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Large Sinergetic effect among meteorological scales to forecast atmospheric dispersion of anthropogenic pollutants on complex terrain

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Abstract

Some of the meteorological approaches commonly considered in urban air pollution models do not take into account the importance of sinergetic effect among meteorological scales to forecast atmospheric dispersion of pollutants on complex-terrain coastal sites. The aim of this work is to estimate the impact of using the proper meteorological scales to reproduce some of the previously observed sinergetic efffects and to simulate the behaviour of the pollutant concentrations emitted in the lower layers over coastal complex terrain areas. The availability of experimental measurements of a power plant plume near the Castelló conurbation (on the Spanish Mediterranean coast) has allowed us to use this plume as a tracer of opportunity of the lower atmosphere to check the results of a simulation exercise using the RAMS mesoscale model coupled to the HYPACT particle model. The results obtained show that in a complex-terrain coastal site, because of the strong effect of the meteorological interactions between the different scales on the integral advection and the turbulent dispersion of pollutants, using an inadequate scale to solve the meteorology can result in a very big gap in the simulation of lower-layer pollutant behaviour at urban scales.

1 Introduction

The aim of the paper is to show the impact of applying incorrect meteorological scales when simulating the behaviour of pollutant concentrations emitted in the lower layers of coastal complex terrain areas. The experimental data for this study were obtained during the BEMA Step 1 campaign, which used an SO_2 plume emitted from a power plant near the Castelló conurbation (fig. 1A) as a tracer of opportunity of the lower atmosphere. With these data we check the results of a simulation exercise using the RAMS mesoscale model coupled to the HYPACT particle model. Our results point out the dependence between the simulation of lower-layer pollutant behaviour and the ability of operational meteorological models to correctly reproduce the daily cycle of the lower atmosphere.

2 Methodology

2.1 Experimental setup

Experimental measurements were taken using two vehicles (mobile units), both instrumented with a COrrelation SPECtrometer (COSPEC) for recording the distribution of pollutants aloft (Millán et al., 1976; Palau et al., 2006).

During the campaign analysed (on 17, 18 and 19 July 1995), measurements were taken around a power plant located near the Castelló conurbation, 2-to-3 km from the seashore. In the plume-measurement strategy, both mobile unites (vehicles) made simultaneous transects around the Castelló conurbation at different distances from the stack (fig. 1A). Measurements were taken throughout the day to record any changes that might occur in the plume transport direction or in the dispersive conditions. Thus, using this plume as a tracer of opportunity of the lower atmosphere, it was possible to track the daily evolution of the wind field and the dispersive conditions.

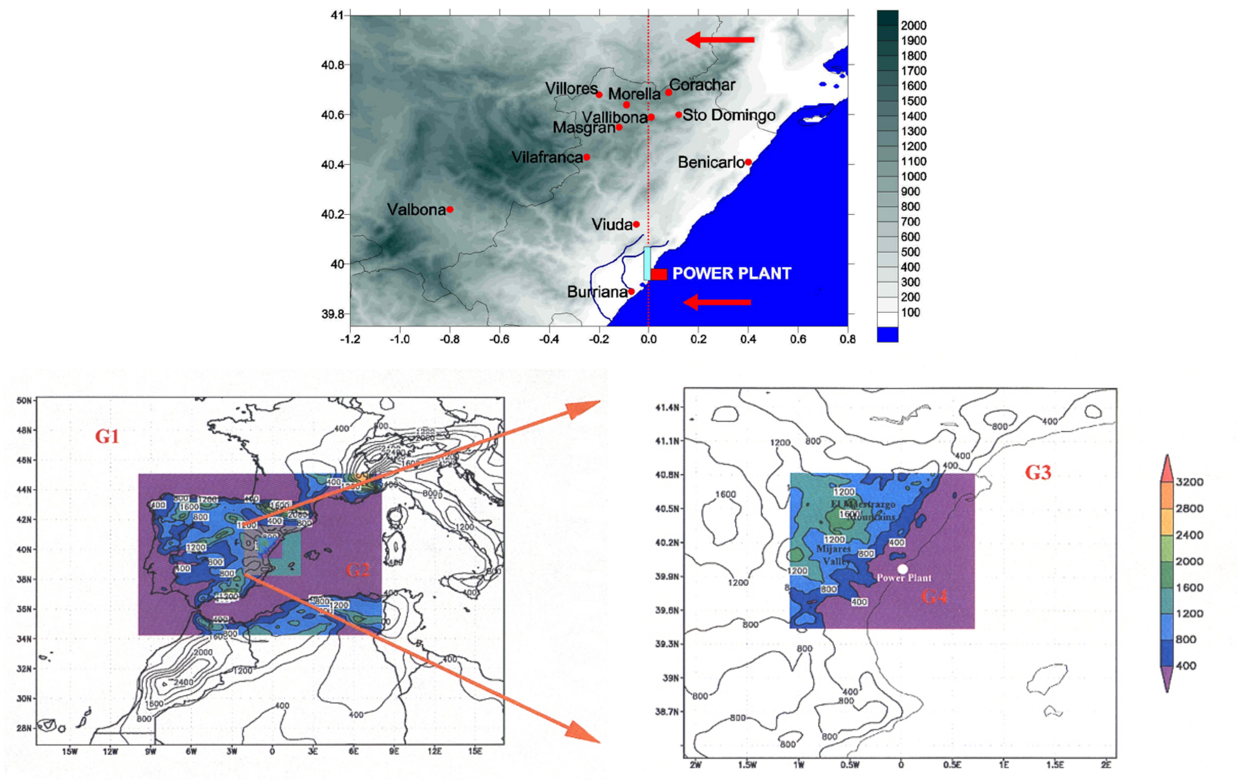


Figure 1. (A) (top fig.) Study area in eastern Spain; the eleven meteorological towers providing experimental measurements are marked with red points. Vertical (longitudinal) red line indicates the transversal section used for generating figures 4 to 6. Road network used by the two mobile units (instrumented with a COSPEC) to take measurements around the power plant is also indicated. (B) (left lower fig.) and (C) (right lower fig.): modelling configuration with the four grids of different resolution employed in the simulations centred over the Castelló power plant (G_1 40.5 km, G_2 13.5 km, G_3 4.5 km, G_4 1.5 km).

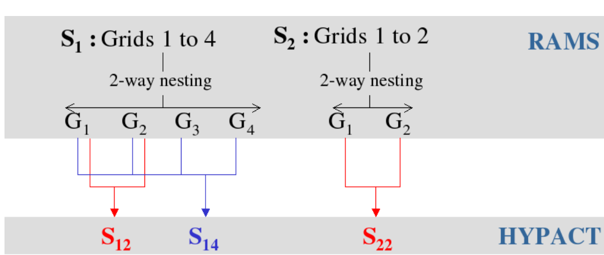


Figure 2. Modelling scheme followed during the simulation exercise. For the first meteorological simulation (S_1) four domains were employed in the meteorological model (RAMS) with two-way nesting domains. Results were obtained for grids G_1 to G_4. To perform the HYPACT simulations (S_{12} and S_{14}), two different configurations were employed: using only the G_1 and G_2 grids from RAMS (simulation S_{12}), and using the four domains from RAMS (S_{14}). The second meteorological simulation (S_2) was configured with the G_1 and G_2 domains only (two-way nested). Its solutions were fed into the HYPACT particle model, generating a new solution (S_{22}).

Moreover, there are eleven sets of measurements obtained from the Regional Air Quality Network (measuring continuously air pollutants and meteorological parameters), and from meteorological towers installed during the BEMA campaign. Sensors are located on different sites in the study area (fig. 1A).

2.2 Model configuration

In this study we used the mesoscale meteorological model, Regional Atmospheric Modeling System (RAMS version 4.3.0 - R. A. Pielke et al. (1992)) coupled to the RAMS HYbrid Particle And Concentration Transport model (HYPACT version 1.2.0 - Trembak et al. (1993)).

We performed simulations of the RAMS coupled to HYPACT model (table 1) to check the effect of different meteorological approaches on the simulation of pollutant behaviour in a complex terrain coastal area. For this, two different meteorological configurations of the RAMS model were employed, but, in both cases, the same initial and boundary conditions were used (figs. 1 and 2): a) Simulation 1 (S_1), using four nested domains centred over the Castelló power plant, and b) Simulation 2 (S_2), using only the outer two

Table 1. Modelling Strategy. Simulation S_{14} was performed with four nested domains and a 1.5 km horizontal grid size in the inner domain. Simulation S_{12} corresponds to the simulation within the second domain (13.5 km horizontal grid size), but considering feedbacks from the four nested domains. Simulation S_{22} was performed with only two nested domains and a 13.5 km horizontal grid size in the inner domain.

Simulation	Grid size (grid number)	Nesting and grids considered
S14	1.5 km (G4)	2-way; grids 1 to 4
S12	13.5 km (G2)	2-way; grids 1 to 4
S22	13.5 km (G2)	2-way; grids 1 to 2

nested domains (with the same resolutions and boundaries, G_1 and G_2).

It is important to note that both configurations permit two-way nesting between grids (table 1 and fig. 2) with the only difference between them being that simulation S_1 resolves the meteorology by considering 1.5 km as the smallest grid size while simulation S_2 resolves the meteorology without feedback from the two inner domains; i.e., by considering 13.5 km as the lowest grid size (fig. 1B and 1C). Thus, the meteorology resolved within the second grid (G_2) for both simulations differs strictly in the fact that in the first case (S_{12}), the results are consistent with inner domains feedback (i.e., the model resolves the inner domain meteorology) while in the second simulation (S_{22}), there is no inner domains feedback because G_2 is the highest resolution domain.

The HYPACT model was run using the Lagrangian dispersion scheme with 3-D wind and turbulence fields provided by the three RAMS outputs (S_{14}, S_{12}, and S_{22}) (table 1 and fig. 2). This model was employed to both simulate the SO_2 emissions from the power plant and analyse the effect that the different meteorological fields obtained within the second domain (simulations S_1 and S_2) have on the dispersive pattern of the SO_2 plume.

To simulate the dispersion of pollutants under different meteorological approaches, the HYPACT (Lagrangian) output for the first RAMS simulation (S1), the 1.5 km grid size domain is denoted as S_{14}; the Lagrangian output for the very same simulation but considering only the wind fields in the first two grids, i.e. reaching the 13.5 km grid size domain, is denoted as S_{12} (fig. 2).

2.3 Model validation

To validate these simulations, within the higher resolution domain, we followed two different and independent procedures, as suggested in various papers dealing with meteorological and air quality model validations (Palau et al., 2005).

The first validation exercise consisted of using the dispersion measurements of the plume aloft to validate the results obtained from the S_{14} dispersive simulations, fig. 2, (performed with the HYPACT model using the meteorological fields produced by RAMS and previously validated). Using the plume measurements aloft as a tracer of opportunity of the wind field at the plume transport height, the simulated dispersion results were compared with the experimental measurements (taken, as described before, with two mobile units driving around the power plant at different times of the day). During this first validating process, fig. 3, we checked the daily evolution in the experimental and simulated integral advections of the plume aloft and evaluated the ability of the model to reproduce the daily cycle of the wind field (associated, as aforementioned, with the development of thermal mesoscale circulations).

During the early morning (fig. 3) the plume is advected southward parallel to the coast within a stable stratum (nocturnal drainage winds). At noon, plume advected inland, perpendicular to the coastline; and, during the late afternoon, the plume has turned towards the North - Northwest with respect to the emission point. This time of the day corresponds to a developed sea breeze.

The second validatation exercise, to validate the model skills, compared the simulated meteorological data on temperature, wind speed and wind direction with the experimental measurements at eleven different meteorological sites located within the inner domain, G_4, (fig. 1). We considered as representative of the model skills within the whole inner domain, the statistics obtained for temperature and wind for the eleven meteorological stations available. Table 2 sumarizes the results obtained.

Although some significant differences in the model's skills were observed at the different stations due to terrain complexity, on average, for the temperature at 2 m above ground level (a.g.l.) a significant and systematic error of the model was detected (root-mean-square error (RMSE) value of 3.5°C as temporal and spatial average on all stations). Therefore, bias and average values of the eleven stations show a clear overestimation of about 2.6°C probably due to topography complexity and to deficiencies in the initialisation of the thermodynamic properties of the soil which play a role in the simulated local energy budget. Moreover, it is important to note that the worst-simulated temperatures were found during the nocturnal hours, probably due to limitations of the RAMS Planetary Boundary Layer (PBL) parameterisation under stable conditions.

Nocturnal cooling of the lower layers of the troposphere has not been well reproduced by the model in most of the sites within the inner domain. Nevertheless, index of agreement is 0.77, i.e. daily and day-to-day evolution of temperature, is quite well reproduced by the model.

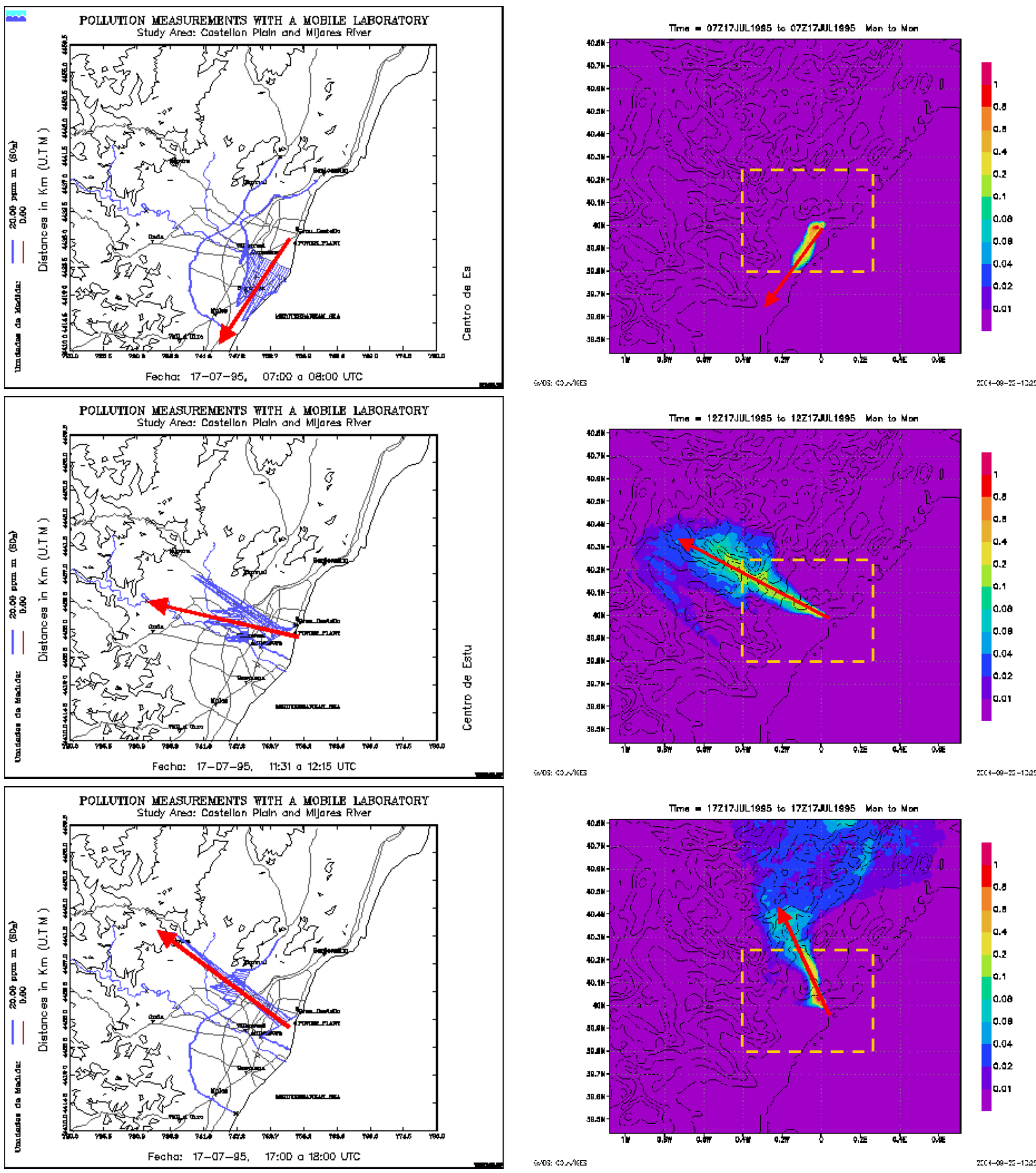


Figure 3. Simulation S_{14} with an inner domain of 1.5 km, first row for 07 UTC on 17 July 1995; second row for 12 UTC on 17 July, and third row for 18 UTC on 17 July. Right column, experimental measurements; and left column: modelling simulation results. Orange square in figure (right column) indicates the experimental area plotted in left column. Red arrow indicates the mean plume transport direction.

Table 2. Average observational and modelled values (AvObs and AvMdl), Bias, Root Mean Square Error (RMSE) of temperature (at 2 m a.g.l.) and wind speed (at 10 m a.g.l.), RMSE-vwd (RMSE of the horizontal vector-wind-difference), at eleven different sites (see geographical locations in figure 2) for the three days simulated. Value on all stations during the three simulated days has been calculated on a total of 729 values for 1h-averaged temperature and 727 values for 1h-averaged wind speed (Nobs). In addition, the I.A. (Index of Agreement) value is calculated as the average of the eleven different sites (index of agreement of 729 pairs of values for temperature and 727 pairs of values for wind speed).

Estació	NObs	AvObs	AvMdl	Bias	RMSE	RMSE-vwd	I. A.
Wind speed at 10 m a.g.l.							
BENICARLÓ	67	2.5	2.3	-0.2	0.9	1.7	***
BURRIANA	67	1.9	2.0	0.1	1.0	1.5	***
VIUDA	67	1.8	2.4	0.7	1.2	2.3	***
STO. DOMINGO	67	3.3	2.4	-0.8	1.2	2.1	***
VALBONA	67	2.2	2.6	0.4	1.0	1.1	***
VILAFRANCA	59	2.8	3.0	0.3	1.2	2.5	***
MAS GRAN	67	3.7	2.8	-0.9	1.7	2.1	***
VALLIBONA	67	3.5	2.4	-1.1	1.9	2.2	***
MORELLA	65	4.2	2.9	-1.3	1.6	2.1	***
CORACHAR	67	2.4	2.6	0.2	1.2	1.5	***
VILLORES	67	3.3	2.1	-1.1	1.8	2.4	***
Value on all stations	**727**	**2.9**	**2.5**	**-0.3**	**1.4**	**1.9**	**0.82**
Temperature at 2 m a.g.l.							
BENICARLO	67	26.6	28.3	1.7	2.1	***	***
BURRIANA	67	27.1	28.0	0.8	1.6	***	***
VIUDA	67	25.2	29.7	4.5	5.0	***	***
STO DOMINGO	67	24.0	26.6	2.6	3.1	***	***
VALBONA	67	24.5	27.0	2.5	3.3	***	***
VILAFRANCA	59	21.7	25.0	3.3	3.7	***	***
MAS GRAN	67	25.0	26.3	1.3	2.4	***	***
VALLIBONA	67	21.7	25.5	3.8	4.2	***	***
MORELLA	67	24.2	26.4	2.2	2.8	***	***
CORACHAR	67	22.7	25.7	3.0	3.5	***	***
VILLORES	67	26.7	29.5	2.8	3.7	***	***
Value on all stations	**729**	**24.5**	**27.1**	**2.6**	**3.5**	*****	**0.77**

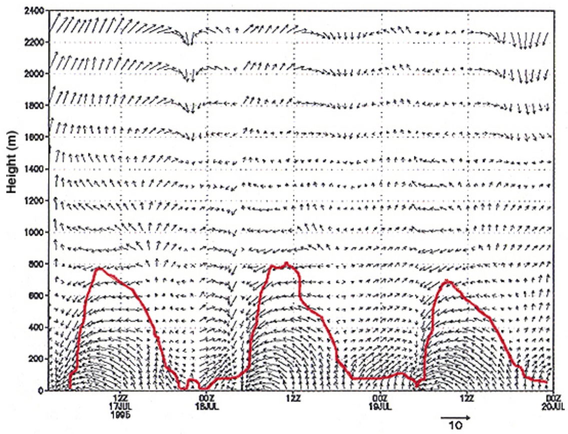
The meteorological observations of wind speed and direction were made at a height of 10 m a.g.l.. Under this summer three-days period (with clear skies and low surface wind speeds), the day-to-day results are fairly consistent and good results for the RMSE of the wind speed at 10 m a.g.l. (1.4 m s^{-1}) and of the vector-wind-difference at the same height (1.9 m s^{-1}) were obtained (table 1 and figure 3). No systematic bias was observed in the model, and the mean bias value obtained (-0.3 m s^{-1}) is the result of a sharp and non-skewed distribution around zero. Coherently, the index of agreement obtained for the whole measurements for the eleven stations (727 hourly values) was 0.82 (table 2).

It is important to note that for light wind speeds (lower than 0.5 m s^{-1}), wind directions measured at the stations are known to be variable and unreliable. This feature makes it difficult to validate the simulated drainage winds on the basis of the wind direction. Nevertheless, by using air pollutants as tracers of opportunity during consecutive daytime periods (2-to-4 days or more), it is possible to infer the nocturnal dynamic of the winds, as well as directly validate the diurnal sea breezes (with wind speeds much higher than the nocturnal ones).

As a first result from the validation, see details in Palau et al. (2005), it is important to note that, as the index of agreement for both magnitudes (temperature and wind speed) is the result of a spatial and temporal average over the whole G_4 domain, the degree to which the observed variate is accurately estimated by the simulate variate is of 77% for temperature and of 82% for wind speed within the higher resolution domain.

3 Effects of feedback from small scales

To check the effect that the different resolved meteorological scales have on the simulation of pollutant behaviour in a complex-terrain coastal area, we compared two meteorological configurations of the RAMS model. As described before (within the “model configuration”), in



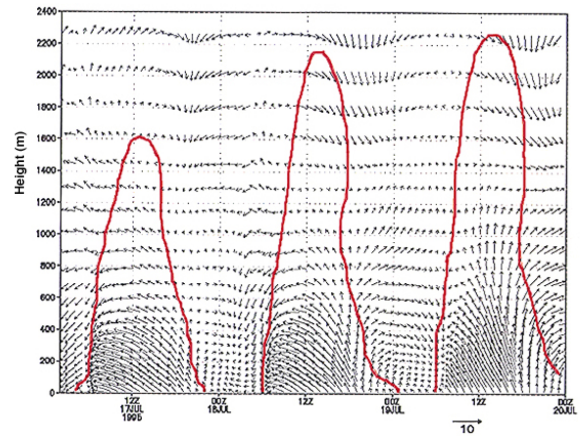


Figure 4. Comparison between (A) (left img.) meteorological simulation within G_2 for simulation S_1, i.e., with inner domain feedbacks and (B) (right img.) meteorological simulation within the same grid G_2 but for simulation S_2, i.e., without inner domain feedbacks. In each simulation the PBL parameterisation behaviour is different. With feedback from the two higher resolution domains, a PBL height of 800 m a.g.l. is simulated. Without any feedback from higher resolution domains, a PBL height of 2100 m a.g.l. is obtained. It is also important to note the different wind-field structure due to feedback from inner domains (mainly during the nocturnal hours). These time series were obtained on the vertical of the power plant. PBL starts at ground level and goes up until TKE is less (or equal) than the specified threshold, 0.001 m^2 s^{-2}.

both cases we have used the very same initial and boundary conditions; the only difference is that the meteorological solution in S_{12} has resolved the finer-scale meteorology. Moreover, simulation S_{22} has no finer-scale meteorological information because of the two-way nested configurations of just two domains (table 1).

The S_{12} wind-field simulation shows the daily cycle of the typical coastal flows with land-driven thermal circulations that die down during the night. In spite of the 13.5 km grid size, the early morning drainage winds to 07 UTC are captured by the S_{12} simulation, because of the model's ability to work with the information resolved within the inner domains (4.5 and 1.5 km). With the S_{22} simulation configuration (without inner domains), the wind field behaviour in the lower levels is essentially different from the previous case. It is of interest to note that the drainage wind is not reproduced during the night-time in the latter case (fig. 4B). Another important feature is the difference in the behaviour of the PBL parameterisation between both simulations. While in S_{12} the maximum height is 800 m a.g.l., in S_{22} it extends to 2100 m a.g.l. (fig. 4). It is necessary to note that these time series were obtained on the vertical of the power plant and that PBL starts at ground level and goes up until TKE is less (or equal) than the specified threshold, 0.001 m^2 s^{-2}.

This analysis of the meteorological data shows important differences in the mesoscale model outputs between the two meteorological approaches: In the first one (S_{12}), the high-resolution effects are included thanks to the two-way option between grids, and in the second one (S_{22}), the model resolves the 13.5 km-grid resolution without any feedback from the inner domains (fig. 4).

To check the implications of the two different meteorological approaches on the simulation of a plume from a point source located in an area like Castelló, both model outputs were employed to run two respective HYPACT simulations. The vertical distribution of the simulated SO_2 concentration at Lon 0°, from 18 July 00 UTC to 18 July 18 UTC, differs greatly in both simulations (S_{12} versus S_{22}); figures 5 and 6.

These results show that in a coastal complex terrain area, the wind flow and the boundary layer estimated by the models can be very different depending on the meteorological scale resolved, which conditions strongly the pollutant behaviour simulated by the HYPACT Particle Model. The results shown were obtained on the basis of a release of particles at 175 m.a.g.l (according to the estimated plume height), however, when we changed the release height to 25 m.a.g.l, in order to represent the emission height of any urban pollutant, we obtained similar results (not shown). Thus, a model's ability to simulate the behaviour of pollutants emitted in the Castelló area, at least in the first 200 m a.g.l., will depend highly on its ability to correctly reproduce the daily cycle of the lower atmosphere.

These results are relevant in light of the fact that some of the meteorological approaches commonly considered to forecast urban air pollution episodes do not take into account the importance of the smaller scales (and the sinergetic effect among meteorological scales) for explaining the meteorology of sites like the Spanish Mediterranean coasts.

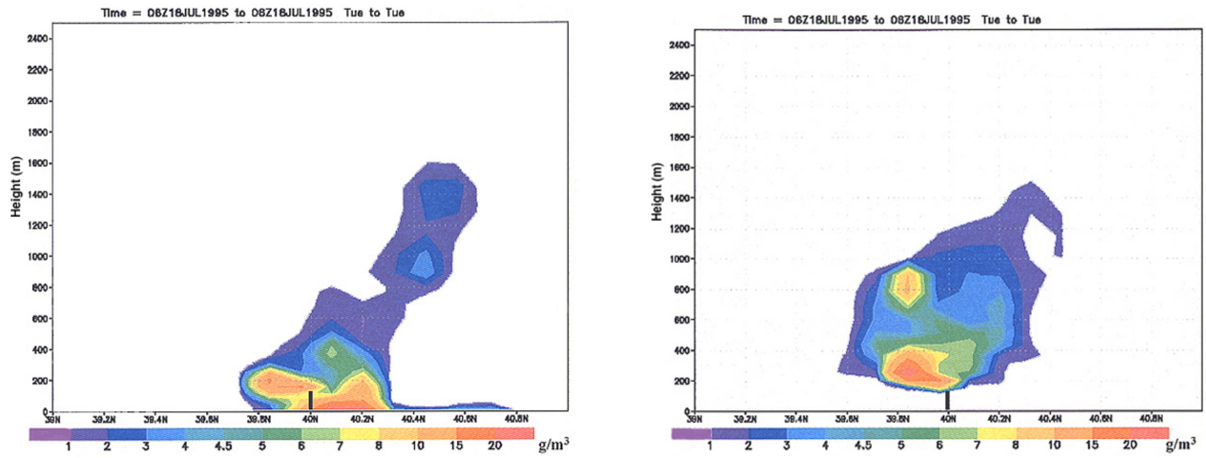


Figure 5. Longitudinal cross section, spatially indicated in figure 1, of the simulated plume within grid G_2 for both meteorological simulations, S_1 and S_2. Black line on Lat. 40N indicates the power plant chimney height. (A) (left fig.) simulation S_{12} and (B) (right fig.) simulation S_{22} of the simulated SO_2 vertical distribution at Lon 0° for 06 UTC on 18 July 1995. New emissions (plume aloft) are advected southward parallel to the coastline within a stable stratum of nocturnal drainage flow. Great differences in ground-level SO_2 concentrations are observed. In case (A) ground concentrations are due to the emissions advected inland with the sea breeze on the previous day and returned towards the coast with the drainage winds.

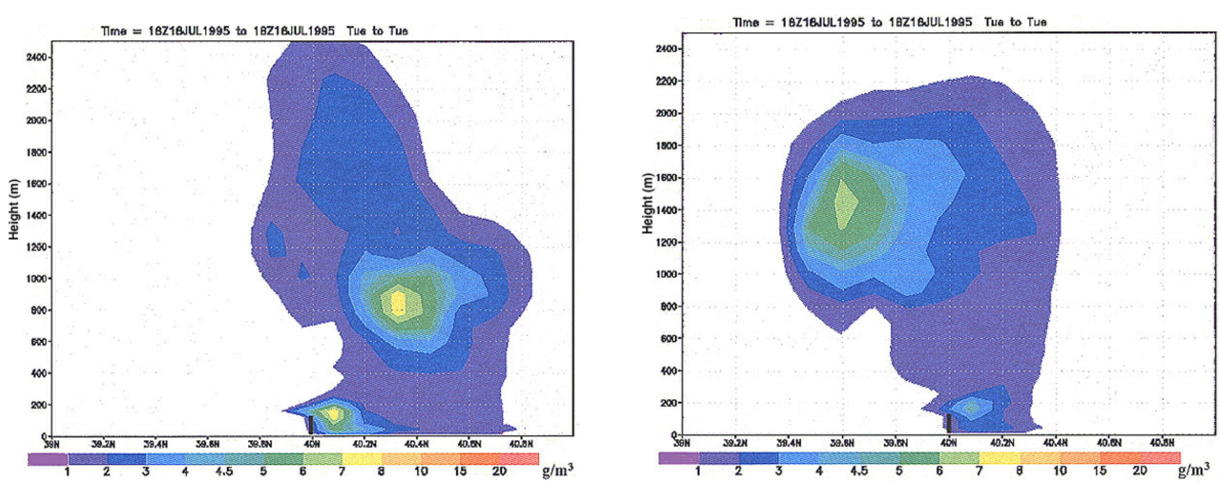


Figure 6. Longitudinal cross section, spatially indicated in figure 1, of the simulated plume within grid G_2 for both meteorological simulations, S_1 and S_2. Black line on lat. 40N indicates the power plant chimney height. (A) (left fig.) simulation S_{12} and (B) (right fig.) simulation S_{22} of the vertical distribution of the simulated SO_2 at Lon 0° for 18 UTC on 18 July 1995. At the end of the daytime period on the second simulated day, differences between the simulations with respect to the maximum concentration height become evident. In the first case (with inner domain feedback) plume fumigations have higher concentrations than in the second case (without feedback from higher resolution domains). Moreover, the return flows of the sea breeze aloft are located at different heights and the simulated plumes aloft are located in different locations according to whether or not feedback effects are considered (differences in the mean plume axis of more than 0.7°).

4 Conclusions

The availability of both 10 m a.g.l. meteorological data and experimental measurements aloft obtained by means of a vehicle equipped with a remote sensor, enabled us to validate a high-resolution simulation (S_{14}; with a grid size of 1.5 km) of the daily behaviour of a Power Plant Plume (located in a coastal complex-terrain area) by means of the RAMS mesoscale model coupled with the HYPACT particle model.

This double model-validation procedure produced two main results: A) We were able to evaluate the degree to which the observed variate was accurately estimated by the simulated variate (index of agreement) on eleven sites located within the high-resolution domain, obtaining values of 77% for temperature and 82% for wind speed; and B) we were able to reproduce the daily cycle of a point-source plume in a coastal area with complex terrain because the highest horizontal resolution used enabled us to simulate the dynamic of the winds (sea breeze development and drainage winds).

Two additional simulations of the coupled models were performed using a grid size of 13.5 km. In the first of these (S_{12}) the high-resolution effects were included thanks to the ability of the model to work with two-way interactions between inner domains, while in the second (S_{22}) there were no feedback effects with finer scales. As a result, in our simulation of pollutant dispersion in the lower layers of the atmosphere in a coastal complex-terrain area, we were able to compare the effects of two different meteorological approaches regarding the scales resolved. The main differences obtained were:

- Pollutant advections in the S_{12} and S_{22} simulations differ greatly during the early morning due to the difference in the drainage winds. This difference accumulates throughout the daily cycle because the emissions advected during the drainage flows are swept inland with the diurnal sea breeze development.
- The vertical distribution of the simulated SO_2 concentration is very different in both simulations as a consequence of the discrepancies in PBL parameterisation behaviour: the S_{12} simulation predicts much higher concentration values for the lower layers than the simulation without high-resolution effects.

The results show that in a complex-terrain coastal site, because of the strong effect of the meteorological interactions between the different scales on the integral advection and the turbulent dispersion of pollutants, using an inadequate scale to solve the meteorology can result in a very big gap in the simulation of lower-layer pollutant behaviour at urban scales.

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