Application of short and 24 hours air pollution forecasting around a power plant

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Abstract

A model-based system for real-time simulation and prediction of SO_2 concentration around a Power Plant has been applied. The real-time simulation is done for 5 minutes average-time periods, from the measurements of nine meteorological towers and one Remtech sodar. A meteorological prediction model has been developed for providing a one-day forecast (for 30 minutes average-time periods), as input in time for the adaptive plume model. This system allows the prediction of SO_2 concentration around a power plant for different emission levels, along the following 24 hours.

Both systems run continously on an area around As Pontes Power Plant, since November 1994. Their ground level concentration (glc) results are compared to the measurements from 17 glc remote stations, 30 km around the Power Plant. This one provides a database for the validation of the real-time and forecasting systems, and both are applied to the control of the SO_2 emissions at the surrounding of As Pontes 1400 MW Coal-Fired Power Plant.

1 Introduction

The legal limit on emissions guarantee, for the majority of locations and under most meteorological situations, the observance of the law for ground level concentrations. However, the existence of single sources of significant magnitude, or the danger of fugitive emissions to the atmosphere, and also

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specific meteorological conditions may cause an impact of the plume on the ground that may go beyond the legal limits for the pollutant. To avoid the occurence of these rare episodes, it is necessary to predetermine the maximum emission allowed for any meteorological condition.

The development of a system for air pollution forecasting based on atmospheric modelling has been presented by several authors for the range that corresponds to regional transport, e.g. ENAMAP-2 (Endlich et al. [1])). On the other hand, Enger [2] developed two combined models, meteorological and diffusion, for the simulation of plume transport at mesoscale distance.

In this work, an air pollution system for real-time simulation and 24 hours forecasting of mesoscale plume transport, is presented. The system is based on a three-dimensional time dependent pseudo-hydrostatic meteorological model, a meteorological diagnostic model and a Lagrangian adaptive plume model.

2 The models

2.1 Plume transport

Different solutions for single plume transport simulation have been developed, but mostly are based in some kind of meteorological diagnostic model and a plume model (Enger [2]). In this system, an objective analysis of wind and temperature measurements is combined to an adaptive plume model (Ludwig [3]). The coupled model provides fast simulation of a single plume transport.

The diagnostic wind model applies the critical streamline concept, that provides the heights of air flux layers above the terrain. As usual, a null divergence condition is performed for each layer, so the model gets 3-D wind fields in short time.

In stable stratified conditions, the model can provide realistic 3-D wind fields if good wind and temperature data both at ground level and at various heights over the terrain are available; but, vertical winds calculated by the model use to be less than the actual wind in other situations. Then, vertical plume transport is mainly obtained from plume growth.

The adaptive plume model (Ludwig et al. [4]) was used with two purposes: a real-time simulation model, that uses the meteorological fields from the diagnostic model; and a batch model, that uses the forecasted meteorological fields along a 24 hours simulation. The coupled diagnostic-plume model calculates new meteorological fields and plume transport for new meteorological measurements every 5 minutes.

Plume transport is extremely sensitive to meteorological fields, so a high-resolution meteorological network is needed for real-time simulation; and the meteorological prediction must be precise. Because of the whole system was designed for running on a 25 Mflops workstation, a new meteorological prediction model has been developed for providing good mesoscale meteorological forecasting with short CPU cost. As the same plume model is used coupled to the diagnostic model and the prediction model, glc simulations and predictions were compared to glc measurements for calibrating and validating the models.

2.2 Meteorological Model

The dynamics of the atmospheric boundary layer depend on complex interactions of various influences: local topography, vegetation, clouds, radiation flux, water sources, and other processes. During the last two decades, a number of three-dimensional models directed towards some special mesoscale phenomena have been formulated (Enger [2], Pielke [5]).

The present dynamical model is a three-dimensional time dependent mesoscale model based on finite difference solutions of the hydro-thermodynamical equations. Only the hydrostatic part has been solved here (Souto et al. [6], Pérez-Muñuzuri et al. [7]). A terrain-following coordinate, η, is used to introduce the topography in the model. The basic equations of the model for the horizontal wind components U,V and the potential temperature ϑ can be written as

$$\frac{dU}{dt}=\left\{\frac{s}{s-z_g}\right\}^2\frac{\partial}{\partial\eta}K_M\frac{\partial U}{\partial\eta}-\overline{u\frac{\partial u}{\partial x}}-\overline{v\frac{\partial u}{\partial y}}-\vartheta\frac{\partial\pi}{\partial x}+g\left(\frac{\eta-s}{s}\right)\frac{\partial z_g}{\partial x}-\hat{f}W+fV \quad (1a)$$

$$\frac{dV}{dt}=\left\{\frac{s}{s-z_g}\right\}^2\frac{\partial}{\partial\eta}K_M\frac{\partial V}{\partial\eta}-\overline{u\frac{\partial v}{\partial x}}-\overline{v\frac{\partial v}{\partial y}}-\vartheta\frac{\partial\pi}{\partial y}+g\left(\frac{\eta-s}{s}\right)\frac{\partial z_g}{\partial y}-fU \quad (1b)$$

$$\frac{d\vartheta}{dt}=\left\{\frac{s}{s-z_g}\right\}^2\frac{\partial}{\partial\eta}K_\vartheta\frac{\partial\vartheta}{\partial\eta}-\overline{u\frac{\partial\varphi}{\partial x}}-\overline{v\frac{\partial\varphi}{\partial y}}+S_\vartheta \quad (1c)$$

where f and $\hat{f}$ denote the Coriolis parameters.

Finally, to complete the calculations of the wind field, the vertical component of the wind velocity, W, is obtained from the conservation of mass relationship, written as

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}+\frac{\partial W}{\partial\eta}=\frac{1}{s-z_g}\left(U\frac{\partial z_g}{\partial x}+V\frac{\partial z_g}{\partial y}\right)-\left(\frac{U}{\rho}\frac{\partial\rho}{\partial x}+\frac{V}{\rho}\frac{\partial\rho}{\partial y}+\frac{W}{\rho}\frac{\partial\rho}{\partial\eta}\right) \quad (2)$$

where ρ is the air density which here is considered to be only a function of the position.

The horizontal subgrid correlation terms in Eqs. (1a-c) are supposed to be small compared to the advection terms and some authors exclude them from the calculations (Enger [2]). Occasionally, these fluxes have been used as free parameters to minimize the discrepancies between the numerical method and the experimental data, or to control nonlinear aliasing by choosing a parameterization depending on the horizontal wind gradients modulated by some coefficient k_D arbitrarily adjusted until the $2\Delta_x$ wavelengths do not appear to degrade the solutions significantly. Here, Tag et al. [8] parameterization for the eddy formulation with $k_D = 0.2$, is followed.

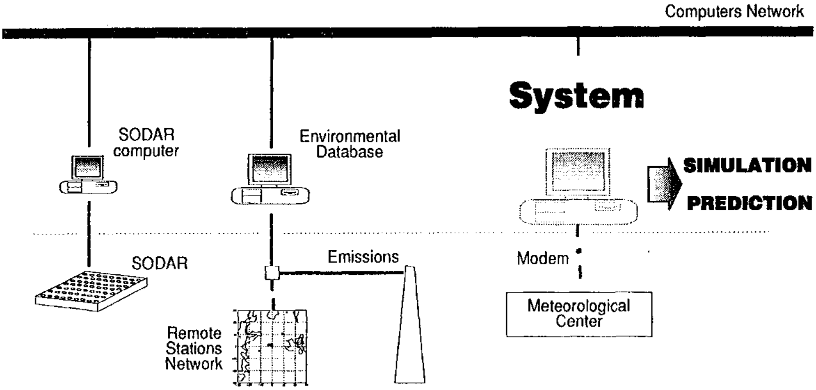

Figure 1: Real-time simulation and prediction system installed at As Pontes Power Plant.

The vertical turbulent fluxes, or diffusion terms, correspond to those terms with the for momentum and heat transfer coefficients, K_M and K_θ in equations (1a-c). They account for the vertical mixing at the atmosphere and their definition depend on the stability of the layer being simulated.

(a) When the layer is stably stratified (such as at night over land or on cloudy days with wet ground), $\partial\vartheta/\partial z > 0$, Blackadar [9] suggested one form of local exchange coefficients

$$K_M = K_\vartheta = \begin{cases} \left\{1.1(Ri_c - Ri)\ell^2\left|\partial\vec{V}/\partial z\right|\right\}/Ri_c & Ri \leq Ri_c \\ 0 & Ri > Ri_c \end{cases} \qquad (3)$$

where $\vec{V} = U\vec{i} + V\vec{j}$ and ℓ is a mixing length related with the average size of the eddies. If the Richardson number, Ri, is greater than 0.25, the stable stratification suppresses turbulence sufficiently so that the flow becomes laminar and then $K_M = K_\theta = 0$. The parameter Ri_c is the critical Richardson number equal to 0.25 in the limit $\Delta z \to 0$.

(b) When the atmospheric layer is unstably or neutrally stratified (such as over land or sunny days), $\partial\vartheta/\partial z \le 0$, the transfer coefficients are then defined as a function of the distance above the ground. Here, O'Brien's [10] Hermite cubic polynomial is used defined as,

$$K(z) = K_{z_i} + \left[\frac{z_i - z}{z_i - h_s}\right]^2 \times \left\{K_{h_s} - K_{z_i} + (z - h_s)\left[\frac{\partial K_{h_s}}{\partial z} + \frac{2(K_{h_s} - K_{z_i})}{z_i - h_s}\right]\right\} \tag{4}$$

where $z_i \ge z \ge h_s$, K_{hs} and $\partial K_{h_s}/\partial z\big|_{h_s}$ are evaluated at the top of the surface layer h_s (h_s = 0.04 z_i). $K(z)$ refers to either $K_M(z)$ or K_θ (z). K_{zi} is usually defined arbitrarily at the top of the planetary boundary layer (PBL) z_i and here it has been considered equal to zero.

The depth of the planetary boundary layer, z_i, is usually associated with an inversion and it is calculated, during the daytime, as suggested by Deardoff [11], by a prognostic equation mainly depending on the surface heating. A method suggested by San José [12] is applied in this study. The Businger-Dyer relationships between turbulent parameters are used to solve the prognostic equation for the PBL (Pielke [5]). During the transition from convective to stable conditions, z_i tends to adjust exponentially toward an equilibrium depth. In this case, the height produced during transition times can be considered as a fictitious height during which the stable layer near the surface develops and becomes well established.

The source-sink term in Eq.(1c), S_θ, is modeled as a sum of two functions depending on the long- and short-wave irradiance, $S_\theta = S_\theta^{SW} + S_\theta^{LW}$.

3 Results

As Pontes Power Plant is located in the north west of Spain; this area is characterized by steep hills and sea inlets bathed by the Atlantic Ocean. The package is running for real-time simulation and forecasting the SO_2 glc around this power plant, within a radius of 30 km. A grid of 9 meteorological towers, one Remtech PA-3 sodar and 17 SO_2 glc remote stations provide 5-minutes average data for real-time simulation and validation of models results.

The whole system is shown on figure 1; for real-time simulation, emissions data and wind & temperature data (by radiowave) arrive to the power plant every 5 minutes, and the Remtech PA-3 sodar provides wind & temperature profiles every 30 minutes (by modem). The diagnostic model computes a new wind & temperature 3-D field every 5 minutes, and the adaptive plume model creates new puffs with new emissions data; then, the past and present plume generated are dispersed by means of the adaptive plume model. Finally, a 3-D SO_2 concentration field is calculated as a 5 minutes average dataset. Every 30 minutes the system computes half-an-hour averages with the 5 minutes averages obtained.

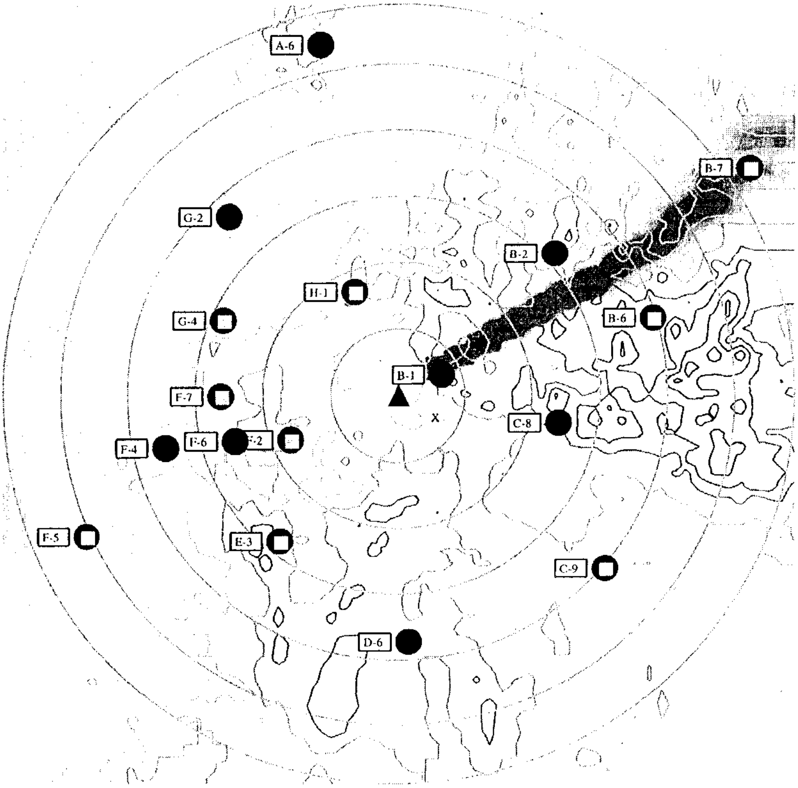

Figure 2: A horizontal projection of the predicted plume (30 min. average) around As Pontes Power Plant at 20:00 LST on November 24th, 1995.

Air pollution forecasting needs to estimate the properties of emission gases; a mass balance is applied for computing SO_2 concentration and gas flux from fuel composition. Constant emission temperature of 190 ºC is assumed. The emissions are calculated as half-an-hour averages for all the next day (0:00 UTC to 23:30 UTC). The meteorological prediction model starts at 7:00 LST and runs up to 3 CPU hours (on a 25 Mflops workstation) to obtain the meteorological forecast for the next day in half-an-hour averages. Meso-α forecasting is provided daily by the Spanish National Meteorological Institute, 24 hours in advance, at four sites separated by 100 km at four known levels of constant pressure. With these data, the meteorological model calculates meso-β forecast of three-dimensional wind, temperature and potential temperature fields, at 18 known levels up to 7000 m over the terrain, with a horizontal resolution of 2 km. After that, the adaptive plume model is used for the calculation of SO_2 glc, with an assumed emission.

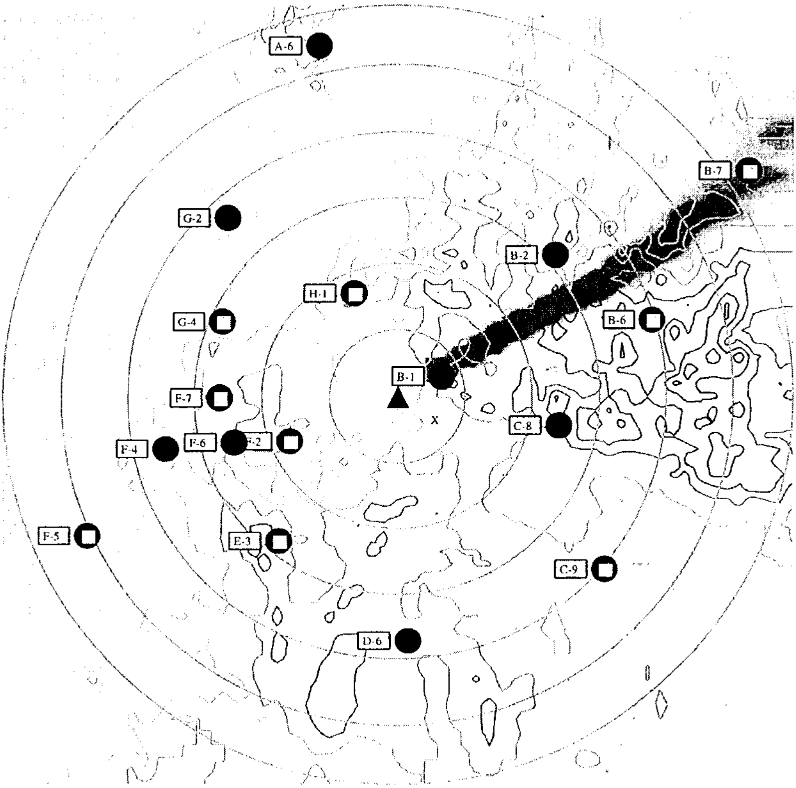

Figure 3: A horizontal projection of the simulated plume (30 min. average) at 20:00 LST on November 24th, 1995.

Figures 2 and 3 show predicted and simulated plume transport around As Pontes Power Plant for November 24th, 1995, at 20:00 LST. Horizontal dispersion is very similar at both systems. However, figures 4 and 5 show different predicted and simulated vertical transport of the same plume; the predicted plume falls mainly because of vertical wind, but simulated plume grows more than predicted, and its centerline follows the terrain. Both predicted and simulated plumes impact B-7 station at the same time.

Figure 6 shows predicted, simulated and observed SO_2 glc at B-7 station; both models get plume impacts similar to measured glc. It's the only plume impact detected along that day, but the models get other similar impacts between A-6 and B-7 stations. Model results are extremely sensitive to wind direction (measured or predicted), so in general, these models can provide other impacts near SO_2 glc stations (not detected) that should be considered in order to improve air pollution control.

Around 80 % of detected plume impacts were predicted since June 1994. No global statistics have been performed for simulation results.

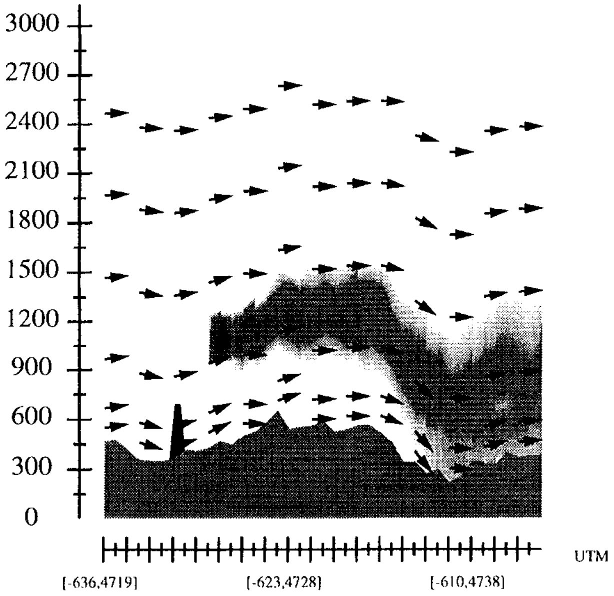

Figure 4: A vertical profile of the predicted plume (30 min. average) at 20:00 LST on November 24th, 1995.

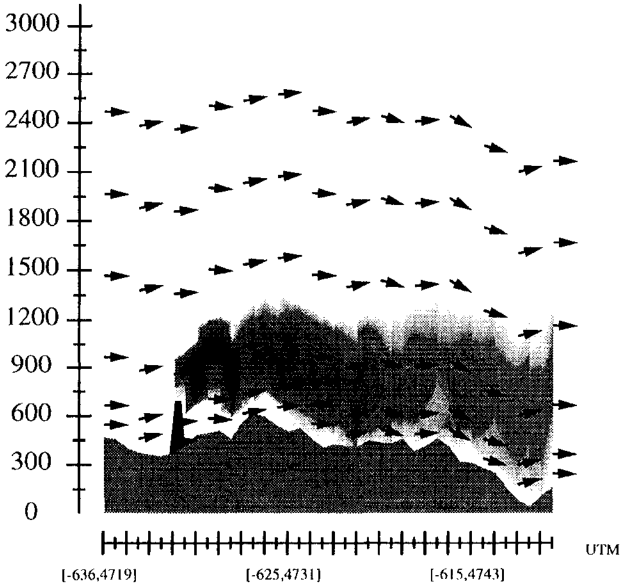

Figure 5: A vertical profile of the simulated plume (30 min. average) at 20:00 LST on November 24th, 1995.

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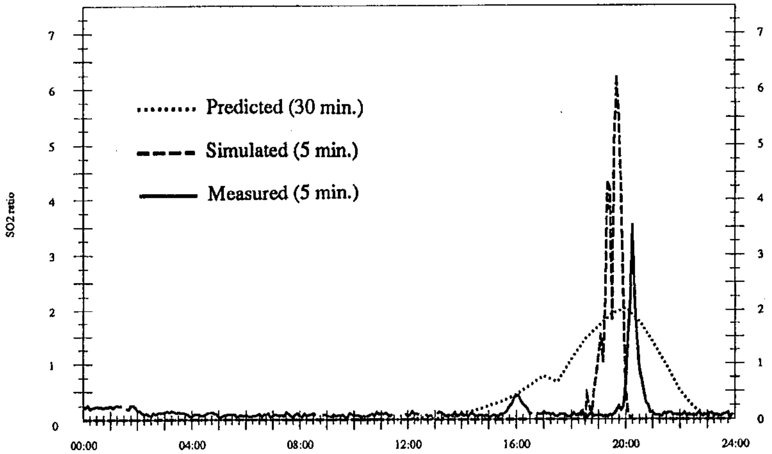

Figure 6: Predicted (30 min. average), simulated and measured (5 min. average) SO_2 glc ratio at B-7 station along November 24th, 1995.

4 Conclusions

Real-time simulation and daily prediction of a plume transport from a power plant is performed by a model-based system. Real-time simulation can run on a medium size workstation, and a new meteorological situation is considered every 5 minutes, because the diagnostic wind model and the Lagrangian adaptive plume model produce results readily. Prediction of plume transport combines a meso-β meteorological model and the mentioned plume model to provide a complete air pollution forecast from 12 to 36 hours in advance; the prediction model only needs a meso-α numerical prediction (i.e., from National Met. Office) for running; the prediction can be obtained in aprox. 3 hours on a medium size workstation.

Both systems are detecting the most significant plume impacts around As Pontes Power Plant, at NW of Spain. In persistent meteorological situations, SO_2 glc predicted values agree to measures. Real-time simulation gets similar results, mainly because of the uncertainty of meteorological measurements in height.

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