Forest fire forecasting tool for air quality modelling systems

Roberto SAN JOSÉ[1], Juan Luis PÉREZ[1], Libia PÉREZ[1], Rosa María GONZÁLEZ[2], Julia PECCI[3], Marino PALACIOS[3]

[1]Environmental Software and Modelling Group, Computer Science School, Technical University of Madrid, Campus de Montegancedo, Boadilla del Monte, 28660 Madrid, Spain.
roberto@fi.upm.es
[2]Department of Geophysic and Meteorology, Faculty of Physics, Ciudad Universitaria, 28040 Madrid, Spain.
[3]Indra S.A., C/ Mar Egeo, 4, Pol. Industrial 1, 28830 San Fernando de Henares, Madrid (Spain)

Abstract

Adverse effects of smoke on air quality are of great concern; however, even today the estimates of atmospheric fire emissions are a key issue. It is necessary to implement systems for predicting smoke into an air quality modelling system, and in this work a first attempt towards creating a system of this type is presented. Wildland fire spread and behavior are complex phenomena due to both the number of involved physic-chemical factors, and the nonlinear relationship between variables. WRF-Fire was employed to simulate spread and behavior of some real fires occurred in South-East of Spain and North of Portugal. The use of fire behavior models requires the availability of high resolution environmental and fuel data. A new custom fuel moisture content model has been developed. The new module allows each time step to calculate the fuel moisture content of the dead fuels and live fuels. The results confirm that the use of accurate meteorological data and a custom fuel moisture content model is crucial to obtain precise simulations of fire behavior. To simulate air pollution over Europe, we use the regional meteorological-chemistry transport model WRF-Chem. In this contribution, we show the impact of using two different fire emissions inventories (FINN and IS4FIRES) and how the coupled WRF-Fire-Chem model improves the results of the forest fire emissions and smoke concentrations. The impact of the forest fire emissions on concentrations is evident, and it is quite clear from these simulations that the choice of emission inventory is very important. We conclude that using the WRF-fire behavior model produces better results than using forest fire emission inventories although the requested computational power is much higher.

Key words: WRF-FIRE, Fire Behavior Model, Fuel Moisture Content, WRF/Chem, Smoke Emissions.

Herramienta de predicción de incendios forestales para sistemas de modelización de la calidad del aire

Resumen

Los efectos nocivos del humo en la calidad del aire es un tema de gran preocupación, sin embargo actualmente las estimación de los emisiones de los incendios forestales son esenciales. Es necesario implementar Sistemas de Predicción del humo para los sistemas de modelización de la calidad del aire y este trabajo es un primer intento hacia la creación de este tipo de Sistemas. El comportamiento de los incendios forestales es un fenómeno complejo debido a la multitud de factores físico-químicos implicados así como por la no linealidad del proceso. El modelo WRF-Fire se ha utilizado para simular el comportamiento de incendios reales en el Sur-Este de España y en el Norte de Portugal. La utilización de

modelos de comportamiento de incendios forestales requiere el uso de datos de alta resolución del entorno y de combustible. Hemos desarrollado un nuevo modelo optimizado para estimar el contenido de humedad en el combustible tanto para combustibles muertos como vivos. Los resultados confirman que el uso de datos meteorológicos precisos y datos del contenido de humedad exactos son cruciales para obtener correctas simulaciones de la evolución y comportamiento de los incendios forestales y sus emisiones. Para simular la contaminación sobre Europa, hemos utilizado el modelo regional meteorológico-químico (online) WRF-Chem. En esta contribución, mostramos un análisis de sensibilidad del impacto de dos diferentes inventarios de emisiones (FINN y IS4FIRES) y cómo el modelo WRF-Fire-Chem mejora los resultados de las simulaciones del humo de varios incendios forestales. El impacto de la modelización de las emisiones en los incendios forestales así como en las concentraciones del humo es evidente y se muestra de forma bastante clara que la elección del inventario de emisiones en las simulaciones de incendios forestales es esencial. Concluimos que usar el modelo de comportamiento WRF-Fire es mucho más recomendable que utilizar los inventarios de emisiones de humo procedentes de incendios forestales como FINN o IS4FIRES, aunque los requerimientos computaciones son mucho más elevados en el caso de WRF-Fire.
Palabras clave: WRF-FIRE, Modelo de incendios, Contenido humedad de combustible, WRF/Chem, Emisiones de humo.

Contents: 1. Introduction. 2. Methodology. 2.1. Fuel moisture model. 2.2 Fire emissions. 2.3 Model description. 2.4. Portugal case study. 3. Results and discussion. 4. Conclusions. Acknowledgements. References.

1. Introduction

Adverse effects of smoke on air quality are of great concern because the fire emissions can result in a violation of the air quality directives. However, even today the estimates of atmospheric fire emissions are arguably known within a factor of a few times even if large-scale and long-term averages are considered. With this in mind, it seems logical to implement a system for predicting smoke into an air quality modelling system. In this work, a first attempt towards creating a system of this type is presented. The dispersion of smoke is clearly a multidisciplinary and very complex task. To estimate the spread of smoke and its effects on air quality, first one has to evaluate the amount of fuel burned, and make it flow issue of particular chemical species. In the next step, the vertical distribution of smoke in the atmosphere (height injection and the vertical profile) has to be estimated, based on the intensity of the fire and weather conditions (winds, atmospheric stability). In the last step, the chemical processes associated with the dispersion of smoke into the atmosphere must be simulated in order to evaluate the impact of smoke in air quality

The work describes an operational information system for wildland fires forecast over Spain and the results of preliminary simulations of a real fire. Our objective is to produce the best estimations of Fuel Moisture Content (FMC) as a key input parameter into the wildland fire simulations.

FMC is usually classified as "live" or "dead" fuel. Live FMC is classified into wood and grass materials and the calculation process involves the estimations of Land Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI) to estimate the live FMC for these two materials. The dead FMC is representing the wood material which is found in the forests as thin dead wood material and larger material. This is usually classified as 1 h, 10 h and 100 h materials. The 100 h material represents the large tree trunks on the floor. Since the observational FMC data sets are very scarce, we decided to use the wildland fire model to evaluate the proposed methodology to estimate the FMC values. The results from the fire model are compared with a real wildfire in Spain where we have the fire extension as a shape file.

To get detailed meteorological information we have used the mesoscale meteorological model Weather & Research Forecasting system (WRF) developed by NCAR and others (Michalakes et al., 2001;Skamarock et al., 2005). WRF model is combined with a spread model by the level set method and the final system is called WRF-Fire, which is the core of our system. WRF-Fire is the successor to the CAWFE model (Clark et al. 1996). The algorithms for fire spread and fuel combustion in WRF-Fire are based on the model of Rothermel (1972), using the fuel descriptors of Anderson (1982). Description of the WRF-Fire physical model with the numerical algorithms used is presented in Mandel et al. (2011). In order for the propagation model to be efficient, forest fuels must be described in a particular way, in which the fuel characteristics are represented by certain average values. The set of these representative values is called "fuel model". We have used the 13 fuel models of Anderson (1982).

Biomass burning emission inventories are critical input for atmospheric chemical transport models. Many fire emission inventories have been developed. The spatial and temporal resolution, speciation and coverage period of the inventories varies considerably. One of the first emission inventories were for year 2000 at spatial resolution of 1 km (Ito and Penner, 2005) and 0.5 degree (Hoelzemann et al., 2004). One of the most used it the Global Fire Emissions Database (GFED), which is available as 8-day and monthly composited at 0.5 and 1 degrees of spatial resolution. The most recent global fire emission inventory was the Fire Inventory from NCAR (FINN), with daily data and 1 km of spatial resolution, which has been used in this experiment. GFED and FINN show excellent agreement in annual, global emissions (Wiedinmyer et al., 2011) but on a continental basis, the disagreement in annual emissions for 2003 for Africa varied by a factor of 2.2 and for North America varied by a factor of 14.5 (Stroppiana et al., 2010). Over shorter time periods, the disagreement between emission inventories can be more significant. Further, the sensitivity of the emission estimates to the model components is generally not well characterized. Understanding the sensitivity of emission estimates to hypothesis and uncertainties associated with each input to the emission model – burned area, fuel map, fuel load, fuel consumption, and emission factors –, is crucial for properly

assessing the impact that these assumptions may have on atmospheric chemical transport model simulations.

In this work, we also show the impact of using two different fire emissions inventories and how the coupled WRF-Fire-Chem model improves the quality of the fire behaviour simulations. We also show the impact of smoke fire emissions on air pollution concentrations in the fire area. The experiment has been designed by using data from Portugal monitoring stations. There are few other satellite-based methods that estimate biomass burning emissions for air quality applications but these methods provide the total smoke emitted during the forest fire. In our application, we are using a forest fire behaviour model which is producing the spatial burned areas and smoke emissions into the atmosphere every hour. We are using satellite information to set the ignition point and start date. The forest ire model gives us enough information to refine the spatial and temporal characterization of biomass burning emissions.

2.   Methodology

The core of the system is the WRF-Fire model, which is a tow-way coupled fire atmosphere model. The atmosphere model is the WRF (Skamarock et al. 2005). It provides forecast of the fire spread based on the local meteorological conditions, taking into account the feedback between the fire and the atmosphere (Mandel et al. 2011). In each model time step, the near-surface wind from WRF is interpolated vertically to a logarithmic profile and horizontally to the fire mesh to obtain height-specific wind that is input into Rothermel fire spread-rate formula (Rothermel 1972). Fuels are given as one of 13 categories (Anderson 1982), and associated with each category are prescribed fuel properties such fuel mass, depth, density, surface-to-volume ratio, moisture of extinction, and mineral content. After ignition, the amount of fuel remaining is assumed to decrease exponentially with time with time, with the time constant dependent on fuel properties, and the latent and sensible heat fluxes from the fuel burned are inserted into the lowest levels of the atmospheric model, assuming exponential decay of the heat flux with height.

The fire model is also coupled with WRF-Chem, so the smoke emitted from the fire is added at the location of the simulated fire and them is transported within the atmosphere, and undergoes chemical reactions resolved by WRF-Chem. The amount of the chemical species released into the atmosphere is computed from the amount of fuel burned directly by emissions, (g/kg fuel or mol/kg fuel for each of the 13 Anderson´s fuel categories used). Emissions are computed at the fire resolution (in this experiment 20 meters) and the averaged to the atmospheric/chemistry resolution (23 km). The fire simulation is only active when a 23 km grid cell contain a fire ignition point. In order to capture the effect of local weather on fuel characteristics, WRF-FIRE is also coupled with a fuel moisture model. A new Fuel Moisture

Content (FMC) model has been developed by the authors and integrated into the WRF-Chem-Fire system.

2.1 Fuel moisture model

McArthur (1966) developed a monogram for predicting the moisture content of cured grass, as part of his Grassland fire Danger Meter (GFDM). The GFDM was converted to equations by Noble et al. (1980), where the prediction of fuel moisture is given by Equation 1. This equation is used as base of our FMC calculations for fine dead fuel (1 hour dead fuel),

$$m = \frac{97.9 + 4.06H}{T + 6} - 0.00854 H_{surf} + \frac{3000}{C} - 30 \tag{1}$$

where H and H_{surf} are the air humidity at 1.5 meters and surface levels, T is the temperature at 1.5 meters and C is the degree of curing (%) and is considered as 100% for the calculation of dead FMC. This equation has now become more accepted than the original meters of McArthur. The GFDM has been found to perform well in predicting moisture content of aerial fuels in pine forest, mallee-heath and button-grass moorlands.

One of the problems in the prediction of FMC was the lack of consideration of the effects of condensation. In our system, we use a physical model to quantify the effects of nocturnal condensation on the moisture content of leaf litter by Equation 2 (Viney and Hatton, 1990). Although the model is complex, because contains many input parameters, these input data can be gotten from the meteorological model WRF.

$$\Delta m = \frac{100}{W} \int_{\Delta t} \frac{G - N}{L + C_p (T - T_{surf}) / (Q - Q_{surf})} \, dt \tag{2}$$

where W is the surface fuel mass, G is the soil heat flux, N is the net all-wave radiation flux, L is the latent heat of vaporization or sublimation, Cp is the specific heat of air at constant pressure, T and T_{surf} are the temperature at 1.5 meters and surface levels and Q and Q_{surf} are the specific humidity at 1.5 meters and surface levels respectively.

In case of not fine dead fuel, as 10 hours and 100 hours dead fuel, we have implemented into WRF-Fire the Nelson model (Nelson, 2000) modified to be operational. Nelson equations describing the transfer of heat and moisture at the surface and within a stick are derived and then solved numerically. The model simulated change in moisture content and temperature in cylindrical wood sticks of any practical size based on "heat loss" is equal to "heat gain".

FMC in live fuels is a critical factor driving wildfire susceptibility and wildfire behavior. Live FMC is calculated following the correlation between vegetation

greenness and its moisture content, consequently the Normalized Difference Vegetation Index (NDVI) can be used in estimating live FMC. Live FMC estimations can be improved by including the Land Surface Temperature (LST), because LST would be expected to increase in drier plants on account of reduced evapotranspiration. Specifically the ratio NDVI/LST was found to be very useful (Sawarvanu et al., 2005).

The FMC module produces 5 FMC values, 3 for dead fuels (1, 10, 100 hours) and 2 for live fuels (wood and herbaceous fuels). These 5 values are aggregated based on a weight average. Weight factors are taken from other fire models as BehavePlus (Andrews, 2007), Farsite (Finney, 2004) and FlamMap (Finney, 2007). This aggregation uses information from the fuel model. The fuel model classification is made with information about landuses from 2000 Corine Land Cover (CLC-2000) with 100 meters of spatial resolution. The final fuel load map was derived by assigning a fuel class to each land uses. The allocation matrix is given in Table 1.

Table 1: Equivalence between fuel model classes and land uses from Corine Land Cover classification (CLC-2000).

FUEL MODEL	CLC LANDUSES
1-Short grass	18,22,26,32,36,12,19,20
2-Timber grass and understory	21,24,29,33,35
4- Chaparral	25,27,15
6- Dormant brush	22
8- Compact timber litter	23

2.2 Fire emissions

In this section we will describe the two different fire emissions inventories that have been used in this experiment (FINN and IS4FIRES), the vertical injection of the fire emissions, the air quality simulations, and the coupled atmosphere-fire-chemical WRF-Fire-Chem model.

The Fire Inventory from NCAR (FINN) provides daily emissions with 1 km resolution, global estimates of the trace gas and particle emissions from open burning of biomass, which includes wildfire, agricultural fires, and prescribed burning. This inventory is ready to use with WRF/Chem. FINN uses satellite observations of active fires and land cover, together with emissions factors (emission/mass of biomass burned) and estimated fuel loadings. Detections of active fires are based on observations from the MODIS instruments. For each 1 km^2 hot spot, we can detect only one fire per day. Fires that prevail in the same location over several days are accounted for. For each identified fire the assumed burned area is 1 km^2, except for fires located in grasslands/savannas, these are assigned a burned area of 0.75 km^2. The main uncertainties and limitations of this inventory are due to: (a) Missed fires causing an underestimation of the number of fires, (b) Satellite overpass

timing and cloud cover may prevent the detection of fires, (c) Overestimating the size of the small fires that are detected, (d) Relationship between fire detections and area burned is highly uncertain and the topic of much on-going research, (e) Identification of the land cover, (f) Inaccurate fuel loading and parameterizations of combustion completeness, and (g) Emission factors.

The second one fire emission inventory is the Integrated monitoring and modelling System for wildland FIRES project (IS4FIRES) (http://is4fires.fmi.fi/) participated by Finnish Meteorological Institute (FMI) and University of Helsinki (Sofiev et al., 2009). IS4FIRES provides daily, 0.1x0.1 degree spatial resolution for a global coverage. Emission dataset has been obtained by re-analysis of fire radiative power data obtained by MODIS instrument. It is based on an explicit scaling factors to convert the TA (4-um Brightness Temperature Anomaly) or FRP (Fire Radiative Power, MJ-1) values to PM emissions and other pollutants. The FRP is physically a better grounded quantity than TA for the determination of the fire emissions. For days, in which the FRP data are either unreliable or do not exist, the system converts TA to FRP. IS4FIRES publishes the data of the Total Particle Matter (TPM), but air quality simulations need fire emission for other pollutants, so we use a factors to go from TPM to other pollutants: CO (6.08*TPM), NO (TPM*0.170), NH3 (TPM*0.080), SO2 (TPM * 0.057) and NMVOC (TPM *0.32). These factors are based on (Andreae and Merlet, 2001). Figure 1 shows the fire emission distribution.
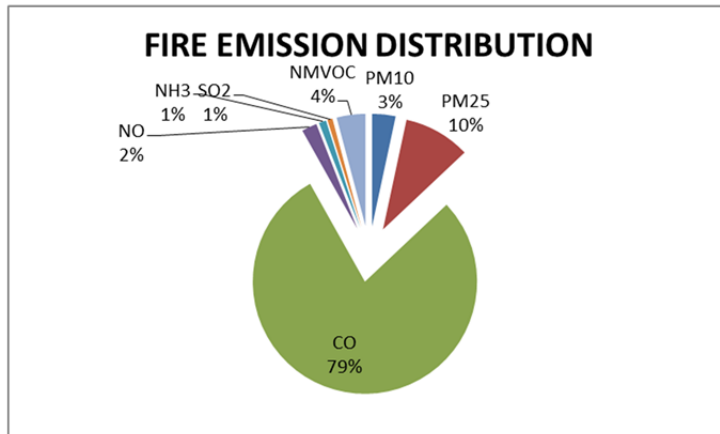

Figure 1: Fire emission distribution based on Andreae and Merlet, 2001.

Emissions from biomass burning can have a direct and rapid transport into the planetary boundary layer, the free troposphere, and even the stratosphere, so it is very important to reproduce the vertical distribution of the fire emissions, that means we need to know the vertical distribution of the emissions from the surface to the top of the plume height which describe the maximum level of emission injection above

surface. Fire emissions from the FINN inventory have been injected using the WRFChem plume rise model (Grell et al., 2011). The plume rise model is a 1D time--dependent cloud model (Freitas et al., 2007) that is taking into account the lower boundary conditions in each column of WRF/Chem. The plume rise model is based on the continuity equations for water in all phases, the vertical equation of motion, and the first law of thermodynamics.

Fire emissions from the IS4FIRES have been injected using the vertical injection profiles distributed together with the emission data (Sofiev et al., 2012). IS4FIRE publishes monthly gridded (1º by 1º) normalized vertical distributions of the fire emissions for day and night. They are based on the semi-empirical formula to calculate the plume top which depends of the fire radiative power (FRP), PBL height and vertical temperature profiles. Fires from 2000 to 2012 extended over the whole globe were analysed to develop the vertical profiles.

Figure 2 shows the different percentages of the distribution of the fire emissions following the WRF-Chem plume rise and the vertical profile of the IS4FIRES. Plume rise model injects more than 50% in the first layer and the vertical profile injects 50% of the emission distributed in the 10 first layers where the vertical resolution is 500 m.

Injection heights distribution (%) WRF/Chem layers (m)

	Plume Rise	Vertical Profile
5385	2,1	0,0
4510	2,1	0,2
3681	2,8	0,9
2953	6,0	1,5
2322	5,6	4,8
1787	3,9	11,5
1353	3,2	7,9
1012	2,7	7,9
746	1,9	3,7
554	1,2	5,4
439	0,7	5,4
357	0,8	5,4
277	1,1	5,4
197	1,0	5,3
137	0,5	7,0
98	0,5	7,0
63	0,4	7,0
35	0,0	7,0
12	63,5	7,0

Figure 2: Percentages of the distribution (%) of the fire emissions following the WRF-Chem plume rise and the vertical profile of the IS4FIRES by each vertical layer of the model. The height of each layer (meters) and his associated color is also showed (left-bottom).

2.3 Model description

In order to simulate the air pollution over Europe, we have used the regional meteorological-chemistry transport model WRF-Chem (Grell et al., 2005). It includes the RADM2 gas phase mechanics, the MADE inorganic aerosol scheme, and the SORGAM aerosol module for secondary organic aerosols (SOA). Model configurations follow the next physical parameterizations, namely the Noah Land Surface Model (Solomon et al, 2007), Morrison double-moment microphysics scheme (Morrison et al., 2009), RRTMG long-wave and shortwave radiation schemes (Rapid Radiative Transfer Model for Global), Grell 3D ensemble cumulus parameterization (Grell et al., 2005), Yonsei University Planetary Boundary Layer (YSU; Hong and Pan, 1996) and Monin-Obukov surface layer. WRF-Chem has been covering Europe and a portion of Southern Africa as well as large areas affected by the Russian forest fires. The set-up was recently evaluated under COST 768 action, and it was concluded that the WRF-Chem, simulations using climate model output were able to capture the major features of the observed distribution of surface O_3, NO_2 and PM over Europe (Brunner et al., 2015; Forkel et al., 2015). The domain is defined in a Lambert Conic Conformal projection that includes 270 x 225 grid points with 23 km of horizontal resolution. The vertical grid extends over 33 stretched layers from the surface to a fixed pressure of 50 hPa (about 20 km), 178 with the lowest level thickness of 24 m close to the ground.

The simulation time period was from 07/08/2010 to 13/08/2010, using a spin-up period from 05/08/2010 to 06/08/2010. The sensitivity experiment, we have performed four WRF-Chem simulations: a) The first run, without forest fire emissions, called NOFIRE; b) the second one, with forest fire emissions from the FINN inventory and with the use of an on-line plume rise model to inject the emissions in the corresponding vertical layer, this simulation is called FINN; c) The third simulation is performed with forest fire emissions and the corresponding vertical profile from IS4FIRES and it is called IS4FIRES simulation and d) The fourth simulation with the WRF-Chem model includes the real forest fire behaviour simulation of two Portugal forest fires with the WRF-Fire model and the on-line plume rise model; this simulation has been identified as FIRE simulation.

2.4 Portugal case study

The fire detection is based on satellite information. The global monthly fire location product (MCD14ML) contains the geographic coordinates of individual fire pixels (1km resolution approx.) for all Terra and Aqua MODIS satellite data fire pixels in a single monthly ASCII file. The MODIS active fire product detects fires that are burning at the time of overpass using infrared data. The burned area product (MCD45A1) contains the date (day) of burning at 500 m.

In this case, the first step was to identify the start date and ignition point for each fire event. For that purpose the active-fires and burnt areas data sets were combined and matched from dates: 08/08/2010 and 09/08/2010. It was also necessary to find fires where data from air quality monitoring stations were available. Summary of the situation is showed in the Figure 3. Several points represent active fire on 8 and 9 of August, 2010 in Portugal, and two main burned areas. As a consequence, we have simulated the following fires: (i) starting on August 8 at 02:00, with duration of 12 hours (first fire), and (ii) starting on August 8 at 24:00, with duration of 12 hours (second fire). The fire ignition moments were picked from MODIS FRP records. The WRF-Fire model was used to simulate the behaviour of the selected fires. The fires have been simulated with 20 meters resolution and the obtained emissions were aggregated to a 23 km grid-cell to be used as an input to the WRF-Chem model (see Section 3).
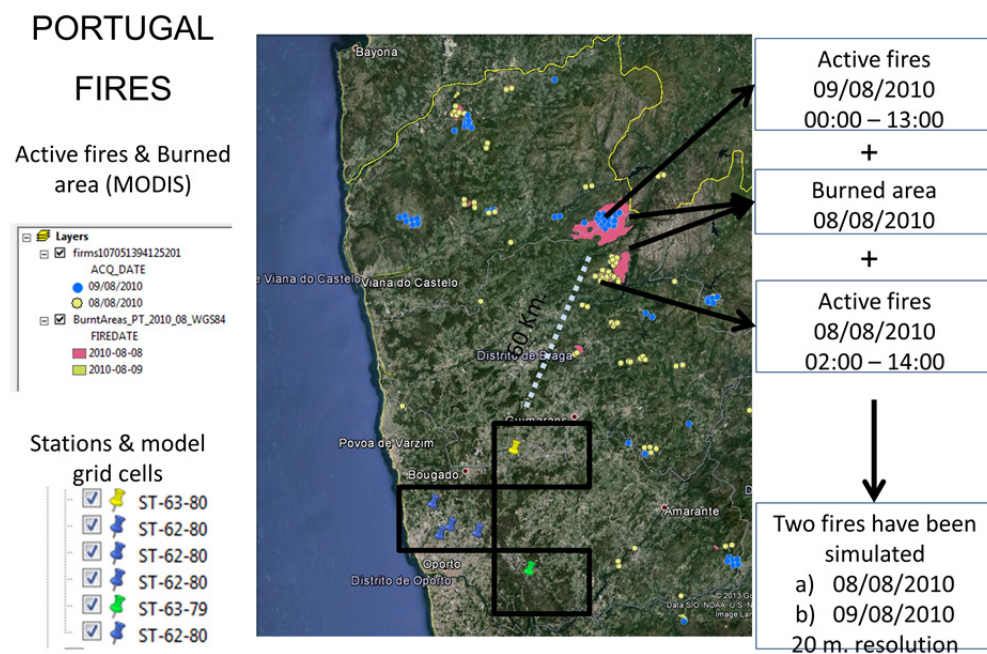

Figure 3: Location of Portuguese air quality monitoring stations (blue, green and yellow pins); MODIS active fire (yellow (measured on 08.08.2010) and blue (measured on 09.08.2010) dots) and burned areas (pink shaded area labelled on 08.08.2010); and WRF-CHEM grid cells (black squares).

3. Results and discussion

In this section, we are going to show different results: (1) we are going to compare the simulation results with observational data from three different real forest fires in the Mediterranean area in Spain; (2) The impact of using the FINN or IS4FIRES emission inventories, in particular, we will show the impact on the ozone and PM10 concentrations in Europe, and (3) the Ozone and PM10 concentration differences in the case of Portugal fires.

(1)   *Model validation*

A preliminary model validation was tested on real cases of forest fires in the Spanish territory. The first fire (FIRE1) ignited in "Sierra el Molino". a region of Murcia (Spain) on September 07, 2010 19:09. The final burned area is 7 km by 1 km after 9 hours. The simulated area was discretized by a matrix of 350 x 100 cells, the cell resolution was 20 m. It is a short fire.The second one (FIRE2) is a fire ignited in "Gabiel" a region of Valencia (Spain) on March 07, 2007 22:15. The fire was controlled on March 09, 2007 12:00 and the final burned area is 4 km by 6 km. The simulated area was discretized by a matrix of 250 x 350 cells, the cell resolution was 20 m. It is a long fire. The last one (FIRE3) is a fire ignited in "Culla" a region of Valencia (Spain) on March 07, 2007 23:36. The fire was controlled on March 09, 2007 12:00 and the final burned area is 3 km by 5 km. The simulated area was discretized by a matrix of 200 x 250 cells, the cell resolution was 20 m. It is long fire addressed by fuel and not by winds.

We have only the fire perimeter at the end of the fire event. In addition, it is known that fire-fighters have made numerous attacks on the fire in order to constrain the fire. As there is no precise data available to these attacks, we ran the simulation without taking into account the effect of the fire-fighters.

Figure 4 represents the superimposition of the real fire and simulated fire at 1 hour, 3 hours, 6 hours, and 9 hours after ignition for case FIRE1. Real fire contour after 9 hours from ignition is displayed as grey, and simulated contour fire is represented as black colour. Arrows indicate the simulated winds from the meteorological model WRF. The fire was increase rapidly after the 3 first hours. The fire was propagating according the wind direction and taking into account the fuel available.
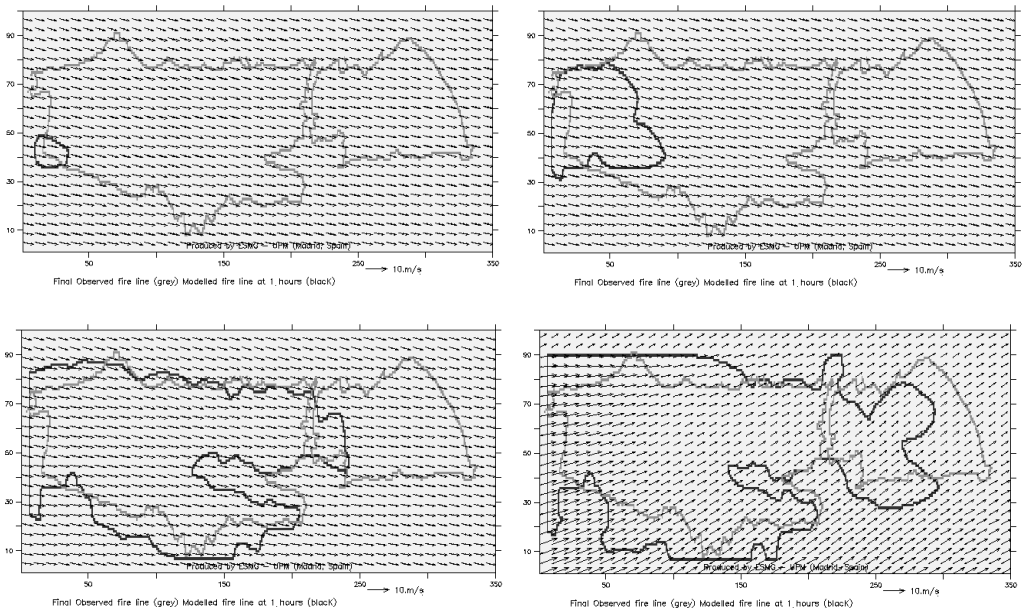
Figure 4: Observed fire line after 9 hours after ignition (grey) to the modelled fire line (black) at 1 hour (upper-left), 3 hours (upper-right), 6 hours (bottom-left), and 9 hours (bottom-right) and simulated wind vectors. Case FIRE1 (Murcia, Spain)

A statistical analysis of the simulated grid cells versus real status has been developed. The analysis calculates percentage of OK grid cells (forecast and real data are the same), percentage of gridcells with overestimation (simulated burned gridcells but in fact they were not burned) and percentage of gridcell with underestimation (non burned gridcells but in fact they were burned), this is the worst scenario. For each simulation a final score is calculates as Equation 3. The best result possible is a final score equal to one. Statistical analysis of the grid cells for the three fires is showed in the Table 2.

$$\text{Final Score} = \text{OK} - \text{Overestimation} - 2 \times \text{Underestimation} \qquad (3)$$

Table 2: Statistical analysis results for the three Spanish fires

	FIRE1 (Murcia)	FIRE2 (Gabiel)	FIRE3 (Culla)
OK	78.75 %	89.94 %	87.63 %
Overestimation	13.93 %	3.68 %	8.84 %
Underestimation	7.32 %	12.39 %	3.53 %
FINAL SCORE	0.5018	0.5548	0.7173

All cases show high percentage of the grid cells that were well forecasted, more than 78%. Percentage of the grid cells where there were overestimations is not very important, about 8% in average and percentage of the grid cells where there were underestimation also about 8% in average. These gridcells are the most dangerous in a warning system. In case of FIRE1 (Murcia), there is more over-prediction than in Valencia fires, due to high wind speeds and because the time period is four times longer. It is important to note that the underestimation level is very similar in FIRE1 and in FIRE2. The best simulation is obtained for FIRE3, which is the most difficult forecasting due to the fire travel in a opposite direction than the wind.

In general the results of the simulation looks good since few areas of the real fire do not appear to be burnt in the simulation and few areas, which were not burnt, are computed to be "burnt". Some differences are probably due to the attack of the fire fighters, because these actions are not modelled. The results of the simulation show a significant fit with the real data.

(2) *Impact of the fire emission inventory*
In this section we show differences of PM10 and O3 concentrations between two fire emission inventories (FINN, IS4FIRES) runs and without fire emissions (NOFIRE) over Europa, for one week (07-13) of August, 2010. During these dates very important forest fires were localized over Russia and Portugal. These differences between with and without fire emissions runs provide an estimate of fire emission inventories impacts on PM10 and O3 concentrations. The hourly outputs of the model runs have been temporal averaged to obtain an overview of the impacts.

Figure 5 shows PM10 differences (%) on averaged near-surface PM10 concentrations between FINN simulation and without fires simulation (NOFIRE) and IS4FIRES simulation and without fires simulation (NOFIRE). Maximum differences are localized over Russian and Portugal fires. Biggest differences over Russia are obtained with the simulation using the FINN but over Portugal the differences are higher with the IS4FIRES simulation. Portugal fire will be analysed and simulated with the WRF-Fire-Chem system in the next section. Differences in PM concentrations associated with different emission inventories input data sources ranged up to 1000% over the European domain with 23 km of the spatial resolution.
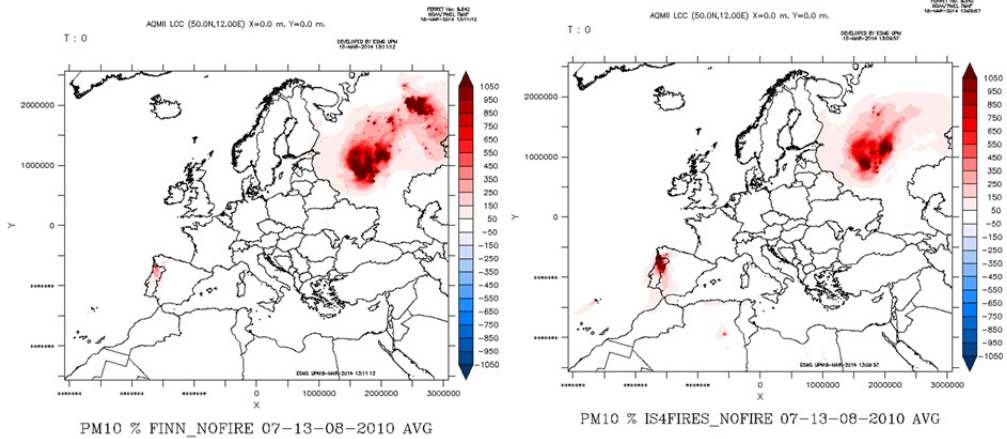
Figure 5: Differences near-surface PM10 (%) due to forest fire emissions (FINN-NOFIRE and IS4FIRES-NOFIRE) calculated by WRF-Chem using FINN emissions (left) and WRF-Chem using IS4FIRES emissions (right) averaged over the week 07-13/08/2010.

Figure 6 shows O3 differences (%) on averaged near-surface O3 concentrations between FINN simulation and without fires simulation (NOFIRE) and IS4FIRES simulation and without fires simulation (NOFIRE). Maximum differences are localized over Russian. South Africa and Iberian Peninsula (including Portugal fires). Biggest differences are obtained with the simulation using the IS4FIRES simulation, especially on the south area of the domain. WRF-Chem simulation with FINN emissions yields much lower ozone impacts from the South Africa forest fires than WRF-Chem with IS4FIRES. It is due to IS4FIRE only produces total particle matter (TPM) and the rest of the species are calculated based on a factors, ozone precursors emissions could be overestimated compared with the fire emissions of the FINN. Fires that took place Russia had a much stronger impact on ozone. Differences in O3 concentrations associated with different emission inventories input data sources ranged up to 70% over the European domain with 23 km of the spatial resolution. PM10 impacts were less widespread than those for O3, a finding consistent with the nature of ozone formation as a secondary pollutant.
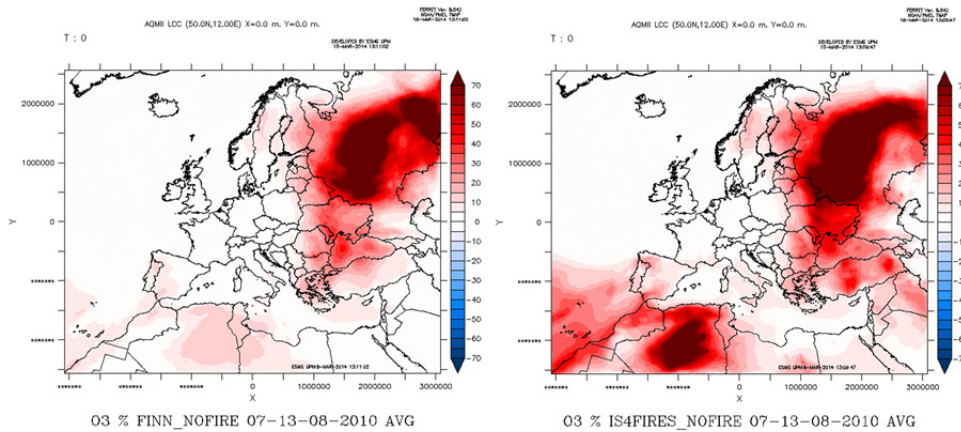
Figure 6: Differences near-surface O3 (%) due to forest fire emissions (FINN-NOFIRE and IS4FIRES-NOFIRE) calculated by WRF-Chem using FINN emissions (left), and WRF-Chem using IS4FIRES emissions (right), averaged over the week 07-13/08/2010.

(3)   Portugal fires

Fire behaviour of two Portugal fires have been simulated with WRF-Fire and the information about the fires has been injected to the WRF-Chem how was explained into the Section 2.4. So we have available a new run, which is called FIRE, the three runs with fire (FINN, IS4FIRE, FIRE) and the simulation without fire emissions (NOFIRE) have been compared with air quality observations which were located close to the Portugal fire events. Results from the WRF-Chem simulations (23 km spatial resolution) with and without simulated fire emissions have been analysed and compared with the Airbase air quality measurements datasets (European Airbase data base). The transport and dispersion of the fire-emitted pollutant as well as the chemical processes simulated by the WRF-Chem were evaluated based on the surface measurements of the PM10 and O3.   The following six air quality monitoring stations from Portugal have been used: PT01052, PT01021, PT01023, PT01034, PT01025, PT01050 (European code station). Three WRF-Chem grid cells (Figure 3) have been identified as representing the air quality monitoring stations that have been influenced by the fire plumes: a grid cell is represented by four stations ST-62-80 (blue pins, PT01021, PT01023, PT01034, PT01050), and the others represented by a single station: ST-63-80 (yellow pin, PT01052) and ST-63-79 (green pin, PT01025). The distance between fire events (blue and yellow dots) and monitoring stations is about 60 km. The concentrations at the four stations inside of the same grid cell have been averaged.   Daily average data are used in this analysis. Time series of the both pollutants concentrations simulated by the model runs and observed values inside of the model grid cells are presented in the next figures.

Figure 7 shows the daily average PM concentrations (μg/m3) for the three grid cells with monitoring stations. Values are shown for the monitoring stations (ST-63-80, ST-63-79, ST-62-80) and WRF-Chem predictions without fire emissions (NOFIRE), fire emissions from IS4FIRES (IS4FIRES), fire emissions from FINN (FINN) and fire emissions from the fire behaviour simulation (FIRE).
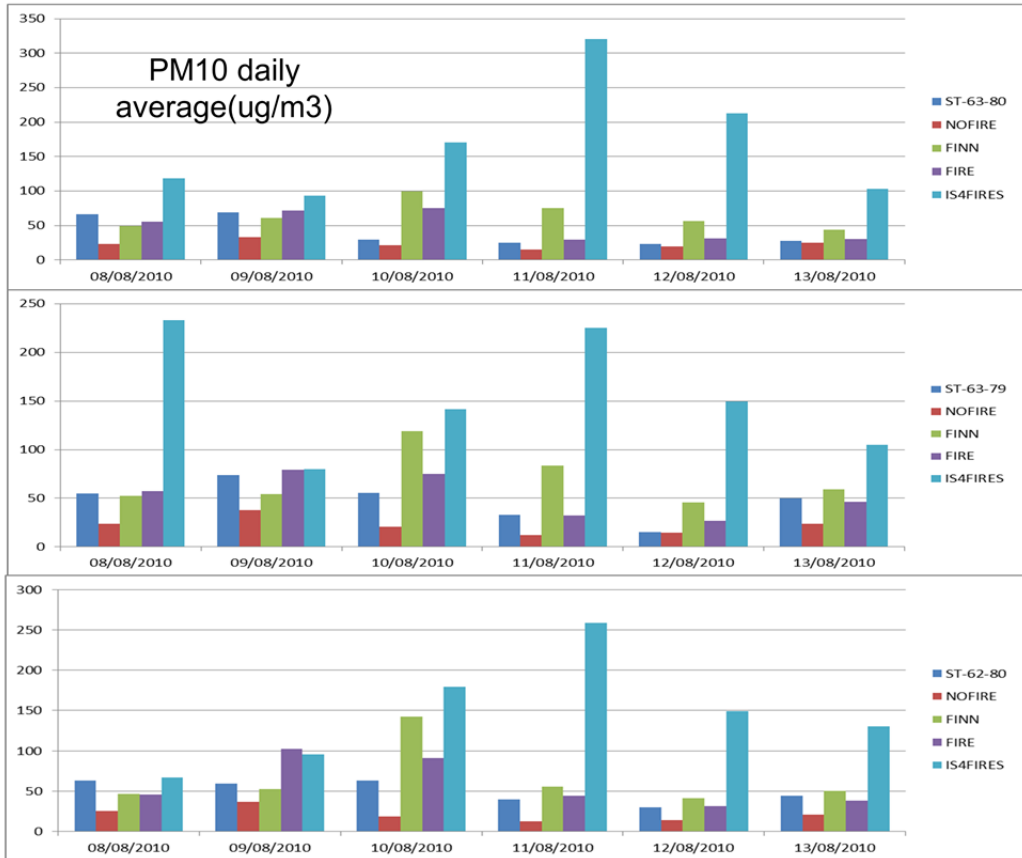

Figure 7: PM10 daily average concentrations measured at the three 23 km grid cells (63-80, 63-79, 62-80) during 08-13 August 2010, WRF-Chem predictions without fire emissions (NOFIRE), WRF-Chem predictions with fire emissions from IS4FIRES, WRF-Chem predictions with fire emissions from FINN, and WRF-Chem predictions with from the fire behaviour model (FIRE).

Figure 7 shows a very good agreement of the predictions with emissions from the two forest fires simulation (FIRE) for all days. In general, we find that the WRF-Chem prediction with fire emissions from IS4FIRES over predict the measurements

concentrations respect to the FINN, specially, the four next days after the fire dates (08/08/2010 and 09/08/2010). This is because after the dates of the fires, the fire emissions, at the model grid cell where the two fires were detected, are set to zero during FIRE simulation, because no more fires are detected, while in the IS4FIRES simulation the dates 10-13 there are emissions due to uncertainties of the Fire MODIS products. The figure also shows the contribution of biomass burning to mass concentrations of PM10 based on the comparison of the WRF-Chem simulations, with and without fires. The results also imply that the impact of biomass burning emissions is only not local, because the monitoring stations are 60 Km. from the fire points. Discrepancies between WRF-Chem results with fire emission from IS4FIRES (in FIRE) or FINN are related with different methodology to calculate the injection heights, IS4FIRES vertical profiles and the vertical plume model used to inject the emissions from the fire behaviour model (FIRE) and FINN and differences values and times of the fire emission inventories.

Figure 8 shows the daily average O3 concentrations (µg/m3)for the three grid cells with monitoring stations. Values are shown for the monitoring stations (ST-63-80, ST-63-79, ST-62-80) and WRF-Chem predictions without fire emissions (NOFIRE), fire emissions from IS4FIRES (IS4FIRES), fire emissions from FINN (FINN) and fire emissions from the fire behaviour simulation (FIRE).

In terms of the O3 the modelled values with fire emission were slightly higher than the no fire simulation (NOFIRE) except to grid cell ST-63-80, which is the close to the fire events and IS4FIRES present the best results and very close to the FIRE simulation, because they present higher values of ozone precursors. No big differences between the different emission data are observed. The runs with fires produced much closer agreement with observations. In a complex modelling system like WRF-FIRE coupled with WRF-Chem, it is very difficult to determine directly reasons for the discrepancies between the simulated and observed pollutants levels.
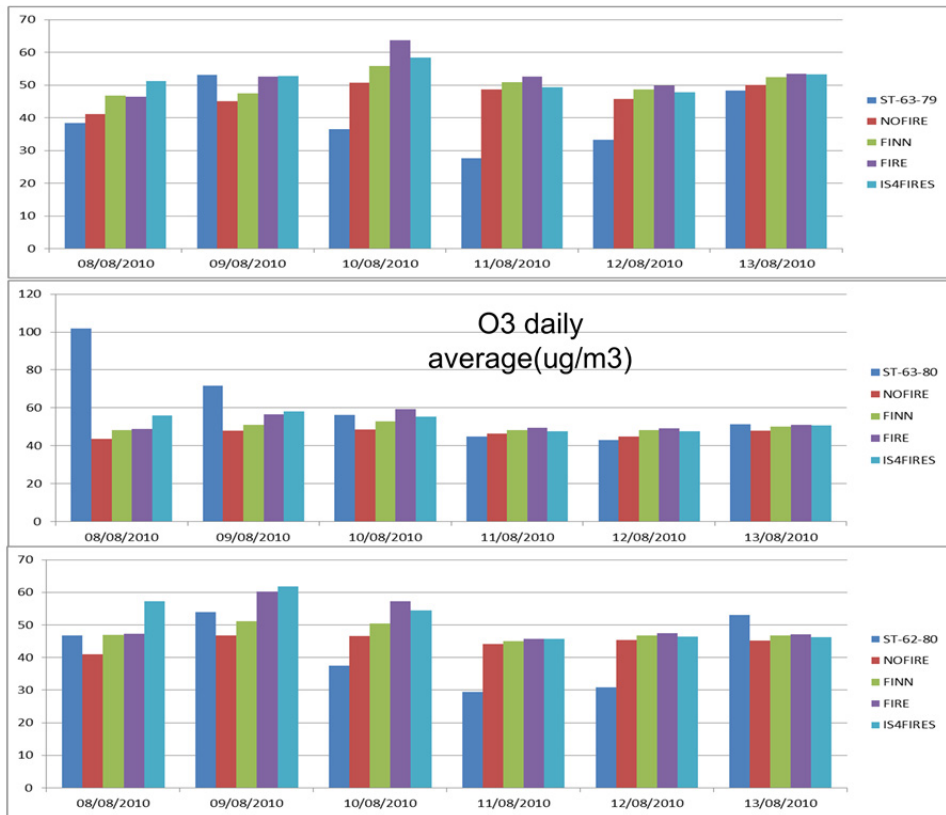
Figure 8: O3 daily average concentrations measured at the three 23 km grid cells (63-80, 63-79, 62-80) during 08-13 August 2010, and WRF-Chem predictions without fire emissions (NOFIRE) and fire emissions from IS4FIRES, fire emissions from FINN and from the fire behaviour model (FIRE).

4. Conclusions

We have developed an operational and integrated simulation forecasting system for fires based on WRF-Fire. Results show that the proposed system can produce realistic simulations using the geographical information available about the fire in a real case scenario. A graphical approach is used to compare the fire perimeters and burned areas. The comparisons show that simulation results are consistent with real data, so the system performs adequately in predicting the fire physics. The validation of the accuracy of the current fire propagation models is challenging problem. The effect of external factors such as human interventions on the model cannot be accurately estimated. Further enhancements to the simulation system are planned

based on more tests of real fire scenarios. For example, we will try to improve the meteorological information because the interpolation from 3 km to 20 meters cannot capture accurate local atmospheric features, but this is the only possibility to run the system in a reasonable time span and in operational way.

We have compared the FINN and ISA4FIRES fire emission methodologies and inventories, running different simulations with the WRF-Chem model using two different ways to calculate the injection height: plume-rise and profiles. The profiles methodology produces a more uniform distribution in the vertical layers than the plume-rise model included in WRF-Fire. The impact of fire emissions in the European pollution maps is very important and the larger impacts are located in Russia and North of Portugal for PM10 and South Africa for O3. ISA4FIRES seems to inject more material than the FINN inventory, which produces higher impacts on pollution concentrations. The impact of the forest fire emissions on concentrations is evident, and it is quite clear from these simulations that the choice of emission inventory is very important. These differences provide an indication of the potential sensitivity in predicted air quality to changes in the fire emissions. The runs with fires produced much closer agreement with observations.

Using daily average values, we have observed an improvement of the results using the WRF-Fire behaviour model when comparing with the fire inventories FINN and ISA4FIRES, special for PM10 concentrations. WRF-Fire model improves the overestimation produced by ISA4FIRES inventory. The PM10 comparison showed very good agreement for the simulation using the fire behavior simulation (FIRE) emissions, confirming the importance of high temporal and spatial resolution emission data.

A pilot study has been designed to demonstrate the potential of WRF-Fire and WRF-Chem as an integrated system for use by researchers and resource managers. In this paper, we presented an integrated system for simulating fire progression and fire impacts on air quality. The system utilizes the WRF-Fire as a component resolving the fire spread forecast and plume rise, and the WRF-Chem handling the chemical transport of fire-emitted pollutants.We have produced different scripts to search for monitoring stations "affected" by the forest fires and we found in the North of Portugal some areas. Using MODIS (burned areas and active fires), we determined the two main forest fires in the Portugal area together with the ignition and end dates.

The two main forest fires in the Portugal area were run using the behaviour forest fire WRF-fire model. A FMC model developed in our group in the past was included. There are uncertainties associated with the fire modelling process such as the satellite time of ignition, end and exact geographical location of the ignition of the fire and we do not have information related to the activities related to stop the fire growing such as helicopters pouring water over the land, fire extinction brigades, ...). The fire behaviour model is an input to produce the pollution emissions using the plume rise model included in WRF/fire. The computational cost associated with running for all

Europe all fires for one year is prohibited since the behaviour fire model needs 20 meters spatial resolution.

The combined use of satellite derived burnt perimeters, active-fires and fire model provide a realistic picture of the complex spatial temporal distribution of wild land fires. The use of satellite data within the fire behaviour model provides valuable information to forecasting forest fire emissions. The methodology presented in this work can be applied to any region of the globe. We demonstrate with a case study how this system can be a useful approach for improving air quality model predictions when extremely limited information is available about the emission from wildfire event, we need only a start point and date.

Acknowledgements

References

ANDREAE, M. O., AND P. MERLET (2001) Emission of trace gases and aerosols from biomass burning. *Global Biogeochemical Cycles*, **15**, 955-966.

ANDERSON, H. (1982) 'Aids to determining fuel models for estimating fire behaviour. general technical report int-122' *United States Department of Agriculture, Forest Service, Intermountain Forest and 233 Range Experiment Station*.

ANDREWS, P. L. (2007) 'BehavePlus fire modeling system: past, present, and future' In: *Proceedings of 7th Symposium on Fire and Forest Meteorological Society.*

BRUNNER, B. EDER, O. JORBA, ET AL. (2015). Evaluation of the meteorological performance of coupled chemistry-meteorology models in phase 2 of the Air Quality Model Evaluation International Initiative *Atmos. Environ.*, **115**, 470–498

CLARK, T., M. JENKINS, J. COEN, D. PACKHAM (1996). A coupled atmosphere-fire model: Convective feedback on fire-line dynamics. *Journal of Applied Meteorology,* **35**, 875–901.

FINNEY, M. A. (2004). '*FARSITE*: Fire Area Simulator–model development and evaluation'. *Research Paper RMRS-RP-4 Revised. Ogden, UT*: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station

FINNEY, M. A. (2007). A computational method for optimising fuel treatment locations. *International Journal of Wildland Fire,* **16**, 702-711

FORKEL, A. BALZARINI, R. BARÓ ET AL. (2015). Analysis of the WRF-Chem contribution to AQMEII phase 2 with respect to aerosol radiative feedbacks on meteorology and pollutant distributions. *Atmos. Environ.*, **115**, 630–645

FREITAS, S. R., LONGO, K. M., CHATFIELD, R. ET AL (2007). Including the sub-grid scale plume rise of vegetation fires in low resolution atmospheric transport models. *Atmos. Chem. Phys.*, **7**, 3385–3398.

GRELL GA, SE PECKHAM, R SCHMITZ, SA MCKEEN, G FROST, WC SKAMAROCK, B EDER. (2005). Fully coupled 'online' chemistry in the WRF model. *Atmos. Environ.*, **39**, 6957-6976.

GRELL, G., S.R. FREITAS, M. STUEFER, J. FAST. (2011). Inclusion of biomass burning in WRF-Chem: impact of wildfires on weather forecasts, *Atmos. Chem. Phys.*, **11**, 5289-5303.

HOELZEMANN, J. J., SCHULTZ, M. G., BRASSEUR, G. P., GRANIER, C., SIMON, M. (2004). Global Wildland Fire Emission Model (GWEM): Evaluating the use of global area burnt satellite data, *J. Geophys. Res.*, **109**, D14S04, doi:10.1029/2003JD003666,

HONG, S.Y. AND PAN, H.L., (1996). Nonlocal boundary layer vertical diffusion in a medium-range forecast model. *Monthly Weather Review*, **124**, 2322–2339.

ITO, A. AND PENNER, J. E. (2005). Estimates of CO emissions from open biomass burning in southern Africa for the year 2000. *J. Geophys. Res.*, **110**, D19306, doi:10.1029/2004JD005347

MANDEL, J., J. BEEZLEY, A. KOCHANSKI (2011). Coupled atmosphere-wildland fire modeling with WRFfire. *Geoscientific Model Development,* **4**, 497–545.

MCARTHUR, A.G. (1966). 'Weather and grassland fire behavior. Commonwealth of Australia'. *Department of National Development. Forestry and Timber Bureau.* Leaflet No. 100.

MICHALAKES, J., CHEN, S., DUDHIA, J., HART, L., KLEMP, J., MIDDLECOFF, J., SKAMAROCK, W. (2001). 'Development of a Next Generation Regional Weather Research and Forecast Model. Developments in Teracomputing', Proceedings of the Ninth *ECMWF Workshop on the Use of High Performance Computing in Meteorology*. Eds. Walter

MORRISON, H., THOMPSON, G., TATARSKII, V. (2009). Impact of cloud microphysics on the development of trailing stratiform precipitation in a simulated squall line: Comparison of one and two-moment schemes. *Monthly Weather Review*, **137**, 991-1006.

NELSON, R M. Jr (2000). Prediction of diurnal change in 1-h fuel stick moisture content. *Canadian Journal Forest Research*. **30**, 1071-1087.

NOBLE, I.R., BARY, G.A.V., GILL, A.M. (1980). Mc Arthur´s fire-danger meters expressed as equations. *Australian Journal of Ecology*, **5**, 201-203

ROTHERMEL, R. (1972). `A mathematical model for predicting fire spread in wildland fires`, *USDA Forest Service Research Paper* INT-115.

SAWARVANU D., JOHN J.Q., XIANJUN H. (2005) 'Evaluating remotely sensed live fuel moisture estimations for fire bejavior predictions'. *EastFIRE Conference* 2005.

SKAMAROCK W.C., J.B. KLEMP, J. DUDHIA, D. GILL, D. BARKER,W. WANG, J.G. POWERS. (2005) 'A description of the advanced research WRF Version 2' *NCAR Technical Note* NCAR/TN-468+STR.

SOFIEV, M., R. VANKEVICH, M. LOTJONEN, M. PRANK, V. PETUKHOV, T. ERMAKOVA, J. KOSKINEN, J. KUKKONEN (2009). An operational system for the assimilation of the satellite information on wild-land fires for the needs of air quality modelling and forecasting. *Atmospheric Chemistry and Physics*, **9**, 6833–6847.

SOFIEV, M., VANKEVICH, R., ERMAKOVA, T., HAKKARAINEN, J. (2012). Global mapping of vertical injection profiles of wild-fire emission, *Atmos. Chem. Phys.* Discuss., **12**, 19209-19241, doi:10.5194/acpd-12-19209-2012.

SOLOMON S, QIN D, MANNING M, CHEN Z, MARQUIS M, AVERYT K, TIGNOR M, MILLER H (eds) (2007). Climate change 2007: the physical science basis. *Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change*. Cambridge University Press, Cambridge, 996 pp

STROPPIANA, D., BRIVIO, P. A., GR´EGOIRE, J.-M., LIOUSSE, C., GUILLAUME, B., GRANIER, C., MIEVILLE, A., CHIN, M., PETRON, G. (2010). Comparison of global inventories of CO emissions from biomass burning derived from remotely sensed data, *Atmos. Chem. Phys.*,**10**, 12173–12189.

VINEY, N.R. AND HATTON, T.J. (1990). Modelling the effect of condensation on the moisture content of forest litter. *Agricultural and Forest Meteorology* **51**, 51-62

WIEDINMYER, C., AKAGI, S. K., YOKELSON, R. J., EMMONS, L. K., AL-SAADI, J. A., ORLANDO, J. J., SOJA, A. J. (2011). The Fire Inventory from NCAR (FINN) – A high resolution global model to estimate the emissions from open burning. *Geosci. Model Dev.*, **4**, 625–641.