Atmospheric Environment 112 (2015) 90–105

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Performance of European chemistry transport models as function of horizontal resolution

M. Schaap [a,*], C. Cuvelier [b], C. Hendriks [a], B. Bessagnet [c], J.M. Baldasano [d], A. Colette [c], P. Thunis [b], D. Karam [b], H. Fagerli [e], A. Graff [f], R. Kranenburg [a], A. Nyiri [e], M.T. Pay [d], L. Rouïl [c], M. Schulz [e], D. Simpson [e,g], R. Stern [h], E. Terrenoire [c], P. Wind [e,i]

[a] TNO, Dept. of Climate, Air and Sustainability, P.O. Box 80015, NL-3508TA, Utrecht, Netherlands
[b] European Commission, DG Joint Research Centre, Institute for Environment and Sustainability, I-21020, Ispra, Va, Italy
[c] INERIS, Institut National de l'Environnement Industriel et des Risques, Parc Technologique, ALATA, F-60550, Verneuil-en-Halatte, France
[d] Earth Science Department, Barcelona Supercomputing Center – Centro Nacional de Supercomutación, c/ Jordi Girona 29, E-08034, Barcelona, Spain
[e] EMEP MSC-W, Norwegian Meteorological Institute, P.O. Box 43, Blindern, N-0313, Oslo, Norway
[f] Umweltbundesamt, Postfach 1406, D-06813, Dessau-Roßlau, Germany
[g] Dept. Earth & Space Sciences, Chalmers University of Technology, SE412 96, Gothenburg, Sweden
[h] Freie Universität Berlin, Institut für Meteorologie und Troposphärische Umweltforschung, Carl-Heinrich-Becker Weg 6-10, D-12165, Berlin, Germany
[i] UiT The Arctic University of Norway, 9037, Tromsø, Norway

HIGHLIGHTS

- Four European CTMs were used to compare model performance at different resolutions.
- CTM resolution increase from ~50 to ~14 km is worthwhile and practical.
- Model performance improves with resolution for NO_2 and PM_{10}.
- For further resolution increase, high resolution emission and meteorological data are crucial.

ARTICLE INFO

Article history:
Received 5 October 2014
Received in revised form
29 March 2015
Accepted 2 April 2015
Available online 3 April 2015

Keywords:
Air quality
Model evaluation
Particulate matter
Ozone
Nitrogen oxides

ABSTRACT

Air pollution causes adverse effects on human health as well as ecosystems and crop yield and also has an impact on climate change trough short-lived climate forcers. To design mitigation strategies for air pollution, 3D Chemistry Transport Models (CTMs) have been developed to support the decision process. Increases in model resolution may provide more accurate and detailed information, but will cubically increase computational costs and pose additional challenges concerning high resolution input data. The motivation for the present study was therefore to explore the impact of using finer horizontal grid resolution for policy support applications of the European Monitoring and Evaluation Programme (EMEP) model within the Long Range Transboundary Air Pollution (LRTAP) convention. The goal was to determine the "optimum resolution" at which additional computational efforts do not provide increased model performance using presently available input data. Five regional CTMs performed four runs for 2009 over Europe at different horizontal resolutions.

The models' responses to an increase in resolution are broadly consistent for all models. The largest response was found for NO_2 followed by PM_{10} and O_3. Model resolution does not impact model performance for rural background conditions. However, increasing model resolution improves the model performance at stations in and near large conglomerations. The statistical evaluation showed that the increased resolution better reproduces the spatial gradients in pollution regimes, but does not help to improve significantly the model performance for reproducing observed temporal variability. This study clearly shows that increasing model resolution is advantageous, and that leaving a resolution of 50 km in favour of a resolution between 10 and 20 km is practical and worthwhile. As about 70% of the model response to grid resolution is determined by the difference in the spatial emission distribution, improved

* Corresponding author.
E-mail address: martijn.schaap@tno.nl (M. Schaap).

http://dx.doi.org/10.1016/j.atmosenv.2015.04.003

emission allocation procedures at high spatial and temporal resolution are a crucial factor for further model resolution improvements.

1. Introduction

Air pollution is associated with adverse effects on human health through population exposure to particulate matter and ozone (Dockery et al., 1993; Bell et al., 2004), loss of biodiversity through acidification and eutrophication (Bobbink et al., 1998), decreased crop yields (Adams et al., 1982; Mills et al., 2011) as well as climate change through interactions of short-lived climate forcers with the earth's radiation balance and carbon and nitrogen cycles (Ainsworth et al., 2012; Kiehl and Briegleb, 1993; Simpson et al., 2014b). Air pollutants like ozone (O_3), particulate matter (PM) and nitrogen oxides (NO_x) play a key role in several of these issues. To guide the design of mitigation strategies 3D chemistry transport models (CTMs) have been developed (e.g., Bessagnet et al., 2004; Schaap et al., 2004; Byun and Schere, 2006; Simpson et al., 2012). For this application CTMs should accurately predict the concentration distributions and temporal variability of pollutants, as well as the response of these concentration distributions to emission changes due to mitigation options. As cheap mitigation options have already been implemented in Europe, further mitigation strategies are anticipated to become increasingly expensive (Wagner et al., 2000). Hence, the quality of the underpinning data and models to develop cost-effective mitigation strategies needs to be as high as possible.

The European Monitoring and Evaluation Programme Meteorological Synthesizing Centre – West (EMEP MSC-W) models (Eliassen and Saltbones, 1983; Berge and Jakobsen, 1998; Simpson et al., 2012) have been instrumental to the development of air quality policies in Europe since the late 1970s. In the 1990s the EMEP models became the reference tools for atmospheric dispersion calculations as input to Integrated Assessment Models RAINS (Regional Air Pollution Information and Simulation) and GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) (Schöpp et al., 1999; Reis et al., 2012), which support the development of air quality polices in the European Union. From 1999 until 2012, the EMEP model has been run on a resolution of $50 \times 50\ km^2$ for policy support purposes. Partly as a result of the work to be presented here, starting 2013 a grid size of 28 km is used for source-receptor calculations. However, rapid computational technology advancements in the past two decades have enabled CTM applications at even higher resolutions. In Europe, Eulerian CTMs currently use resolutions between 12 and 25 km for operational European wide applications (e.g., Pay et al., 2010; Zhang et al., 2012; Mues et al., 2014), 4–10 km for application to a single country (e.g., Vieno et al., 2010; Baldasano et al., 2011; Hendriks et al., 2013) and reaching 1 km for some European regions (Pay et al., 2014). A major motivation for the present study was therefore to assess the impact of using finer grid resolution for policy support applications of the EMEP model within the Long Range Transboundary Air Pollution (LRTAP) convention. As an increase in horizontal model resolution will increase the computational costs quadratic or cubically and poses additional challenges concerning high resolution input data and model formulation, it is important to determine the "optimum resolution" at which additional efforts do not pay off in terms of increased model performance for the application at hand.

CTMs are sensitive to grid resolution as the models work with mixing ratios, which are generally assumed constant in a model grid-box. The nonlinearity of photochemistry and aerosol formation raises the possibility that, because variations on the sub-grid scale are not represented, systematic errors occur in CTM chemical budgets (Pyle and Zavody, 1990). Several studies have evaluated the impact of model resolution on ozone production (Jang et al., 1995a,b; Esler et al., 2004; Arunachalam et al., 2006; Cohan et al., 2006; Wild and Prather, 2006; Queen and Zhang, 2008; Valari and Menut, 2008; Tie et al., 2010; Hodnebrog et al., 2011; Lauwaet et al., 2013), PM and its components (Queen and Zhang, 2008; Stroud et al., 2011; Wolke et al., 2012; Fountoukis et al., 2013), ozone and PM precursors (Valin et al., 2011; Kryza et al., 2012), as well as wet deposition fluxes (Queen and Zhang, 2008; Appel et al., 2011). Hence, most studies in literature have focused on ozone formation. High resolution simulations may provide a much better separation between regions defined by high concentrations of biogenic volatile organic carbon (BVOC) and high NO_x levels (Esler et al., 2004; Pugh et al., 2013). The degree of artificial mixing induced by the grid resolution impacts O_3 formation efficiency and night-time titration (e.g., Cohan et al., 2006; Wild and Prather, 2006). Most studies have addressed the resolution sensitivity for 36, 12 and 4 km^2 for a US state and found that the 36-km^2 resolution leads to an under-prediction of daily maximum 8-h O_3 averages, and an over-prediction of daily minimum 8-h O_3 averages (Jang et al., 1995a,b; Arunachalam et al., 2006; Tie et al., 2010). Some studies support the finding that modelled O_3 formation systematically increases with resolution for regional and global scale applications (Wild and Prather, 2006; Hodnebrog et al., 2011). Evaluations of global, hemispheric and regional CTMs show that regional models typically perform better (van Loon et al., 2007; Emery et al., 2012; Simpson et al., 2014a). Both Arunachalam et al. (2006) and Cohan et al. (2006) found similar model performances for 12-km and 4-km resolutions, except for the texture of local variability. For O_3 health impact, Thompson and Selin (2012) show that there were no significant further differences between assessments at 12-, 4- and 2-km resolution. In contrast, Valari and Menut (2008) did not find positive effects on model performance for O_3 by increasing their grid resolution from 48 to 6 km, which they linked to uncertainties in the emission data. Valin et al. (2011) found that a model resolution in the range of 4–12 km was sufficient to model NO_2 concentrations. PM and its components were found to be more sensitive to resolution than O_3 (Queen and Zhang, 2008). Differences are predicted mostly for primary rather than secondary PM components (Fountoukis et al., 2013). For all species, some studies show that finer grid resolutions do not give a better performance or provide a mixed picture per component, due to the complexity in chemistry and meteorology and their nonlinear interactions and responses to grid resolution (Queen and Zhang, 2008; Valari and Menut, 2008; Wu et al., 2008; Misenis and Zhang, 2010).

The magnitude of the impact of resolution changes depends on the lifetime of the component under investigation, variability in and correlation with precursor concentrations, inhomogeneity of land use, topography of the study area and meteorology, and the quality of the input data. Moreover, optimal resolution depends on the expected application (e.g., health impact assessment, impact on ecosystems through deposition, compliance to legislation), scale of