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On the importance of the meteorological coupling interval in dispersion modeling during ETEX-1

U.S. Korsholm*, A. Baklanov, A. Gross, J.H. Sørensen

Danish Meteorological Institute (DMI), Research Department, Lyngbyvej 100, DK-2100 Copenhagen Ø, Denmark

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ABSTRACT

Traditionally, transport and dispersion models are offline coupled to meteorological drivers, receiving pre-processed output at regular coupling intervals. However, today meteorological models have reached urban and cloud resolving scales and online models integrating meteorological and dispersion models have been developed. In this study the online coupled model, Enviro-HIRLAM, which can also run in offline mode, was used to compare online and offline representations of meso-scale disturbances. The online model was evaluated using data from the first European Tracer Experiment (ETEX-1) and produced satisfactory results. Meso-scale influences during the simulation pertube the plume during long-range transport, leading to a double peak structure at a specific measurement station. The meso-scale influence was investigated by varying the offline coupling interval which was shown to be important in constraining the influence of meso-scale disturbances on plume structure in coarse resolution.

1. Introduction

Modeling studies of urban air-quality and the dispersion of air pollution has traditionally been carried out using offline[1] models. Such models are often convenient when considering various emission scenarios with fixed meteorology, such as in air-quality impact assessments or when performing sensitivity analysis on dispersion models. They require time-averaged output from meteorological models to force transport and dispersion of pollutants. Such output is typically available every 1, 3 or 6 h (here denoted the coupling interval) and in between updates the meteorological fields are interpolated retrospectively in time. Hence, offline models rely on the fundamental assumption that the variability present in the meteorological driver which is produced by disturbances with timescales shorter than the coupling interval can be satisfactorily reproduced during interpolation.

In the planetary boundary layer short-term variability in the pollutant concentration field is generated by meso-scale disturbances in the mean flow (Anderson et al., 2003). Generation mechanisms include atmospheric instability (e.g., conditional instability (Holton, 1992; Wallace and Hobbs, 2000)), surface inhomogeneities and bifurcations in the wind field. Specific examples include flow over and around orographical features (Pielke, 2002a; Kim and Stockwell, 2007), the effect of mega-cities on plume transport and meteorology, urban circulations, urban breeze circulations (Oke, 1987; Masson, 2006), changes in wind structure due to enhanced roughness over urban agglomerations (Wong and Dirks, 1978), interactions between urban and sea breezes (Lemonsu et al., 2006), building effects inside the urban canopy (Rotach et al., 2005), lake effects (Pielke, 2002b), sea breezes, frontal circulations and associated rapid changes in wind direction (Gryning et al., 1998), development of clouds and precipitation and up- and downdraughts in connection with single- and multi-cell storms. The horizontal scale of such disturbances range from a few kilometers to several hundred kilometers while the timescale range from less than one hour to days.

Pollutant concentration fields are known to contain large temporal and meso-scale variability (Pielke, 2002c; Anderson et al., 2003). The presence of such disturbances may significantly alter plume spread and structure and therefore the detailed pollution patterns (Ganev et al., 2003). Hence, uncertainties in plume development may be induced if the coupling interval does not resolve the developments in meso-scale disturbances. Unresolved horizontal variability is typically accounted for by tuning horizontal diffusion coefficients, leading to large values in the range 10^3–10^5 $m^2\,s^{-1}$ (Desiato et al., 1998). While smoothing may be an appropriate representation of subgrid-scale turbulent eddies it is not the case when meso-scale disturbances are resolved by the

* Corresponding author. Tel.: +45 39157439; fax: +45 39157460.
E-mail address: usn@dmi.dk (U.S. Korsholm).

[1] The use of the term offline in this context has been ambiguous. A formal definition may be given as separate chemical transport models forced by output from meteorological models, analyzed or forecasted meteorological data from archives or data sets, pre-processed meteorological data, measurements or output from diagnostic models.

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meteorological model, since growth, decay and structural changes to the plume are not considered.

Consequently, the basic assumption may not be fulfilled if the meteorological fields contain meso-scale fluctuations not explicitly resolved by the coupling interval. This is particularly relevant for high resolution wind fields in which most of the variability stems from explicitly resolved eddies. This has recently been demonstrated in a study which showed that offline models are susceptible to large errors when variability in the vertical wind field is large. During a particular frontal passage the coupling interval of an offline model had to be as low as 10 min to capture 85% of the variability in the vertical velocity (Grell et al., 2004). Hence, the basic assumption may be more appropriate for applications which do not require spatially detailed pollution fields.

The importance of the coupling interval has previously been highlighted (Brost et al., 1988; McNider et al., 1996; Moran and Pielke, 1996; Gupta et al., 1997; Pielke, 2002d). In most of these studies the coupling interval was changed from 12 to 6 h, demonstrating the importance of resolving the diurnal cycle, especially in relation to vertical mixing in the boundary layer. Meso-scale eddies, superposed on the diurnal cycle, have also been shown to affect plume structure both at its initial stage and during long-range transport (Nastrom and Pace, 1998; Sørensen et al., 1998).

Due to the great advances in computer power, within recent decades meteorological models have reached high spatial resolution, resolving urban features (horizontal grid spacings typically between 3 and 15 km), and it has become feasible to develop meteorological models which include transport and dispersion of particles and gases at each advection time step (Grell et al., 2004; Jacobson et al., 1996). In this context it is reasonable to question whether offline models are sufficient in applications where detailed (high spatial and temporal resolution) pollution levels are required (such as the spread of air pollution in complex terrain or urban exposure modeling). The purpose of this study is to demonstrate that even at coarse resolution (approximately 40 km grid spacing) errors may be induced in offline models if the coupling interval does not resolve the evolution of horizontal meso-scale eddies. Section 2 contains a description of the methodology, while model description, results and conclusions are found in Sections 3–5, respectively.

2. Methodology

In the first European Tracer Experiment (ETEX-1) a controlled release of an inert tracer gas, along with measurements of its air concentrations at 168 stations were conducted (Nodop et al., 1998). The release was carried out from a site in northern France (Brittany, 2.01° W and 48.06° N) 8 m above ground at a constant average rate of 7.95 g s^{-1} during meteorological conditions producing only little dispersion, i.e. the plume did not break up due to dispersional effects (Gryning et al., 1998). It commenced on 23 October 1994 at 16:00 UTC and lasted 11 h and 50 min. Measurement stations in northern and central Europe were employed in deriving the horizontal and temporal development of the plume. During real-time and retrospective analysis offline long-range dispersion models were evaluated against the measurements (Graziani et al., 1998; Mosca et al., 1998).

Employing a recently developed online[2] coupled environment model Enviro-HIRLAM (High Resolution Limited Area Model) which has the ability to run in offline mode, the ETEX-1 measurements were used in a case study and the effects of meso-scale disturbances on transport and dispersion were considered. Using a 10-min coupling interval (which is also the length of the meteorological time step), corresponding to an online access run the model was evaluated against the ETEX-1 measurements.

In order to simulate the extreme case, where meso-scale disturbances are not resolved by the coupling interval, variability was restricted by keeping the meteorological input, used for advection, constant between updates. Full variability was retained in the vertical so that only the effect of advection was considered. In five simulations the coupling interval was progressively increased (without changing the time step) attaining the values 30, 60, 120, 240 and 360 min (offline simulations). The concentration fields at two measurement stations, F15 (49.05° N, 6.08° E) and DK02 (54.50° N, 10.58° E), located at different distances from the release site (corresponding to short- and long-range transport) were analyzed allowing for an evaluation of the importance of the length of the coupling interval at those sites.

3. Model description

Enviro-HIRLAM is an online coupled meteorological, chemical transport and dispersion model developed at the Danish Meteorological Institute (DMI). At its core lies the High Resolution Limited Area Model (HIRLAM) version 6.3.7 which is employed for limited-area short-range operational weather forecasting at DMI (Chenevez et al., 2004). For a detailed description of the features in HIRLAM the reader is referred to the HIRLAM reference guide (Undén et al., 2002). In this study the transport and dispersion of a passive tracer was simulated using a one-way coupling from meteorology, i.e. there were no feedbacks and the model was run as an online access and offline model.

Point sources are parameterized by assuming that the tracer distribution is uniform within the grid box containing the release site. The emission is ascribed to the grid point closest to the release site in the lowest model layer, corresponding to a height of approximately 30 m above the surface. In a well-mixed boundary layer this height is not believed to affect the results away from the emission grid box.

The model contains several choices for advection, but in order to achieve sufficient tracer mass conservation and at the same time maintain large time steps in the meteorological model, advection was treated differently for meteorological quantities and for the tracer. The Bott scheme (Bott, 1989a,b) was employed for the tracer while a Semi-Lagrangian scheme was employed for meteorological fields. The mass conservation properties of the Bott scheme, during these meteorological conditions, have been tested (Chenevez et al., 2004) and found appropriate, hence, the inconsistency thus introduced is not believed to be of importance during this case study.

In the present study horizontal diffusion was switched off hence, the numerical diffusion arising from the Bott scheme was the only representation of subgrid-scale horizontal eddies (Chenevez, 2000). In the vertical a modified version of the Cuxart, Bougeault, Redelsperger (CBR)-scheme developed for HIRLAM is employed (Cuxart et al., 2000). It is based on turbulent kinetic energy, which is a prognostic variable in the model, and a stability-dependent length scale formulation (Undén et al., 2002).

The model is hydrostatic and horizontal discretization is done on an Arakawa C grid, while in the vertical a hybrid between terrain-following Sigma and pressure coordinates is employed (Undén et al., 2002). In the present set-up the model covered most of Europe (Fig. 1) with a horizontal resolution of 0.40° (92 × 86 points) on a rotated latitude–longitude grid, with 40 levels in the vertical, where 30 of these are inside the troposphere and the top level is at 10 hPa.

[2] The use of the term online in this context has been ambiguous. A formal definition may be given as chemical transport models in which the meteorological forcing fields are available at each time step of the meteorological driver (online access models) and online integrated models, which include feedbacks between pollutants and meteorology (online coupled models.)