposition dominates the combined effect. The increasing effect of nitrogen deposition on vegetation-C is lower compared to the decreasing effect of O_3 for the entire simulation period. '

Q: 1. The main methodological issue is that the model framework does not represent the empirically observed interactions between reactive N deposition and ozone exposure as summarized in Mills et al., Ozone impacts on vegetation in a nitrogen enriched and changing climate, Environmental Pollution, 2016 e.g. "The beneficial effect of N on root development was lost at higher O_3 treatments whilst the effects of increasing O_3 on root biomass became more pronounced as N increased". At the least, these observed interactions and their implications for the results presented here need to be discussed, as a separate paragraph in Section 4.

A: In OCN, the root-shoot ratio decreases with increasing N alongside with decreases in plant C:N and increases in fine root respiration as in the Mills study. Whether these changes results in an increase in fine root biomass depends on the initial nitrogen limitation of the ecosystem with high responses in fine root in N limited ecosystems with a strong NPP response, and a decline in fine root biomass is closed-canopy, highly productive forest ecosystems with low levels of nitrogen limitation (Meyerholt et al. 2015, NP). In the model, ozone affects this response simply by changing the NPP response to N addition, with higher ozone induced reductions in the NPP response (and thus also the root biomass response) in N limited ecosystems with a larger N addition response (and subsequently higher LAI and ozone uptake). Where the model does differ from the inferences of Mills et al., is that higher ozone exposure reduces carbon availability for root growth because of the higher carbon costs for detoxification. These extra-costs are not explicitly taken into account in the model and may reduce the effect of ozone on root growth as hypothesised by Mills et al.. One should note that the study by Mills was based on a meta-analysis of a total of four studies and 51 data points, which showed that there was no interaction between O_3 and N deposition unless the rate of N deposition was very high, at rates that are not occurring during much of our simulations. One can therefore not generally say whether the responses of OCN and Mills et al. are in disagreement, and it is not entirely clear how representative the suggested root biomass response to ozone by Mills et al. is.

Q: It is not exactly clear how the combined effects of N deposition and ozone damage are treated mathematically in the model integration scheme? Based on the given information, we deduce a sequential calculation, i.e. the model algorithm reduces (increases) Vcmax for ozone (reactive N) impacts. Does it matter in the code which process is treated first, the ozone damage or the reactive N stimulation? Each process is essentially considered linearly additive in the current code? Or is there a set of coupled equations that are solved numerically for Vcmax?

A: The N-effect and O_3 effect impact photosynthesis (PS) on different time scales. The effect of nutrients are calculated on a daily basis and impose a long-term effect on growth and the leaf C:N ratio. PS and gas exchange (gs) are calculated on a half hourly time step. O_3 directly impacts on the PS calculated in each half hourly time step during day light hours. Following this NO_x effects the nutrient status of the plant and it's growth on longer time scales where as O_3 impacts on half hourly calculated processes. They do not directly interact, and there is no sequential treatment of the effects. Changing N limitation affects ozone uptake through its influence on photosynthesis and stomatal conductance, and reduced carbon uptake due to ozone reduces the nitrogen requirements of plants and therefore reduces N limitation.

Q: 2. What temporal period is the ozone flux accumulated over? i.e. for the CUO0 and CUO1 variables, what time period are these calculated for in the model? Please specify. What would happen to the ozone damage calculation if the model stopped half way through the NH growing season?

A: The $CUOX$ is calculated every half hour for all days of the year. Deciduous trees start with zero $CUOX$ at the beginning of the year and accumulate $CUOX$ once their leaves emerge. When leaves are shed a proportionate amount of $CUOX$ is 'shed' as well. Once all leaves are shed at the end of the growing season $CUOX$ is zero again. Evergreens can accumulate $CUOX$ throughout the entire year if abiotic factors allow for PS and gs. They 'shed' proportionate amounts of CUO when leaves are shed.

Ozone damage is calculated every half hour starting the first day of the year to the last day of the year, as is $CUOX$. If $CUO1$ is zero, damage is zero.

Added to manuscript to clarify:

'Emerging leaves are undamaged and accumulate $CUOX$ during the growing season. The $CUOX_l$ is reduced by the fraction of newly developed leaves per time step and canopy layer. Deciduous PFTs shed all $CUOX$ at the end of the growing season and grow uninjured leaves the next spring. Evergreen PFTs shed proportionate amounts of $CUOX$ during the entire year whenever new leaves are grown.'

Regarding: ' What would happen to the ozone damage calculation if the model stopped half way through the NH growing season', I guess the question is whether a fixed O_3 accumulation period is defined? In OCN this is not the case, the O_3 uptake and damage is determined by the vegetation being active (not dormant).

Q: 3. The authors have developed their own approach to account for the strong ozone concentration gradients near the surface around forest canopies, essentially ozone near the surface is substantially reduced compared with the ozone concentrations at 45m altitude taken from the global CTM due to the strong uptake processes going on at various surfaces and with meteorological processes near the surface. Figure 9 shows that the deposition scheme has a large influence on the C-cycle impact results. There needs to be some further justification and explanations around this ozone canopy concentration approach. Firstly, 45m is not the “free atmosphere”, it is still in fact the boundary layer air flow. Why was 45m chosen?

A: We extracted the lowest (closest to the surface) level of ozone concentrations available in the forcing data. To our knowledge the lowest layer is in about 45 m height. The O_3 concentration in 45 m height is higher than at canopy level. We apply the deposition model to calculate the canopy level O_3 concentration to prevent an overestimation of ozone uptake into the leaves. Please see Franz et al. 2017 for an evaluation of the O_3 deposition scheme.

Q: Secondly, the ozone concentrations taken from the global CTM have already undergone surface depositional processes through the continuity equation at each time-step. Is the model approach here effectively double counting the surface ozone depositional processes?

A: There is no double counting of ozone destruction, as the destruction of O_3 at the surface feeds back on the O_3 conc. in 45 m height through turbulent mixing within the boundary layer. The O_3 concentration provided by CTMs need to already account for destruction at the surface to get a realistic estimate of the O_3 concentration in 45 m height. In a coupled biosphere-atmosphere model surface destruction of O_3 would feed back on the O_3 concentration in 45 m height, which then in return impacts on the amount of O_3 that reaches the surface.

Q: Finally, please provide quantitative validation and evaluation of the sur-

face ozone concentrations from the CAM model against present day network observations e.g. TOAR. All global CTMs and CCMs over-predict surface ozone concentrations, in some places quite substantially (e.g. Turnock et al., Historical and future changes in air pollutants from CMIP6 models, 2020: https://acp.copernicus.org/articles/20/14547/2020/acp-20-14547-2020.html).

A: We agree that it would be interesting to validate the near surface O_3 concentrations. However we feel this is beyond the scope of this paper. However, we included a paragraph in the discussion section to address the issue raised by Turnock et al.:

'Turnock et al. 2020 found that the CMIP6 models overestimate observed surface O_3 concentrations by up to 16 ppb across most regions of the globe. This will likely lead to a general overestimation of simulated O_3 damage by terrestrial biosphere models. However, the ozone deposition scheme included into OCN has the potential to ameliorate this observed discrepancy. The calculation of canopy level O_3 concentrations from the lowest level O_3 concentrations of the forcing data are lower and thus probably closer to the obervations.'

Q: Is this 45m ozone concentration taken from the CAM model the lowest model layer available?

A: Yes.

Q: Is a surface tracer diagnostic available in the CAM model?

A: Not to our knowledge.

Q: 4. Similar to (3), please provide information regarding validation and evaluation of reactive N deposition fluxes – how realistic are these fluxes for present day? What is actually included in the reactive N depositional flux from the global CTM? All of the results in the paper depend upon the realism of the surface ozone exposure concentrations and the reactive N depositional fluxes.

A: The reactive N fluxes comprise the sum of the reduced and oxidised wet and dry deposition as described and evaluated by Dentener 2006, Lamarque 2011.

To be more precise the regarding the composition of nitrogen depositional flux the respective sentence is changed to:

'Reduced and oxidised nitrogen deposition in wet and dry form and near surface O_3 concentrations are provided by CAM, the community atmosphere model (Lamarque et al. 2010, Cionni et al. 2011).'

Q: 5. Figure 1 Ozone units are ppb not ppm. Suggest to state “surface ozone concentrations” in Figure 1 and throughout instead of “tropospheric ozone”. The troposphere extends to 10-12km.

A: Done.

Q: Please check and fix ozone units in Figures throughout paper.

A: Done.

Q: Has this ozone units error led to other mistakes in the calculation of the stomatal uptake and injury model framework?

A: The error in unit is a pure typo while plotting the figure and not all all related to any model simulations.

Q: 6. Where exactly are the ozone and N deposition data from in Figure 1? Is this the exact forcing data applied in this study?

A: Yes.

Q: 7. All the line plot Figures show a distinct temporal evolution behavior, for both RCP8.5 and RCP2.6. Very slow changes over the past 150 years, then a turning point around 2005 after which both RCP8.5 and RCP2.6 show strong increasing rates for the next few decades. It would be useful to compare the vegetation model output to the real world for the 2005-2020 period for which there is plenty of observational data. Such comparisons can support the realism of the results and increase confidence.

A: We agree that this would be interesting. However we believe that such a model-data-intercomparison would be topic of its own, especially since this paper is already quite long. For an evaluation of OCN excluding O_3 damage please see Friedlingstein et al. 2020, ESSD.

Q: 8. RCP8.5 Fig 4(a) and (b) results. Ozone is by far dominant control on F_{st} and CUO1;but is this contradicting with earlier statement about reduced stomatal conductance due to increased CO_2 driving the changes in uptake into the future?

A: Elevated levels of CO_2 reduce peak values of F_{st} and hence the O_3 flux threshold is exceeded less often. This results in lower values of CUO1 and hence damage. CO_2 imposes less impact on F_{st} than the O_3 concentration itself. However, the effect of CO_2 on the effective O_3 uptake that damages the plants is major.

Q: (surface ozone concentration actually increases in RCP8.5?).

A:Yes, see Fig. 3a O_3 concentration under RCP8.5.

Q: 9. Figure 4(f). N deposition has a tiny influence on land carbon sink in this model? Page 10 Line 217 “Nitrogen deposition stimulates the simulated land carbon sink (land

C flux) the strongest in the period between 1950 and 2050 by 5–25 % (-0.02– -0.15 PgC yr-1) compared to pre-industrial values." It is quite hard to see this in Figure 4(f). It is difficult to see how Figure 5(f) comes from Figure 4(f) and Figure 2.

A: The land carbon sink strongly increased in magnitude during the simulation period (Fig. 2d). Because of the low values of the land carbon sink at the beginning of the simulation period, small changes can result in considerable %-changes. In Fig. A3f the absolute changes in land carbon sink are better visible than in Fig. 4f. Thus, fig. A3 might be better suitable to make a connection between fig. 2 the %-change in Fig. 5.

Q: Since the paper discussed previous studies estimating ≈ 50% of residual land carbon sink due to reactive N deposition, it would be helpful to have some explanation for why N is less important in this new study.

A: The respective sentence says: 'N deposition may be responsible for 10 to 50 % of the global residual land carbon uptake', what indicates a considerable amount of uncertainty in the estimates. We here simulate the impact of N deposition to 5–25 %.

OCN has a lower N sensitivity to compared to other models (e.g. Thomas et al. 2013, GCB), because it encodes a range of acclimation mechanisms that lead to a lower response (including the decrease in C:N ratios and the shift in root:leaf allocation, which increases N demand with increasing N availability) (see Meyerholt et al. 2015 for a discussion). As a consequence, OCN tends to simulate a lower contribution of N deposition to the residual land carbon sink, while being well able to reproduce the total residual sink (le Quere et al. 2018)

Q: 10. Page 2 lines 44-49. Why does ozone decrease but reactive N deposition stay at similar levels into the future? Please provide an explanation. Because NOx emissions are main precursors for ozone production, it seems like ozone concentrations and reactive N deposition should respond in a similar way to future changes in short-lived

precursor emissions.

A: Ozone formation and destruction is a complex process in the atmosphere dependent on several factors besides the availability of reactive N species. Other factor impacting the abundance of O_3 in the atmosphere are for example the availability of CO, CH_4, some volatile organic compounds, irradiation and the absolute humidity. O_3 is destroyed when reacting with water vapour. A more moist atmosphere e.g. induced by climate change can increase O_3 destruction. Furthermore, at high levels of NO_x, for example at polluted sites, O_3 is destroyed through it's reaction with nitric oxide (NO), whereas at low NO_x levels O_3 is formed (Parrish et al., 2012).

Q: 11. "For instance, modelling studies by Sitch et al. (2007) and Oliver et al. (2018) suggest a reduction in O_3 induced damage of global gross primary production (GPP) by 4-15 % and an associated reduction of land carbon storage by 3-10 %." For which time period do these quantitative estimates refer? Does it mean for the present day and/or future world? Are these estimate ranges global or do they refer to ranges across different regions?

A: Added: 'Where Sitch et al. 2007 simulated global ozone impacts between 1901–2100 and Oliver et al. 2018 focused on a European scale damage between 1901–2050.'

Q: 12. Figure A.6 Spatial Pattern of PI to PD change in CUO1 induced by ozone. There are high values of CUO1 in high latitude boreal evergreen ecosystems. This seems unrealistic given that ozone surface concentrations are typically very low at these high latitudes. Please offer an explanation for the high CUO1 in those high lat boreal ecosystems.

A: Evergreens keep some of their leaves/needles for several years. Following this CUOX is accumulated over several years. This results in high CUOX values for evergreens.

Added: 'Evergreen trees accumulate ozone damage over several years, because of the longer life time of their leaves compared to deciduous trees. This can result in high values of CUO1, even if O_3 concentrations are moderate. '

Q: 13. Table 3. In caption, need to define '. . .' ranges as done for Table 4 i.e. "estimates according to both approaches to calculate the ozone impact".

A: Done.

Q: Is it necessary to show both 1850:2099 and 2006:2099 for the RCPs, given that 1850-2005 is already presented?

A: We dropped 2006:2099.

Q: Instead of presenting values for differences between single years, it may be more informative to show differences for decadal averages i.e. 2000-2009 minus 1850-1859 etc., to account for some interannual variability in the effects (interannual variability is large according to many of the line plots of impacts). Could also include standard deviation / uncertainty ranges (and statistical significance) relative to interannual variability – would be helpful for Tables 3-5.

A: Differences for decadal means are presented in Tab. 4 (O_3) and Tab. 5 (N-dep). These tables present the difference between the decade of 1990 (1990-1999), 2040 (2040-2049) and 2090 (2090-2099)compared to the decade of 1850 (1850-1859). The spread in the effect sizes due to interannual variability, derived from error propagation of the yearly estimates, is now added to table 4 and 5.

Q: 14. The data presented in Table 3 indicates that ozone plays a large role for the

future RCPs in influencing GPP and Land C flux, notably much larger than that of N deposition. Is this in conflict with manuscript text as written? For example, Page 18 Line 302: "The growth stimulating effect on GPP induced by nitrogen deposition becomes higher in magnitude during the 21st century compared to the detrimental effect of ozone (see Fig. 4c and Tabs. 4 and 5)." The larger influence of ozone on GPP and Land C flux as compared to N deposition and in general is striking as shown in in Table 3. Ozone always appears to dominate over N deposition in Table 3? Furthermore, the conclusions section states: "Nitrogen deposition increases GPP less than O_3 impacts decrease it for most of the simulated period."

A: The effect of Ndep starts to slightly outweigh the effect of O_3 on GPP in the first half to middle of the 2th century. When comparing the negative O_3 effect in Tab. 4 and the stimulating effect of Ndep in Tab. 5 for the decade of 2040 one can see that for RCP2.6 the Ndep effect is already a little larger in magnitude. For RCP8.5 the magnitude of both effects are similar. In the decade of 2090 the Ndep effect outweighs the O_3 effect under both RCPS.

The effect of Ndep on GPP does not change as much during the 21st century as does O_3, especially under RCP2.6. This causes the lower values in Tab. 3.

Q: 15. From Tables 4 and 5, ozone dominates over N deposition for vegetation-C and Land C (but not GPP) for both futures and all regions?

A: For GPP, Ndep dominates over O_3 for the decade of 2090 (both RCPs) for the entire simulation area, China, and Europe, but not in the USA. For vegetation C ozone dominates over Ndep during both decades, for both RCPs and all regions. Even though O_3 induced effects on GPP strongly decrease during the 21st century, the effect on biomass persists longer, because of decades of the many decades of reduced biomass production.

The ozone impact on the land C flux is positive for the decades of 2040 and 2090 for both RCPs and all regions except China. The explanation for this is given on page 14 line 270-273:

'This seemingly counter-intuitive effect is the result of lower ozone-induced net primary production, which reduces the formation of soil carbon. The resulting lower stock in soil carbon in simulations accounting for ozone damage results in lower increases in heterotrophic respiration due to climate change during the 21st century, which causes the reversal of the O_3 effect on the land C sink.' '

Q: Why does ozone have positive influence on GPP in USA for 2090 RCP2.6 (Table 4)?

A: Because the CUO1 is smaller in magnitude compared to pre-industrial times, induced by reduced O_3 uptake due to elevated CO_2 levels. See page 16 lines 289–291.

Q: 16. The different spatial locations of the ozone versus N depositional impacts are interesting and important e.g. Page 21 Line 344 "However, regions that experience strong ozone-induced negative effects do not always coincide with regions that benefit from the stimulating effect of nitrogen deposition." Realize that there are already many Figures, but many research communities would be extremely curious to see a spatial map plot of the combined/net effects of ozone and N deposition on e.g. GPP at the various time slices.

A: Added a figure to the Appendix where the sum of the N deposition and O_3 effect is plotted for GPP.

Q: 17. Comparisons with JULES model studies. Page 21 Line 354 "A possible reason for the higher estimates by Sitch et al.(2007) and Oliver et al. (2018) is the absence of an ozone deposition scheme in JULES, what might have caused higher surface

ozone concentrations and hence increased ozone uptake and incurred damage." This could be true, however, there is a more obvious reason in Sitch et al., 2007 for the higher estimates. In Sitch et al., 2007, Figure 1 (a) and (b) showed very high surface ozone concentrations over the Amazon and tropical regions. These high surface ozone concentrations are unrealistic according to atmospheric chemistry knowledge including from multi-model global CTM & CCM studies (e.g. ACC-MIP for CMIP5 and AerChemMIP for CMIP6) and multiple observations in those regions. The erroneously high surface ozone concentrations in the Amazon and tropical regions applied as forcings result in the relatively high estimates of ozone-induced GPP and land carbon sink losses in the Sitch et al., 2007 study (currently, no other global process-based model simulates substantial ozone vegetation damage losses in tropical regions).

A: We agree that the applied forcing data impose an important impact in simulated damage values. Thus we discuss that this issue restricts the comparability between modeling studies in section 4.3. Nevertheless, we could show here that the application of canopy level O_3 concentrations instead of directly applying the lowest level O_3 data available in the forcing data can impose a considerable impact on damage estimates.

Q: Note that Oliver et al., 2018 does include a non-stomatal deposition term.

A: Removed Oliver et al. from the sentence.

Q:18. The authors work to compare results with other global model assessments is valuable. Page 22 Line 393 "Our damage estimates here are lower compared to at least most of the previous estimates suggested by biosphere models." Might be worth comparing with the various coupled and offline YIBS model estimates (e.g. Yue et al.) that predict very similar regional GPP losses to those with the O-CN model here i.e. 8-11% in the 3 key regions (even though YIBs and O-CN have quite different mathematical approaches).

A: Included: 'The YIBS model simulates a 4–8 % damage to GPP due to O_3 in the eastern US and 8–17 % damage in hot spots for the decade of 1998–2007 Yue et al. 2014.'

Q: 19. Page 24 Line 434 "For example Sitch et al. (2007) simulated a 6–9 % reduction in O_3 induced damage to GPP due to elevated levels of CO_2 and a 5–10 % reduction in land carbon storage between the years 1901 and 2100. Oliver et al. (2018) simulated a 1–2 % decrease in O_3 induced damage to GPP and land carbon storage caused by elevated levels of CO_2 between 1901 and 2050." Please check the estimated percentage values here. In Sitch et al. it is more like a one third reduction in O_3-induced GPP losses due to the co-increases in CO_2 and associated stomatal closure & reduced uptake in the model? Please include the relevant time frames and CO_2 concentration changes that are influencing the ozone-induced GPP reductions here.

A: This sentence on Page 24 Line 434 refers to the extend elevated CO_2 levels reduce simulated ozone damage. In the supplement Tab. S3 in Sitch et al. 2007 you can find that the alleviation of O_3-damage by CO_2 increase is 8.5 % for the for 'High' Plant-O_3 Sensitivity and 6.2 % for 'Low' Plant-O_3 Sensitivity.

Might be you were referring to ozone induced damage to GPP that reaches regional reductions above 30 % ?

The simulation period is already included in the sentence 'between the years 1901 and 2100' for Sitch et al. and 'between 1901 and 2050' for Oliver et al.

Sitch et al. applied CO_2 concentrations according to the A2 SRES scenario. However I would like to abstain form including this in the sentence. The applied forcing data in the cited modelling studies are not generally mentioned throughout the manuscript.

Q: 20. Page 6 Line 146 "Land cover, soil, and N fertiliser application are used as

in Zaehle et al. (2011) and kept at 2000 values throughout the simulation. Through all simulations present day land-use information are applied for the year 2000 (Hurtt et al., 2011)." It is useful to have all the simulations available without changing land use land cover data, but it is likely that the historical and future land use land cover change 1850-2100 can have a dramatic influence on the results presented here. At the least, there should be some discussion about the implications of land cover change and not including it in Section 4. Furthermore, land use change has actually implicitly been included in the ozone concentration and reactive N fields taken from the global CTM in terms of the evolving short-lived air pollutant precursor emissions from different sources on the land.

A: This is an offline simulation, there will always be inconsistencies between the atmospheric forcing and the land fluxes, this is unavoidable, but it does not invalidate the sensitivity of the land carbon cycle simulation to this forcing. The key point here is that the PFT distribution change will in addition affect trajectories of damage (in addition to what it already discussed with the adjustment at the community level).

We have taken up the impact of a fixed land-use in the discussion: 'The application of present day land-use information fixed to the year 2000 in our simulations here likely leads to a discrepancy in simulated GPP, canopy conductance, biomass accumulation, litter formation and soil organic matter formation in regions where land cover and/or land-use changed within the simulation period. This in return will lead to a discrepancy in the simulated effect of nitrogen deposition and O_3 damage. For example O_3 damage differs between plant functional types and a shift to highly productive crops would results in an increase in damage.'

Q: 21. Please explain the relevance of the N fertilizer application held at year 2000 values and how this links to the surface ozone and reactive N deposition fields from the global CTM? For example, those atmospheric chemistry model offline fields will have incorporated the time evolving response to soil NOx emissions from N fertilizer application. Is this consistent between land model and forcings?

A: We included the relevance of holding the fertiliser application at year 2000 levels in the discussion:

'Holding the N fertiliser application at the year 2000 levels in our simulations here imposes a bias on the simulated GPP, biomass production and O_3 damage in regions where fertiliser application changed. Regions where fertiliser application decreased would show a reduction in growth stimulation along with a reduction in O_3 damage. Regions exposed to increases in fertiliser application would exhibit a stimulation in growth along with an increase in O_3 damage.'

Lamarque et al. 2010 and Cionni et al. 2011 do not mention fertilizer application. Thus we can not be sure regarding the connection between N fertilisation and the O_3 and nitrogen deposition fields applied here. But it is likely that they did not account for fertilizer application the same way we did here.

Our simulations here are run offline. Differences between the applied forcing and the simulations are inevitable. The lack of feedback between the simulated biosphere and the atmosphere (forcing) will always create discrepancies. For example NO_x emissions in OCN vary with N status and climate, which they don't generally do in a CTM. Also the NO_x emissions calculated by OCN do not feedback on the atmosphere. The energy and water cycles are as well not coupled to the atmosphere what creates a discrepancy as well.

Editorial comments

Q: 1. Be consistent throughout, use either "ozone" or "O_3".

A: Changed to O_3.

Q: 2. There are typo, spelling and grammar errors throughout. Please do spell check and revise. Text needs a thorough editing e.g. Sp. "extend" – "extent" throughout

A: Done.

Q: 3. Fig 4 caption – should be NO_3 leaching not N_2O

A: Changed.

Q: 4. The paper is quite long, understandable because it covers a large amount of simulations and complex interactions. A possible option is to try to reduce the Figures. For example, Figure 8 could be merged with A.7 showing absolute value for 1990s but then differences in percent for the other panels (and similarly Figure 10 merging with A.8).

A: The regional pattern differs considerably between absolute and % change. Thus we would like to keep the figures indicating the absolute change as they are. We could set up a document with supplementary information and move all Appendix figures over there?

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