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Declining risk of ozone impacts on vegetation in Europe 1990–2050 due to reduced precursor emissions in a changed climate

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Abstract

The impacts of climate change and changes in ozone precursor emission on ozone exposure (AOT40) of the vegetation in Europe were investigated. In addition, meteorological conditions influencing stomatal uptake of ozone were analysed to find out if climate change is likely to affect the risk for ozone damage to vegetation. Climate simulations based on the IPCC SRES A1B scenario were combined with ozone precursor emission changes from the RCP4.5 scenario and used as input to the Eulerian Chemical Transport Model MATCH from which projections of ozone concentrations were derived. Provided that the climate projections are realistic and the emission reductions of the emission scenario are undertaken, the ozone exposure of vegetation over Europe will be significantly reduced between the two time periods 1990–2009 and 2040–2059. This decline in AOT40 is larger than the reduction in average ozone concentrations. The reduction is driven by the emission reductions assumed by the RCP4.5 emission scenario, rather than changes in the climate. Higher temperatures in a future climate will result in a prolonged growing season over Europe as well as larger temperature sums during the growing season. Both the extended growing season and higher temperatures may enhance ozone uptake by plants in colder parts of Europe. The future climate suggested by the regional climate model will be dryer in terms of higher vapour pressure deficit (VPD) and lower soil moisture in southern Europe, which may reduce ozone uptake. VPD and soil moisture was not projected to change in north and northwest Europe to an extent that would influence ozone uptake by vegetation. This study shows that substantial reductions of ozone precursor emissions have the potential to strongly reduce the risk for ozone effects on vegetation, even if concurrent climate change promotes ozone formation.

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1 Introduction

Surface ozone (O_3) is the most important gaseous air pollutant with respect to effects on vegetation on regional and global scales (Hollaway et al., 2012; Mills et al., 2011; Royal Society, 2008). Experiments where ambient O_3 concentrations were reduced by air filtration have shown that current levels of O_3 are sufficient to cause significant yield loss in sensitive crops such as wheat (Pleijel, 2011). In addition, O_3 affects forest growth (Braun et al., 1999; Braun et al., 2007; Karlsson et al., 2006) and human health (Royal Society, 2008) and acts as an important greenhouse gas (Sitch et al., 2007).

O_3 is formed in the troposphere in reactions driven by the energy of solar radiation, involving the precursors nitrogen oxides (NO_x), volatile organic compounds (VOC) and carbon monoxide (CO). The concentrations of surface O_3 is affected by a number of factors including: (1) amount of ozone precursors, which is a function of anthropogenic emissions and the mixing and transport in the atmosphere, (2) effects of temperature on the rate of chemical reactions and on emissions of biogenic VOCs, which may enhance O_3 formation (Doherty et al., 2013), and (3) deposition to vegetated and non-vegetated surfaces, which depends on both vertical air mixing (Klingberg et al., 2012) and the effects of air and soil humidity, solar radiation and temperature on vegetation gas exchange (Tuovinen et al., 2009).

The conductance for gas exchange of plants is of critical importance for the uptake of O_3 and thus for its toxic effects on e.g. photosynthesis (Wittig et al., 2009) and leaf senescence (Uddling et al., 2006). For example, dry air and low soil moisture tend to promote stomatal closure of plant leaves thus reducing plant water loss and at the same time limiting plant stomatal uptake of O_3 (Emberson et al., 2000; Pleijel et al., 2007).

Several investigations have shown that climate change is likely to enhance O_3 formation over Europe (Demuzere et al., 2009), more so in the southern parts than in the north (Andersson and Engardt, 2010). These investigations assumed constant O_3 precursor emissions. However, emissions in Europe are likely to decline, both as a re-

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sult of existing international legislation and as an indirect effect of attempts to reduce carbon dioxide emissions (Rafaj et al., 2013). It is difficult to accurately predict the level of O_3 precursor emissions during the present century, since it depends on political decisions that are not known. To handle this problem four so called RCP (Representative Concentration Pathway) scenarios have been identified to represent different developments of global emissions of greenhouse gases and other air pollutants (Moss et al., 2010). Langner et al. (2012a) have shown that RCP4.5, the second most optimistic RCP scenario (Thomson et al., 2011), has the potential to significantly reduce O_3 concentrations over Europe and that this effect is likely to be much larger than concurrent promotion of O_3 formation by climate change.

In this study the chemical transport model MATCH, with O_3 precursor emissions according to the RCP4.5 scenario, was used to estimate the influence of climate change and emissions reductions on a number of environmental variables relevant for the assessment of future risk of O_3 effects on vegetation in Europe. These include both exposure to O_3 in the ambient air and meteorological factors relevant to the physiological uptake of O_3 by plants, such as the duration of the growing season, temperature, air humidity and soil moisture.

The aims of this study were:

- To estimate the O_3 index AOT40, used across Europe to set target values for the protection of the vegetation against harmful effects of O_3 (Mills et al., 2007), today and as projections for a 20 yr period centred around year 2050, assuming O_3 precursor emission reductions according to scenario RCP4.5 and climate change under the SRES A1B scenario.

- To assess changes in climate and phenology settings until 2050 that might affect the O_3 toxicity for vegetation in ways that are not included in the AOT40 concept.

- To provide time series of the present century AOT40 and length of the growing season including a test of how well the models represents current conditions for four sites in a north-to-south gradient over Europe.

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2 Materials and methods

2.1 MATCH and RCA3 model setup

MATCH is an Eulerian, off-line, chemistry transport model. It is a flexible system aimed at describing the regional distribution of air pollution given relevant meteorology and emission data. Detailed description of the model can be found in Robertson et al. (1999) and Andersson et al. (2007). Previous studies have demonstrated the ability of MATCH to realistically simulate O_3 concentrations over Europe when forced with meteorology from a regional climate model (Andersson and Engardt, 2010; Engardt et al., 2009; Langner et al., 2012a; Langner et al., 2012b). The present study is based on the set-up described in Langner et al. (2012a), experiment "ECH_RCP4.5_BC2000". Here MATCH is operated with gridded and temporally evolving (1960–2100) air pollutant emission data from the RCP4.5 inventory (Thomson et al., 2011) and meteorology from ECHAM5 A1B (initial condition r3; see Kjellström et al., 2011) downscaled over Europe with the Rossby Centre's regional climate model (RCA3) covering the same period. The tracer boundary concentrations are varying seasonally, but remain the same for all years.

RCA3 is described and evaluated in Samuelsson et al. (2011). Specifically, we use simulation number 11 in Table 1 of Kjellström et al. (2011). The SRES emission scenario A1B (Nakicenovic et al., 2000) was used, both in RCA3 and in the driving global model ECHAM5. Characteristics of the climate projection of relevance for near-surface O_3 concentrations are discussed in Langner et al. (2012a, 2012b), which both use this data set for studies of future O_3 across Europe.

The hourly O_3 concentrations are from the lowest model layer in MATCH ($\sim$ 30 m) but downscaled to 3 m at every time-step. Modelled temperature and relative humidity (from RCA3) correspond to 2 m height above ground and had 3 h temporal resolution.

2.2 O_3 risk assessment: AOT40, growing season and meteorological variables

AOT40 is the Accumulated exposure Over a Threshold of 40 ppb(v) O_3 (Fuhrer et al., 1997) given by:

$$AOT40 = \sum([O_3] - 40), \quad \text{for every } [O_3] > 40 \tag{1}$$

where $[O_3]$ is the 1 h mean O_3 concentration, expressed in ppb(v). AOT40 is accumulated over a time window which differs with vegetation type and for daytime only. It has been used widely in air pollution regulation in Europe (Fuhrer et al., 1997; Mills et al., 2007) to assess the risk for O_3 effects on vegetation and is included in the Mapping Manual of the Convention on Long-Range Transboundary Air Pollution (CLRTAP, 2004). In the EU legislation (directive 2008/50/EC) a May–July AOT40 of 9000 ppb h is used as target value not to be exceeded and 3000 ppb h as a long-term objective to protect vegetation. CLRTAP uses a three-month AOT40 critical level of 3000 ppb h for agricultural crops and a growing season critical level of 5000 ppb h for forest trees.

The only way in which the AOT40 index reflects that O_3 uptake by plants varies with the stomatal conductance is that the index is accumulated during daylight hours only. During the night stomata are largely closed and the leaf gas exchange is small. It is well established that several meteorological factors affect the stomatal gas exchange of plants. These include air humidity, expressed as the water vapour pressure deficit (VPD), reflecting the drying power of the air (Jones, 1992) and soil water content (SWC, the water content of the soil column available for transpiration, varying between 0 at the wilting point and 100 % at field capacity (Samuelsson et al., 2011). In this study, the fraction of time, during the growing season, when VPD was above 0.8 kPa and SWC was below 15 % by volume was calculated. These specific values were chosen since they are the thresholds above/below which the stomata in coniferous trees in northern Europe start to close to avoid drought stress according to the Mapping Manual (CLRTAP, 2004).

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Rising temperatures may at northern latitudes cause increased stomatal conductance, enhancing O_3 uptake, in the low to moderate temperature range (Uddling et al., 2005). In addition, especially in cold-temperate climates, rising temperatures will extend the length of the growing season and thus the duration of the period during which plants can take up O_3. The start of the growing season for trees was calculated as when the 24 h mean temperature exceeded 5 °C for five consecutive days and the end as when the 24 h mean temperature was below 5 °C for five consecutive days (Morén and Perttu, 1994). For crops a fixed three-month time window of May–July was used to assess AOT40 exposure in line with the EU directive (2008/50/EC) on Ambient Air Quality and Cleaner Air for Europe.

2.3 Comparison of simulations and observations

The MATCH-RCA3 performance have earlier been evaluated and shown good agreement with O_3 measurements in Europe. In Langner et al. (2012a) a comparison with summer observations revealed that the modelling system has a tendency to overestimate average O_3 concentrations by 1–7 %, but underestimate daily maximum concentrations by 2–7 %. According to Kjellström et al. (2011) the mean absolute error in temperature over land in RCA3 (ECHAM5 A1B-r3) is 0.90–1.05 °C in spring, summer and autumn.

In this study, observed O_3 concentrations and temperature were used to estimate the performance of the MATCH-RCA3 modelling system for AOT40 and length of the growing season. Four monitoring sites within the European Monitoring and Evaluation Programme (EMEP) were selected for in depth comparison between observations and simulations, representing different parts of Europe from north to south. Further comparison was made for thirteen EMEP monitoring sites with O_3 concentration observations and available nearby temperature measurements (within the same grid cell in MATCH). Hourly O_3 data was obtained from the EMEP website (www.emep.int) and daily temperature from the Swedish Meteorological and Hydrological Institute (www.smhi.se), European climate assessment and dataset (Tank et al., 2002) or personal communi-

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cation. Only years with less than 10 % missing data were included. More information about the sites is given in Table 1 and locations are shown in Fig. 1a.

The results of the comparisons are displayed in Table 2. The length of the growing season was on average well captured by the model with only a small overestimation of 3.5 %. However, for individual sites the differences can be rather large as shown by the RMSE of 31.5 days. The same was the case for the May–July AOT40 with only a small average bias of −1.8 %, but a RMSE of 1903 ppb h. The daily average O_3 concentrations had notably low spatial correlation for stations north of 50° N, which was also seen in Langner et al. (2012a).

An in depth comparison between the four selected EMEP monitoring sites and the simulations can be found in the Supplement. These sites are used in Figs. 4 and 6 to indicate the observed yearly variability in observations in relation to simulated time series of AOT40 and length of growing season.

3 Results and discussion

3.1 Changes in AOT40

The estimated daylight AOT40 across Europe, accumulated during the growing season for trees, is shown in Fig. 1a for the period 1990–2009 and in Fig. 1b as a projection for the period 2040–2059. For the period 1990–2009, the CLRTAP critical level of 5000 ppb h was exceeded over most of Europe including a large part of UK and the southern parts of Fennoscandia. For the period 2040–2059, AOT40 was estimated to exceed 5000 ppb h only in the Mediterranean area and at some spots along the coasts of Spain, France, Belgium, Netherlands and the southern parts of UK. The high levels along some coastal areas are likely to be a result of the higher O_3 concentrations over the sea, in turn resulting from low deposition and strong vertical air mixing, which also affect coastal areas (Pleijel et al., 2013).

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The estimated daylight AOT40 during May–July across Europe is shown in Fig. 2a as a mean value for the period 1990–2009 and in Fig. 2b as a projection for the period 2040–2059. The long-term EU objective and CLRTAP critical level of 3000 ppb h was exceeded 1990–2009 over most of Europe, including most of UK and the southern parts of Fennoscandia. By the period 2040–2059, the exceedance was greatly reduced and again restricted to the Mediterranean region and some coastal spots around Spain, France, Belgium, Netherlands and UK.

The credibility of the projections regarding the decline in the exceedance of AOT40 for forests and crops (Figs. 1 and 2) depends strongly on the reduction of O_3 precursor emissions suggested by the RCP4.5 scenario. Langner et al. (2012a) showed that even though climate change leads to increasing surface O_3 concentrations during April–September in some areas of Europe, the projected emission reductions in Europe have a stronger effect, resulting in net reductions of O_3 concentrations. Provided that the substantial emissions reductions suggested by the RCP4.5 scenario are performed, O_3 concentrations will reach levels where the risk for effects on vegetation decline strongly and may disappear over large areas, but not the whole of Europe. The AOT40 index, which is based on the exceedance of a threshold and thus highly sensitive to modest changes in concentrations near that threshold (Sofiev and Tuovinen, 2001), declines much more than the average O_3 concentrations. This is illustrated in Fig. 3a and 3b where it is shown that average concentrations were likely to be reduced by 10–20 % over large parts of Europe and by 20–30 % for parts of Central Europe, while the reduction in AOT40 suggested by the model was mostly in the range of 50–100 % over Europe. Thus, the risk for adverse effects on vegetation by O_3 based on AOT40 was more sensitive to emission reductions compared to concentration averages.

Figure 4 shows time series of the growing season AOT40 values over the period 1960–2100. It suggests that the AOT40 peaked before year 2000 and will continue to decline after the period 2040–2059. The performance of the MATCH model was indicated by the inclusion of observed data at the four sites considered. The large between-years variation in AOT40 derived from observations was not reflected by the

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model. Also the model tended to overestimate AOT40 at Illmitz, but underestimate it at Montelibretti. However, the model captures the range of AOT40 from low in the north and high in the south.

Regional scale models often tend to underestimate the high O_3 concentrations during O_3 episodes (Langner et al., 2012b). This is the case also with the MATCH model in this study (e.g. see Fig. S1 in the Supplement). As a result, the AOT40 values that are based on modelled O_3 concentrations were underestimated to a greater extent as compared to modelled average O_3 concentrations. O_3 precursor emission reductions in Europe will probably reduce the frequency of O_3 episodes (Solberg et al., 2005). On the other hand, future episodes of high temperatures as part of the climate change might lead to an increasing frequency of O_3 episodes (Solberg et al., 2008).

3.2 Changes in length of growing season

In Fig. 5a the length of the growing season for trees is shown as mean values for the period 1990–2009 and in Fig. 5b as the estimated change between the periods 2040–2059 and 1990–2009. The duration of the growing season for trees is projected to increase over most of Europe, with the most pronounced increases in continental and northern Europe and in the UK. It is important to note that in this study calculation of the growing season length is only based on temperature. In southern Europe drought is an additional and important factor influencing the growing season. If drought were to be included in the calculations, the growing season would be shorter in southern Europe.

As a consequence of the extended growing season suggested by the model, the period during which AOT40 was accumulated in Fig. 1b was longer than in Fig. 1a. Thus, the strongly reduced AOT40 between the two periods resulted despite the fact that the accumulation period was longer in Fig. 1b and the promotion of O_3 formation by climate change. It further emphasises the strong reduction in O_3 exposure, resulting from the RCP4.5 emission scenario used in the model setup.

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An earlier onset of the growing season during spring is of particular importance in northern Europe (Karlsson et al., 2007) since the O_3 concentrations can be high at northern latitudes during this time of year (Klingberg et al., 2009). The spring peak in O_3 in relation to onset of the growing season is an aspect which requires further study.

Figure 6 shows the length of the growing season for trees, based on modelled air temperatures, over the period 1960–2100 at four sites across Europe. The length of the growing season was projected to continue to increase after the period 2040–2059, especially at northern latitudes. Included in the figure is the length of the growing season based on observed air temperatures for the four sites. The between-years variation in the observations were to a large extent captured by the model, which also has the adequate range in growing season length between north and south.

3.3 Changes in climatic conditions affecting the phytotoxicity of O_3

The concept of daylight AOT40 does only to a very limited extent (through exclusion of the dark hours during which stomata are mostly closed) include factors that affect the rate of O_3 uptake through the stomata to the leaf interior, i.e. aspects of the phytotoxicity of a certain concentration of O_3 in the air next to the leaf.

Besides light conditions, which are not likely to be altered by climate change in a way important to stomatal conductance, the most important meteorological factor determining the O_3 uptake to the leaf interior through the stomata is VPD. In Fig. 7, the modelled time fraction during daytime when VPD is above the threshold 0.8 kPa during the growing season is shown as a 20 yr average 1990–2009 (Fig. 7a) and the calculated change up to 2040–2059 (Fig. 7b). According to the model set-up the time fraction of VPD above 0.8 kPA was less than 10 % in northern Europe. In southern Europe high VPD reduced stomatal conductance 10–60 % of the time in current climate. The fraction of time with VPD above 0.8 kPA was projected to increase in the southern part of Europe in 2040–2059. High VPD occurs at high temperature and since high temperatures are generally underestimated by the model (e.g. see Fig. S2 in Supplement) it is likely that

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also VPD is underestimated. The coarse spatial resolution in the model (50 km × 50 km) limits the details of important processes, such as diurnal range and extremes.

Low soil moisture is one further factor with large potential to reduce stomatal conductance in different climate regions across Europe (Emberson et al., 2007). Figure 8 shows the fraction of time with the estimated SWC below 15 % (by volume), both for the current climate (Fig. 8a) and as a difference between the future (2040–2059) and present (1990–2009) climate (Fig. 8b). In northern and central Europe the modelled SWC was below 15 % less than 10 % of the time. In southern Europe low SWC reduced stomatal conductance 10–60 % of the time and up to 90 % of the time in a few grid cells in current climate. The fraction of time with SWC below 15 % was projected to increase in the southern part of Europe in 2040–2059. The climate model is not optimized to model soil water, which vary over short distances e.g. due to soil texture and Fig. 8 should therefore be interpreted with care. It is likely that SWC limits stomatal uptake of O_3 also in northern Europe, as for example shown by Büker et al. (2012).

Another important meteorological variable affecting the leaf O_3 uptake is air temperature. Figure 9 shows the temperature sums above 5 °C (24 h-mean temperatures) accumulated over the growing seasons, both for the current climate (Fig. 9a) and as a difference between future (2040–2059) and present (1990–2009) climate (Fig. 9b). For northern Europe, the temperature sums were projected to increase considerably, in the order of 20 %. This will probably increase the leaf O_3 uptake to some extent, i.e. to increase the phytotoxicity of a certain AOT40 value. In continental and southern Europe, the temperature sums will increase even more (in absolute values) and this will most likely contribute to a reduction of the leaf O_3 uptake in the warmest areas.

In summary, in northern Europe higher temperatures and a prolonged growing season were projected to counteract the decline in ambient O_3 concentrations, by increasing leaf O_3 uptake and thereby the phytotoxicity of a certain AOT40 value. However, modelled VPD and SWC are likely to be underestimated as explained above, which indicates that VPD and SWC could limit O_3 uptake to vegetation also in northern Europe to a larger extent than indicated in Fig. 7 and 9. In southern Europe higher tempera-

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tures, dryer air and soil were projected to reduce the stomatal uptake of O_3 and thereby reduce the O_3 toxicity to the plants. These modifications of the O_3 risk to vegetation due to climatic conditions were however small in relation to the projected large decline in AOT40. Thus, it seems likely that the O_3 risk for vegetation by the year 2050 will be low, provided that the substantial emission reductions assumed in the RCP4.5 scenario can be realized, despite that changed climatic conditions to some extent might increase O_3 phytotoxicity in northern Europe.

3.4 Uncertainties and future work

In this study we have described how AOT40 is affected by projected climate change and O_3 precursor emission reductions according to the RCP4.5 scenario. Then we showed how VPD, SWC and temperature are influenced by climate change and discuss how the changes in these environmental factors one by one are likely to modify the phytotoxicity of a certain AOT40 value. A way to quantitatively estimate the combined influence of climatic conditions on the O_3 risk for vegetation is to model the O_3 uptake through the stomata. This was however not within the scope of this study, but recommended for future work.

An additional factor with potential to significantly reduce O_3 toxicity is the projected reduction in stomatal conductance under rising CO_2 concentrations in future climate (Klingberg et al., 2011). The sensitivity of vegetation to O_3 is also affected by potential future changes in land-use and changes in the composition of species. Further uncertainties lie in potential changes in antioxidative defence capacity and secondary effects such as pest and diseases (Fuhrer, 2009). These factors have not been considered in this study, but needs further investigation.

The results presented in this study are strongly dependent on the choice of emission scenario for O_3 precursors in Europe. The RCP4.5 emission scenario assumes substantial air pollution abatement measures and it remains to be seen if these reductions can be realized. As a comparison, the European O_3 concentrations in 2050 are under all four RCP scenarios substantially smaller than those in the SRES A1B, A2 and B2

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scenarios as shown by Wild et al. (2012). It reflects the assumptions of much more stringent O_3 precursor emission controls under the RCP scenarios.

Furthermore, the tracer boundary concentrations are constant in this study. It remains unclear how regional emission controls may be offset by for example global "background" O_3 increases, by changes in the abundance of the longer-lived O_3 precursor CH_4 (Wild et al., 2012) or by changes in atmospheric chemistry and transport patterns due to climate change (Jacob and Winner, 2009).

The emission reductions undertaken in the RCP4.5 scenario is only one of several possible futures. However, with this study we would like to illustrate that if substantial air pollution control measures are undertaken, it is possible to significantly reduce the negative effects of O_3 on vegetation in a not so distant future.

4 Conclusions

This study considered the combined effect of projected climate change and emission reductions according to the RCP4.5 scenario during the present century. A number of important conclusions can be drawn, including:

- Powerful, but realistic, emission reductions have the potential to strongly reduce the phytotoxic O_3 exposure in Europe. Over wide areas AOT40 will decrease to levels which are well below O_3 critical levels used by the LRTAP convention as well as in the EU legislation in the time period 2040–2059.
- The beneficial effect of emission reductions is much larger than the counteracting effect of climate change on O_3 formation. It has to be kept in mind that if emissions are not substantially reduced, surface O_3 will continue to be a serious problem to European vegetation, which is aggravated by climate change.
- The AOT40 index used in risk assessment for O_3 effects on vegetation is likely to decline much more (by 50–100 % over large parts of Europe) than average O_3

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concentrations (by 10–20 % over large parts of Europe) as precursor emissions are reduced.

- Dryer conditions in terms of higher VPD and lower SWC in south and central Europe in a future climate will promote stomatal closure and thus lead to stronger limitation of plant O_3 uptake. Higher temperatures will on the other hand extend the duration of the growing season in colder parts of Europe and also promote a larger stomatal uptake of O_3, thus increasing the risk of O_3 effects on vegetation.

Supplementary material related to this article is available online at http://www.biogeosciences-discuss.net/11/625/2014/ bgd-11-625-2014-supplement.pdf.

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References

Andersson, C. and Engardt, M.: European ozone in a future climate: Importance of changes in dry deposition and isoprene emissions, J. Geophys. Res.-Atmos., 115, D02303, doi:10.1029/2008JD011690, 2010.

Andersson, C., Langner, J., and Bergström, R.: Interannual variation and trends in air pollution over Europe due to climate variability during 1958–2001 simulated with a regional CTM coupled to the ERA40 reanalysis, Tellus B, 59, 77–98, 2007.

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Braun, S., Rihm, B., Schindler, C., and Fluckiger, W.: Growth of mature beech in relation to ozone and nitrogen deposition: an epidemiological approach, Water Air Soil Poll., 116, 357–364, 1999.

Braun, S., Schindler, C., Rihm, B., and Fluckiger, W.: Shoot growth of mature Fagus sylvatica and Picea abies in relation to ozone, Environ. Pollut., 146, 624–628, 2007.

Büker, P., Morrissey, T., Briolat, A., Falk, R., Simpson, D., Tuovinen, J.-P., Alonso, R., Barth, S., Baumgarten, M., Grulke, N., Karlsson, P. E., King, J., Lagergren, F., Matyssek, R., Nunn, A., Ogaya, R., Peñuelas, J., Rhea, L., Schaub, M., Uddling, J., Werner, W., and Emberson, L. D.: DO_3SE modelling of soil moisture to determine ozone flux to forest trees, Atmos. Chem. Phys., 12, 5537–5562, doi:10.5194/acp-12-5537-2012, 2012.

CLRTAP: Manual on Methodologies and Criteria for Modelling and Mapping Critical Loads and Levels and Air Pollution Effects, Risks and Trends, UNECE Convention on Long-range Transboundary Air Pollution, Updated 2011, available at www.icpmapping.org , 2004.

Demuzere, M., Trigo, R. M., Vila-Guerau de Arellano, J., and van Lipzig, N. P. M.: The impact of weather and atmospheric circulation on O_3 and PM_10 levels at a rural mid-latitude site, Atmos. Chem. Phys., 9, 2695–2714, doi:10.5194/acp-9-2695-2009, 2009.

Doherty, R. M., Wild, O., Shindell, D. T., Zeng, G., MacKenzie, I. A., Collins, W. J., Fiore, A. M., Stevenson, D. S., Dentener, F. J., Schultz, M. G., Hess, P., Derwent, R. G., and Keating, T. J.: Impacts of climate change on surface ozone and intercontinental ozone pollution: a multi-model study, J. Geophys. Res.-Atmos., 118, 3744–3763, 2013.

Emberson, L. D., Ashmore, M. R., Cambridge, H. M., Simpson, D., and Tuovinen, J. P.: Modelling stomatal ozone flux across Europe, Environ. Pollut., 109, 403–413, 2000.

Emberson, L. D., Büker, P., and Ashmore, M. R.: Assessing the risk caused by ground level ozone to European forest trees: a case study in pine, beech and oak across different climate regions, Environ. Pollut., 147, 454–466, 2007.

Engardt, M., Bergström, R., and Andersson, C.: Climate and emission changes contributing to changes in near-surface ozone in Europe over the coming decades – results from model studies, Ambio, 38, 452–458, 2009.

Fuhrer, J.: Ozone risk for crops and pastures in present and future climates, Naturwissenschaften, 96, 173–194, 2009.

Fuhrer, J., Skärby, L., and Ashmore, M. R.: Critical levels for ozone effects on vegetation in Europe, Environ. Pollut., 97, 91–106, 1997.

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Hollaway, M. J., Arnold, S. R., Challinor, A. J., and Emberson, L. D.: Intercontinental trans-boundary contributions to ozone-induced crop yield losses in the Northern Hemisphere, Biogeosciences, 9, 271–292, doi:10.5194/bg-9-271-2012, 2012.

Jacob, D. J. and Winner, D. A.: Effect of climate change on air quality, Atmos. Environ., 43, 51–63, 2009.

Jones, H. G.: Plants and Microclimate. A Quantitative Approach to Environmental Plant Physiology, 2nd edn., Cambridge University Press, Cambridge, 1992.

Karlsson, P. E., Örlander, G., Langvall, O., Uddling, J., Hjorth, U., Wiklander, K., Areskoug, B., and Grennfelt, P.: Negative impact of ozone on the stem basal area increment of mature Norway spruce in south Sweden, Forest Ecol. Manag., 232, 146–151, 2006.

Karlsson, P. E., Tang, L., Sundberg, J., Chen, D., Lindskog, A., and Pleijel, H.: Increasing risk for negative ozone impacts on vegetation in northern Sweden, Environ. Pollut., 150, 96–106, 2007.

Kjellström, E., Nikulin, G., Hansson, U., Strandberg, G., and Ullerstig, A.: 21st century changes in the European climate: uncertainties derived from an ensemble of regional climate model simulations, Tellus A, 63, 24–40, 2011.

Klingberg, J., Björkman, M. P., Pihl Karlsson, G., and Pleijel, H.: Observations of ground-level ozone and NO_2 in northernmost Sweden, including the Scandian Mountain Range, Ambio, 38, 448–451, 2009.

Klingberg, J., Engardt, M., Uddling, J., Karlsson, P. E., and Pleijel, H.: Ozone risk for vegetation in the future climate of Europe based on stomatal ozone uptake calculations, Tellus A, 63, 174–187, 2011.

Klingberg, J., Karlsson, P. E., Pihl Karlsson, G., Hu, Y., Chen, D., and Pleijel, H.: Variation in ozone exposure in the landscape of southern Sweden with consideration of topography and coastal climate, Atmos. Environ., 47, 252–260, 2012.

Langner, J., Engardt, M., and Andersson, C.: European summer surface ozone 1990–2100, Atmos. Chem. Phys., 12, 10097–10105, doi:10.5194/acp-12-10097-2012, 2012a.

Langner, J., Engardt, M., Baklanov, A., Christensen, J. H., Gauss, M., Geels, C., Hedegaard, G. B., Nuterman, R., Simpson, D., Soares, J., Sofiev, M., Wind, P., and Zakey, A.: A multi-model study of impacts of climate change on surface ozone in Europe, Atmos. Chem. Phys., 12, 10423–10440, doi:10.5194/acp-12-10423-2012, 2012b.

Mills, G., Buse, A., Gimeno, B., Bermejo, V., Holland, M., Emberson, L., and Pleijel, H.: A synthesis of AOT40-based response functions and critical levels of ozone for agricultural and horticultural crops, Atmos. Environ., 41, 2630–2643, 2007.
Mills, G., Hayes, F., Simpson, D., Emberson, L., Norris, D., Harmens, H., and Buker, P.: Evidence of widespread effects of ozone on crops and (semi-)natural vegetation in Europe (1990–2006) in relation to AOT40- and flux-based risk maps, Glob. Change Biol., 17, 592–613, 2011.
Morén, A.-S. and Perttu, K. L.: Regional Temperature and Radiation Indices and Their Adjustment to Horizontal and Inclined Forest Land Studia Forestalia Suecica (ISSN 91-576-4915-4), 194, 19 pp., 1994.
Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P., and Wilbanks, T. J.: The next generation of scenarios for climate change research and assessment, Nature, 463, 747–756, 2010.
Nakicenovic, N., Alcamo, J., Davis, G., Vries, B. d., Fenhann, J., Gaffin, S., Gregory, K., Grobler, A., Jung, T. Y., Kram, T., Rovere, E. L. L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Riahi, K., Roehrl, A., Rogner, H.-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., Rooijen, S. v., Victor, N., and Dadi, Z.: Emission scenarios. A special report of IPCC Working Group III, Cambridge University Press, 599 pp., 2000.
Pleijel, H.: Reduced ozone by air filtration consistently improved grain yield in wheat, Environ. Pollut., 159, 897–902, 2011.
Pleijel, H., Danielsson, H., Emberson, L., Ashmore, M. R., and Mills, G.: Ozone risk assessment for agricultural crops in Europe: further development of stomatal flux and flux–response relationships for European wheat and potato, Atmos. Environ., 41, 3002–3040, 2007.
Pleijel, H., Klingberg, J., Karlsson, G. P., Engardt, M., and Karlsson, P. E.: Surface ozone in the marine environment – horizontal ozone concentration gradients in coastal areas, Water Air Soil Poll., 224, 1603, doi:10.1007/s11270-013-1603-4, 2013.
Rafaj, P., Schopp, W., Russ, P., Heyes, C., and Amann, M.: Co-benefits of post-2012 global climate mitigation policies, Mitig. Adapt. Strateg. Glob. Change, 18, 801–824, 2013.
Robertson, L., Langner, J., and Engardt, M.: An Eulerian limited-area atmospheric transport model, J. Appl. Meteorol., 38, 190–210, 1999.

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11, 625–655, 2014

Royal Society: Ground-level ozone in the 21st century: future trends, impacts and policy implications. RS Policy document 15/08, London, available at: http://royalsociety.org, 133 pp., 2008.
Samuelsson, P., Jones, C. G., Willen, U., Ullerstig, A., Gollvik, S., Hansson, U., Jansson, C., Kjellstrom, E., Nikulin, G., and Wyser, K.: The Rossby Centre Regional Climate model RCA3: model description and performance, Tellus A, 63, 4–23, 2011.
Sitch, S., Cox, P. M., Collins, W. J., and Huntingford, C.: Indirect radiative forcing of climate change through ozone effects on the land-carbon sink, Nature, 448, 791–794, 2007.
Sofiev, M. and Tuovinen, J. P.: Factors determining the robustness of AOT40 and other ozone exposure indices, Atmos. Environ., 35, 3521–3528, 2001.
Solberg, S., Bergström, R., Langner, J., Laurila, T., and Lindskog, A.: Changes in Nordic surface ozone episodes due to European emission reductions in the 1990s, Atmos. Environ., 39, 179–192, 2005.
Solberg, S., Hov, O., Sovde, A., Isaksen, I. S. A., Coddeville, P., De Backer, H., Forster, C., Orsolini, Y., and Uhse, K.: European surface ozone in the extreme summer 2003, J. Geophys. Res.-Atmos., 113, D07307, doi:10.1029/2007JD009098, 2008.
Tank, A., Wijngaard, J. B., Konnen, G. P., Bohm, R., Demaree, G., Gocheva, A., Mileta, M., Pashiardis, S., Hejkrlik, L., Kern-Hansen, C., Heino, R., Bessemoulin, P., Muller-Westermeier, G., Tzanakou, M., Szalai, S., Palsdottir, T., Fitzgerald, D., Rubin, S., Capaldo, M., Maugeri, M., Leitass, A., Bukantis, A., Aberfeld, R., Van Engelen, A. F. V., Forland, E., Mietus, M., Coelho, F., Mares, C., Razuvaev, V., Nieplova, E., Cegnar, T., Lopez, J. A., Dahlstrom, B., Moberg, A., Kirchhofer, W., Ceylan, A., Pachaliuk, O., Alexander, L. V., and Petrovic, P.: Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment, Int. J. Climatol., 22, 1441–1453, 2002.
Thomson, A. M., Calvin, K. V., Smith, S. J., Kyle, G. P., Volke, A., Patel, P., Delgado-Arias, S., Bond-Lamberty, B., Wise, M. A., Clarke, L. E., and Edmonds, J. A.: RCP4.5: a pathway for stabilization of radiative forcing by 2100, Climatic Change, 109, 77–94, 2011.
Tuovinen, J. P., Emberson, L., and Simpson, D.: Modelling ozone fluxes to forests for risk assessment: status and prospects, Ann. For. Sci., 66, 401, doi:10.1051/forest/2009024, 2009.
Uddling, J., Hall, M., Wallin, G., and Karlsson, P. E.: Measuring and modelling stomatal conductance and photosynthesis in mature birch in Sweden, Agr. Forest Meteorol., 132, 115–131, 2005.

BGD
11, 625–655, 2014

Uddling, J., Karlsson, P. E., Glorvigen, A., and Sellden, G.: Ozone impairs autumnal resorption of nitrogen from birch (Betula pendula) leaves, causing an increase in whole-tree nitrogen loss through litter fall, Tree Physiol., 26, 113–120, 2006.
Wild, O., Fiore, A. M., Shindell, D. T., Doherty, R. M., Collins, W. J., Dentener, F. J., Schultz, M. G., Gong, S., MacKenzie, I. A., Zeng, G., Hess, P., Duncan, B. N., Bergmann, D. J., Szopa, S., Jonson, J. E., Keating, T. J., and Zuber, A.: Modelling future changes in surface ozone: a parameterized approach, Atmos. Chem. Phys., 12, 2037–2054, doi:10.5194/acp-12-2037-2012, 2012.
Wittig, V. E., Ainsworth, E. A., Naidu, S. L., Karnosky, D. F., and Long, S. P.: Quantifying the impact of current and future tropospheric ozone on tree biomass, growth, physiology and biochemistry: a quantitative meta-analysis, Glob. Change Biol., 15, 396–424, 2009.

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Table 1. Description of the thirteen EMEP monitoring sites and nearby temperature (T) observations included in the comparison between observations and simulations.

EMEPID	Station O_3 obs	Latitude Longitude	Altitude (m a.s.l.)	O_3 data*	Station T obs	Latitude Longitude	Altitude (m a.s.l.)	T data*
SE13	Esrange	67°53′ N 21°04′ E	475	1991–2012 (21)	Esrange	67°52′ N 21°05′ E	328	1994–2009 (15)
FI22	Oulanka	66°19′ N 29°24′ E	310	1990–2011 (19)	Kuusamo Kiutakongas	66°22′ N 29°19′ E	160	1990–2012 (23)
SE35	Vindeln	64°15′ N 19°46′ E	225	1990–2012 (22)	Vindeln-Sunnansjönäs	64°08′ N 19°46′ E	237	1990–2011 (20)
NO39	Kårvatn	62°47′ N 08°53′ E	210	1992–2011 (20)	Sunndalsora III	62°41′ N 08°34′ E	33	1990–2008 (18)
SE11	Vavihill	56°01′ N 13°09′ E	175	1990–2012 (23)	Munka-Ljungby	56°14′ N 12°59′ E	48	1990–2012 (23)
DK41	Lille Valby	55°41′ N 12°08′ E	10	1992–2009 (17)	Koebenhavn: Landbohojskolen	55°41′ N 12°32′ E	9	1990–2012 (23)
GB02	Eskdalemuir	55°19′ N 03°12′ W	243	1990–2012 (22)	Eskdalemuir	55°19′ N 03°12′ W	242	1990–2012 (23)
GB06	Lough Navar	54°27′ N 07°52′ W	126	1990–2011 (17)	Ballyshannon	54°30′ N 08°11′ W	38	1990–2012 (22)
DE07	Neuglobsow	53°10′ N 13°02′ E	62	1992–2010 (19)	Neuglobsow	53°09′ N 13°02′ E	62	1995–2009 (15)
NL10	Vredepeel	51°32′ N 05°51′ E	28	1990–2010 (19)	Volkel	51°40′ N 05°42′ E	20	1990–2012 (23)
AT02	Illmitz	47°46′ N 16°46′ E	117	1990–2010 (21)	Illmitz	47°46′ N 16°46′ E	117	1991–2011 (21)
CH02	Payerne	46°49′ N 06°57′ E	489	1990–2010 (20)	Payerne	46°49′ N 06°57′ E	490	1990–2012 (23)
IT01	Montelibretti	42°06′ N 12°38′ E	48	1996–2009 (13)	Roma Ciampino	41°47′ N 12°35′ E	105	1990–2012 (23)

* Within brackets number of years with less than 10 % missing data.

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Table 2. Comparison between observations and simulations of daily average and minimum temperature (T in °C) over the whole year, length of growing season (GS in days), daily average and maximum O_3 (ppbv) over the whole year and AOT40 accumulated from May to July (ppb h) of the thirteen EMEP monitoring sites and nearby temperature observations described in Table 1.

	T mean	T min	Length GS	O_3 mean	O_3 max	AOT40mjj
# stations	13	13	13	13	13	13
RMSE	1.6	2.4	32	4.9	2.6	1903
Spatial correlation	0.94	0.90	0.89	0.03	0.83	0.89
Mean obs	7.8	3.7	244	27.2	38.6	4940
Mean model	7.2	5.1	251	29.5	38.2	4683
Bias	−0.6 °C	1.4 °C	3.5 %	10.3 %	−0.8 %	−1.8 %

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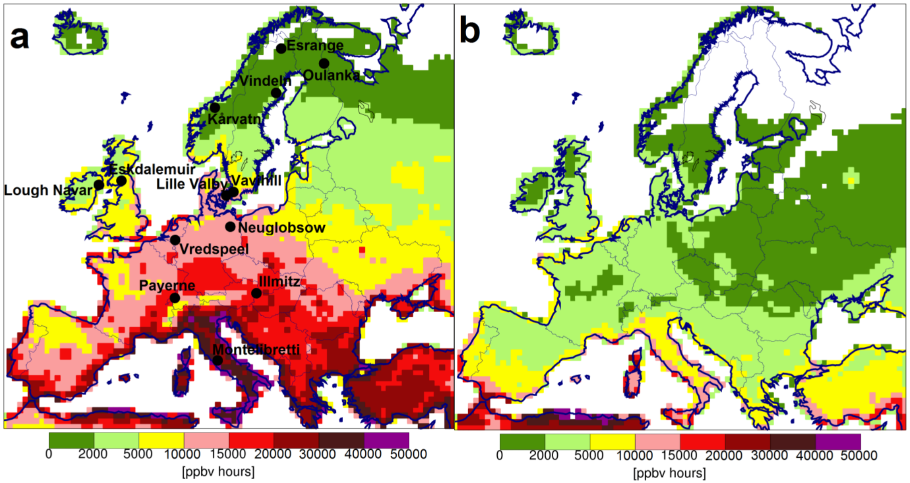

Fig. 1. Present and future modelled AOT40 (ppb h) accumulated over the growing season for trees as 20 yr averages, 1990–2009 **(a)** and 2040–2059 **(b)** assuming O_3 precursor emission reductions according to the RCP4.5 scenario.

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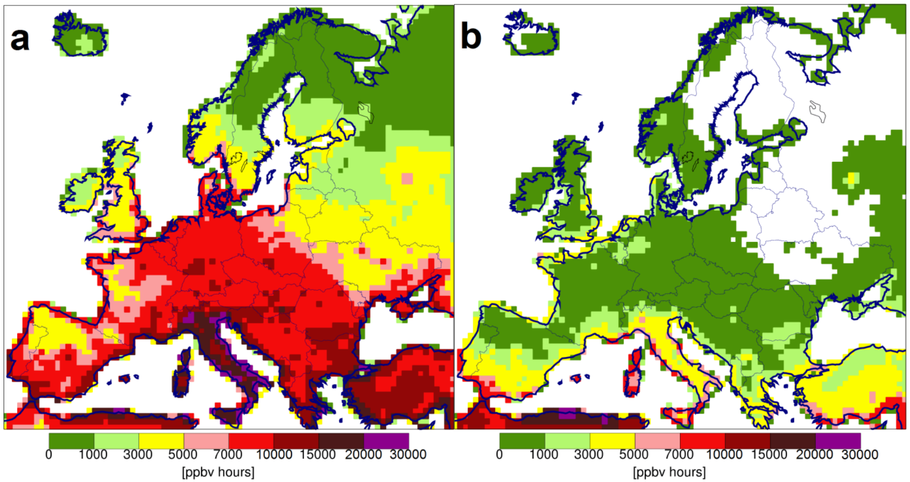

Fig. 2. Present and future modelled AOT40 (ppb h) accumulated over May–July as 20 yr averages 1990–2009 **(a)** and 2040–2059 **(b)** assuming O_3 precursor emission reductions according to the RCP4.5 scenario.

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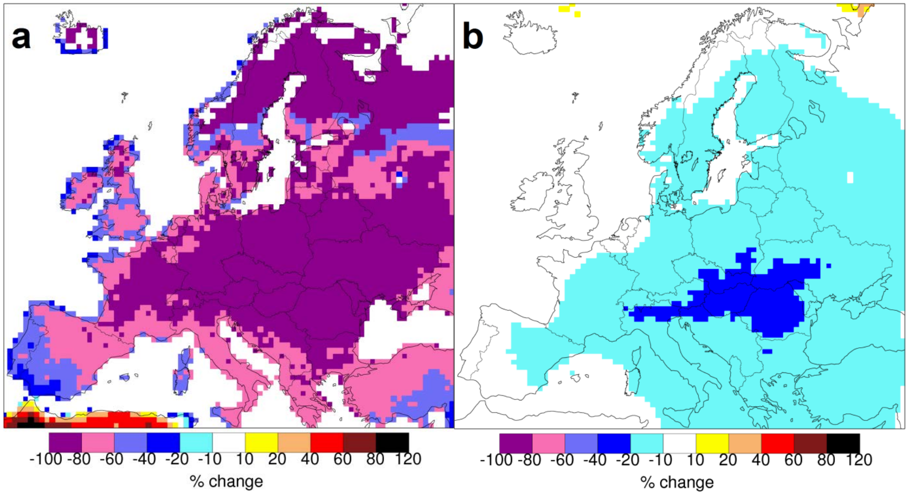

Fig. 3. The modelled percentage change in AOT40 **(a)** and average O_3 concentration **(b)** between the periods 1990–2009 and 2040–2059 assuming O_3 precursor emission reductions according to the RCP4.5 scenario.

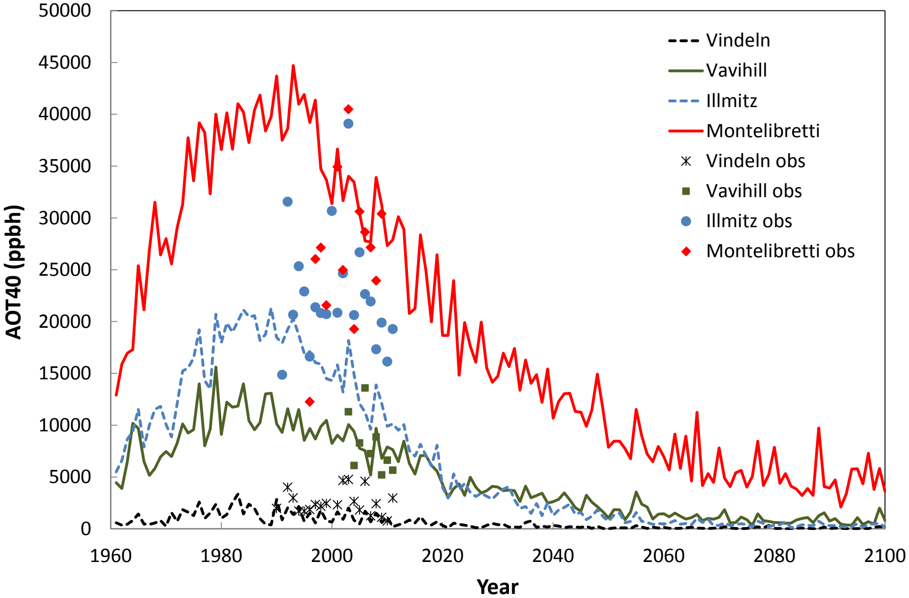

Fig. 4. Modelled AOT40 (ppbh) accumulated over the growing season for trees during 1960–2100 at four sites in Europe assuming O_3 precursor emission reductions according to the RCP4.5 scenario. Discrete symbols represent observations of O_3 concentration ∼ 1990–2012.

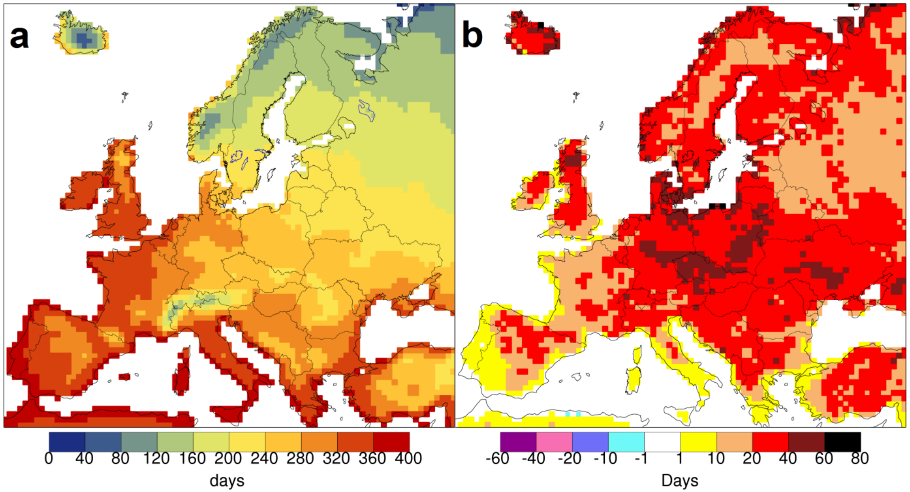

Fig. 5. Modelled length of growing season for trees (days) as a 20 yr average 1990–2009 **(a)** and the change up to 2040–2059 **(b)**.

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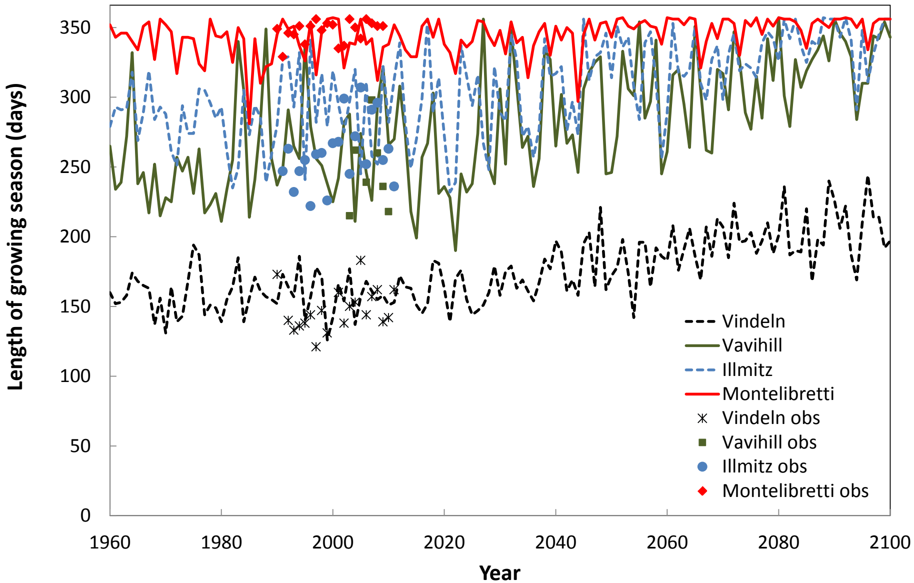

Fig. 6. Modelled length of growing season for trees (days) during 1960–2100 at four sites in Europe. Discrete symbols are based on observations of temperature ~ 1990–2012.

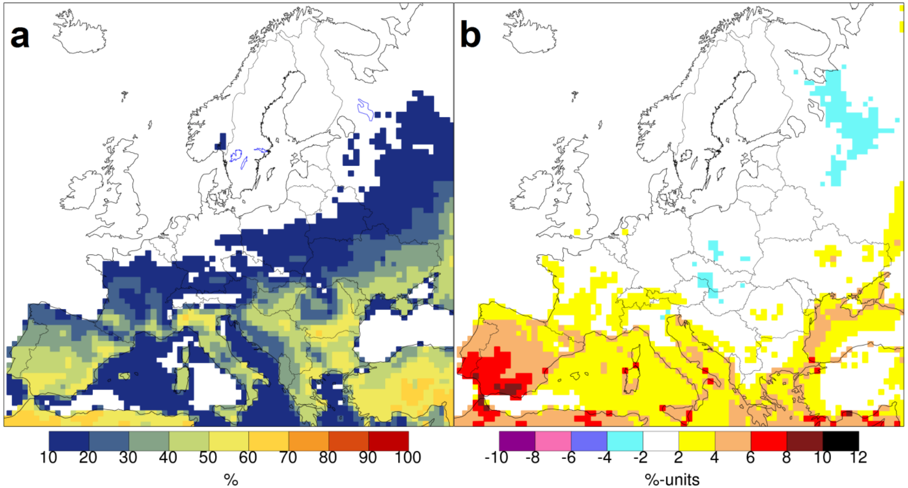

Fig. 7. Modelled time fraction daytime VPD was above the CLRTAP Mapping Manual threshold 0.8 kPa during the growing season for trees as a 20 yr average 1990–2009 **(a)** and the change up to 2040–2059 **(b)**.

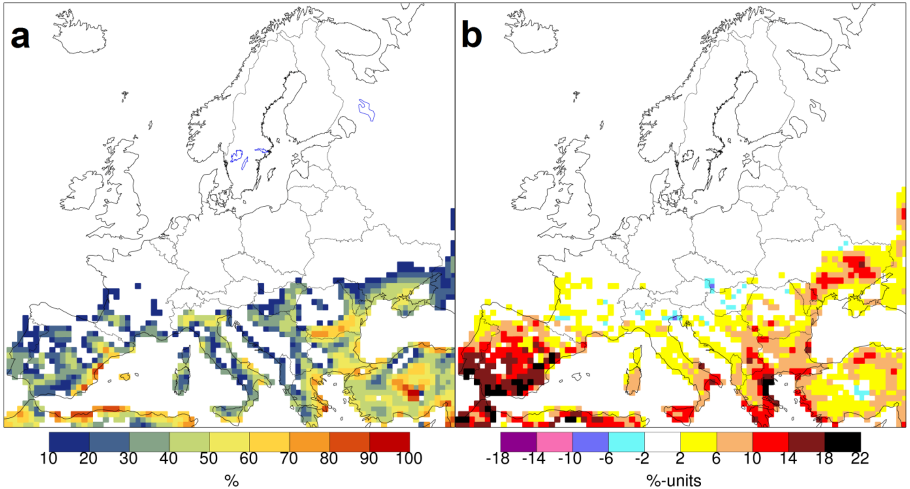

Fig. 8. Modelled time fraction SWC was below the CLRTAP Mapping Manual threshold 15 % by volume during the growing season for trees as a 20 yr average 1990–2009 **(a)** and the change to 2040–2059 **(b)**.

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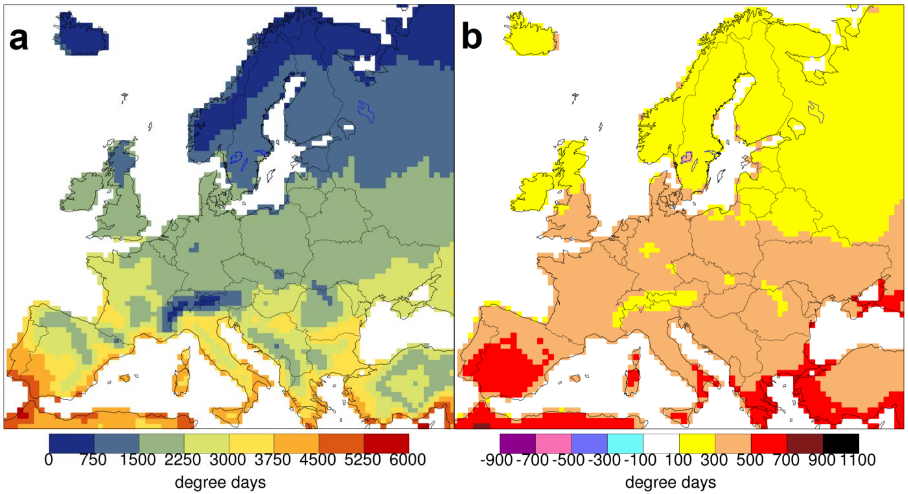

Fig. 9. Modelled temperature sum during the growing season for trees as a 20 yr average 1990–2009 **(a)** and the change up to 2040–2059 **(b)**.