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The effect of improved nowcasting of precipitation on air quality modeling

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ABSTRACT

The predictive potential of air quality models and thus their value in emergency management and public health support are critically dependent on the quality of their meteorological inputs. The atmospheric flow is the primary cause of the dispersion of airborne substances. The scavenging of pollutants by cloud particles and precipitation is an important sink of atmospheric pollution and subsequently determines the spatial distribution of the deposition of pollutants. The long-standing problem of the spin-up of clouds and precipitation in numerical weather prediction models limits the accuracy of the prediction of short-range dispersion and deposition from local sources. The resulting errors in the atmospheric concentration of pollutants also affect the initial conditions for the calculation of the long-range transport of these pollutants. Customary the spin-up problem is avoided by only using NWP (Numerical Weather Prediction) forecasts with a lead time greater than the spin-up time of the model. Due to the increase of uncertainty with forecast range this reduces the quality of the associated forecasts of the atmospheric flow.

In this article recent improvements through diabatic initialization in the spin-up of large-scale precipitation in the Hirlam NWP model are discussed. In a synthetic example using a puff dispersion model the effect is demonstrated of these improvements on the deposition and dispersion of pollutants with a high scavenging coefficient, such as sulphur, and a low scavenging coefficient, such as cesium-137. The analysis presented in this article leads to the conclusion that, at least for situations where large-scale precipitation dominates, the improved model has a limited spin-up so that its full forecast range can be used. The implication for dispersion modeling is that the improved model is particularly useful for short-range forecasts and the calculation of local deposition. The sensitivity of the hydrological processes to proper initialization implies that the spin-up problem may reoccur with changes in the model and increased model resolution. Spin-up should be an ongoing concern for atmospheric modelers.

1. Introduction

The strong relation between air quality and weather is evident from the large body of literature on air quality monitoring, modeling and regulation. It has long been established that pollution is not simply a local problem but transgresses regional and national boundaries because of the long-range transport of pollutants through the atmosphere. Precipitation may subsequently deposit this pollution at places remote from its industrial and traffic sources. Eliassen and Saltbones (1983) for instance found that for many European countries the deposition of sulfate from foreign sources outweighed that from indigenous sources. Emission controls at a supranational level to combat acid rain require a clear attribution of pollution to sources. Mueller (2005) in a study of sulphate trends in the eastern United States finds that it can be difficult to separate the influence of meteorology and changes in emission levels.

Large local differences in deposition trends may result from the day-to-day and spatial variability of atmospheric flows and precipitation in combination with the high-frequency variability of emissions. Dvonch et al. (2005) find that for the wet deposition of mercury it is possible to establish source–receptor relationships only if detailed meteorological conditions are taken into account. This sensitivity to the exact weather conditions is even stronger in the case of accidental releases. Puhakka et al. (1990) investigated the meteorological factors influencing the radioactive deposition in Finland after the nuclear accident at Chernobyl. They found that an explanation of small-scale features in the deposition required a detailed study of the atmospheric flow. Furthermore they established a good correlation between the radioactive fallout and the corresponding areal distribution of rainfall measured by a weather radar.

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The accident at Chernobyl prompted a strong development in European emergency modeling. This development was supported by the European tracer experiment ETEX (Girardi et al., 1998). Geertsema et al. (1997) studied the local weather at the ETEX release site and found a strong effect on the long-range transport from the timing and detailed structure of a passing weather front. In addition Sørensen et al. (1998) found that measured surface concentration time-series of the ETEX gas could only be reproduced by detailed modeling of a mesoscale anti-cyclonic eddy.

Air quality modeling and emergency modeling thus require meteorological input from high-resolution weather models. Theoretical consideration of scavenging, the process of removal of pollutants by cloud particles and precipitation, shows that the microphysical processes in a cloud, in particular the timing process, have a significant effect on the start and duration of rainfall and the uptake of pollutants and thus significantly affect the wet deposition of chemical species (Respondek et al., 1995; Alheit et al., 1990; Flossmann et al., 1985, 1987; Flossmann and Pruppacher, 1988; Spiridonov and Curic, 2005). Cloud chemical modeling therefore requires a consideration of the ice phase in clouds. Coupled chemical transport models and atmospheric models should use identical cloud parameterizations (Mölders et al., 1994). Many dispersion models and weather models lack this degree of sophistication and instead rely on a bulk removal rate, a direct relation between the modeled precipitation and wet deposition. This approach is justifiable for modeling on regional scales of the average deposition (Hicks and Shannon, 1979). It is supported by the observed relation between scavenging and radar reflectivity (Jylhä, 1999).

Bulk removal schemes are not universal, but as they are averages over varying complex processes they depend on the situation and the application, e.g. plume type (Hales, 2002), convective versus large-scale precipitation and short-range versus long-range transport (Rodhe and Grandell, 1981). The application of a single scheme for different meteorological conditions therefore introduces uncertainty in the outcome of dispersion models. However, sophistication in the modeling of scavenging will not greatly reduce the uncertainty in the outcome if weather models fail to accurately model the required hydrological parameters. In this respect the spin-up of the hydrological cycle in weather models is probably the biggest problem in their coupling with dispersion models.

Spin-up in the operational meteorological model context is due to the assimilation of observations in the model. The analyzed atmospheric state is in imbalance with respect to the model equations. This leads to an initial adjustment of the forecast fields towards a dynamically and physically realizable model evolution. This initial adjustment phase is commonly referred to as the "spin-up" of a model (Illari, 1987).

The spin-up of cloud formation and precipitation in numerical weather prediction models can be substantial. Betts et al. (1998) find a spin-up of 29% in precipitation during the first 12–24 h of forecasts with the ECMWF model, as an average over the spin-up of large-scale precipitation (39%) and convective precipitation (18%). For the same model Jakob (1999) finds a (position dependent) spin-up of cloud-cover in the order of 15%.

Spin-up is a relaxation process that attempts to restore the dynamical equilibrium between the modeled flow, thermodynamics and hydrology, that has been disturbed by an inconsistent treatment of these processes in the model analysis, initialization and, in the case of limited area models, boundary specification. This inconsistency can be alleviated by diabatic initialization, diabatic forcing and the assimilation of liquid water (Raymond et al., 1995; Wang and Warner, 1988; Turpeinen et al., 1990; Nehrkorn et al., 1993; Wu et al., 1995; Zou and Kuo, 1996). Huang and Lynch (1993) developed a diabatic initialization method based on digital filtering techniques for the Hirlam model.

Huang (1996) demonstrated that diabatic digital filtering initialization improves cloud evolution and reduces the spin-up time of the Hirlam model with intermittent data assimilation. In this article the improvement in spin-up of the Hirlam model is evaluated and its effect on dispersion calculations is assessed with a coupled puff model developed by Verver and De Leeuw (1992) over a two week period in August 2004, a period of moderate smog in the Netherlands which ended with rain from a passing low-pressure system.

The aim of this article is to demonstrate to air quality modelers the benefits of these improvements and to demonstrate to NWP (Numerical Weather Prediction) modelers the sensitivity of dispersion calculations to the model's hydrology and the continuing need to control spin-up in future model versions. In Section 2 the overall spin-up characteristics of different Hirlam versions are diagnosed. In Section 3 the setup and weather conditions of a dispersion experiment with two versions of Hirlam are discussed. The results for two types of pollutants are discussed: in Section 3.3.2 sulphur, which is highly susceptible to scavenging, and in Section 3.3.1 cesium-137, which is more inert. In Section 4 the spatial distribution of the spin-up effect and its effect on dispersion is analyzed. Section 5 is a summary of the main findings with a discussion of the implication of the improvement in spin-up characteristics for dispersion modeling based on Hirlam.

In conclusion the trend of increasing resolution in NWP is touched upon and the consequences this may have for precipitation spin-up. This provides support for the advocacy of Baklanov et al. (2002) for a more integrated development of air quality models and NWP models.

2. Spin-up characteristics of Hirlam

As spin-up is caused by an inconsistent treatment of the modeled flow, thermodynamics and hydrology in the analysis, initialization and boundary specification of a model it has both temporal and spatial aspects. To focus on the temporal aspects of spin-up it is useful to employ model diagnostics averaged over the model domain. For this research the limited area numerical weather prediction model Hirlam is used, for which we have access to these model diagnostics.

2.1. Hirlam versions used in this study

The Hirlam NWP models used in this study differ in terms of their model formulation, but are otherwise identical. A rotated latitude–longitude grid is used to get an optimal grid over the area of interest. The horizontal resolution of 0.2°. The horizontal computation domain covers Europe, Greenland, a large fraction of the Atlantic Ocean and part of the United States and Canada. In the vertical a hybrid coordinate is used with 40 levels for Hirlam-6 and with 31 levels in the Hirlam-5 runs, with a lowest level at 30 m above ground for all Hirlam versions used in this study.

The boundary conditions are supplied by the ECMWF operational model. The model versions used reflect the development in operational forecasting at KNMI. In the transition from Hirlam 5.0.6 to Hirlam 6.3.5 the Optimum Interpolation assimilation scheme was replaced by a 3D variational assimilation scheme, a surface analysis scheme was added, the ISBA surface parametrization scheme was introduced instead of the earlier simple surface scheme and the STRACO convective parametrization scheme was improved. Probably the most important modification in terms of spin-up characteristics, as mentioned in the introduction, was the introduction of a diabatic initialization scheme.

The Hirlam-6 model has been documented in Undén et al. (2002). Hirlam is run operationally at some 8 national meteorological