Atmospheric Environment 43 (2009) 4822–4832

Contents lists available at ScienceDirect

Atmospheric Environment

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

Skill and uncertainty of a regional air quality model ensemble

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ARTICLE INFO

Article history:
Received 30 January 2008
Received in revised form
24 September 2008
Accepted 24 September 2008

Keywords:
Ensemble modelling
Air quality model
Model evaluation
Uncertainty

ABSTRACT

Recently several regional air quality projects were carried out to support the negotiation under the Clean Air For Europe (CAFE) programme by predicting the impact of emission control policies with an ensemble of models. Within these projects, CITYDELTA and EURODELTA, the fate of air quality at the scale of European cities or that of the European continent was studied using several models. In this article we focus on the results of EURODELTA. The predictive skill of the ensemble of models is described for ozone, nitrogen dioxide and secondary inorganic compounds, and the uncertainty in air quality modelling is examined through the model ensemble spread of concentrations.

For ozone daily maxima the ensemble spread origin differs from one region to another. In the neighbourhood of cities or in mountainous areas the spread of predicted values does not span the range of observed data, due to poorly resolved emissions or complex-terrain meteorology. By contrast in Atlantic and North Sea coastal areas the spread of predicted values is found to be larger than the observations. This is attributed to large differences in the boundary conditions used in the different models. For NO_2 daily averages the ensemble spread is generally too small compared with observations. This is because models miss highest values occurring in stagnant meteorology in stable boundary layers near cities. For secondary particulate matter compounds the simulated concentration spread is more balanced, observations falling nearly equiprobably within the ensemble, and the spread originates both from meteorology and aerosol chemistry and thermodynamics.

1. Introduction

To effectively reduce the adverse effects of air pollutants on human health, thorough process knowledge, resulting in reliable predictions for the future air quality, is mandatory. The evolution of air quality in the next decades depends on many factors, such as the growth of pollutant emissions due to the worldwide economic development and its concentration in areas of high activity like megacities, or climate change (Stevenson et al., 2005; Langner et al., 2005; Forkel and Knoche, 2006; Hedegaard et al., 2008; Meleux et al., 2007; Giorgi and Meleux, 2007 and references therein) and its consequences like more frequent heat waves (Meehl and Tebaldi, 2004) inducing poor air quality episodes (Vautard et al., 2005a; Ordonez et al., 2005; Hodzic et al., 2006; Solberg et al., 2008; Struzewska and Kaminski, 2008). Besides climate change effects, the evolution of air quality in Europe will be affected by a combination of the change in european emissions, and the hemispherical background concentrations (Szopa et al., 2006). While the latter factor is impossible to control at the European scale, the former mainly results from the combination of increased

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1352-2310/$ – see front matter © 2008 Published by Elsevier Ltd.
doi:10.1016/j.atmosenv.2008.09.083

economic activity and the concerted efforts put into regional environmental policies. The evaluation of how efficient such policies might be in controlling air pollution can only be carried out with the use of numerical models.

Supporting the definition of the European Strategy for Air Pollution through the Clean Air For Europe (CAFE) Programme and in the framework of the Convention on Long Range Transport of Atmospheric Pollution, (CLRTAP United nations – Economic Commission for Europe), several projects have been set up in order to evaluate the regional responses to emission reduction scenarios. These projects rely strongly on long-term air quality simulations using several chemistry-transport models. CITYDELTA, the first project (Cuvelier et al., 2007), was devoted to the evaluation of emission scenarios for 2010 at the scale of European cities. EURODELTA is its regional counterpart (Van Loon et al., 2007; Schaap et al., submitted for publication), and deals with air quality changes at the European scale. In both projects several models are used, revealing the spread of possible modelling responses to emission scenarios.

Using an ensemble of models rather than a single model to predict air quality for emission scenarios actually gives two new informations:

(i) The average (or the median) over this ensemble of responses is a new response by itself, which is expected to have a smaller RMS because individual model error cancel each other to a certain extent.
(ii) The spread of the ensemble can be a measure of the uncertainty in model predictions.

For obvious reasons, it is not possible to directly verify responses of several emission scenarios and their associated uncertainties. However, a first evaluation whether these new possibilities, offered by model ensembles, are realistic can be achieved by simulating a period in the past. For point (i) a direct comparison between individual models skills and ensemble mean model skills can be carried out using routine air quality observations. The better performance of the ensemble average or median has been shown in several recent studies for air quality (Delle Monache and Stull, 2003; Pagowski et al., 2005; McKeen et al., 2007; Van Loon et al., 2007; Schaap et al., submitted for publication) as well as for transport of passive tracers (Galmarini et al., 2004; Riccio et al., 2008). The evaluation of the relation between the spread of values obtained in the model simulations and the actual uncertainty in air quality simulation has received focus in a few studies (Delle Monache et al., 2006; Vautard et al., 2006). It can be tackled using methods developed in the framework of ensemble weather forecasting (Molteni et al., 1996; Talagrand et al., 1998; Jollife and Stephenson, 2003). The variability in the EURODELTA model ensemble spread has been shown to give a fair representation of the uncertainty for ozone and secondary inorganic aerosols (Vautard et al., 2006; Schaap et al., submitted for publication). However, this finding was based on global, average information without distinguishing regions within Europe or individual sites, neither for skill nor for spread analyses. This article is designed to provide a more general and spatially detailed analysis of the features of air quality ensemble modelling for Europe. For this purpose we use the EURODELTA modelling results for several pollutants: ozone, nitrogen dioxide and secondary organic aerosols, as already used in two previous studies (Van Loon et al., 2007; Schaap et al., submitted for publication).

Section 2 contains a brief description of the models and observations used. Section 3 describes the skill characteristics of the ensemble. The ensemble spread properties and its origins are described in Section 4. Section 5 contains a conclusion and a short discussion.

2. Models and observations

2.1. Models

Within the EURODELTA project, seven air quality models have been run over an extended period of time, the year 2001. The models are CHIMERE (Schmidt et al., 2001; Bessagnet et al., 2004), DEHM (Christensen, 1997; Frohn et al., 2002), EMEP (Simpson et al., 2003; Fagerli et al., 2004), LOTOS-EUROS (Schaap et al., 2008 and references therein), MATCH (Andersson et al., 2007 and references therein), REM-CALGRID (RCG; Stern et al., 2003; Beekmann et al., 2007) and TM5 (Krol et al., 2005). All models simulate ozone, precursors, and chemically speciated particulate matter (PM) with at least 2 size categories: fine (size less than 2.5 μm) and coarse particles (size between 2.5 and 10 μm). All models, except the global TM5 research model, have been used in their regional-scale, limited-area versions designed for long-term simulations, which implies some compromise between vertical/horizontal resolutions and the extent of processes description. The horizontal resolution of the models ranges from 25 to 100 km, while the vertical resolution varies from one model to another. The lowest model layer lies in the range 20–100 m, and only a few model layers generally resolve the boundary layer. The models are off-line chemistry-transport models forced either by global or regional meteorological analyses or nudged meteorological simulations. For more details about model formulations and comparisons the reader is referred to Van Loon et al. (2007) and Schaap et al. (submitted for publication) and references therein.

Models were run over the full 2001 year and concentrations were saved every hour. Surface concentrations are interpolated to the sites where observations are available. All the results presented along this article are calculated from statistics of these models output and the corresponding observed concentrations.

2.2. Observations

For ozone and nitrogen dioxide, most observations used in this study are gathered from the EMEP database (http://www.emep.int) and some are taken from the AIRBASE database (http://dataservice.eea.europa.eu/dataservice). To provide comparisons with spatial scales consistent with models resolution, urban or industrial sites were removed from the databases. Data for one station in Switzerland was obtained from the Swiss Environmental Agency. Due to the poor representation of mountainous areas in coarse-resolution models, only stations below an altitude of 1000 m were considered. However this did not excluded valley sites. In order to homogenise data coverage, a reduced set of stations was selected in densely covered areas. The selection was based on the availability of observations of additional compounds, such as NO_2. Finally, only stations lying within all model domains are considered. These choices, together with the constraint of data availability, led to a set of 96 sites for ozone and 69 for NO_2. Additional diagnostics were carried out using the "O_x" mixture ($O_x = O_3 + NO_2$). These diagnostics were possible only over sites where the two species are measured simultaneously (67 sites).

The difficulty for models to simulate the mass of particulate matter (PM10 or PM2.5) over Europe has been recognized (Van Loon et al., 2004; Schaap et al., 2008). The underestimation of total particulate mass is, among others, a result from the lack of emissions of fugitive dust, resuspended matter (Vautard et al., 2005b), a plausible underestimation of primary carbonaceous particles (Schaap et al., 2004; Tsyro, 2005), the inaccuracy of secondary organic formation (Simpson et al., 2007), the difficulty of representing primary PM emission from wood burning and other sources (Tsyro et al., 2007) and a more general lack of process knowledge (Stern et al., 2008). By contrast, simulated secondary inorganic