METEOROLOGICAL MODELLING INFLUENCE ON REGIONAL AND URBAN AIR POLLUTION PREDICTABILITY

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Abstract: ARPA Piemonte performs yearly air quality assessment running a modelling system based on a chemical transport model. The model is capable to simulate air pollutant emission, transport, diffusion and chemical transformation, to provide concentration fields of the main atmospheric pollutants (CO, NO_X, SO_2, PM_{10}, $PM_{2.5}$, O_3, and benzene) on a hourly basis and to compute all the indicators required by EU legislation. Meteorological fields to drive air quality simulations are reconstructed assimilating ARPA Piemonte meteorological network observations within background fields obtained by ECMWF analyses. The reliability of mesoscale and urban scale meteorology is one of the key issues in determining an air quality modelling system effectiveness. Diagnostic meteorological analysis takes advantage of the wide local measurement network but cannot guarantee the dynamic and thermodynamic variables consistency provided e.g. by prognostic weather prediction models. Since July 2006 ARPA Piemonte operationally uses an air quality forecasting system driven by a numerical weather prediction model. The simultaneous availability of the two systems results provides the possibility to compare different meteorological modelling techniques effects on air pollution predictability. The two modelling systems results are compared by means of model evaluation statistical indexes showing very similar performances over a six months period. The comparison is completed by the analysis of short term critical episodes to highlight meteorological modelling effectiveness in reproducing severe air pollution episodes and short term concentrations variation. The prognostic meteorological fields showed a better capability to simulate peak episodes even if weather forecast errors can cause "false alarm" conditions due to concentration overestimation.

Key words: *air quality assessment, air quality forecast, meteorological modelling.*

1. INTRODUCTION

The EU legislation fosters the development and use of air quality modelling systems for both air quality assessment (AQA) and air quality forecast (AQF). The Air Quality Framework and Daughter Directives (1996/62/EC; 1999/30/EC, 2000/69/EC and 2002/3/EC) encouraged European air quality management and assessment institutions to implement air quality modelling as one of the main sources of information to support periodic air quality assessment. Moreover, the new air quality directive 2008/50/EC requires the distribution of air quality information for current day, together with trend and forecast for the next days. Different scientific projects and initiatives have been supported by EU to enhance international cooperation on integrated meteorological and air quality modelling (COST 728) and on air quality forecast (COST ES0602, 5FP project FUMAPEX and 6FP project GEMS). Different air quality modelling and forecasting system are presently in operational and pre-operational phase over Europe. From 2005 ARPA Piemonte is performing yearly air quality assessment with an Eulerian modelling system (Bande et al., 2007). On 2006 an air quality forecasting system composed by similar modules has been implemented to forecast air quality over Torino city and regional domain coincident with that covered by the yearly air quality assessment (Finardi et al., 2008).

Analysing performances of coupled modelling systems and evaluating air quality predictability, it is quite difficult to separate the influences of the three major modelling tasks: emissions, meteorology and air quality modelling. For the second half of year 2006 the simultaneous availability of air quality simulations from the assessment and forecasting modelling systems offered the possibility to investigate the influence of meteorology on air quality simulations and to analyse the different meteorological modelling techniques effects on air pollution predictability. The AQF modelling system shares with the AQA system the computational domain (the whole Piemonte Region, western Po valley, northern Italy), the emissions treatment and the chemical transport model, while meteorological fields are provided by the numerical weather forecast model COSMO-I7, the Italian version of COSMO-MODEL (Consortium for small Scale Modelling). The results of two modelling systems are compared by means of more common model evaluation methods and statistical indexes applied to pollutant concentrations. The comparison is completed by the analysis of short term critical episodes to verify the meteorological modelling effectiveness in reproducing severe air pollution episodes. In principle better results are expectable from the air quality assessment system, which is based on diagnostic meteorological fields reconstructed from local surface observations. The cross comparison should provide indications on which modelling parts have to be improved to enhance both long term air quality assessment and short term forecast.

2. MODELLING SYSTEMS CHARACTERISTICS AND DIFFERENCES

The AQA and AQF modelling systems (Bande et al., 2007; Finardi et al., 2008) are built around the same Eulerian chemical transport model FARM (Gariazzo et al., 2007) and share the same emissions processing system EMMA (ARIANET, 2005) and interface module GAP/SurfPRO (Finardi et al., 2005) for the estimation of atmospheric turbulence and dispersion parameters. The computational systems architecture is sketched in Figure 1. FARM, originally derived from STEM II (Carmichael et al., 1991) implements different gas-phase chemical mechanisms and two aerosol modules: the aero3 modal aerosol module (Binkowsky et al., 1999) and a simplified bulk aerosol module aero0 based on the EMEP Eulerian Unified model approach (EMEP, 2003). FARM implements two-way nesting techniques and can perform parallel computation using openMP approach. To limit computational time, the SAPRC90 (Carter, 1990) gas-phase chemical mechanism and the simplified aerosol scheme are presently adopted in the operational AQA and AQF system configuration.

Emission data coming from different resolution inventories available over the area (high resolution regional inventories for Piemonte, Lombardia and Valle d'Aosta regions, national CORINAIR inventory for the remaining Italian regions and EMEP for foreign countries) are processed to compute gridded emissions. The data processing involves space and time disaggregation - according to cartographic thematic layers and specific time modulation profiles (yearly, weekly and daily) - and non-methanic hydrocarbon speciation, to produce gridded hourly emission rates for the all the chemical species considered by the air quality model over all computational domains. The only relevant difference between the AQA and AQF emissions regards the largest point sources. Continuously monitored emission data are available for the AQA modelling, while for AQF the emissions have to be estimated from emission inventory data. This difference should have no relevant effect on the present comparison that is focused on urbanised areas, where more influent emissions are car traffic, house heating and small industrial activities. The AQA modelling system reconstructs meteorological fields assimilating ARPA Piemonte meteorological network observations within background fields obtained by ECMWF analyses. For the operational AQF system, meteorological fields are provided by the numerical weather forecast model COSMO-I7, the Italian version of COSMO-MODEL (Consortium for small Scale Modelling), running at ARPA Emilia-Romagna Meteorological Service and available at ARPA Piemonte as member of COSMO. COSMO-I7 provides two daily forecasts (12 and 00 UTC) lasting 72 hours, with three hours time frequency, over a geographic coordinates grid covering the whole Italian territory with about 7 km horizontal resolution. The meteorological fields on model levels produced by the 12 UTC run are adapted to all computational domains through the interface module GAP/TINT (Finardi et al., 2005), carrying out space and time interpolation. Eddy diffusivities and deposition velocities are evaluated using parameterisations based on the surface energy balance and similarity theory, by the interface module SurfPRO, which uses the same supplementary geographic and physiographic data sets (Figure 1) for both computational systems. Air quality boundary values are defined from continental runs of the chemical transport model CHIMERE, from the INERIS Prev'Air service (http://prevair.ineris.fr).

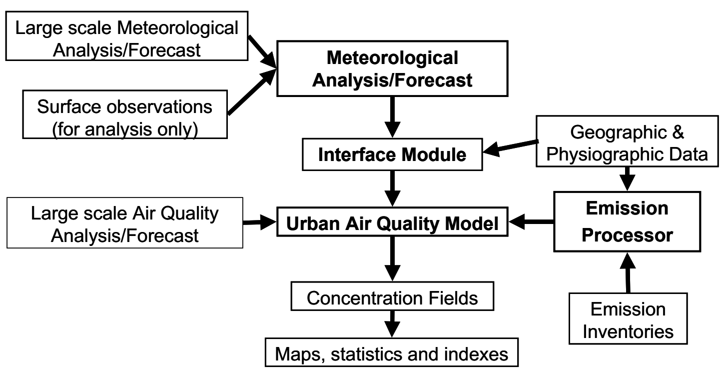

Figure 1. Air Quality Modelling system general architecture.

The AQA modelling system works on a computational domain of 220x284 km^2, covering the whole Piemonte and Valle d'Aosta Regions, part of Liguria, the eastern part Lombardia (including Milan urban area) and portions of France and Switzerland (Fig. 2), with an horizontal resolution of 4 km and 12 vertical levels, spanning the lower 3500 metres of the atmosphere. The forecasting modelling system performs a nested simulation with an outer domain, coincident with the AQA domain, and an inner domain, with 1 km horizontal resolution, centred over Torino metropolitan area (Fig. 2).

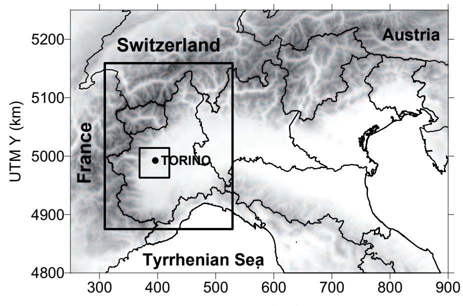

Figure 2. Air quality assessment and forecasting modelling systems computational domains.

The forecasting system runs on a daily basis in order to produce air quality forecasts for current day and the following one, while the AQA system runs once a year, usually in early spring, to estimate concentration fields for the main atmospheric pollutants (CO, NO_X, SO_2, PM_{10}, $PM_{2.5}$, O3, and benzene) for the previous year, on a hourly basis and over the whole Region territory. The modelling system is completed by post-processing tools to compute and provide to the Regional authorities all the indicators required by EU air quality legislation.

3. MODELLING SYSTEMS PERFORMANCES COMPARISON

The different modelling system results have been compared with observations from the regional air quality monitoring network. The comparison has been limited to the time period July-December 2006 that was covered by simulations of both air quality modelling systems. For the AQF system a concentration time series has been built selecting for each daily air quality forecast the second day of the simulation (from +24 to +48). From previous verifications the second day showed a low influence of initial concentrations and was considered more suitable for comparison with the AQA system results.

Modelling systems results statistical comparison

A first analysis consisted in the overall comparison of the AQA and AQF systems results over the whole six months period. Model performances have been compared using some statistical indexes selected among the more frequently used in model evaluation studies: mean bias (*MB*), fractional bias (*FB*), index of agreement (d), factor two (F2), root mean square error (RMSE) and correlation index (coor.). The definition of the first three indexes is described in Equation (1), where N is the number of observed-predicted data couples, O_i and P_i represent respectively the i^{th} observed and predicted values and overbar indicates arithmetic mean. The other indexes correspond to standard definitions.

$$MB = \frac{1}{I}\sum_{i=1}^{I}(O_i - P_i); \quad FB = \frac{(\overline{O} - \overline{P})}{(\overline{O} + \overline{P})/2}; \quad d = 1 - \frac{\sum_{i=1}^{I}\left(O_i - P_i\right)^2}{\sum_{i=1}^{I}\left(\left|P_i - \overline{O}\right| + \left|O_i - \overline{O}\right|\right)^2} \tag{1}$$

Tables 1-3 report the different indexes values obtained from the AQA and AQF modelling system results over the whole period covered by the simulations (six months). The stations listed in the tables have been selected to cover the two major urban areas of Piemonte Region (Torino and Novara) and the different possible stations classification. Within Torino area, Druento is a rural background station, Alpign., Borgaro and Vinovo are sub-urban stations, ToCons is a urban background stations and ToPRiv is a roadside station. Inside the Novara area, Cameri, Cerano and Roment. are sub-urban stations, located in small towns, while NoVerd and NoLeon are urban background and roadside stations located inside Novara city.

The comparison of statistical indexes values obtained by the two modelling system shows slightly better results for the AQA system for NO_2, with higher values of F2, d and lower RMSE in the majority of the stations. MB and FB show different results in different stations, with some of the urban and sub-urban stations (e.g. Borgaro, ToPRiv and NoVerd) where the AQF system gets better results. For PM10 we obtained better results from the AQF system in almost all the considered measuring stations, while for ozone the two systems got different results in the different stations, for a very similar overall performance, with a more pronounced tendency to overestimation for the AQF system.

Table 1. Comparison of AQF (right) and AQA modelling system performances for NO_2 hourly average concentrations.

Air Quality Forecast System							Air Quality Assessment System						
station	MB	FB	F2	d	RMSE	Corr.	Station	MB	FB	F2	d	RMSE	Corr.
Alpign.	4.0	0.12	0.66	0.72	23.0	0.54	Alpign.	-2.7	-0.07	0.74	0.75	21.3	0.57
Borgaro	-1.9	-0.05	0.76	0.74	25.9	0.56	Borgaro	2.9	0.08	0.80	0.79	20.8	0.65
Druento	-4.8	-0.29	0.46	0.60	19.8	0.40	Druento	-5.1	-0.31	0.46	0.62	17.8	0.41
ToPRiv	17.0	0.21	0.84	0.69	41.3	0.52	ToPRiv	28.5	0.37	0.76	0.63	45.7	0.55
ToCons	-11.5	-0.17	0.75	0.61	38.7	0.39	ToCons	-2.2	-0.04	0.77	0.65	32.8	0.42
Vinovo	1.6	0.04	0.62	0.67	27.5	0.46	Vinovo	2.4	0.06	0.65	0.65	26.9	0.41
Cameri	7.4	0.23	0.60	0.72	23.7	0.55	Cameri	7.0	0.22	0.69	0.76	20.8	0.61
Cerano	-0.3	-0.01	0.65	0.70	25.0	0.55	Cerano	-0.6	-0.02	0.77	0.70	21.8	0.48
NoLeon	6.9	0.18	0.63	0.69	24.9	0.50	NoLeon	2.4	0.06	0.75	0.75	20.7	0.57
NoVerd	1.7	0.05	0.73	0.79	21.7	0.63	NoVerd	-2.2	-0.06	0.78	0.80	20.0	0.65

Table 2. Comparison of modelling system performances for PM_{10} daily average concentrations.

Air Quality Forecast System							Air Quality Assessment System						
station	MB	FB	F2	d	RMSE	Corr.	Station	MB	FB	F2	d	RMSE	Corr.
Borgaro	-1.4	-0.03	0.87	0.80	25.5	0.66	Borgaro	18.5	0.47	0.76	0.61	31.8	0.65
Druento	3.0	0.11	0.73	0.67	20.8	0.48	Druento	8.9	0.34	0.73	0.59	22.4	0.52
ToPRiv	3.7	0.06	0.92	0.83	27.0	0.72	ToPRiv	19.0	0.35	0.85	0.69	34.6	0.73
ToCons	3.1	0.05	0.94	0.83	24.6	0.72	ToCons	15.4	0.29	0.89	0.72	30.2	0.76
Cerano	7.5	0.21	0.66	0.67	30.0	0.52	Cerano	8.7	0.24	0.70	0.62	28.9	0.54
NoLeon	10.9	0.29	0.68	0.64	30.4	0.53	NoLeon	9.3	0.25	0.81	0.65	27.4	0.61

Table 3. Comparison of modelling system performances for O_3 daily maximum of 8-hours average concentrations.

Air Quality Forecast System						
station	MB	FB	F2	d	RMSE	Corr.
Alpign.	-5.1	-0.07	0.90	0.95	22.9	0.91
Borgaro	-13.6	-0.21	0.83	0.94	25.8	0.92
Druento	-5.5	-0.06	0.90	0.95	25.5	0.90
Vinovo	-9.4	-0.13	0.86	0.95	21.5	0.92
NoVerd	-7.7	-0.09	0.87	0.97	21.1	0.94
Roment.	-6.3	-0.08	0.83	0.97	21.1	0.94

Air Quality Assessment System						
Station	MB	FB	F2	d	RMSE	Corr.
Alpign.	7.5	0.10	0.91	0.93	25.0	0.91
Borgaro	-4.9	-0.08	0.82	0.94	22.3	0.90
Druento	9.5	0.11	0.91	0.90	30.1	0.88
Vinovo	-2.3	-0.03	0.86	0.94	21.2	0.90
NoVerd	5.4	0.07	0.94	0.96	21.2	0.93
Roment.	2.1	0.03	0.88	0.96	22.8	0.92

The two simulation results are statistically of the same quality and their overall performance is quite similar showing a weak influence of the meteorological modelling technique over global results statistics. This outcome was not totally expected because a better reliability of the simulation based on diagnostic meteorological reconstruction could be foreseen due to the large number of local meteorological observations employed. It has to be noticed that both simulations results can be considered reasonably good for a long term performance evaluation, with significant correlation in most stations, limited values of MB and FB and good F2 and d values.

Short term episodes analysis

The statistical evaluation of results can be considered satisfactory for long term applications finalised to air quality assessment. The main request for those simulation is to reproduce concentration distribution, providing a reliable evaluation of average and peak values through the estimation of indicators prescribed by EU directives. The requests become more stringent for air quality forecast, when concentration variations should be described with the correct space and time correlation. For a better insight on the possible influence on air quality simulations of different meteorological fields, the time series of computed and observed concentrations have been analysed with particular attention to air pollution episodes characterised by relevant time variation of measured concentrations. It has been observed that prognostic meteorology used by the AQF system exerts a more intense forcing causing larger short time variations of modelled concentrations than diagnostic meteorology. Figure 3 and 4 compare model results for two monitoring stations located within Torino urban area from November 14th to December 19th 2006. It is clearly observable as the AQF system obtained a better performance for the air pollution episode recorded during the second decade of December, when observed PM_{10} concentration vales reached more than 100 µg/m^3.

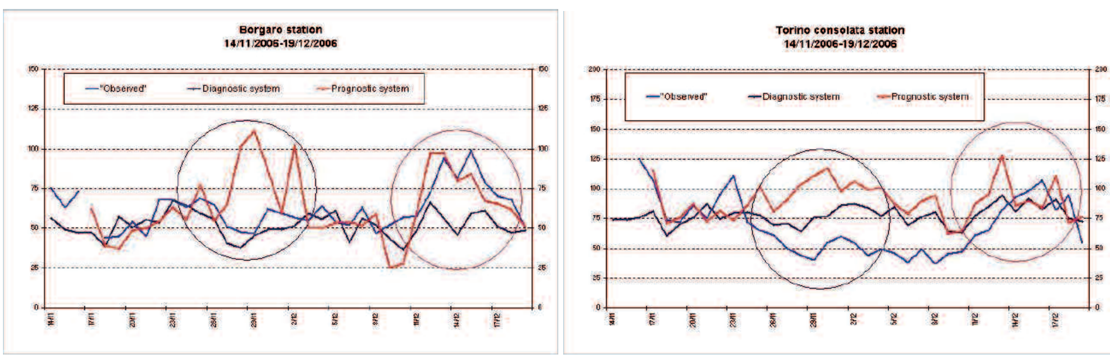

Figure 3. Comparison of observed (blue line) NO_2 daily average concentrations with simulation results driven by diagnostic (black) and prognostic (red) meteorological fields. Borgaro sub-urban station (left) and Torino Consolata urban background station. Circles indicates main episodes.

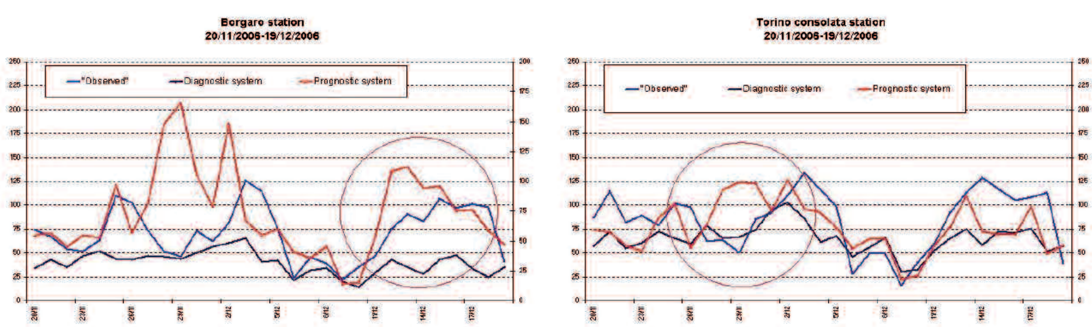

Figure 4. Comparison of observed (blue line) PM_{10} daily average concentrations with simulation results driven by diagnostic (black) and prognostic (red) meteorological fields. Borgaro sub-urban station (left) and Torino Consolata urban background station. Circles indicates main episodes.

A “false alarm” condition is instead detected during the last decade of November, when the air quality forecast produced a quick growth of concentrations, while NO_2 and PM_{10} observations showed a decrease, growing again towards the end of the period. This behaviour is better described by the simulation driven by diagnostic meteorology. The reason of the AQF system “false alarm” should therefore be found in a wrong weather forecast. Previous evaluation of COSMO-I7 performances over Torino area showed satisfactory reproduction of surface meteorological variables. In particular, wind speed was well described, with a slight tendency to overestimation. Therefore, the dynamic should not be the reason of the observed differences, that should be searched in the thermodynamic structure of the atmosphere. Temperature vertical profile and gradient can probably be better described by prognostic meteorological fields due to the lack of local vertical profiles as input data to the diagnostic meteorological model.

4. CONCLUSIONS

The simultaneous availability of results of two modelling systems built around the same chemical transport model and implementing the same emission treatment and interface module allowed to investigate the effect of different meteorological modelling techniques on air pollution predictability. The air quality assessment model was driven by diagnostic meteorological fields built from local observations and mesoscale meteorological analyses fields, while the air quality forecast system was driven by a numerical weather prediction model. The analysis of model results over a six months period, performed by means of model evaluation statistical indexes, showed very similar performances suggesting the possibility to use the air quality forecast system results for air quality assessment without significant performance decay. The analysis of modelling system performances during critical air pollution episodes showed that prognostic meteorological fields can provide a better capability to simulate meteorological forcing that can cause peak pollution episodes, even if weather forecast errors cause the occurrence of “false alarm” conditions due to concentration overestimation. The diagnostic meteorological fields induce a “smoother” time variation of predicted concentrations that causes underestimation of peak episodes. The correct reproduction of major air pollution episodes is the most critical aspect of air quality forecast and severe episodes causes investigation. Meteorological modelling and dispersion parameterisations are some of the aspects to improve, even if a major role is certainly played by the emission modelling, whose approximation and weak correlation with actual emission at a specific place and time limits the possibility to reproduce local events and small scale concentration variability. One of the direction chosen for he upgrade The implementation of meteorological data assimilation techniques can probably enhance performances of both AQA and AQF applications, allowing to take advantage of both physical consistence of meteorological fields produced by prognostic meteorological models and reliability of local measurements. Moreover the implementation of new generation meteorological analysis tools capable to use remote sensing meteorological measurements can provide a better reconstruction of the mesoscale and local structure of atmospheric circulation. Those possibilities will be explored for the upgrade of ARPA Piemonte modelling tools.

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