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A comparison of Lagrangian dispersion models coupled to a meteorological model for high stack air pollution forecast

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Abstract

Since 1994, operational air pollution forecast is routinely applied at the As Pontes coal-fired power plant, with a 350-m stack, in order to prevent local fumigation episodes. Over the last ten years, several improvements in the numerical models were done, to obtain more accurate air pollution forecasts on a daily basis.

In this work, a comparison of the results obtained for different periods, using two different lagrangian dispersion models, Adaptive Puff Model 2 (APM2) and Lagrangian Particle Model (LPM), is presented. Both models, in different ways, were coupled to the same non-hydrostatic meteorological prediction model, Advanced Regional Prediction System (ARPS) adapted to this environment.

From the results obtained, it can be seen that both models can reproduce the location of the main plume impacts measured in the area. However, LPM impacts are usually farther and shorter in time than APM2 impacts, in agreement with field data.

1 Introduction

In the design and development of a forecasting air pollution control system (FAPS, Souto et al., [1]) based in meteorological and dispersion models, accurate results of these numerical models are a critical issue, specially during complex convective conditions. In this case, even though the application of a high resolution non-hydrostatic meteorological model can provide an accurate estimation of the mean variables (wind, temperature), turbulence parameters applied in different dispersion models will offer significant different results.

In this work, a comparison of the results of two Lagrangian dispersion models, Lagrangian Particle Model (LPM) and Adaptive Puff Model 2 (APM2), coupled to a non-hydrostatic meteorological model (Advanced Regional Prediction System, ARPS) is done, during a complex air pollution episode with strong wind shear in the domain of a coal-fired power plant.

2 Meteorological Model

The Advanced Regional Prediction System (ARPS) is a comprehensive regional to stormscale atmospheric modeling / prediction system developed at the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma [2,3].

ARPS has been undergoing real-time prediction tests at the synoptic level through storm scales in the past several years over the continental United States as well as in part of Asia. For the last two years, ARPS has also tested as an operational numerical weather prediction model for regional weather forecast in Galicia (NW of the Iberian Peninsula) [4].

2.1 PBL parameterization

The surface layer physics ARPS calculations allow the evaluation of surface drag coefficients. This is done in an stability dependent way according to bulk Richardson number values. Some modifications have been introduced in the original ARPS model in order to obtain, from those drag coefficients, the boundary layer parameters [5]: friction temperature (θ^*) and friction velocity (u^*) and then, Monin-Obukhov length (L) and friction humidity (q^*).

Once this parameters are known, under unstable conditions PBL height, z_i, is computed by using a prognostic equation proposed by Pielke & Mahrer [6]. On the other hand, an exponential variation in time towards an equilibrium height [7] is applied in stable conditions.

Modeling of the dispersion of air pollutants in the PBL, requires an accurate estimation of the standard deviations of velocity fluctuations ($\sigma_{u,v}$, σ_w) which are calculated using the estimated value of z_i. In this work, expressions compiled by Pielke [5] from Hanna [8] have been applied, with modifications on σ_w formulation for convective conditions proposed by Ryall & Maryon [9]. This scheme has already been implemented in particle dispersion models such as FLEXPART [10]. Finally, expressions for $\sigma_{u,v}$ and σ_w are obtained,

- Unstable conditions,

$$\sigma_{u,v} = u_* \left(12 + \frac{z_i}{2|L|} \right)^{1/3} \tag{1a}$$

$$\sigma_w = w_* \left[1.2 \left(1 - 0.9 \frac{z}{z_i} \right) \left(\frac{z}{z_i} \right)^{2/3} + \left(1.8 - 1.4 \frac{z}{z_i} \right) u_*^2 \right]^{1/2}$$

- Stable conditions,

$$\sigma_{u,v} = 2.3 u_* \tag{1b}$$

$$\sigma_w = \begin{cases} 1.2 l \left(\dfrac{Ri_C - Ri}{Ri_C} \right)^{0.58} \left[\left(\dfrac{\partial u}{\partial z} \right)^2 + \left(\dfrac{\partial v}{\partial z} \right)^2 \right]^{1/2} & Ri < Ri_C \\ 0 & Ri > Ri_C \end{cases}$$

3 Dispersion models

3.1 Lagrangian particle model

The Lagrangian particle model (LPM) [11] releases for each iteration a number *n* of fictitious particles from the stack while the total number of particles in the whole domain does not exceed a maximum number of 30000 particles, which statistically represent the turbulent transport and simulate the pollutants plume growth.

The location of a single particle, using a following-terrain coordinate system, is defined by,

$$\begin{aligned} x_j(t + \Delta t) &= x_j(t) + [\overline{u}_j(t) + u'_j(t)]\Delta \mathrm{t}, \quad j = 1,2 \\ z(t + \Delta t) &= z(t) + [\overline{u}_3(t) + u'_3(t) + u_{3_p}]\Delta \mathrm{t}, \end{aligned} \tag{2}$$

where $\overline{u}_j$ represents the mean value of horizontal and vertical components of the Lagrangian particle velocity; u_{3p} is the plume rise contribution, as in APM2 [15, 16]. The turbulent fluctuation is represented by u_j', and its estimation follows a statistical approach (as the Monte-Carlo models), where u_j' is a semirandom component obtained by the manipulation of random numbers, using a Markov process (first-order autocorrelation process),

$$u'_j(t) = u'_j(t + \Delta t) R_{u_j}(\Delta t) + u''_j, \quad j = 1,2,3 \tag{3}$$

where R_{uj} are the autocorrelations of the u_j' components, and u_j'' are the components of a purely random vector with zero-mean normal distribution. Using this approach, the motion of a particle is not affected by the position of other particles.

For the estimation of plume growth, R_{uj} can be related to the Lagrangian turbulence time scale by $R_u(\Delta t) = \exp(-\Delta t/T_{Lu})$, where this Lagrangian time scale T_L is estimated for each component as follows,

- Unstable conditions,

$$T_{L_{u,v}} = 0.15 \frac{z_i}{\sigma_{u,v}},$$

$$T_{L_w} = \begin{cases} 0.1 \dfrac{z}{\sigma_w \left[0.55 - 0.38 \dfrac{z}{L} \right]}, & \dfrac{z}{z_i} < 0.1,\ z > -L \\ 0.59 \dfrac{z}{\sigma_w}, & \dfrac{z}{z_i} < 0.1,\ z < -L \\ 0.15 \dfrac{z_i}{\sigma_w} \left[1 - \exp\left(\dfrac{-5z}{z_i} \right) \right], & \dfrac{z}{z_i} > 0.1 \end{cases} \tag{4a}$$

- Stable and neutral conditions,

$$T_{L_{u,v,w}} = 0.2 \beta_{u,v,w} \frac{\lambda_{m_{u,v,w}}}{V}, \quad \beta_{u,v,w} = \min(0.6 \frac{V}{\sigma_{u,v,w}}, 10) \tag{4b}$$

where λ_m is the peak wavelength in the turbulent spectra, V is the particle mean velocity and β is the ratio between Lagrangian and Eulerian time scales.

3.2 Adaptive puff model 2

APM2 (Souto et al., [12]) is a new version of the model based in the Lagrangian adaptive puff (Ludwig et al., [13]). This version uses the same type of adaptive Gaussian puff to describe the plume growth, that allows a non-symmetric vertical concentration distribution, using 5 puff centers. In APM2, new approaches for plume rise and plume growth estimation were included.

For the estimation of plume growth, Draxler [14] expressions were applied, using the standard deviations of velocity fluctuations estimated by ARPS: σ_w, and σ_θ obtained from σ_u and σ_v. The use of these expressions is dependable on the atmospheric stability, so the potential lapse rate estimated by ARPS was applied at each puff location.

4 Results and discussion

The main current application of ARPS+LPM and ARPS+APM2 models is the forecasting of the SO_2 plume dispersion from As Pontes Power Plant, over a radius of 30 km. This area is located in the Northwest of Spain (figure 1), and it is characterized by steep hills and sea inlets bathed by the Atlantic Ocean, with the power plant in the center. The top of the region is Serra do Xistral, 1036 asl-m. This area has been modeled in a 35x35 grid centered in the Power Plant location, with an horizontal spacing of 2000 m, and with 33 vertical stretched levels reaching up to 15000 m. Time step has been set to 10 s, except for APM2 that was set to 60 s.

Meteorological and Lagrangian dispersion models were run to estimate the SO_2 concentration (specially, ground level concentration) around the power plant. A real-time meteorological and air quality monitoring network (see figure 1), with one 80 m meteorological tower, eight 10 m towers, and 17 SO_2 glc remote stations, provides measurements continuously to the power plant.

For comparison of both Lagrangian models, a convective air pollution episode during June 1st, 2001 was chosen, in order to evaluate the models response to wind shear, with severe changes in wind direction at different levels.

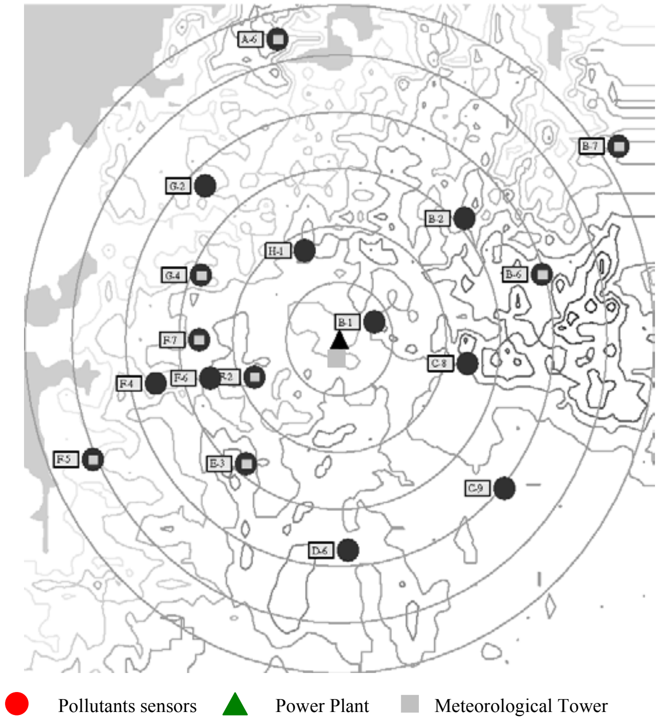

Figure 1: As Pontes Power Plant air quality monitoring network.

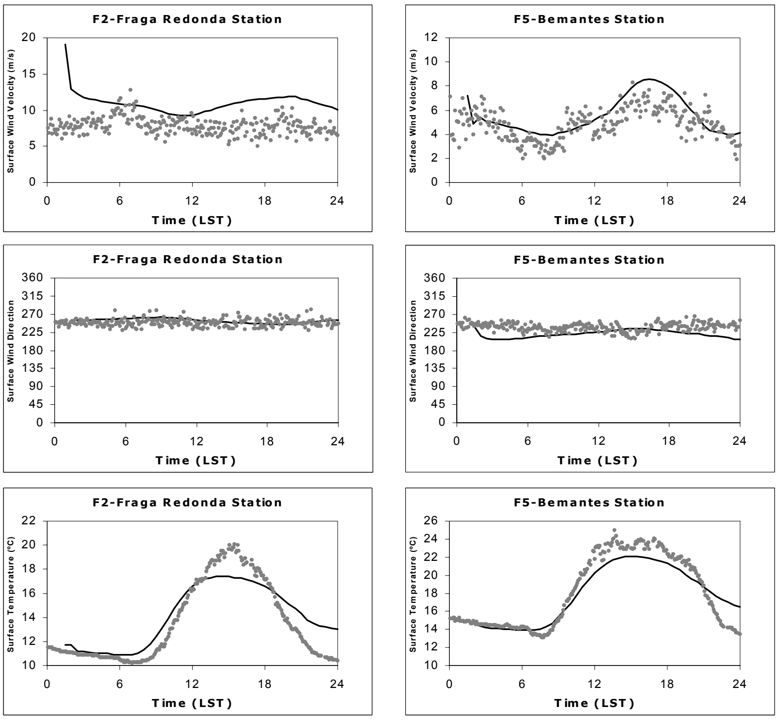

Figure 2: Comparison of surface wind velocity, wind direction and temperature estimated by ARPS (line) and measured (dots) at two locations (F2, F5) along the pollutants' plume trajectory, on June 1st, 2001.

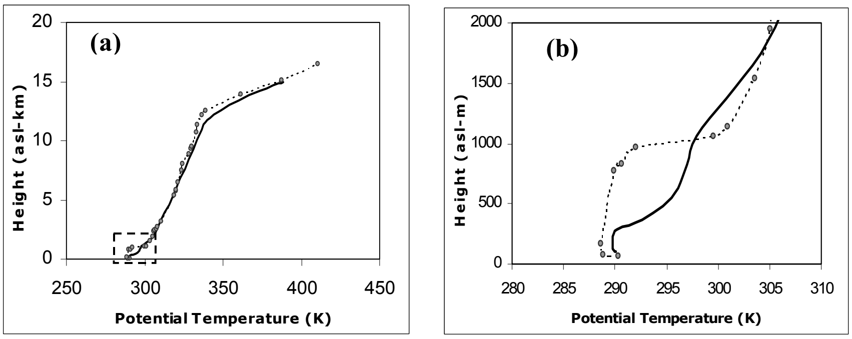

Figure 3: Potential temperature profile (a) estimated by ARPS (line) and measured rawinsonde (dot line) at 12Z on June 1st, 2001. (b) Detail of estimated (line) and measured (dot line) profiles up to 2000 m.

June 1st, 2001 corresponds to a situation with strong high pressure centered in the Atlantic Ocean around the West of Ireland; there is also a relative low centered in the Iberian Peninsula. This implies moderate northeastern surface winds in the area under study, and a significant convective circulation.

Estimated surface temperature (figure 2) is in a good agreement with data in both stations (F2 and F5), with only some relevant differences in diurnal heating and nocturnal cooling. The agreement in wind direction prediction is very high, with maximum differences around 5º. Wind velocity is also in a good agreement with measurements, with a slight overestimation, specially on model startup.

On figure 3a, the model reproduces quite well the behavior of potential temperature in the upper layers, compared to rawinsonde measurements; near the surface (figure 3b), although some differences can be noticed in the structure of both estimated and observed profiles, at the layers where the transport of the plume takes place (about 600-800 agl-m) the atmospheric stability in both, model results and observed data, is the same.

Although both dispersion models use the same plume rise equations, different time steps may cause quite different plume centerline height prediction as it is shown on concentration vertical profiles (figure 4). Both models reproduce in different ways the vertical growth of the plume: LPM shows a well defined plume, with only great dispersion in the central hours of the day, (under unstable conditions), while APM2 gives a greater vertical dispersion. This may cause more localized and intense impacts from LPM results than those from APM2. Besides, due to the higher plume estimated by APM2, during the last hours of the day, this model reproduces a weak southwestern transport in the upper layers of the plume, following the convective circulation.

SO_2 glc remote stations in the southwestern part of the domain (namely, Fs stations) detected relevant levels of glc in June 1st, 2001. In order to compare the relative impacts estimated and observed, a relative ground level concentration (rglc) was defined for each station, that is, the ratio between the estimated or measured glc and the maximum measured glc along this day. With this approach, figure 5 shows that stations located about 10-15 km (F2, F6) from the power plant measured persistent SO_2 glc values during night time and the central hours of daytime, and a maximum peak in the afternoon; meanwhile farther stations (F5, F4, more than 20 km downwind the power plant) detected time-located impacts.

From the analysis of LPM and APM2 results, both estimated rglc levels are similar to measured on the farthest Fs stations (F5, F4) during the afternoon and evening, and quite similar to the observed rglc levels on F6 in the afternoon. In addition, APM2 results show an impact in F2 around 16:00 LST, that was reproduced by APM2, but not by LPM because its plume growth is lower so the plume reaches to ground farther than the APM2 plume. This agreement corresponds mainly to convective conditions and strong wind shear. However, persistent rglc measured during night time is not represented by the models.

In general, both models estimate the episodic impact of the pollutants' plume, during this day, therefore both are operationally useful for air pollution prevention. However, APM2 produces more persistent plume impacts than LPM, which is more in agreement with the irregular impacts measured during daytime; but LPM fails in the plume impacts observed in the F2 station (as the closest station to the power plant, among the affected).

5 Conclusions

In this work, two different Lagrangian dispersion models (LPM and APM2) have been coupled to the same non-hydrostatic meteorological model (ARPS) in order to forecast single plume transport around a power plant.

The vertical plume growth structures are different for both models: LPM shows a narrower plume, while APM2 estimates a more spread one.

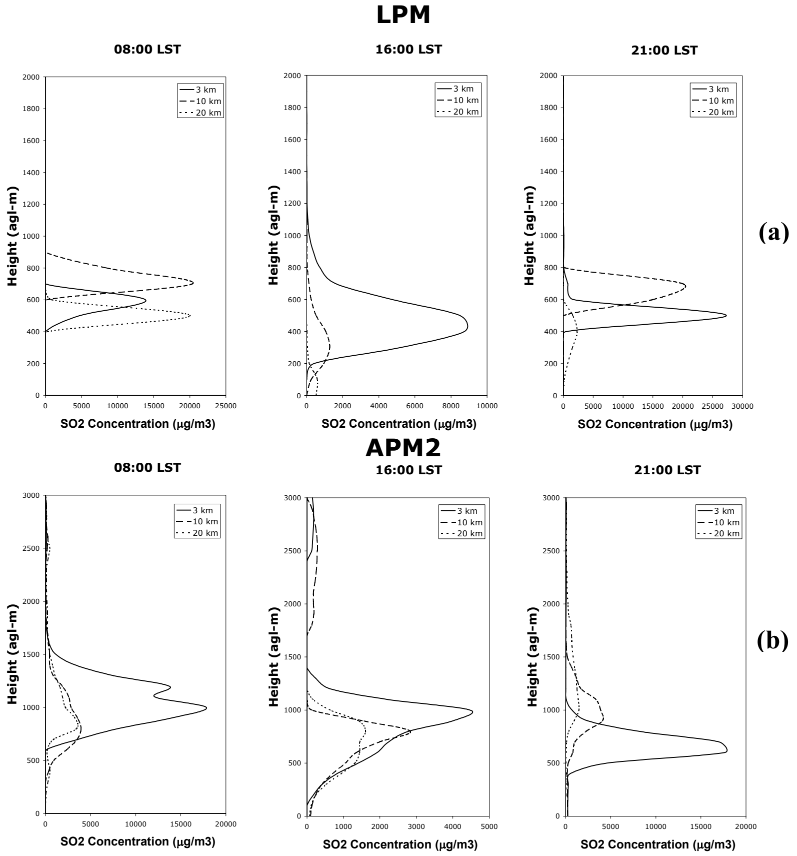

Figure 4: SO_2 concentration profiles estimated by LPM (a) and APM2 (b) at different time on June 21st, 2001, at 3, 10 and 20 km downwind the power plant.

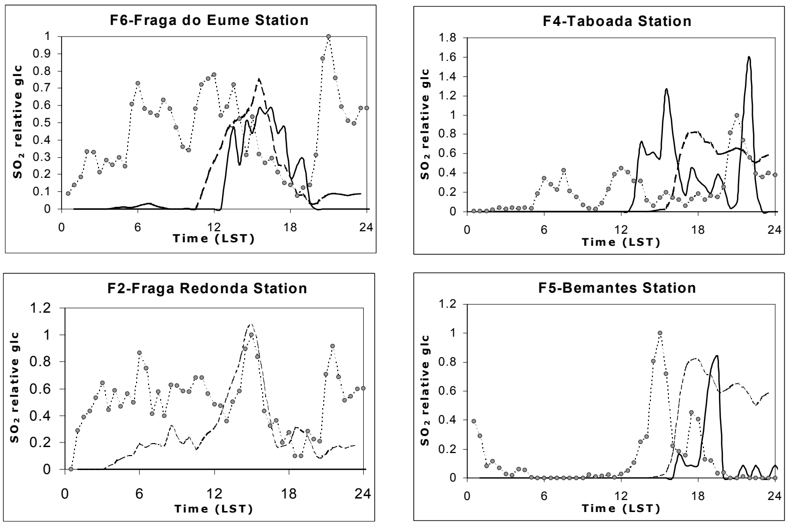

Figure 5: SO_2 relative ground level concentration (rglc) (respect to the maximum measured glc) on June 1st, 2001: Measured (dot line), estimated by APM2 (dashed line) and estimated by LPM (continuous line) over four locations where SO_2 glc was detected.

Estimation of SO_2 rglc concentrations shows that LPM impacts are usually farther than APM2 impacts, and shorter in time, but during the daytime impact periods LPM estimations are more in agreement to measurements than APM2 estimated impacts.

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