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Ozone concentrations and damage for realistic future European climate and air quality scenarios

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HIGHLIGHTS

- Evaluating the impact of EU's energy and air quality policy on ground-level ozone damage.
- Combined impacts of land use change, trend in anthropogenic emissions and climate change.
- Effect of trend in emissions on ozone is more important than effect of land use change.
- Impact of climate change may outweigh effect of reduced ozone precursor emissions.

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ABSTRACT

Ground level ozone poses a significant threat to human health from air pollution in the European Union. While anthropogenic emissions of precursor substances (NO_x, NMVOC, CH_4) are regulated by EU air quality legislation and will decrease further in the future, the emissions of biogenic NMVOC (mainly isoprene) may increase significantly in the coming decades if short-rotation coppice plantations are expanded strongly to meet the increased biofuel demand resulting from the EU decarbonisation targets. This study investigates the competing effects of anticipated trends in land use change, anthropogenic ozone precursor emissions and climate change on European ground level ozone concentrations and related health and environmental impacts until 2050. The work is based on a consistent set of energy consumption scenarios that underlie current EU climate and air quality policy proposals: a current legislation case, and an ambitious decarbonisation case. The Greenhouse Gas-Air Pollution Interactions and Synergies (GAINS) integrated assessment model was used to calculate air pollutant emissions for these scenarios, while land use change because of bioenergy demand was calculated by the Global Biosphere Model (GLOBIOM). These datasets were fed into the chemistry transport model LOTOS-EUROS to calculate the impact on ground level ozone concentrations. Health damage because of high ground level ozone concentrations is projected to decline significantly towards 2030 and 2050 under current climate conditions for both energy scenarios. Damage to plants is also expected to decrease but to a smaller extent. The projected change in anthropogenic ozone precursor emissions is found to have a larger impact on ozone damage than land use change. The increasing effect of a warming climate (+2 −5 °C across Europe in summer) on ozone concentrations and associated health damage, however, might be higher than the reduction achieved by cutting back European ozone precursor emissions. Global action to reduce air pollutant emissions is needed to make sure that ozone damage in Europe decreases towards the middle of this century.

1. Introduction

Ozone is a natural component of the troposphere and necessary because of its cleansing role. However, since pre-industrial times concentrations have risen to levels harmful to human health, crops and ecosystems (Fowler et al., 2008). In the EU28, ground-level

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ozone is associated with at least 16 thousand excess deaths each year, making it the second most important pollutant in terms of health damage after particulate matter (EEA, 2014). Ozone production is driven by emissions of the ozone precursor substances nitrogen oxides (NO_x), methane (CH_4), non-methane volatile organic compounds (NMVOC) and the availability of light. While NO_x has some natural sources, the vast majority of the emissions in Europe is of anthropogenic origin (Sutton et al., 2011). For NMVOCs, emissions from vegetation make up about 90% of total emissions globally, whereas in Europe anthropogenic and biogenic emissions contribute about equally to the total (Guenther et al., 1995). Biogenic NMVOC emissions (of which isoprene and monoterpenes are the most important) are driven by the type and density of vegetation as well as temperature and light.

EU climate and energy policies promote renewable energy production and increased energy efficiency measures (European Commission, 2009). One expected effect of these policies is a significant expansion of commercial bioenergy crop production such as short-rotation coppice (SRC) plantations and an increasing use of forests (European Commission, 2014). Bioenergy crops and trees typically emit more isoprene than the crops or grassland they replace because of a higher isoprene emission factor as well as higher leaf density, whereas monoterpene emissions are equal or reduced since bioenergy species have generally low monoterpene emission factors (Benjamin and Winer, 1998; Steinbrecher et al., 2009). The increase in isoprene emissions could increase ground level ozone production and concentrations. Previous studies have explored the impact of a significant increase in SRC bioenergy plantations on ozone in Europe using chemistry transport models (CTMs) concluding that the increase in ground level ozone damage for human health and crop production could be significant (Beltman et al., 2013; Ashworth et al., 2013; Lathière et al., 2006). While some of these studies used country-specific projections of future SRC plantation areas (Ashworth et al., 2013), most used general and/or extreme assumptions about the amount and location of SRC plantations and used a CTM at a coarse scale, limiting the extent to which regional ozone formation is resolved (Wild and Prather, 2006; Emery et al., 2012).

The EU air quality directive (EC, 2008) restricts emissions of air pollutants from anthropogenic sources, leading to a significant decrease in European NO_x and NMVOC emissions in the near future (Amann et al., 2014). Results of energy policies such as an increasing share of renewable sources in the energy mix or increasing use of electric vehicles could cause a further decline in emissions of NO_x, NMVOCs and methane from the energy and transport sector (Cofala et al., 2012). These trends in anthropogenic emissions act towards a reduction in ground level ozone formation (Lacressonnière et al., 2014). Because some steps in the ground level ozone formation process are driven by absorption of light and/or proceed faster with higher temperatures, climate conditions influence ozone formation and ground level ozone concentrations could increase in future due to climate change nonetheless (Varotsos et al., 2013; Katragkou et al., 2011). The combined effect of increasing global ozone precursor emissions and climate change has been studied by Revell et al. (2015), who project a significant increase in ground level ozone concentrations and damage globally.

While the isolated impacts of changing land use and anthropogenic emissions on ozone levels have been investigated before (in- or excluding the possible impacts of a changing climate), the combined effect of these two correlated trends has not received a lot of attention so far. In this work, we investigate the change in ozone concentration and associated health and vegetation damage caused by the combined land use and emission changes projected by policy-relevant EU energy and emission scenarios. For this, we use the regional CTM LOTOS-EUROS at a $0.5 \times 0.25°$ resolution (approx. 28×28 km) to model ground level ozone concentrations and damage indicators SOMO35 and POD_1 (a health and ecosystem damage indicator, respectively) based on consistent and policy-relevant emission and land use scenarios for the EU28. Also, we provide a decomposition of the total effect on ozone levels and explore the impact of the projected trend in hemispheric background concentrations as well as the possible effects of climate change.

2. Methods

2.1. The LOTOS-EUROS model

In this study, the 3D regional chemistry transport model (CTM) LOTOS-EUROS v.1.10 (Beltman et al., 2013) was used to assess the influence of EU climate and air quality policies on ground level ozone concentrations. Previous versions of the model have been used for air pollution assessments, some of which were aimed at ozone (e.g. Manders et al., 2012), NO_x (Curier et al., 2014; Schaap et al., 2013), and scenario studies (Mues et al., 2013; Hendriks et al., 2015). LOTOS-EUROS is used to provide operational forecasts of ozone, nitrogen dioxide and particulate matter within the CAMS (Copernicus Atmosphere Monitoring Service) ensemble (Curier et al., 2012; Marécal et al., 2015). Furthermore, LOTOS-EUROS has frequently participated in international model comparisons concerning ozone (Hass et al., 2003; Van Loon et al., 2007; Solazzo et al., 2013; Schaap et al., 2015). For a detailed model description we refer to Schaap et al. (2009) and Wichink Kruit et al. (2012). Here, only the most relevant aspects for the current study are presented.

The model uses a normal longitude–latitude projection and was run at a resolution of $0.5 \times 0.25°$ over Europe (15°W-25°E, 35–70°N). For boundary conditions of O_3 and NO_x, monthly climatological steady state values were used. The model top is placed at 3.5 km above sea level and consists of three dynamical layers: a mixing layer and two reservoir layers on top. The height of the mixing layer at each time and location is extracted from ECMWF meteorological data used to drive the model. The height of the reservoir layers is set to the difference between ceiling (3.5 km) and mixing layer height. Both layers are equally thick with a minimum of 50 m. If the mixing layer is near or above 3500 m high, the top of the model exceeds 3500 m. A surface layer with a fixed depth of 25 m is included in the model to monitor ground-level concentrations. Advection in all directions is represented by the monotonic advection scheme developed by Walcek (2000). Gas phase chemistry is described using the TNO CBM-IV scheme (Schaap et al., 2009), which is based on Whitten et al. (1980). The isoprene chemistry description follows Adelman (1999) and N_2O_5 hydrolysis is described in Schaap et al. (2004a). Dry deposition for gases is modelled using the DEPAC3.11 module (Van Zanten et al., 2010), while the description of particle deposition follows Zhang et al. (2001). Stomatal resistance is described by the parameterization of Emberson et al. (2000a,b) and the aerodynamic resistance is calculated for all land use types separately. Wet deposition of trace gases and aerosols are treated using simple scavenging coefficients for gases (Schaap et al., 2004b) and particles (Simpson et al., 2003).

Biogenic NMVOC emissions are calculated based on detailed information on tree types in Europe because the biogenic emission factors are extremely variable between species. Therefore, the CORINE land use dataset (Büttner et al., 2012) is combined with the distributions of 115 tree species over Europe (Koeble and Seufert, 2001). During each simulation time step, biogenic isoprene and monoterpene emissions are calculated as a function of the biomass density and standard emission factor of the species or land use class (Schaap et al., 2009), taking into account the growing season of deciduous trees and agricultural crops. The role of local temperature and photo-synthetically active radiation are taken into account in the biogenic emissions by following the empirically designed