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Interactive comment on "Declining risk of ozone impacts on vegetation in Europe 1990–2050 due to reduced precursor emissions in a changed climate" *by* J. Klingberg et al.

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We would like to thank all three reviewers for their time and their constructive comments, which will certainly improve the manuscript. Since the major concerns of the reviewers were quite similar they will be addressed together.

AOT40 vs POD

Our intention with the study was to show how decreasing European precursor emissions together with climate change affect the risk of ozone damage to vegetation in Europe. We did so through calculating the ozone exposure index AOT40 used in European legislation and policy contexts. Changes in climate and phenology settings that

might affect the ozone toxicity for vegetation in ways that are not included in the AOT40 concept were also included in the study, but mainly qualitatively discussed.

All three reviewers unanimous point out that the use of the flux-based approach (e.g. calculation of the POD-index) is more relevant. We acknowledge the criticism and agree that calculating the POD-index and quantifying the influence of a changing climate on stomatal conductance would be a better focus for the study.

The calculations needed to estimate the phytotoxic ozone dose (POD) accumulated through the stomata are not incorporated in the MATCH-model. However, to meet the reviewers concerns in our revised manuscript, we will calculate the POD-index offline at the four different sites/grid cells, representing different parts of Europe, already used for Figures 4 and 6. At these four sites we will show the changes in the flux based risk of ozone damage to vegetation 1960-2100 as well as a quantification of the modifications in the POD-index due to climate change. We agree that this represents a major improvement of our manuscript, but we believe it is correct to retain the AOT40 figures since they are relevant in the policy context (EU, CLRTAP). Figure 7-9 will be excluded from the revised manuscript.

Choice of parameterization

Another major concern of the reviewers is that the limits adopted for SWC and VPD effects on vegetation are based on the parameterization for northern European conifer forests, which is then used in a study which covers entire Europe. We agree that this is inconsistent and in the revised manuscript different parameterizations will be used, taken from the Mapping Manual of the LRTAP Convention (2011) and relevant for the different parts of Europe which the four sites represent, both concerning length of growing season and the effect of T, VPD and SWC on stomatal conductance.

Emission scenario

The reviewers ask for an explanation to why two different emission scenarios were used (RCP4.5 and SRES A1B) and an analysis of the RCP4.5 scenario. We agree that this needs to be clarified and discussed further.

The reason for the use of two different emission scenarios is that we rely on the published downscaled climate projections from RCA3 that were available when we initiated the study. The RCA3 climate projections are based on greenhouse gas emissions following the SRES A1B scenario. The RCP4.5 data were only used for air pollutant emissions in MATCH. In terms of greenhouse gas concentrations the RCP4.5 and SRES A1B scenario are not very different in the period up to 2050 so the difference in the projected climate would not have been much different using RCP4.5 instead of SRES in RCA3. For ozone precursors there are however large differences between SRES and RCP4.5. RCP4.5 assumes much larger emission reductions in Europe than SRES A1B in line with more recent projections.

Aggregated over the European CTM domain used in the study the NOx, NMVOC and CO emissions decrease by 53, 22 and 17 % respectively, from year 2000 to 2050 according to the RCP4.5 scenario (Langner et al., 2012a). A more detailed analysis of the RCP4.5 emission scenario including a comparison with current emission abatement legislation will be included in the revised manuscript.

Model performance

RC: There is a major inconsistency between the model results and observations e.g. at the Montelibretti station. Given this striking difference between the modelled and observed trends, how is it possible to reach the key conclusion of the study, i.e. that the risk of ozone impacts is declining? Please discuss.

AC: The overall (i.e. at 13 monitoring sites across Europe with long ozone data series and available nearby temperature measurements) performance of MATCH is summarized in Table 2. The spatial correlation and average bias are encouraging and indicate that systematic errors in the calculations of AOT40 are likely minor. The average RMSE (root-mean-square error) is, however, substantial which illustrate the difficulty to repro-

duce a quantity based on exceedances of a threshold close to ambient concentration at discrete stations. Figs. 4 and 6 were meant to illustrate this local problem (i.e. an additional, subjective, model evaluation), as well as showing the modelled temporal trend at the four sites chosen for the in-depth comparison.

RC: What is the difference between in-depth comparison (4 sites) and normal comparison (9 or 13 sites) and was there a particular reason for choosing these four sites for in-depth comparison over the other ones?

AC: Observed ozone concentrations and temperature from 13 measurement sites were used to evaluate the performance of the MATCH-RCA3 modelling system in this study. Four out of the 13 sites were selected for in-depth comparison and shown in Fig. 4 and Fig. 6. These four sites were chosen because they represent four different climatic regions of Europe. To show more than four sites in Fig. 4 and Fig. 6 is certainly possible, but was considered to result in an unclear and messy figures.

Clarifications of the methods chapter

The reviewers remark that the methods chapter is partly unclear and lacks some key pieces of information. We are thankful that this is brought to our attention. Below follows clarifications that will of course also be included in the revised manuscript.

RC: Where do the tracer boundary concentrations come from? The assumption of constant boundary conditions is inconsistent with RCP4.5, which suggests significant changes in the ozone precursor emissions outside Europé.

AC: Langner et al. (2012a) (which the current study is based on) present future ozone over Europe under different climates, tracer emissions and hemispheric background concentrations. The current study uses the simulations with ECHAM5 A1B climate, temporally varying RCP4.5 tracer emissions and “constant” tracer boundaries (ECH_RCP4.5_BC2000). The uniformly increasing boundary concentrations of ozone in Langner et al. (2012a) should be regarded as a sensitivity test rather than a realistic projection of future boundary concentrations of all tracers of interest. The main conclusions about the future ozone in both southern and northern Europe are not radically affected by altered boundaries, which leads us to select the simplified, but less speculative, “constant” boundary simulation for the current study. The “constant” boundary concentrations were based on observations at background locations and large scale model simulations. Further details are given in Andersson et al. (2007).

RC: How have VPD and SWC been calculated?

AC: VPD is calculated as ESAT*(1-RH), where RH is the grid-averaged 2 m relative humidity taken from the climate model. ESAT is the saturation water vapor pressure deduced from the climate model's grid-averaged 2 m temperature and applying the Magnus approximation. RH and temperature at 2 m are available from the climate model every 3 hours. SWC is taken directly from the regional climate model and is available with daily resolution. The surface scheme of the climate model is detailed in Samuelsson et al. (2011).

RC: Please clarify how you calculated the temperature sums.

AC: The temperature sum displayed in Fig. 9 is the growing season sum of the differences between daily average temperature and a base temperature of 5 °C for all days when the daily temperature exceeded the base temperature. E.g. a 100-day growing season with daily mean temperatures of 7 °C would result in a temperature sum of 200 degree days (i.e. 100*(7-5)).

RC: What is the rationale for applying a common, simple temperature limit for the growing season across the whole continent? The citation provided for this criterion reports about a study that only covers a limited area (Sweden).

AC: We agree with the reviewers that a simple temperature limit for the growing season across Europe is not optimal and mainly valid for northern Europe. Mapping Manual (CLRTAP, 2011) suggest a simple latitude model to define the start and end of growing

season across Europe. However, this method does not reflect changes in the length of the growing season due to altered future climate, which was our intention to show in Fig. 5 and Fig. 6. In southern Europe drought is an additional and important factor influencing the growing season. In Mapping Manual a mid-season dip in the phenology function is used to simulate the effect of the mid-season water stress on stomatal conductance for Mediterranean species (CLRTAP, 2011). As a result, it is very difficult to quantify the effect of water stress on the growing season in a changing climate. Either profound simplifications have to be made or southern Europe has to be excluded from this part of the study. A discussion of these difficulties will be included in the revised manuscript.

Detailed, specific comments

We are grateful for the effort the reviewers put in detailed comments on unclear phrasing and apologize for unnecessary spelling mistakes. They will of course be corrected in the revised manuscript.

References

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