

Interactive comment on “Development and evaluation of an ozone deposition scheme for coupling to a terrestrial biosphere model” by Martina Franz et al.

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Received and published: 9 November 2016

Dear Referee,

we thank you for your detailed and constructive comments that helped considerably to improve the manuscript.

Yours Sincerely
Martina Franz

C1

1 General comments

Q: The authors use “ozone” and “O3” fairly randomly throughout the manuscript. I would suggest sticking with one or the other.

A: ‘Ozone’ and ‘O₃’ are not used randomly. ‘O₃’ is used when we refer to the chemical substance and ‘ozone’ is used when we refer to the damage O₃ causes or the included deposition scheme. In the cases where this was not consistent we changed it to the above mentioned rule. We would like to keep it that way if it is not distracting.

1.1 Abstract

Q: P1, L6 - This is the first use of the acronym OCN - please explain what it is.

A: Added: ‘(the OCN terrestrial biosphere model)’

Q: P1, L12 - “update” should read “uptake”

A: Done.

Q: P1, L15-6 - Please re-word, this is hard to follow. I think that you are saying: “When applied at the European scale, we find that including our new ozone deposition scheme substantially affects simulated ozone”

A: Changed to: ‘When applied at the European scale, we find that the inclusion of the deposition scheme substantially affects simulated ozone ...’

C2

1.2 Introduction

Q: P2, L22 - replace “consequence” with “result”

A: Done.

Q: P2, L24 - replace “extend” with “extent”

A: Done.

Q: P2, L27-29 - I suggest making the point here that AOT40 is currently used for regulatory assessment purposes in Europe.

A: Changed from 'A widely used example' to 'The initial standard tool' And furthermore is added: 'Observed ozone damage in the field seems to be better correlated to flux-based risk assessment compared to concentration based methods (Mills et al., 2011). Following this the LRTAP Convention recommends flux based methods as the preferred tool for risk assessment (LRTAP Convention, 2010).'

Q: P2, L32-33 - Please could the authors explain what they mean by “regional provenances”. Do they mean that the same species in different geographical locations differ? Or that different regions have different ecosystems?

A: It is meant that canopy conductance of the same species differs when grown in different geographical locations as well as differences exist between species. Changed to: 'A significant caveat of concentration-based assessments of ozone toxicity effects is that species differ vastly in their canopy conductance as well as regional provenances of one species.'

Q: P3, L8 - Up until this point the authors have referred to AOTX. As AOT40 is the regulatory metric and one that they use in subsequent analysis and discussion I suggest they clearly define AOT40 at this point.

C3

A: '(AOTX above a threshold of 40 ppb)' is added.

Q: P3, L23 - I suggest the authors make the point that the threshold values are species-specific to account for plant sensitivity/tolerance to ozone.

A: ', depending on the specific species sensitivity to ozone. ' is added to the sentence.

1.3 Methods

Q: P4, L20 - The model acronym EMEP MSC-W should be defined here rather than at the end of the paragraph, e.g. “The ozone and N-deposition data used for this study are provided by the EMEP MSC-W (European Monitoring and Evaluation Programme Meteorological Synthesising Centre - West) chemical transport model (CTM; Simpson et al., 2012a).”

A: Done as suggested.

Q: P4, L22 - insert “been” between “have” and “documented”

A: Done.

Q: P5, L1 - replace “in” with “at” and remove “height”

A: Done.

Q: P5, L7 - replace “in” with “at” and remove “height”

A: Changed to 'between 45 m height and the canopy' according to F. Dentener's comment.

Q: P5, L15-6 - replace “leafs internal” with “internal leaf”

C4

A: Done.

Q: P5, L16 - parentheses should only be around “2005”

A: Done.

Q: P5, L17 - replace “ozone to water vapour” with “ozone from water vapour”

A: Done.

Q: P5, L19 - is this factor of 0.7 included in Zaehle and Friend or is this new for this current study?

A: It is new in this study. Yet this calibration is generally necessary to yield reasonable conductance values in OCN.

Q: P6, L11 - please explain more clearly what is meant by a low temperature correction factor and why it is needed.

A: According to Simpson et al. (2012) and Zhang et al. (2003) F_T is needed since at temperatures below $-1\text{ }^\circ\text{C}$, non-stomatal resistances increase up to two times (hence also the boundary of $1 \leq F_T \leq 2$). Added: For temperatures below $-1\text{ }^\circ\text{C}$ non-stomatal resistances are increased up to two times (Simpson et al., 2012; Zhang et al., 2003)..

Q: P6, L11 - suggest rewording to: “is scaled by a low temperature correction factor, F_T , such that”

A: Changed to: 'is scaled by a low temperature correction factor F_T and'

Q: P6, L13 - suggest rewording to: “where TS is the 2m air temperature (C; Simpson et al., 2012a, eq. 60) and $1 < F_T < 2$.”

C5

A: The reference by Simpson et al. (2012) also refers to $1 \leq F_T \leq 2$, hence the proposed alteration would take away information.

Q: P6, L20 - replace “Like” with “As”

A: Done.

Q: P7, L1 - parentheses should only be around “2003”

A: Done.

Q: P7, L4 - suggest combining to give: “0.5, to prevent negative values in the first fraction of eq. 10”.

A: Done.

Q: P8, L4 - Why PODI? My understanding of PODY is that the Y stands for the threshold value not the canopy level.

A: Yes. The PODY usually refers to the top canopy layer and not the canopy integrated value contrary to CUO. The 'l' was there to indicate the same canopy layer as in CUO, however I also see that it is misleading. I erased the 'l'.

Q: P8, L13 - What is the physical (real-world) interpretation of the parameters 0.22 and 6.16 in eq. 16?

A: The parameter 6.16 suggests that at zero ozone uptake net photosynthesis is damaged by 6.16 %. Per mmol accumulated ozone uptake the net photosynthesis is further damaged by 0.22 %.

Q: P8, L13-4 - Why not just divide by 100 in the equation itself?

C6

A: The equation in the numerator is the original equation by Wittig et al. (2007) which gives the damage in percent. Since we needed the fraction [0,1] instead of the percentage it seemed the clearest way to indicate this.

Q: P8, L17 - Please explain to the general audience why a reduction in A_n results in reductions in G_{st} and (particularly) C_i . It is not intuitive why this would reduce internal concentrations.

A: The stated reduction of C_i was wrong. ' and C_i' was erased.

Q: P8, L23 - parentheses should only be around "2010"

A: Done.

Q: P9, L2-3 and throughout - I would suggest that the authors re-define or at least use a word description each time these parameters are re-introduced at the start of a new section; else provide a table listing the key parameters for the reader to refer back to.

A: Are reintroduces again.

Q: P9, L11 - Are the "summer months" defined here the same as what is then referred to as the "growing season"; if so, please make clear, if not, please define growing season separately.

A: Growing season is not equal to summer month. Growing season is defined: 'To derive average growing-season fluxes (bud break to litter fall), ...'

Q: P9, L21 - Please explain what is meant by "site levels". Is this "site-specific" i.e. OCN is run as a column model rather than a 3-D regional model?

A: site level means that the simulation is run only on a single set of coordinates and not for a region. Changed to: 'The site levels simulations (single point simulations) ...'

C7

Q: P9, L22 - square parentheses are not required around CO₂ as the text includes the word "concentrations".

A: Parentheses are erased.

Q: P9, L23 - parentheses should only be around "2015".

A: Done.

Q: P9, L23 - rearrange this to read: "Reduced and oxidised nitrogen deposition in wet and dry forms and hourly"

A: Done.

Q: P9, L27 - O₃ should be subscript

A: Done.

Q: P9,L28-9 - Why not use GCM output or reanalyses data where there is a lack of observation data?

A: We have observation data for all stations but only for the observation period. The model however needs to be in equilibrium to yield sensible results hence a Spinup has to be run (approximately 1200 years for the vegetation). To be able to use the GCM climate it would have to be bias corrected for all climate variables to prevent a step change when changing to use the observed data at the FLUXNET stations for the observation period. This bias correction is much work besides the fact that bias correction except of temperature is not trivial. The use of the observed climate for the Spinup period constitutes a secure way to prevent step changes at the start of the observation period.

C8

Q: P9, L30 - what do the authors mean by time-varying here? Surely the progressive simulations also used data that varied with time. Do the authors mean that here it is observations from the site in question for the years in question?

A: Meant is the year in question. Rephrased to: 'The observation years (see Appendix Tab. 1) are simulated with the climate and atmospheric conditions (N deposition, CO_2 and O_3 concentrations) of the respective years.'

Q: P10, L2 - Why have the authors chosen to base LAI on single point, time-specific observations rather than e.g. MODIS LAI data? It seems that this introduces a considerable source of uncertainty.

A: MODIS data are also subject to a considerable amount of uncertainty. Furthermore the resolution of MODIS data is an additional source of uncertainty. Using observation directly from the site in question seemed to be the most reliable source.

Q: P10, L5 - parentheses should only be around "2015"

A: Done.

Q: P10, L6-7 - suggest rewording to read: " are filtered prior to deriving average growing-season fluxes to reduce the effect of model biases on the model-data comparison. Night-time and "

A: Done.

Q: P10, L9 - please explain what a "modelled soil moisture constraint factor" is, and why a threshold of 0.8 has been chosen as a filter. Is this based on observations suggesting severe drought impacts alter fundamental plant functioning?

A: The soil moisture constraint factor is the Θ in Eq. 5. It constrains net photosynthesis when soil moisture decreases and takes values between zero and one. The threshold

C9

of 0.8 secures relative humid soils since site specific soil moisture constraints are hard to capture with a global model. The drying of soils is hard to capture for a model operating on 1 degree resolution since it depends e.g. on soil type and texture as well as the degree of root penetration). By excluding data under soil moisture stress this bias is removed.

Q: P10, L10-1 - suggest rewording to "Daily mean values are calculated from the remaining time steps only where both modelled "

A: Done.

Q: P10, L14 - why only use July here when the rest of the analysis is conducted for JJA?

A: Only one month (July) was chosen since it is easier to compare means of one month to reported values in the literature than mean values over several months.

Q: P10, L14-15 - why not use the same light level to define daylight as you used to filter the data previously?

A: For the hourly mean values the threshold of $100 Wm^{-2}$ is used to have a sharp cut-off of values with small light intensities where photosynthesis is little active and dew might bias the estimated G_c of FLUXNET. To calculate daily mean values such a restrictive boundary is not necessary since the early morning hours are not investigated separately.

Q: P10, L16 - suggest rewording to "..FR and for both modelled and FLUXNET-observed GPP"

A: Done.

C10

Q: P10, L22-3 - suggest rewording to “1999). Reduced and oxidised nitrogen deposition in wet and dry forms and ozone”

A: Done.

Q: P10, L25 - parentheses should only be around “2014b”

A: Done.

Q: P10, L25 - insert “and are” before “scaled back”

A: Done.

Q: P10, L27 - parentheses should only be around “2011”

A: Done.

Q: P10, L28 - square parentheses are not needed around CO₂.

A: Skipped.

Q: P10, L28 - parentheses should only be around “2015”

A: Done.

Q: P10, L29-30 - Please check dates. If 1961-1970 is used as a spin-up shouldn't the simulation then start at either 1961 (repeating the first 10 years) or from 1971?

A: The transient simulation starts at 1961 and ends in 2011 (since the MTE period extends to 2011). Changed to '1961-2011'.

Q: P10, L32 - Please explain what an MTE product is.

A: MTE is a machine learning technique. Changed to: 'An up-scaled FLUXNET-MTE-

C11

product of GPP (Jung et al., 2011), using the machine learning technique: model tree ensembles (MTE),'

Q: P11, L2 - replace “Different” by “In contrast”

A: Done.

Q: P11, L3 - O₃ should be subscript

A: Done.

Q: P11, L3-4 - Please explain for the non-specialist audience why the resistances result in a lower canopy concentration.

A: Changed to: 'Due to these resistances, the deposition of ozone to leaf-level is reduced, and the canopy O₃ concentration is lower than the atmospheric O₃ concentration.'

1.4 Results

Q: P11, L11 - what do the authors mean that they agree “within the standard deviations”? Are they stating that the data overlap? It would be better to demonstrate this goodness of fit with robust statistical analysis.

A: 'within the standard deviation' is substituted by 'well'. A table reporting the: 'Coefficient of determination (R^2) and Root Mean Square Error (RMSE) for GPP , canopy conductance (G_c), and latent heat fluxes (LE) for all sites, sites dominated by broadleaved trees, needle-leaved trees, C3 grass, and C3 grass except of the AT-Neu site (outlier).' is added to the Appendix and cited in section 3.1 Evaluation against daily eddy-covariance data '(see Appendix Tab. 2 for R^2 and RMSE values)'. Given

C12

the observational uncertainty, the model performance appears to be acceptable.

Q: P11, L13 - should read "very close, with only slight under-"

A: Changed.

Q: P12, L3 - remove extra ")" after 10 a

A: Done.

Q: P12, L5-6 - please give an example of site management that might result in such variability

A: Mowing can change LAI strongly and through this impact estimated GPP and G_c . '(e.g. mowing)' is added.

Q: P12, L8 - why should LE be overestimated and GPP underestimated by OCN at broadleaved forest sites?

A: We can only speculate that a bias in the estimation of the FLUXNET LE might be the cause for this. It might also be possible that the observed water use efficiency (WUE) is not properly captured by OCN, what however seems unlikely to be the major reason since GPP and G_c do not show such a bias when compared to each other.

Q: P12, L13 - what do the authors mean by "vary more widely"? Do they mean that there is a greater difference between modelled and measured values or that there is greater variability in the differences?

A: There is greater difference between modelled and measured values compared to the needle-leaved tree sites mentioned in the preceding sentence.

C13

Q: P12, L14 - Do the means still lie within one standard deviation or not? Is there a tendency for the model to consistently under- or overestimate?

A: Changed to 'The modelled G_c at sites dominated by C3 grasses is in very good agreement to FLUXNET G_c with slightly overestimating G_c at 2 out of 3 sites except for the DE-Meh site, where means differ outside the standard deviation (see Appendix Fig. 10 b).'

Q: P12, L15-22 - move to SI

A: We would like to keep this paragraph included (like Referee 1), however we can move it to SI if demanded.

Q: P12, L23 - general comment regarding section 3.2: Do the reported "biases" in the diurnal cycles reflect those of the means? i.e. is GPP underestimated at the broadleaf site.

A: The biases are partly reflected by the hourly value. For instance the fact that the needle-leaved trees site matches observed values best. For the broadleaved trees GPP shows a bias towards underestimation by the daily mean values, however is overestimated on the site shown for the hourly values. The G_c shows a slight bias towards overestimated by the mean and is also overestimated by hourly values. There seems to be little benefit for the readers gain of knowledge to compare the exemplary site to the bias of the category so much in detail. A sentence to compare the general pattern of daily means and hourly values is added: 'Similar to the daily mean values (see Fig. 1 a,b) the mean hourly values show the best match of GPP and G_c for the needle-leaved tree site and stronger deviations for the sites covered by broadleaved trees and C3 grasses.'

Q: P12, L24 - diurnal profiles of which variables? State here

A: Done.

C14

Q: P12, L32 - remove unnecessary parentheses after m and n.

A: Done.

Q: P12, L32 - should read: "with particularly good agreement"

A: Changed.

Q: P12, L32 - surely it's more relevant that it is an evergreen needle-leaf forest that it is Finnish?

A: Changed to 'needle-leaved site'.

Q: P12, L34 - again, state the type of landcover at this site

A: 'Italian' substituted by 'grassland'.

Q: P13, L1 - Again please explain what is meant by the means being within the standard deviation.

A: Changed to: 'The modelled hourly values fall in the range of the observed values.'

Q: P13, L2 - The maximum variability at CH-Oe1 seems to occur during the middle of the day

A: Yes, this fact was erased and changed. Changed from 'where the observed values became highly variable. ' to 'where the observed values increase again.'

Q: P13, L3 - "whereas" is all one word

A: Changed.

C15

Q: P13, L4 - what about the peak GC at the CH-Oe1 site? Is it also overestimated by the model?

A: Yes. Respective sentence changed to: 'and overestimates peak G_c at the CH-Oe1 site.'

Q: P13, L5 - "simulate" rather than "simulated"

A: Changed.

Q: P13, L5-6 - is this not a serious short-coming of the model water response parameterisation? I thought the midday depression in GC was a well observed response to water stress. Please comment on the likely implications for your results and conclusions?

A: The midday depression of G_c is a well observed phenomena and ought to be captured better by the model. However how strong the midday depression is and if it occurs at all is species and site specific. It does not occur for instance at the FI-Hyy site. The IT-Ro1 site shows that the model is at least in some cases able to capture important patterns like the midday depression of G_c . OCN however is a global model and not especially tuned for the specific sites such that the features of some sites will be captured better than others. Furthermore the observations at the CH-Oe1 site show very wide error bars, which also indicates the uncertainty in the observations! In times when G_c is underestimated the ozone uptake will also be underestimated and will result in a lower estimated damage. However since it is not a general pattern that the midday dip is not reproduced, this seems not to have a strong impact on the reported results and conclusion. One has to keep in mind that the modelling of ozone damage underlies many uncertainties as well as the observations against which the modelling results are evaluated.

Q: P13, L7-> Please either change the order of the panels in Figure 2 or the order of

C16

the text so that you are presenting the results of the panels in the order in which they appear.

A: Order in the text is changed.

Q: P13, L9- 15 - How is R_c measured? or is it back-calculated from observed ET and LE? Please comment on the reliability of the observations.

A: R_c can be inferred from measurements by the eddy covariance technique (Coyle et al., 2009; Gerosa et al., 2004; Mikkelsen et al., 2004). The total deposition of ozone is calculated from the ozone concentration at measurement height and the fluxes measured by the eddy covariance technique (total ozone deposition). R_c can be inferred from the total deposition as the residual when subtracting R_a and R_b . Eddy covariance measurements and derived flux and conductance estimates are subject to a diverse set of random and systematic errors (Richardson et al., 2012). A lack of energy balance closure can cause underestimation of sensible and latent heat as well as an overestimation of available energy, with a mean bias of 20 % where the imbalance is greatest during nocturnal periods (Wilson et al., 2002). Since R_c is inferred from measured fluxes the calculation of R_c underlies the uncertainties of the flux measurements.

Q: P13, L9-15 - what are the implications of the model deviations from observations?

A: The main purpose of this evaluation is to show that our model produces realistic values for key ozone variables. The modelled values are within the range of observed values and show the expected diurnal pattern. Deviations from the values reported in the literature are expected since we neither model the specific sites nor the species. That also means that also the climate and ozone concentrations of the observations can not be reproduced by OCN which both have a major impact on the modelled ozone variables. Since the modelled values are within the observed range reported in the literature it can be assumed that our model works fairly well.

C17

Q: P13, L15 - should read “ observed which is slightly lower”

A: Changed.

Q: P13, L16 - the minimum velocities appear to be lower than this value for crops

A: I am not sure what 'for crops' refers to, since we do not model crops here. In case it is meant that for the CH-Oe1 (grassland site) site minimum V_g is lower than 0.002: Yes, it is approximately 0.0015 for CH-Oe1, however I think it is 'approximately 0.002 m s^{-1} ' when stating the mean minimum V_g for all three sites.

Q: P13, L18 - “barely” should read “barley”

A: Changed.

Q: P13, L16-20 - The modelled velocities at your crop site are well below these.

A: We do not model a crop site, the CH-Oe1 site is a grassland site. The crop values only indicate the observed range, since trees might also not be the best choice to compare with. Besides our modelled peak values of V_g are approximately 0.0055 m s^{-1} which in our notion compares well to observed ranges of 0.003-0.009 m s^{-1} at noon (Gerosa et al. 2004) for a barley field and approximately 0.006 m s^{-1} at noon for a wheat field (Tuovinen et al., 2004).

Q: P13, L20 - please rephrase to “The estimates for Hyytiälä also agree”

A: Changed to: 'The estimates for FI-Hyy also agree'.

Q: P13, L16-23 - It would be helpful if you compared the data site by site as before

A: This is done here, only that we start with the CH-Oe1 site, followed by FI-Hyy and last IT-Ro1. The reason for evaluating IT-Ro1 last is that for broadleaved trees we found only daily mean values to compare with, such that the actual diur-

C18

nal cycle can not be properly evaluated. Hence it seems better not to start with this site.

Q: P13, L23 - Why is V_g so noisy for IT-Ro1?

A: V_g is determined by the total ozone uptake which is composed of a stomatal and a non-stomatal fraction. The noise in the stomatal component of the total uptake (F_{stC}) causes the noise in V_g . F_{stC} is determined by G_c and leave-level ozone concentrations. Since G_c shows not much noise it can be assumed that the day to day variability of the leave-level ozone concentration is the cause of the noise in F_{stC} and V_g .

Q: P13, L24 - Perhaps it is worth making the point that V_g is not zero because of non-stomatal deposition.

A: The sentence on P13, L24 deals not anymore with V_g but with F_{stC} . And F_{stC} is not zero during the night since a minimum conductance occur also during the night even though photosynthesis is zero.

Q: P13, L27-28 - Why is there such large variability in the afternoon at IT- Ro1? Is that another sign of water stress?

A: As already mentioned above: F_{stC} is determined by G_c and leave-level ozone concentrations. Since G_c shows not much noise it can be assumed that the day to day variability of the leave-level ozone concentration is the cause of the noise in F_{stC} .

Q: P12-13 - general comments: For R_c , V_g , FR , $FStC$: what are typical/expected profiles of these variables? Do we really only have observations at 1 or 2 times per day with which to assess model skill? How do these output data compare with estimates from other models? I would strongly recommend that much of the content here is moved to SI and/or presented in a table, with this section only highlighting a few key or interesting features.

C19

A: The expected diurnal profiles are as modelled by OCN, with peak value during the day for all variables except of R_c where maximum values are expected during the night. Hence the diurnal pattern is modelled appropriately. Certainly there are observations that do report on a high temporal resolution (Mikkelsen et al., 2004; Gerosa et al., 2004, 2003). However, we do not model the sites where the observations are conducted, it does thus not seem appropriate to compare details of model and data, especially since differences between species are high (see ranges of cited values for different species). In our notion it is interesting to show the diurnal pattern including the hourly standard deviation. It seems important to show that the diurnal pattern of the variables can be reproduced by the model and how this varies between the sites. Information about when standard deviation is typically high or low and how and why it is high for some variables would be skipped when condensing Fig. 2 into a table. For instance the fact that the high noise level for F_{stC} at IT-Ro1 can not be explain by noise in G_c is information that would get missing.

Q: P14, L2 - add a reminder in the parentheses that $GCO_3=GC/1.51$

A: Changed to: ' $G_c^{O_3} = \frac{G_c}{1.51}$ '

Q: P14, L3 - Is this ratio essentially the proportion of deposition that is stomatal?

A: Yes.

Q: P14, L3-9 - Why have the authors chosen to report the 24-hour average for this variable and not for the others? Section 3.3 This section and the accompanying figure should be moved to SI, with only a few key headline findings included in the main text.

A: The 24-hour average is given for F_R since for instance in Cieslik (2004) the reported flux ratios are mean values (for diverse sites listed in a table) and the daily mean value in our graph should facilitate the comparison with this table. If this 24-hour mean value is a distraction to the reader it can be removed, otherwise we would like to keep it.

C20

The included ozone deposition module is the key component for simulating ozone uptake and damage. Since it is done the first time to include such a detailed deposition model into a global terrestrial biosphere model it seems to be very important to show that this inclusion worked properly. That means that the results are fairly robust against the exact parametrisation (Fig. 4) but also that perturbations in one variable cause expected effects in related/depending variables (Fig. 3). Furthermore it seems quite important to show which variables of the deposition scheme mainly impact the estimated ozone uptake and hence damage (Fig. 3).

Q: P14, L12 - replace "constraint" with "constrained"

A: Changed.

Q: P14, L13 - "boreal" would be a more useful descriptor than "Finnish"

A: Changed.

Q: P14, L13 - replace "except of" with "except for"

A: Done.

Q: P14, L14 - replace "describing" with "which describes"

A: Done.

Q: P14, L17 - replace "compared" with "relative"

A: Done.

Q: P14, L22 - insert "canopy conductance" before "GC"

A: Done.

C21

Q: P14, L23 - replace "what causes" with "resulting in"

A: Done.

Q: P14, L24 - replace "compared" with "relative"

A: Done.

Q: P14, L25 - remove "changed values for"

A: If changed values would be removed it would sound as if only r_{ext} and G_c are important for the fluxes however this is not the case. The message is that r_{ext} and G_c need to be properly modelled because changes in their values impact the modelled fluxes. Thus we would like to keep the sentence unchanged.

Q: P14, L26 - explain the units (%/%)

A: '0.1 (%/%)' is substituted by '0.1 % due to a 1% change in the variables/parameters of the deposition scheme.'

Q: P14, L27 - remove "very" and "varying"

A: 'very' is removed. Varying is not removed since the message is that perturbations (variations) of r_{ext} and G_c little effect F_R . It is not the case that F_R is little affected by r_{ext} and G_c !

Q: P15, L1-2 - has this phenomena (the effect of needle-shedding on CUO) been evaluated?

A: I am not sure what is meant by 'if the phenomena has been evaluated'. As in our response to reviewer one, we believe that the use of f_{shed} has caused some confusion,

C22

and therefore we have replaced this with f_{new} . The CUO itself is only representative of what actually happens in the plant. Ozone does not actually accumulate in the plants. However, CUO is a substitute to estimate potential damage to the leaves/plant. It can be assumed that new grown leaves are healthy. Deciduous plants grow a complete set of new leaves each year and shed all damaged leaf at the end of the growing season and hence also shed the CUO. Evergreen plants keep their leaves for several years but if they would keep accumulating the CUO they would die since damage keep increasing. Hence it is reasonable to assume that if old/damaged leaves are shed also the fraction of CUO they took up will be shed too.

Q: P15, L6-7- what percentage is 250 gC/m2/yr?

A: The range of $\pm 250 \text{ g C m}^{-2} \text{ yr}^{-1}$ is skipped and substituted by the European mean deviation of OCN from MTE, since this seems to be more informative. The respective sentence is rewritten to: 'Simulated mean annual GPP for the years 1982-2011 shows in general good agreement with an independent estimate of GPP based on up scaled eddy-covariance measurements (MTE, see Section 2.5), with OCN on average underestimating GPP by 16 % (European mean).'

Q: P15, L8 - remove "to this acceptable agreement"

A: Done.

Q: P15, L9 Again what percentage is 400 to 900 gC/m2/yr?

A: Added: '(58 % overestimation on average)'

Q: P15, L12-3 - It also makes it difficult to assess the reliability of the model!

A: Yes, because there might be no reliable source to compare with.

Q: P15, L16 - Please explain how N limitation can lead to overestimation of GPP

C23

A: In the North OCN underestimates GPP compared to MTE not overestimates. Changed to : 'North of $60^{\circ}N$ OCN has the tendency to produce lower estimates of GPP'. The underestimation might result from N limitation.

Q: P15, L20 - Fig. 6d does not show GPP. Should this read Fig. 5a?

A: Yes, changed to 5a.

Q: P15, L23-4 - Is it not to be expected that AOT40 closely follows absolute ozone concentrations?

A: Yes, it is expected and it is good to be able to compare the AOT40 pattern to the CUO pattern.

Q: P15, L26 - replace "averaged" with "ranged from 60 to 120"

A: Changed.

Q: P15, L27 - move "(Fig 7 a)" to between "Europe" and "and"

A: Done.

Q: P15, L28 - "larger" should read "large"

A: Changed.

Q: P15, L28 - does this refer to Fig. 7b?

A: Yes. '(Fig. 7b)' is inserted at the end of the sentence.

Q: P15, L29 - suggest rewording: "with high cover of C4 PFTs, e.g. Black Sea area (see Appendix 12 a,b)."

C24

A: Done. The graph Appendix 12 is skipped due to its minor value in explaining observed results.

Q: P15, L30-1 - suggest rewording: "where productivity is low and stomatal O₃ uptake reduced by low O₃ concentrations or drought control on stomatal fluxes respectively."

A: Changed to : 'where productivity is low and stomatal O₃ uptake is reduced by e.g. low O₃ concentrations or drought control on stomatal fluxes respectively.'

Q: P15, L31-2 - suggest removing the sentence beginning: "Slight increases or strong decreases"

A: We would like to keep the sentence since it puts the displayed outliers, the positive damage, and the strongest fractional damage into context.

Q: P15, L32 - "increases" should read "increase"

A: Changed.

Q: P16, L3 - replace "by" with "of"

A: Changed.

Q: P16,L4 - insert "Fig. " before "7 c"

A: Done.

Q: P16, L4 - insert "of transpiration" after "3-4%"

A: Done, and European changed to Europe.

Q: P16, L4 - remove "to" before "4-6%"

C25

A: Done.

Q: Q: P16, L5 - insert "relative" before "reductions"

A: Done.

Q: P16, L7 - should read "Black Sea"

A: Changed.

Q: P16, L8 - insert "Fig." before "7 d" and replace "They are" with "These are"

A: Done.

Q: P16, L10 - please explain why a reduction in transpiration matters.

A: Changes in transpiration might impact run-off and surface cooling.

Q: P16, L15 - suggest rewording: "CUO1.6 increases more strongly by 35% "

A: This sentence has been removed since the flux threshold and hence CUO₅^{1.6} has been removed.

Q: P16, L18-9 - It seems to me that in this study simulation D is effectively the base case and D-STO and ATM are sensitivity tests. It would therefore make more sense to swap panels a and c in Figure 9. Furthermore, it seems to me that this is the real headline message of this study - that the ozone deposition scheme substantially alters estimates of impacts. this needs far more emphasis (it is currently hidden by the wealth of detail in the rest of this discussion) and Figure 9 should include further panels showing how CUO changes (see below).

A: We put the ATM case first because this is the common approach if no deposition

C26

model is included (base case). The D-STO model here accounts for impacts of stomatal uptake on leaf-level O_3 concentration but still does not account for the non-stomatal fraction and can be seen as an intermediate approach. Our standard scheme accounting for both stomatal and non-stomatal uptake on leaf-level O_3 concentrations is the one that comes last such that complexity increases from panel a to c. We would like to keep the present order but can change it if it hampers the understanding of the graph. Furthermore in our notion the general pattern of a decrease in CUO from ATM to D-STO and D is easy to observe from the present graph. Additional panels showing the exact values seem to add little gain of knowledge. Thus we would like to not include them.

To highlight the importance of the deposition scheme more we changed in the Abstract: 'When applied at the European scale, we find that the added complexity of the ozone uptake simulation substantially affects simulated ozone uptake ' to 'When applied at the European scale, we find that accounting for stomatal and non-stomatal uptake substantially affects simulated ozone uptake, ...'

Furthermore we incorporate the importance of the deposition scheme into section 4.1 (Atmosphere-leaf transport).

2 Discussion

Q: This section seems redundant. Much of it is either already stated in the Results section or could be moved to form part of a more robust conclusion.

A: We would like to keep the conclusion short stating briefly the main insights from our work. To reduce redundancy between the results and discussion section we shortened the first paragraph in the discussion section as well as the subsection '4.1 Atmosphere-leaf transport', and '4.2 Site-level evaluation'. The subsection '4.3 Regional damage estimates' seems to us little redundant.

C27

Q: P16, L24-5 - replace "with the aim" with "in order to"

A: Done.

Q: P16, L25 - replace "effect to net" to "effect on net"

A: Done.

Q: P16, L25 - remove "the" before "regional"

A: Done.

Q: P16, L28 - replace "assuming" with "the assumption"

A: Respective sentence is omitted.

Q: P16, L28 - replace "would be identical" with "is identical"

A: Respective sentence is omitted.

Q: P16, L29 - replace "in 45m" with "at 45m"

A: Respective sentence is omitted.

Q: P16, L30-1 - suggest rewording: "and deposition variables i.e. calculated ozone uptake"

A: Respective sentence is omitted.

Q: P16, L32 - P17, L2 - suggest rewriting: "Our sensitivity analysis does show that a correct estimate of canopy conductance is crucial for calculating plant ozone uptake. We find that the model produces reasonable estimates"

C28

A: The respective sentences are omitted in this paragraph. The first sentence ('Our sensitivity analysis ...') is included in subsection 4.1.

Q: P17, L2 - replace "a range of" with "some"

A: Done (the respective half sentence is moved to subsection 4.2).

Q: P17, L7-8 - suggest rewriting: "Reliable estimates of surface ozone concentrations are also essential for calculating canopy ozone uptake F_{stC} "

A: Changed to: 'Reliable estimates of surface ozone concentrations – besides a reliable estimate of G_c – are also essential for calculating canopy ozone uptake (F_{stC}).'

Q: LP17, 8-9 - suggest rewriting: "airspace due to biogenic volatile organic compounds (BVOCS) emitted by vegetation is (at least partly) implicitly included in the"

A: We would like to skip the respective sentence since after rewriting the discussion it does not fit anymore.

Q: P17, L9-10 - Does this mean there is a degree of double accounting?

A: No. EMEP accounts for BVOCS (to a certain extend) in the calculation of the O_3 concentration in 45 m height. OCN to a certain extend accounts for BVOCS in the calculation of the leaf-level O_3 concentration.

Q: P17, L11 - suggest "performance" or "efficacy" in place of "functionality"

A: Respective sentence is omitted.

Q: P17, L15 - suggest combining these to form a single sentence: "changes in GC emphasising the importance"

C29

A: Respective sentences are omitted.

Q: P17, L15-16 - How can reliable estimates be obtained?

A: The respective sentence is omitted. It is of course not possible to simulate the true ozone uptake. However when variables determining ozone uptake are simulated in a reasonable range compared to observations one might call also the calculated uptake reliable (considering the uncertainty in both model simulations and observations). It will anyhow still be an estimate.

Q: P17, L18 - replace "indicates" with "indicate"

A: Respective sentence is omitted.

Q: P17, L26 - replace "impose" with "introduce"

A: Done.

Q: P17, L29 - replace "suitable" with "well able"

A: Respective sentence is omitted.

Q: P17, L30 - remove first occurrence of "finding" and replace "encourages" with "supports"

A: The respective sentence does not anymore exist. "encourages" is replaced by "supports" in a similar sentence.

Q: P18, L2 - reword: "Estimates of the regional damage to annual average"

A: Done.

C30

Q: P18, L2 - make clear this is transpiration rather than temperature (I assume)
A: Transpiration is spelled out.

Q: P18, L2-3 - remove "the period of the years"
A: Done.

Q: P18, L3 - replace "lower" with "low" and "previous" with "previously"
A: Changed to 'lower than previously reported'.

Q: P18, L3 - should read "Meta-analyses" and "an 11%"
A: Changed.

Q: P18, L6 - should read "Land Model"
A: Changed.

Q: P18, L7 - reword: "..transpiration have been estimated as 5-20 % for Europe and 2.2% globally "
A: Done.

Q: P18, L9 - reword: "plant types. Damage was only related to cumulative ozone uptake for one plant type with a very small slope"
A: Changed.

Q: P18, L9 - please explain the real-world meaning of a small slope.
A: The higher the slope the more damage occurs per accumulated ozone. The respective sentence is extended to: 'with a very small slope and hence little increase

C31

in damage due to increases in cumulative O_3 uptake.'

Q: P18, L14 - use "discrepancies" or "differences" rather than "deviations"
A: Changed to 'discrepancies'.

Q: P18, L14-15 - replace "the usage of very different" with "differences in" and then remove "different", "differing" and "non-identical"
A: Done.

Q: P18, L16 - replace "differences in simulating" with "simulation of"
A: Done.

Q: P18, L17 - reword: "The key difference from the previous study is our use of the ozone"
A: Changed to 'A key difference from the previous study is our use of the use of the ozone'.

Q: P18, L17 - remove "included in our study"
A: Done.

Q: P18, L21 - remove "the" before "non-stomatal"
A: Done.

Q: P18, L22 - should read "To obtain as accurate as possible an estimate "
A: Done.

C32

Q: P18, L23 - replace "it's" with "their"
A: Done.

Q: P18, L24 - replace "considered" with "accounted for"
A: Done.

Q: P18, L25 - suggest moving "(possibly PFT specific)" to come before "flux threshold"
A: Done.

Q: P18, L25 - "it's" should read "its"
A: Changed.

Q: p18, L25 - should the "Y" in "CUOY" be a subscript?
A: No, similar to AOTX the Y is not a subscript.

Q: P18, L32 - insert "see" before "LRTAP"
A: The respective sentence is omitted.

Q: P18, L33 - replace "but only" with "there are" and "exists for" with "of"
A: Done.

Q: P19, L2-4 - What is the implication of this disadvantage to the findings reported here?

A: Two sentences explaining the implications are added: 'This might be an important factor explaining the lower ozone damage estimates of OCN compared to other terrestrial biosphere models. An evaluation of the different proposed damage functions

C33

implemented in terrestrial biosphere models (e.g. Wittig et al. (2007); Lombardozzi et al. (2015); Sitch et al. (2007)) is necessary to elucidate which are able to e.g. reproduce observed patterns of biomass damage and hence might be suitable to predict regional or global damage estimates.'

Q: P19, L5 - replace "damage estimates" with "relationships"
A: Done.

Q: P19, L6 - replace "estimates" with "metrics"
A: Done.

Q: P19, L13 - replace "should be regarded too" with "also requires further analysis"
A: Done.

3 Conclusion

Q: This section needs to be substantially expanded. The authors would also do well to identify (even using bullet points if necessary) the key findings of their study and the implications for the land surface and atmosphere research communities. Much of Section 4 could be distilled and included in the Conclusion section.

A: As mentioned above we would like to keep the conclusion short stating briefly the main insights from our work. The Discussion section was shortened to remove redundancy.

Q: P19, L20-1 - replace "to generally consider" with "that"

C34

A: Done.

Q: P19, L21 - reword: "non-stomatal ozone uptake is routinely included in model assessments of ozone damage" and remove "estimate" after "better"

A: The rewording is done. The 'estimate' is not removed since it is an estimate.

Q: P19, L22 - remove "used"

A: Done.

Q: P19, L23 - insert "used here" after "scheme"

A: Done.

Q: P19, L23 - reword: "importance of reliable modelling of canopy conductances as well as realistic"

A: Done.

Q: P19, L24 - insert "as" before "accurate"

A: Done.

Q: P19, L26 - remove "Desirable are"

A: Done.

Q: P19, L27 - insert "are also desirable" after "types"

A: Done.

Q: P19, L29 - replace "regarded" with "considered"

C35

A: Done.

Q: P19, L29 - insert "," after "thresholds"

A: Done.

4 Appendix

Q: A P20, L1 - capitalise "Aerodynamic Resistance" and remove "(Appendix material)"

A: Done.

Q: P20, L3 - remove "," after "heights" and replace "This data is" with "These data are"

A: Done.

Q: P20, L4 - replace "in 45m height" with "at 45m"

A: Done.

Q: P20, L7 - what does U10 mean? If at 10m, why is this an appropriate height at which to calculate u^* ?

A: ' u_{10} ' is now explained as 'from the wind speed at 10 m height (u_{10})'. u_* is assumed to be constant within the surface near atmosphere layer. Since OCN is run offline (not coupled to a climate model) the necessary variables to calculate the friction velocity (e.g. wind speed and aerodynamic resistance) are only available in 10 m height.

Q: P20, L9 - replace "in 45m height" with "at 45m"

A: Done.

C36

Q: Appendix B P20, L21 - Why not use ORCHIDEE to calculate biogenic emissions?

A: OCN was developed from a ORCHIDEE version where biogenic emissions are not calculated. Modules of the current ORCHIDEE can not easily be included in OCN.

Q: P20, L22 - remove "NO from"

A: Done.

Q: P20, L24 - Volcanic emissions of what? Which compounds?

A: Volcanic emissions of SO_2 are meant. Respective sentence is changed to: 'Volcanic emissions of sulfur dioxide (SO_2) were set to a constant value from the year 2010.'

5 References

Please check references carefully.

Q: Tuovinen et al., 2004a and 2004b are the same paper Tuovinen et al., 2009a and 2009b are the same paper

A: This issue is resolved.

6 Figures

Q: Throughout - I would suggest that rainbow scale is not the most effective and that limited color graduated scales would be easier to interpret.

C37

A: The color palettes are changes from rainbow to restricted color gradients (palettes from ColorBrewer 2.0).

Q: Fig. 1 Panel (d) - Again, why choose a non-varying measure of LAI (i.e. point samples) rather than MODIS or similar, particularly as you comment on the validity of these measurements for the specific time period modelled? Panel (d) - In its present form this is not a useful panel and I would suggest that it is removed or moved to SI. It distracts from the good fit the model shows to other (more important) variables. Caption - line 4 should read "which are based on point"

A: MODIS data are also subject to a considerable amount of uncertainty. Furthermore the resolution of MODIS data is an additional source of uncertainty. Using observation directly from the site in question seemed to be the most reliable source. We would like to keep panel d) however can remove it or move it to SI when really requested. Caption is changed to "which are based on point".

Q: Fig. 2 x-axis scale - Hours should have a 4-hour or 6-hour scale, not 5. Please state explicitly whether this is local time or UTC. y-axis scale - As the scale is the same across each row I would suggest only one axis scale is required. y-axis scale - for variables that can be negative please add a dashed horizontal line to indicate 0.0; otherwise the axes should cross at zero.

A: X-axis is changed to 3 hour scale (3h - 21h). The time is local time (added to figure caption). Y-axis: the separate scales for each plot secure the readability of the plot. Excluding all but the one in the left column would make it hard to see which values the variable in the other columns take. The minimum for the Y-axes is set to zero.

Q: Fig. 3 scales - please define the scales used in Fig 3 more carefully, either here in the caption or in the appropriate place in the main text. Fig. 4 This figure should be SI. In addition, it is virtually unreadable. I had to view at 600% zoom to make out the yellow and red lines

C38

A: We would like to keep the figure in the main text since it illustrates the robustness of the included deposition module against the exact parameterisation. To make it better readable we skipped the interquartile-range (dark grey area) and stretched the plot. The red and yellow line lie on top of each other. The red line is dashed to show that the yellow line lies directly underneath. Furthermore we added a sentence in the text to explain this fact: 'For all four variables the unperturbed model and the ensemble mean lie on top of each other (see dashed red and yellow line in Fig. 4 a-d).'

Q: Fig. 5 scales - don't use the same colour scales for both absolute values and changes; changes are best shown on blue-red scales. Use e.g. green scale for crop cover.

A: Done.

Q: Fig. 7 scale - please improve the scales; I suggest using a graduated single or limited colour range. panel labels - please use more descriptive panel captions (not just "damage")

A: The color palette is changed.

Regarding the panel label: Since there is only restricted space within the graph corner we choose to state only that damage is plotted and the respective unit which indicates which variable is plotted. In the figure caption it is also stated what is plotted where. To us this seems quite explanatory however we can add also the plotted variable in the corner of the plot what however might overload it.

Q: Fig. 9 To me, this is the KEY figure in this paper. I suggest that you add panels showing changes in CUO from D to D-STO and ATM respectively (giving a 5 panel plot)

A: In our notion the general pattern of a decrease in CUO from ATM to D-STO and D is easy to observe from the present graph. Additional panels showing the ex-

C39

act values seem to add little gain of knowledge. Thus we would like to not include them.