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Differences in particulate matter concentrations between urban and rural regions under current and changing climate conditions

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HIGHLIGHTS

- PM10 urban increments were quantified as differences between urban and rural regions.
- Different measured PM10 urban increments were found for three urban areas in Europe.
- These urban increments were also investigated using a chemistry transport model.
- Model simulations showed a small impact of climate change on the urban increment.

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ABSTRACT

Pollution levels in urban areas and their surrounding rural regions differ due to different sources and density of emissions, different composition of pollutants as well as specific meteorological effects. These concentration differences for PM10 are investigated and compared in this study for three different north-west European urban agglomerations: The German Ruhr area, the Dutch Randstad and the German city of Berlin. Measurement data for PM10 for the years 2003–2008 at urban and rural background stations are selected from the AirBase database to specify the PM10 concentration difference between these urban areas and their surrounding rural regions, here defined as the urban increment. Whereas the absolute and relative measured urban increment averaged over the years 2003–2008 for the Ruhr area (7.4 $\mu g\ m^{-3}$, 35%) and Berlin (8.5 $\mu g\ m^{-3}$, 46%) are comparable in magnitude, a significantly smaller value is found for the Randstad (3.1 $\mu g\ m^{-3}$, 12%). To analyze whether the regional chemistry transport model LOTOS-EUROS is able to reproduce the measured urban increment simulation runs were performed for 2003–2008 on a $0.5° \times 0.25°$ lon-lat grid covering Europe and for the year 2008 on a finer grid of $0.125° \times 0.0625°$ covering the Netherlands and Germany, both with ECMWF meteorology as input. Although the model underestimates the absolute PM10 urban increment averaged over the years 2003–2008 for the Ruhr area (3.3 $\mu g\ m^{-3}$, 33%), the Randstad (1.5 $\mu g\ m^{-3}$, 12%) and Berlin (1.7 $\mu g\ m^{-3}$, 27%), the relative urban increment for the Ruhr area and the Randstad is in general agreement with the measurements. The tested increase of the horizontal resolution gives no systematic improvement of the simulated urban increment. However, an even higher resolution than used here seems to be more appropriate to capture the urban increment (especially for Berlin).

The variability of the PM10 urban increment with weather is tested by means of the summer 2003, such an extreme synoptic situation is expected to occur more often in future. Measured and simulated PM10 concentrations in summer 2003 were compared to the summer average of 2003–2008. The response of the observed urban increment was found to depend on the urban area. In general the model reproduces the main features for the Randstad and Berlin.

In order to investigate the impact of a changing climate on the PM10 urban increment, simulations were performed with the off-line coupled model system RACMO2 (regional climate model) – LOTOS-EUROS (air quality model) over Europe. Different sets of simulations were carried out using RACMO2 meteorology with ECHAM5 A1B and with MIROC3.2-hires A1B boundary conditions for the time period 1970–2060, as well as with ERA-interim boundary conditions for the time period 1989–2009. Anthropogenic emissions were kept constant in the LOTOS-EUROS simulations. Simulated concentrations differ

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between the runs using ECHAM and MIROC boundary conditions and both runs differ from the present-day simulations with ERA-interim forcing. The impact of climate change on the modeled PM10 concentrations and the urban increment was found to be small in both scenario runs. However the concentration differences between the simulations forced by either ECHAM or MIROC indicate that PM10 concentration levels are sensitive to circulation patterns rather than temperature change alone, and that PM10 concentration levels may thus change when circulation patterns change in the future.

1. Introduction

Particulate matter (PM) receives a special interest in research and politics as the most severe health effects of air pollution are attributed to PM (EEA, 2012). Therefore, threshold values for PM10 and PM2.5 are defined in current EU directives (EU, 2008), but even below this threshold considerable health impacts (up to 12 months lower life expectancy (EEA, 2007)) are found. In this context urban areas are very important because they represent the main areas of anthropogenic emissions and threshold values at hot spot locations in urban and industrial areas are still exceeded on many locations (EEA, 2012). In order to develop mitigation strategies one needs to determine the origin of PM and its components as well as its response on emission reductions in urban areas. For air quality assessments it is important to consider both emissions and meteorology. Meteorological conditions in Europe are anticipated to change in future due to climate change. Hence it is important to also assess the impact of a changing climate on the concentration of pollutants. This is of special interest for urban areas because a high and even increasing proportion of the population lives in urbanized regions and is therefore exposed to the consequences of climate change and to air pollution.

The urban air quality depends on the pollution regime inside as well as outside an urban area. There is a large interest to specify the contribution of the regional background concentration, determined by regional emission sources and long-term transport, and of the concentration resulting from the local urban emissions to the urban pollution level. PM concentrations and composition were found to differ substantially between an urban area and its surrounding rural region (e.g. Lenschow et al., 2001; Putaud et al., 2010), resulting in a positive urban increment of PM concentrations. However, the size of the urban increment might differ per area because of differences in its size and structure (isolated city versus urban agglomeration), climate, population density, as well as in main emission sources and the contribution from long-range transport. A central question in the present paper is: what is the PM10 concentration difference between an urban and its surrounding rural region and how much does the resulting urban increment depend on the urban area.

It is a common approach to use regional chemistry transport models (CTM) to evaluate air quality policies and the impact of emission reduction strategies on the national and European scale (e.g. Builtjes et al., 2010). Hence it is important that regional CTMs are able to reproduce the concentration level and the different response of emission reductions in urban and rural regions. A central question in this context is therefore if a state-of-the-art regional CTM like LOTOS-EUROS (Schaap et al., 2008) is able to reproduce the measured urban increment.

In many model evaluation studies CTM simulations showed a considerable underestimation of PM10 concentrations of up to 50% (e.g. Cuvelier et al., 2007; Stern et al., 2008). This is mainly due to missing but important components and emissions sources or uncertainties therein (e.g. windblown dust, secondary organic aerosols, and wild fires). As a consequence it is expected that the absolute urban increment is also underestimated in the models. However, assuming that the relative ratio between emissions in the urban and rural regions is captured, we can expect a reproduction of the measured relative urban increment. In general, the horizontal resolution of a regional CTM (10×10 to 50×50 km^2), which is needed to cover an appropriate area and time period is not sufficient to reproduce the concentration variability within an urban agglomeration (Stern, 2010). Furthermore small scale features associated to the structure of a built-up area (e.g. urban heat-island, modified wind field) are not explicitly taken into account in these models. Hence, with such a model system the focus should be on large-scale feature (synoptic situations). In view of recent studies on the impact of climate change on air quality, it is relevant information how well such a model performs, because long-term simulations with urban scale models are still too time-consuming in terms of computation time.

One method to investigate the impact of climate change on air pollution is to analyze a specific synoptic situation in the past (e.g. extreme summer 2003) which is expected to occur more often in future in terms of its effect on air quality (Vautard et al., 2007a; Mues et al., 2012). The advantages of this approach are that such an effect can be directly analyzed using observations, and that an evaluation of the CTM performance as function of meteorology is possible. In contrast to this approach, which only considers one specific synoptic situation, one-way coupled model systems consisting of a regional CTM forced by a regional climate model (RCM) give the opportunity to take into account the variability of the future climate. The available studies using such a model system (e.g. Meleux et al., 2007; Langner et al., 2005; Manders et al., 2012) show a consistent picture of increasing summer ozone concentrations but the extent of the changes differ. For PM the response to changes in climate is weaker and the limited number of studies does not even agree on the sign of the change (Jacob and Winner, 2009). Furthermore PM consists of several components which may respond differently to meteorology and therefore it is reasonable to look into changes of the individual PM components (Tai et al., 2012). The question discussed here is which conclusions can be drawn on the impact of a changing climate on the urban increment based on the two approaches using regional models.

In the present study we aim to quantify the size of the average measured PM10 urban increment for the time period 2003–2008. The urban increment is here defined as the difference between the urban and regional background concentrations represented by PM10 concentrations at urban and rural background stations located in the urban and its surrounding rural region, respectively. We selected three different areas in north-west Europe: the German Ruhr area, the Dutch Randstad and the city of Berlin (Germany). In a second step we tested whether the state-of-the-art regional CTM LOTOS-EUROS is able to reproduce the observed urban increment as a function of the urban area. To this end model simulations were produced for the years 2003–2008 on a 25×25 km^2 grid resolution covering Europe. To test the sensitivity of the simulation results to the spatial resolution of the model a simulation with a higher resolution of 7×7 km^2 for the year 2008 was performed. These measurement and simulation data were also used to compare the urban increment for the extreme summer