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Forest fires and air pollution: A local and a global perspective

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Abstract

A numerical system developed to simulate the effects of forest fires in the air quality is presented. This system integrates several related features, like emissions and progression of forest fires, and atmospheric flow. The interaction between the fire and the atmospheric flow considered as crucial is also taken into account in the system.

Aiming to estimate the contribution of forest fires to the air pollution, two study cases (a local and a global one) were analysed. The first one is related to urban/wildland forest fires. The Étoile fire, occurred during the summer of 97 near Marseille in France was studied attempting to estimate its effects on the air quality of the city. Results indicate a considerable impact on the quality of the air of the suburban area of Marseille.

Concerning the global scale impact of forest fires, greenhouse gases (GHG) emissions from Brazilian fires in 1997 were calculated and compared to the annual global GHG anthropogenic emissions. The contribution of Brazilian fires to the greenhouse effect is significant. An analysis of forest fires GHG emissions, oriented toward the problem of global warming and the goals of Kyoto Protocol, is also presented.

1 Introduction

Biomass burning is a locally, regionally, and globally important biospheric phenomenon, which includes burning of the world's forests (tropical, temperate, and boreal), grasslands, and agricultural fields after the harvest [1]. It is an important global source of various environmentally significant gases and solid particulates [2]. Its combustion products include carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), non-methane hydrocarbons (NMHC), nitric oxide (NO), nitrous oxide (N_2O) and atmospheric particulates. CO_2, CH_4 and N_2O are important GHG which impact global climate. CO, CH_4, NMHC, and NO are chemically active gases that strongly influence the local/regional concentrations of the major atmospheric oxidants ozone (O_3) and the hydroxyl radical (OH). Recent measurements suggest that biomass burning may be a significant global source of methyl bromide [1]. Bromide leads to the chemical destruction of O_3 in the stratosphere and is about 40 times more efficient in that process than is chlorine on a molecule-for-molecule basis. Production of aerosols is also very important, giving rise to local pollution, and affecting the radiation budget of the Earth and, hence, impacting global climate.

In addition, wildfires can produce severe degradation of air quality on a local scale. They are a considerable source of pollutants, for several hours, or even days, and their effects on the air quality may be of relatively short-term duration, but considerable [3].

Air quality studies usually do not take into account this source of pollutants. The University of Aveiro has been studying from the last seven years the effects of fires on the air quality and a numerical integrated system was developed. This system of models, named AIRFIRE, simulates the dispersion of pollutants in the atmosphere during a fire.

The main purpose of this paper is to describe the achieved work, illustrating the AIRFIRE application by the presentation of two study cases (a local and global one).

2 Developed Work: AIRFIRE

Modelling the dispersion of pollutants emitted during a wildland fire implies the combination of several related features: (i) forest fire emissions; (ii) atmospheric flow; (iii) fire progression; and (iv) dispersion of pollutants. An integrated system, AIRFIRE, based in the non-hydrostatic model MEMO, in the Rothermel's fire progression model and in the atmospheric dispersion model for reactive species MARS was developed [3].

MEMO is a non-hydrostatic prognostic mesoscale model [4], which describes the atmospheric boundary layer for unsaturated air. The atmospheric physical phenomena is simulated by the numerical resolution, in terrain-following co-ordinates, of a set of equations, including continuity, the momentum and some equations for the transport of scalar quantities, such as energy, water vapour, and kinetic turbulent energy.

Rothermel developed a semi-empirical fire spread model, which resulted essentially from laboratory experiments [5]. It is based in an equation that expresses an energy balance within a unit volume of the fuel ahead of the flame.

The MARS model simulates numerically photo-oxidants formation considering the chemical transformation process of pollutants together with its transport in the atmospheric boundary layer [6]. The model solves the parabolic differential concentration transport equation system in terrain-following co-ordinates, with the meteorological variables calculated by MEMO, e.g., the mass conservation equations are driven by the momentum equation.

Figure 1 presents a scheme of AIRFIRE [7].

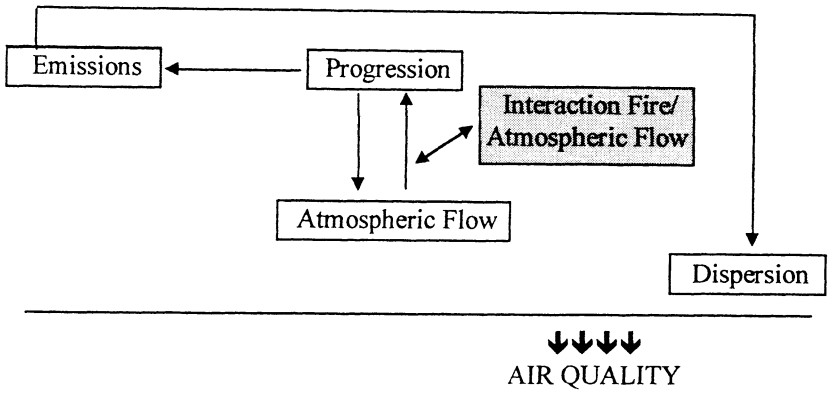

Figure 1. Scheme of the AIRFIRE system [7].

The key component of AIRFIRE is the fire spreading along the time, which is highly related to wind and fuel conditions and to the topography. Therefore, for a chosen fire progression domain, described by grid cells, one should know for each cell: the altitude, the land cover and the wind. Each type of land cover should be associated to one combustible, clearly described in terms of physical and chemical characteristics, like the heat and mineral content or like the fuel loading. Wind information will be calculated by MEMO linked with Rothermel's model to estimate the fire progression.

Since the spatial definition of the fire front requires a more refined grid than the fluid flow calculation, information of wind is transferred to a finer grid, where the fire shape is computed using the two semi-ellipse model of fire shape presented by Anderson [8]. Fire grown simulation is performed using the simple deterministic model, based on Huygen's principle, which uses an elliptical spread at each point of the fire front [9].

After each time step defined for the fluid flow calculation, fire front characteristics are transferred to the coarser grid, where the velocity field is recalculated on the basis of a new temperature distribution, assigned to each cell as function of the percentage of cell area that is burning. This new temperature calculation has been included in MEMO aiming to consider the effect of the fire, as a source of heat, in the atmospheric flow [10]. The inclusion of the interaction between fire and the atmospheric flow was a fundamental aspect of the integrated system.

Taking into account that the final purpose of the integrated system is the calculation of air pollutant dispersion, a fire emissions module was developed in order to be integrated in AIRFIRE. Ward and Radke [11] use

$q_n = (Ef_n)^* w^* R$ to determine the fire emissions, where: q_n – source strength of emission n, ($g.m^{-1}.s^{-1}$); n – specific emission; Ef_n – ratio of the mass of emission n released to the mass of consumed fuel, ($g.kg^{-1}$); w – mass of available fuel per unit area, ($kg.m^{-2}$); R –rate of spread of the fire, ($m.s^{-1}$). This expression is used for purposes where a specific q_{yn} rate is needed.

Often the resolution needed only requires a measurement of the total area burned by the fire. In this case, when a general estimate of emissions released on a regional scale is adequate, the biomass consumption per unit area, and the area burned by the fires are the only parameters evaluated. This technique is used in making estimates of the release of emissions to the atmosphere on a global basis.

The fire emissions module was integrated in MARS, which constitutes the final model of AIRFIRE. It uses information from MEMO and from the fire progression model to estimate the dispersion and photochemical production of the emitted gases during a wildland fire.

3 The Local Problem

Attending to the large source of pollutants that forest fires can constitute and to their potential local effects on the air quality a local study case was chosen. The Étoile fire seemed very interesting due to its proximity of Marseille.

3.1 The Étoile Fire

Étoile mountain is part of a very complex topographic region situated Northwest Marseille with an altitude reaching up 750 m. The Étoile fire was the biggest in the region since 1990, burning more than 3500 ha of mostly pine trees and shrub bush.

The 25 of July was a day particularly dangerous in terms of fire risk, all the parameters indicated that the occurrence of a fire could be imminent, e.g., it had not rained for a long time, the temperature was over 30°C and the NW winds were already above 15 $m.s^{-1}$. The fire started at midday of 25 of July in an industrial dump, near a pine forest, in the hills of Septémes Les Vallons, a tiny community NW of Marseille. On the hill a powerful ally, a turbulent wind with violent gusts in excess of 28 $m.s^{-1}$, affected the fire. Under this conditions fire progression was very fast, starting to threaten human lives and properties.

The wind had blown throughout the night. It was still just as strong and was adding its breath to the heat given off by the fire, to produce violent updrafts. The fire continued during Saturday, forcing about 1000 people from their homes near Marseille. The efforts of the teams of fire fighters were able to bring the fire under control on Sunday, but the fire just extinguish in the night of 28 of July.

3.2 AIRFIRE Application

AIRFIRE was applied in order to simulate the dispersion and photochemical reactions of the emitted pollutants during this urban/wildland fire.

The wind flow was simulated considering the synoptical meteorological

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conditions associated to the fire occurrence, a strong general wind from NW and neutral atmospheric conditions. In order to simulate meteorological phenomena from different scales, the simulation comprised two nested model domains, which coincide with two numerical grids: (i) the large grid domain has an extension of 50 x 80 km^2 and an horizontal resolution of 2.5 x 2.5 km^2; (ii) the 25 x 25 km^2 fine grid domain is given at 1 x 1 km^2 resolution. In the vertical direction the grid consists of 20 layers non-equidistant, extending over 6000 m height and with a minimum grid spacing of 20 m near the ground.

Due to the lack of important information, namely topography and vegetation cover with the appropriate resolution, it was not possible to apply the system as a whole and the fire progression module was left out. Information about fire progression and vegetation cover were used to estimate emissions, in space and in time, based in emission factors appropriate for Mediterranean conditions [3].

These emissions were used as input to MARS, which was applied to the fine grid domain using the same horizontal resolution and vertical structure than MEMO. In order to specify the boundary concentrations and typical trace constituent concentrations, a suburban air approach was assumed

3.3 Results

Three-dimensional atmospheric and concentration patterns were obtained with AIRFIRE for the fine grid domain. Figures 2 and 3 present the surface wind and CO concentration fields estimated at 13 and 19 hours, respectively, of the second day of the fire. CO is the most abundant air pollutant produced by forest fires and it is a direct hazard to human health.

Results concerning the atmospheric flow indicate a very interesting feature observed during the fire. Although the main synoptical flow from NW,

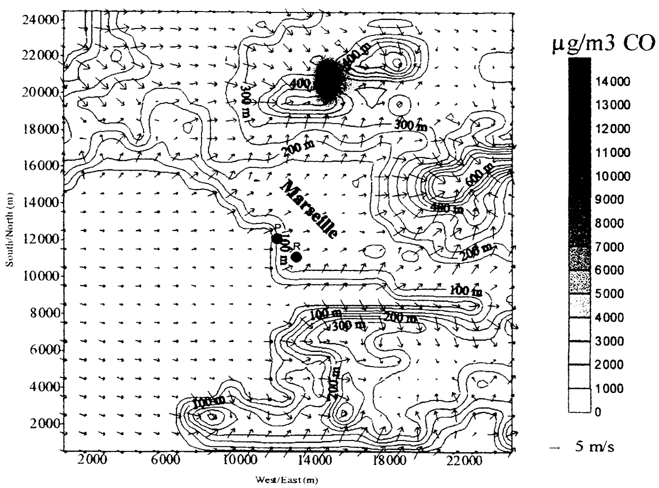

Figure 2: Hourly surface wind and CO concentration patterns at 13 hours.

topographical effects are visible in the wind field calculated for the fine grid domain. These smaller scale effects were noticed in the fire progression behaviour. The fire during the afternoon, located in the crest of the hill, suffered the influence of winds coming from two opposite directions, and a very difficult fire situation was created.

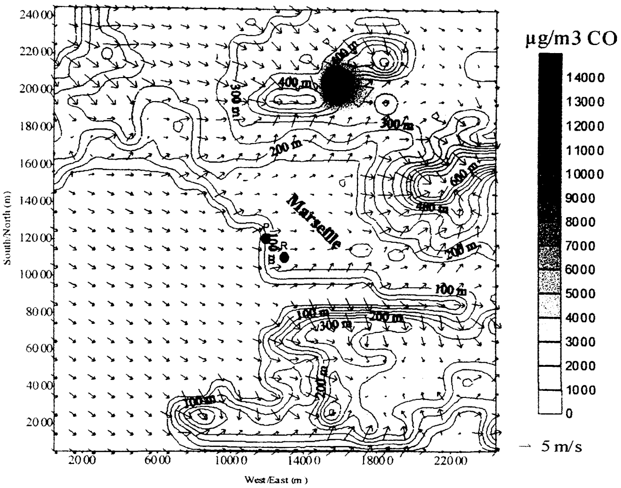

Figure 3: Hourly surface wind and CO concentration patterns at 19 hours.

Pollutant concentrations estimated by AIRFIRE are considerably high. For the CO case, concentration values in the area of the fire are always above 10000 $\mu g.m^{-3}$. Therefore a significant impact of the fire in the air quality should be expected. Comparison of these results with the hourly averages of CO concentration measured at the air quality network of Marseille during July confirms that. During this month an average of 1100 $\mu g.m^{-3}$ was calculated for Paradis station and a value of 1230 $\mu g.m^{-3}$ for Rabateau, both air quality stations located in the centre of the town (see black circles in figures 2 and 3).

Successfully the fire spread North of the city, not affecting the air quality in its centre. However, high levels of air pollution should have affected suburban area in the North part of Marseille.

4 A Global Perspective

Human activities are transforming the global environment and these global changes have many faces: ozone depletion, tropical deforestation, acid deposition, and increased atmospheric concentrations of gases that trap heat and may warm the global climate. These five processes of global change are all related to biomass burning.

According to estimates [12] 154000 km^2, i.e., 0.8 % of the total forest cover, are deforested annually around the globe. An important long-term effect of this deforestation process can be expected caused by emissions of greenhouse gases. Calculation point to about 1.6 Gt. C emitted yearly on a global scale due to land use and deforestation, contributing about 23 % to the overall carbon emissions of the world [13]. This is particularly clear in the tropics where fire emissions from vegetation can often dominate those from industrialisation.

In terms of burned biomass and emissions released into the atmosphere, tropical fires are estimated to account for 85 % of all biomass burning [2]. The fires that burned in the rain forest of Amazonia, Indonesia and Philippines in 1997 contributed to one of the most broad-ranging environmental disasters of the century. These damaging fires and the resulting air pollution affected the health of tens of millions of inhabitants.

4.1 Brazilian Fires

The 1997 burning in Brazil resulted in severe environmental impacts. Roraima State, in the north of Brazil contributed significantly to the total burned area. More than 30 % of Roraima forest and open areas like agricultural land, pastureland and savannahs were consumed. Annual emissions from this burning were estimated considering emissions factors typical of tropical vegetation [2, 14] and 40000 km^2 of open areas and 10000 km^2 of devastated forest. Recent data on the total biomass and on the combustion factor for each different type of vegetation were assumed, respectively, 7.5 $kg.m^{-2}$ and 80 %, and 30 $kg.m^{-2}$ and 57 % [15]. The fire emitted to the atmosphere nearly 73 Tg of CO, 492 Tg of CO_2, 2 Tg of CH_4 and 0,17 Tg of N_2O. These emissions represent a considerable contribution to the global amounts of emitted gases, i.e. Roraima's fire contribution is about 1.5 % for CO_2, 2.8 % for CO, 0.39 for CH_4 and 0.41 for N_2O.

CO_2 is by far the most important gas, either in terms of Roraima biomass burning, or in terms of global emissions. Comparing emissions to the annual CO_2 emissions of each of the most industrialised nations one can also see the extent of Roraima CO_2 contribution to the greenhouse effect. Table I presents this comparison. It should be noted that biomass burning releases rapidly to the atmosphere CO_2 that has been incorporated in the atmosphere/biosphere greenhouse system along decades or even centuries.

Table I: Relation between CO_2 emissions of Roraima fires and total CO_2 emissions of some industrialised countries.

Country	% CO_2 emissions of Roraima
France	134
Germany	55
Italy	114
Japan	43
Russia	20
United Kingdom	87
United States	10

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It is quite obvious from Table I that 1997 fires in Roraima State constituted a huge amount of GHG emissions to the atmosphere.

Taking into account that some gases are potentially more effective than others in changing climate the Intergovernmental Panel on Climate Change proposed the application of the Global Warming Potential (GWP) to obtain a first order estimate of the total radiative effect of the greenhouse emissions. The GWP of a gas is the warming effect of an instantaneous emission of 1 kg of each gas relative to CO_2. It is dependent on the chosen time horizon, because the cumulative radiative absorption of an emitted gas is dependent of the atmospheric lifetime of the gas.

Equivalent potential CO_2 emissions from Roraima were estimated, using the GWP concept for a time horizon of 100 years. Figure 4 presents the relation between calculated values for Roraima's fire and the total equivalent emissions in Portugal [16].

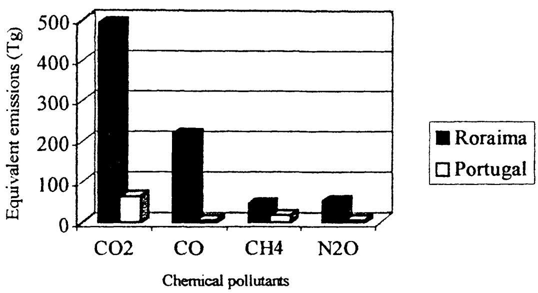

Figure 4: Equivalent potential emissions (Tg) for a time horizon of 100 years.

It is possible to verify in figure 4 that contribution of each GHG is different for the two considered situations. CO equivalent emissions represent the second contribution to the total GHG emitted by Roraima burning, but in what concerns Portugal the second contribution comes from CH_4. CO is considered as an indirect GHG but it is largely emitted by biomass burning. N_2O is produced during this process in small quantities, however due to its large GWP it has a considerable impact in terms of greenhouse effect.

The total Portuguese equivalent gases emissions are not significant compared with Roraima's fire. Portugal accounts only 11 % relatively to the fire equivalent emissions.

5 Conclusions

Biomass burning emissions are an important source of pollutants at several scales, from local to global. Concerning local scale forest fires could be responsible for air pollutant levels exceeding values of the air quality legislation. Urban/wildland fires exacerbate this question due to the already higher levels of air pollutants in the atmosphere and due to the higher population density potentially exposed to the smoke emitted.

Tropical biomass burning during 1997 raised the question about the competence of the Kyoto Protocol on Climate Change. This Protocol, agreed in 1997, requires developed countries to reduce six GHG, including CO_2, by an average of 5.2 % beginning in 2008. However, the proposed GHG reduction will be more than cancelled out if the world's forests continue to burn on this scale. Unfortunately, tropical burning can be expected to continue since it is used extensively for agriculture, clearing and land management.

However, it should be noticed that current global estimates of gas and particulate emissions from biomass burning are extremely approximate and vary considerably. The major uncertainties lie in the accuracy of the estimate of burned area, the amount and type of fuel consumed. Additionally, annual net emissions of CO_2 should be considered, incorporating vegetation regrowth follows burning.

Another important point of this question is related to the occurrence of El Nino Southern Oscillation (ENSO) phenomenon in 1997 with exceptional amplitude and causing global climate change. Therefore, 1997 was a special year in what concerns high fire risk situations in some zones of the world. Nevertheless, according to Bakun [17] the increase of the greenhouse effect will probably lead to more frequent and intense ENSO events.

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References

1. Levine, J., Cofer, W., Cahoon, D. & Winstead, E. Biomass Burning: A Driver for Global Change, *Environmental Science and Technology*, **29**, **3**, pp. 120A-125A, 1995.

2. Andreae, M., Biomass Burning: its History, Use, and Distribution and its Impact on Environmental Quality and Global Climate, Chapter I.1, *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*, ed. J. Levine, The Massachusetts Institute of Technology Press, Cambridge, Massachusetts, London, pp. 3-21, 1991.

3. Miranda, A. I., *Efeito dos incêndios florestais na qualidade do ar. Ph.D Thesis*, University of Aveiro, Aveiro, Portugal, 1998.

4. Flassack, T., *Ein nicht-hydrostatiches mesoskaliges modell zur beschreibung der dynamic der planetaren grezschicht. Fortsch. Ber.* Reihe, Nr 74, VDI-Verlag, 1990.

5. Rothermel, R., *A mathematical model for predicting fire spread in wildland fuels*. U.S. Dept. of Agriculture, Forest Service Research Paper INT-115, Intermountain Research Station, Ogden, UT, 1972.

6. Moussiopoulos, N., Sahm, P. & Kessler, C. Numerical simulations of photochemical smog formation in Athens, Greece: a case study. *Atmospheric Environment*, Pergamon, Great Britain, pp. 3619-3632, 1995.

7. Borrego, C., Miranda, A.I. & Lopes, M., Introduction of a forest fire effect in a mesoscale dispersion model, *Proc. of the 22th NATO/CSM International Technical Meeting on air Pollution Modelling and its Applications*, Clermont-Ferrant, France, Tome II, pp.292-299, 1997

8. Anderson, H., *Predicting the wind-driven wild land fire and shape*. Research Paper INT-305. Intermountain Forest and Range Experiment Station. Ogden, US 84401. United States Department of Agriculture, 1983.

9. Anderson, D., Catchpole, E., de Mestre, N. & Parkes, T. Modelling the spread of grass fires. *Journal Australian Math. Society*, Series B, pp. 451-466, 1982.

10. Miranda, A. I. & Borrego, C., Pattern changes in the atmospheric flow induced by forest fires, *Proc. of the 3rd Internacional Conf. on Forest Fire Research*, ed. D.X. Viegas, ADAI, University of Coimbra, pp. 1099-1115, 1998.

11. Ward, D. & Radke, L., Emission measurements from vegetation fires: a comparative evaluation of methods and results, *Fire in the environment. The ecological, atmospheric, and climatic importance of vegetation fires*, ed. P. Crutzen and J. Goldammer, John Wiley & Sons, Chichester, England, pp. 53-76, 1993.

12. FAO, *State of the worlds' forests*. FAO Report, 1997.

13. Zwick, A., Leone, F. & Sorup, P., *The Indonesian forest fires*, European Commission Institute for Prospective Technological Studies, Seville, 1997.

14. Lacaux, J., Cachier, H. & Delmas, R., Biomass burning in Africa: an overview of its impact on atmospheric chemistry, Chapter 10, *Fire in the environment. The ecological, atmospheric, and climatic importance of vegetation fires*, ed. P. J. Crutzen and J. G. Goldammer, Jonh Wiley & Sons, Chichester, England, pp.159-191,1993.

15. Fearnside, P., Roraima and global warming: annual balance of greenhouse gases originated by changes in land use, ed. R. Barbosa, E. Ferreira and E. Castellón, INPA, Manaus, 1997.

16. Borrego, C., Miranda, A.I., Conceição, M., Carvalho, A.C., Lopes, M. & Tchepel, O., Climate change and air quality management: emissions and consequences, *Proc. of the 6th Conf. o Environmental Sience and Technology*. To be published 1999.

17. Bakun, A. Global Climate Change and Intensification of Coastal Ocean Upwelling, *Science*, **247**, pp. 198-201, 1990.