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SHORT TERM HEALTH IMPACT ASSESSMENT OF INDOOR AIR QUALITY IN A MADRID OFFICE

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Abstract

The present study is a short term health impact assessment of indoor pollution. To know the indoor pollution is necessary to get information about outdoor pollution and meteorological conditions. In this work, the outdoor data coming from a mesoscale meteorological and air quality simulation with WRF/Chem. Effects on health of different ventilation modes and indoor *emission scenarios have been analyzed for the NO2 and PM2.5 pollutants. A general office building located in Madrid has been simulated with the EnergyPlus model during full year 2016. The energy model includes the Generic Contaminant Model so the simulation system is an integrated framework for indoor pollution and energy demand. Results show that when the emitting sources are active, ventilation through windows improves health and if there are no active sources, the health of the building occupants is slightly deteriorated by the outdoor pollution. Ventilation during all year increases the demand of gas for heating four times. The health impacts of emitting sources are highest in the warm months due to the operation of the air conditioning system. The health impact of indoor emission sources is higher than the outdoor pollution. People in the zone where the emitting sources are located would experience a mortality and morbidity of 2.5 times more than in the non-emitting zones.*

Keywords

Indoor Pollution, Health Impact, WRF/Chem, Energy Plus

1. Introduction

Several researches have studied the epidemiological relations between air quality and possible health effects (Atkinson et al., 2013). Traditionally, these works focus on concentrations of outdoor pollution and the health of the population and do not take into account indoor air pollution. People spend most of their time inside buildings. The quality of indoor air in buildings affects the health of their occupants. Epidemiological studies often use measurements of pollution from observational stations or outdoor simulated concentrations of pollutants to calculate the exposure function; however, the methodology doesn´t provide a real estimation of the exposure of a people that spends a lot of time indoors.

In general, the ventilation increases indoor pollution coming from outdoor sources, especially in high polluted environments. There are several factors that affect how external pollution infiltrates buildings: the location of the building, the permeability of its surface, ventilation systems, weather conditions, and the behaviour of building occupants (opening windows and switching HVAC systems off and on). But the concentrations inside the building not only depend on what comes in from outside but also on the sources of internal emissions (Shrubsole et al., 2012). Elimination of indoor and outdoor air contaminants from indoor and outdoor air sources can be produced by exfiltration, deposition on the surface and by filtration using mechanical ventilation equipment. The objective is to reduce the energy demand of the ventilation systems but getting a healthy indoor environment for the people. But, when the simulation of energy and indoor air quality are separate, the combined effects are not simulated and it is impossible to get the objective.

The correlation between indoor and outdoor concentration levels could be examined from observations or using modeling techniques. Several researches have measured the indoor pollutions of different pollutants and in several regions (Chen and Zhao, 2011). Modeling techniques can also be used to characterize the concentration of indoor pollutants. Multi-zone mass transport models calculate concentration values in buildings to assess exposure (Milner et al., 2011). Multi-zone models allow us to study how ventilation and filtration strategies affect indoor concentrations (Das et al., 2013).

The novelty of this study is that it uses outdoor concentrations and simulated meteorology to know the indoor concentrations of the building, since until now studies of indoor contamination levels have used data measured by nearby monitoring stations. It is usual uses measured outdoor concentration and meteorological data for the location of the building. Our simulation tool allows to make future simulations of the outdoor and indoor pollution how is described in the next sections, so it is a simulation and forecasting tool. Outdoor air quality and meteorological simulation has been run with the EMIMO-WRF/Chem modelling tool. It was setup with 1 km of spatial resolution over Madrid during 2016 year. Indoor air quality simulations have been run with the EnergyPlus model for an office building located in the Madrid city center. Finally a short term health impact assessment of different ventilation and emission scenarios has been done. The next section explains the simulation tool and the test cases.

2. System Description

Figure 1 represents the flow chart of the modelling system Simulation modules are the purple boxes, while the green barrels correspond to the data sources used.

The WRF/Chem modeling system (Grell & Dévényi, 2002), is the Weather Research and Forecasting (WRF) model coupled with Chemistry. WRF is 3-D non-hydrostatic prognostic model that simulates mesoscale atmospheric circulations. The emission, transport, mixing, and chemical transformation of trace gases and aerosols is simulated by the Chem module. Meteorological and chemical simulation is simultaneously run. The data fomr the GFS (Global Forecast System) model of the United States National Meteorological Service (NWS) are used as initial and lateral boundary conditions for the meteorological. These data are freely accessible, with an update interval of six hours. Anthropogenic emissions data are obtained from a top-down strategy implemented in the EMIMO emission model, developed by UPM (San Jose et al., 2008). EMIMO downscales the TNO-MACC-II inventory (Kuenen et al., 2014) horizontally, vertically and on time to provide emissions to the WRF/Chem model. Horizontal disaggregation is carried out through the use of surrogates such as land use, population density and transport networks; temporary disaggregation follows monthly, daily and hourly factors depending on the issuing activity and the countries, in this case Spain. Vertical disaggregation uses tabulated factors depending on the sector of the Selected Nomenclature for Air Pollutants (SNAP) considered. In this case, the disaggregation factors provided by EMEP, as set out in (Bieser et al., 2011) are the most commonly used. Guenther online scheme (Guenther, Zimmerman and Wildermuth, 1994) is used to calculate the biogenic emissions. It is integrated in the WRF/Chem modelling system.

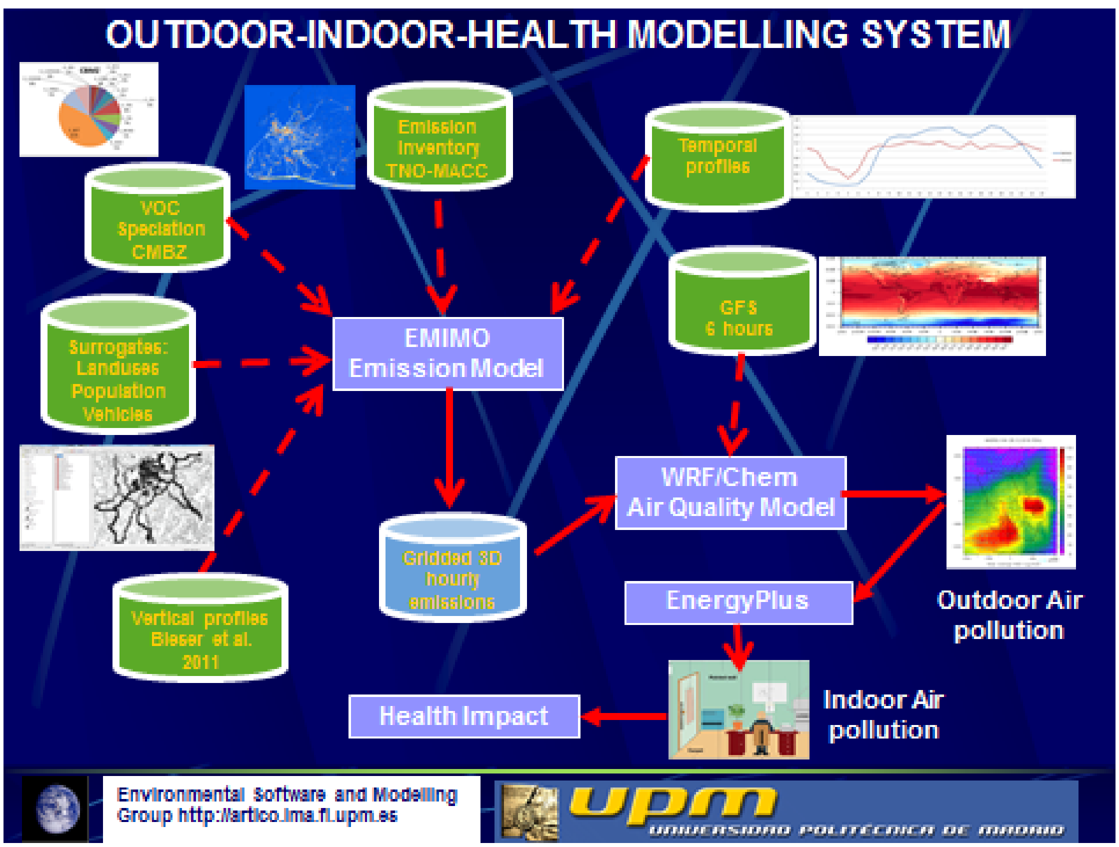

Figure 1: *Flow chart of the simulation system EMIMO-WRF/Chem, EnergyPlus and Health impact assessment module*

EnergyPlus (EnergyPlus, 2018) is a full building energy/indoor pollution simulation tool. EnergyPlus take into account the building envelop and the HVAC (Heating, Ventilation and Air Condition) systems. It also contains airflow network and pollutant balance modules. The

Generic Pollutant Model (GCM) included in the EnergyPlus allows the modeling of indoor pollutant concentrations. For this purpose, the dispersion has been modelled driven by airflow, adsorption and desorption in building materials, filtration and deposition on building surfaces. The benefits of using a dynamic thermal and pollutant coupled model are that the effect of the opening behavior of the occupants' windows in response to interior temperatures can be addressed instead of using fixed schedules. The Generic Pollutants EnergyPlus model has been intermodal compared with the CONTAM model, with good results (Taylor et al., 2014).

Using the health impact assessment module we calculate the estimated change in human mortality and morbidity between different emissions and ventilation modes scenarios for each zone of the buildings. For our analysis of health impacts, we base on the US EPA’s Benefits Mapping and Analysis Program (BenMAP) (Sacks et al., 2018). Input data to the health impact module include the modeled contaminant concentrations (average daily concentrations of NO2 and PM2.5) and the relationships between the daily concentrations of these contaminants and the risk of adverse human health effects that have been defined in epidemiological studies. The relationship between exposure variables and their health effects can be modelled using log-linear regression (Poisson). This function is known as exposure response (ER) function. If we derive the function we obtain Equation 1 that allows us to calculate the change in mortality or morbidity as a function of the variation of the exposure variable analyzed.

$$\Delta y = y_0 (e^{\beta \Delta C} - 1) \qquad (1)$$

Where y0 is the baseline incidence rate of the studied health effect, β is a parameter that gives us an estimate of the effect of mortality and that has been obtained from epidemiological studies, ΔC is the change of the exposure variable (scenario – base scenario) (McCubbin, Hallberg and Davison, 2004).

As mentioned above, the concentration-response functions used by the health impact module are obtained from international epidemiological studies of high scientific acceptability. Changes in concentrations are used as input for the logarithmic relationship between changes in concentrations and changes in mortality or morbidity. The functions describe the relationships between average/maximum daily concentrations of air pollutants and the risk of dangerous health effects on the same day or in the days following exposure to these levels, also taking into account the meteorological conditions of those days. The concentration-response functions used in our tool are based on the relative risks (RR) found in scientific studies that have found correlations between decreased concentrations of PM2.5 and NO2 and health benefits. They provide relationships between mortality or hospital admissions due to cardiovascular and respiratory causes and levels of exposure to air pollutants. The RR values used are recommended by the HRAPIE project (Recommendations for concentration-response functions for cost-benefit analysis of particulates, ozone and nitrogen dioxide).

For the mortality and morbidity analysis the following exposure-response (E-R) relationships from studies were used (Table 1).

Table 1: *Relative Risks (RRs) for Health Impact Studies*

Outcomes		**RR by 10 ug/m^3**	**95% C.I.**
Mortality all causes	NO2	1.0027	[1.0016, 1.0038]
	PM25	1.0123	[1.0045, 1.0201]
Hospital admissions, respiratory causes	NO2	1.0015	[0.9992, 1.0038]
	PM25	1.0190	[0.9982, 1.0402]
Hospital admissions, cardiovascular causes	NO2	-	-
	PM25	1.0092	[1.0017, 1.0166]

3. Case Study

In this case WRF/Chem was implemented to simulate meteorology as well as the dispersion and transport of pollutants in Madrid during 2016. The model has been configured with three one way domains of 25, 5 and 1 km of grid resolution representing Spain, the Community of Madrid and the city of Madrid with its surroundings. The grid point dimensions for each domain are 60 × 50, 30 × 30 and 40 × 45 respectively. The top of the model is 50 hPa, with 33 vertical levels. The first model layer is approximately 25 m above the surface, with 12 levels in the first 3 km. In this work, we have configured WRF/Chem to simulate using the same parameters as in the ES1 simulations carried out for phase 2 of the International Air Quality Assessment Model Assessment Assessment Initiative (AQMEII) (San José et al., 2015). This configuration has already been tested and evaluated with very good results in different applications. We constructed a file with hourly averages over 365 days of NO2, PM2.5 concentrations solar radiation and weather conditions (e.g. temperature, relative humidity, wind speed and direction) for 2016 year based on the outputs for the WRF/Chem outdoor simulation. This is the first time that an EnergyPlus simulation is run using modelled data from outdoor environment. Building simulations have been run for the full year 2016 using hourly weather file and outdoor concentrations files generated from the WRF/Chem outdoor simulation outputs.

For indoor simulations a 3 zone office building has been modelled. It has 130 m2 with a North orientation. The building is not a specific building it just a typical building which is used in this simulation exercise to demonstrate the capabilities of the WRF/Chem and EnergyPlus models. The building is located in Madrid city center. Figure 2 shows the schematic view of the 3-zone office building, with the number of people (3 west zone, 3 east zone and 4 north zone), windows (W) and doors (D).

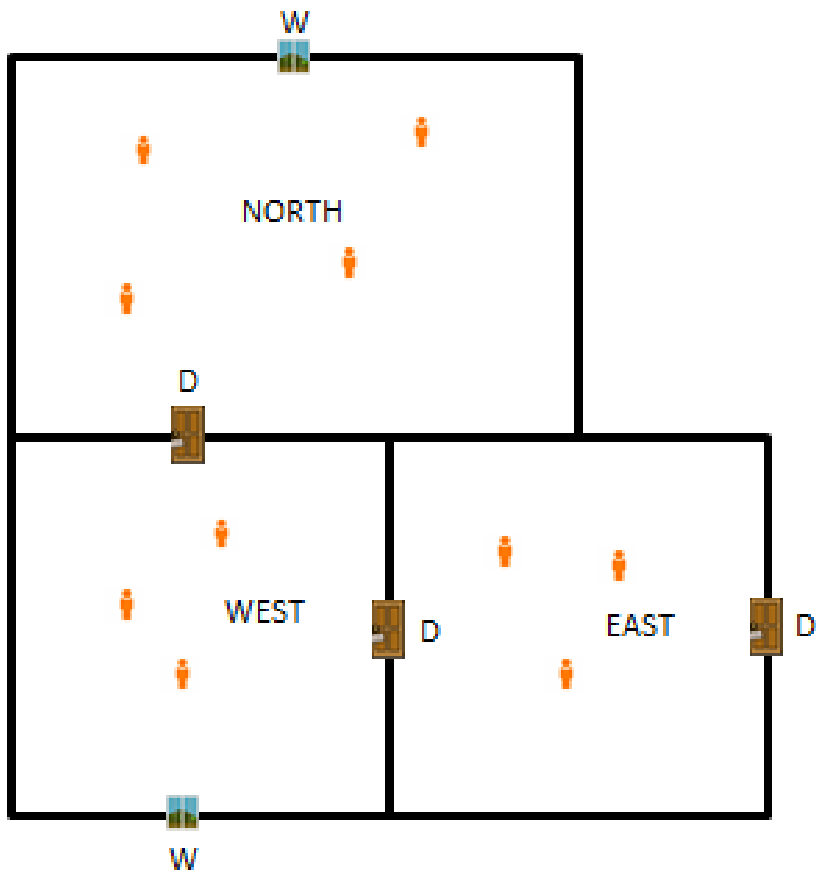

Figure 2: *Flow chart of the simulation system EMIMO-WRF/Chem, EnergyPlus and Health impact assessment module*

The case study is designed to simulate the NO2 and PM2.5 concentration in the 3-zone building. The office building is occupied during weekdays from 6:00 to 19:00 with a maximum occupancy from 9:00 – 12:00 and 14:00 – 17:00. The HVAC system is a 3 zone central system using single air loop. The Heating (H) and Ventilation (V) system is always ON expect non labour hours during warm period (01/04 – 30/09). The Air Conditioner (AC) is ON during labour hours for the warm period.

Emission sources can be used to simulate the impact of different emission scenarios because they generate pollutants in the areas. PM2.5 deposition process was simulated using a constant deposition rate of 5.0E-5 m3/s (Long et al., 2001), and NO2 deposition rate was 2.0E-4 m3/s (Persily, Musser & Emmerich, 2010). We have simulated two sources of emission. Both sources are located in the North zone of the office. NO2 emitted by a oven for heating with a flow rate of 3.0E-8 m3/s (Fabian, Adamkiewicz and Levy, 2011) and the source is not thermostat controlled. The oven for heating is operating during weekdays of the cold periods (01/01-31/03 and 01/10-31/12) from 8:00 to 18:00 (labour hours). PM2.5 source is a photocopy machine with a flow rate of 6.7E-9 m3/s (Destaillats et al., 2008). The use of the photocopy machine is defined by a hourly profile with a maximum use of the 25% between 8:00 – 12:00. We have defined two emissions scenarios: ON and OFF.

The have defined three possible modes of ventilation (North and West zones because the East Zone doesn´t have window). The three cases are designed to represent three ventilation control strategies Mode no ventilation. Mode ventilation during warm period, in this case the ventilation is controlled by temperature. Windows are automatically opened if the zone temperature is larger than 21.11 ºC and it is the time period 0-7h or 18-13h. It is a Temperature-driven window opening. Finally the third mode is the Ventilation always on, during all year and all hours. This mode spent 4 times more of gas for heating the office because the windows are opened. Simulation were run with six different scenarios, combining the two emission scenarios (ON, OFF) and the three ventilation modes (No Ventilation, Warm Period and Always).

4. Results

WRF/Chem has been evaluated in different applications and the results obtained are very satisfactory (Forkel et al., 2012) but to determine the reliability of the simulation results, it is necessary to develop the evaluation of the simulated values using the WRF/Chem model for this specific case. The modelling system has been comprehensively evaluated to ensure reasonable estimates of concentrations of the pollutants involved. For the evaluation, data from 23 monitoring stations of the Madrid region's air quality network and 24 monitoring stations of the Madrid city's air quality network were used, so that a total of 47 different sites were used to compare hourly modelled concentrations with the measured values. Note that the station and model are in fact providing concentrations at different locations, as the station reflects concentrations at a single point and the modelled concentrations reflect the average of a grid cell of 1 km by 1 km.

Figure 3 shows that there are no large differences between the values modeled and observed in terms of variability measured by the three most important statisticians.

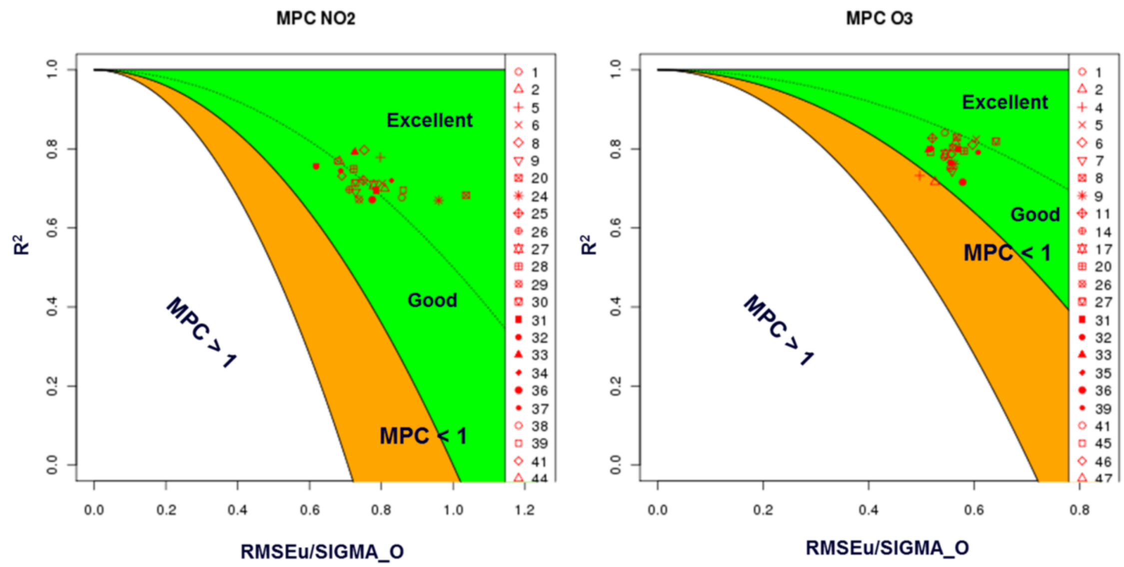

Figure 3: *MPC plots of R for NO2 (left) and O3 (right) concentrations WRF/Chem year 2016*

We can observe that in the case of NO2, the values of R2 are between 0.7 and 0.8, for O3 all the locations of the stations are very close to 0.8. In all station locations, the mean square error of the central root (CRMSE) is less than 1 and in the case of O3 the values are very close to 0.5. Only modelled ozone values tend to be less variable (standard deviation) than observations (Sigma_M/Sigma_O > 0.5 and < 1.0). The Model Performance Criteria (MPC) are used as an indicator of the minimum levels of quality to be achieved by a model for use in air quality decisions. The MPCr diagram (Figure 3) help in understanding the model behavior by plotting R as functions of U/σo. The fulfilment of MPCr is identified by the green area. Orange area zone means fulfilment of the MPC but the error is dominated by R. The white zone means that the minimum quality criterion is not met and the model must be improved. Figure 3 confirms the good results for O3 and NO2 predictions, as all stations are in the compliance zone (MPC<1). For NO2, half of the stations are located in the MPC<0.5 area, which means that the model is "perfect" taking into account measurement uncertainty. The MPCr correlation graph (Figure 3) confirms the goodness of the model in terms of the correlation coefficient for NO2 and O3 concentration. R2 is greater than 0,65 and 0,7;100 % of the sites fulfil the MPC criterion. MPC plot analysis reveals that WRF/Chem performs very well during 2016 and the model meets the MPC criteria.

Figure 4 shows the spatial distribution of the yearly average of the NO2 outdoor concentrations with 1 km of spatial resolution produced by the EMIMO-WRF/Chem models. We can observe that the maximum concentrations are in the city center of Madrid where the traffic emissions are high.

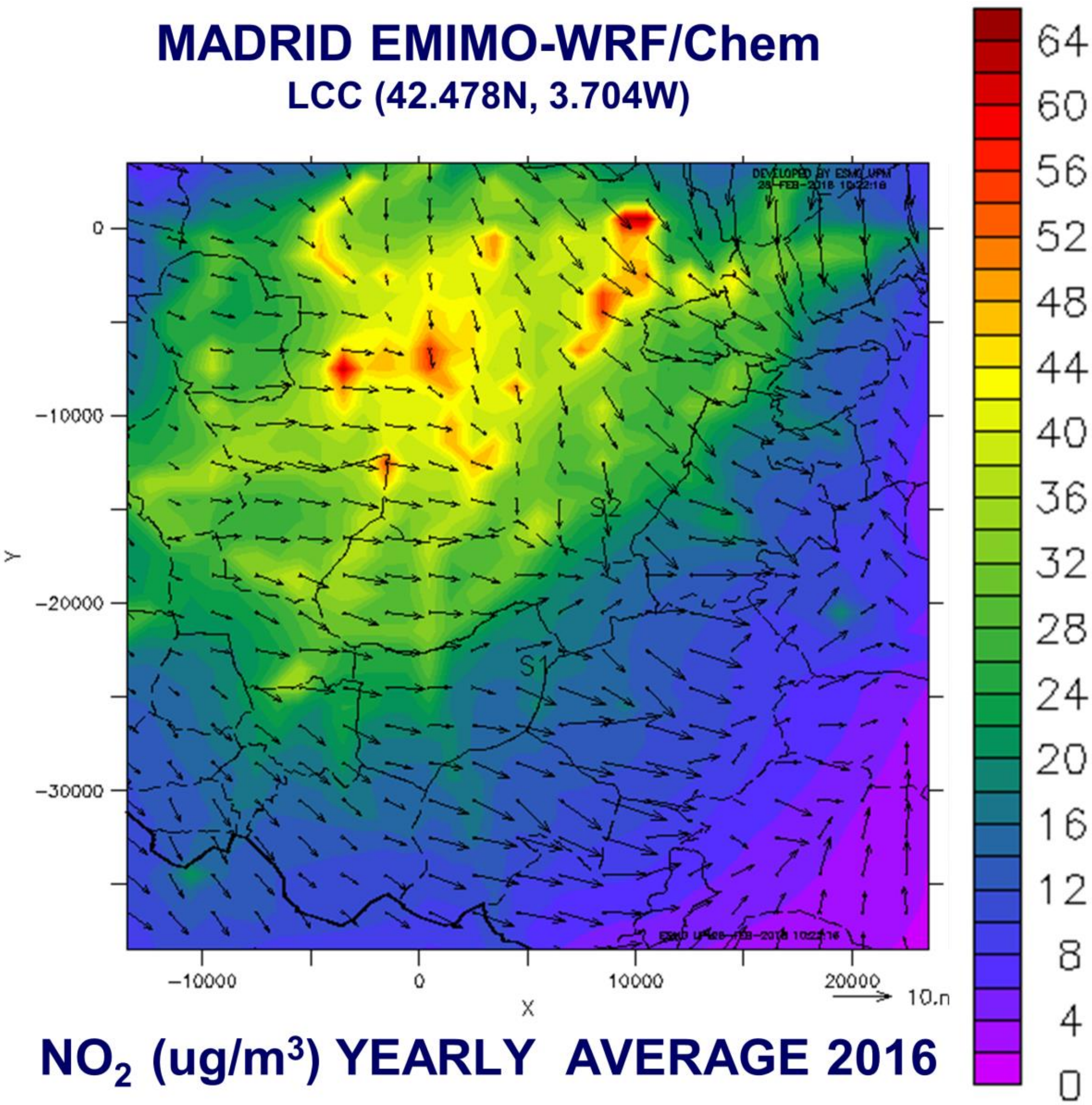

Figure 4: *Madrid, NO2 yearly average concentrations. Year 2016*

Even though annual simulations are preformed, with hourly outputs, only the simulation results for yearly and monthly averages are discussed in the following sections as summary.

Table 2 shows the annual mean of daily mortality change (%) due to emission sources ON– OFF in the three zones for the three simulated ventilation modes.

Table 2: *Annual mean of daily mortality change (%) for emission scenarios ON-OFF*

	North		West		East	
Ventilation Mode	PM_{25}	NO_2	PM_{25}	NO_2	PM_{25}	NO_2
No	0.628	0.883	0.261	0.411	0.225	0.431
Warm Period	0.287	0.882	0.136	0.410	0.148	0.429
Always	0.138	0.220	0.057	0.061	0.067	0.077

As we can see from the results in Table 1, the most healthy ventilation mode is to keep the windows always open (Always). However, this would result in a large increase in the demand of gas for heating the building. The Warm Period ventilation mode would allow us to reduce the mortality caused by emissions from sources without a significant increase in energy demand. But this mode of ventilation would not reduce the effects of NO2 emissions, as its source only emits out of the warm period, when ventilation is switched off. If the North zone were not ventilated, the mortality of its occupants due to exposure to NO2 would increase to 0.883 %. Health effects are more important from exposure to NO2 concentrations than from exposure to PM25. The worst area to work would be the North area where the emitting sources are located, although the other two areas are also affected by the movement of concentrations between the areas through the doors and ventilation system.

Figure 5 shows the monthly mean of daily change (%) due to PM2.5 emissions from photocopy machine in the North zone.

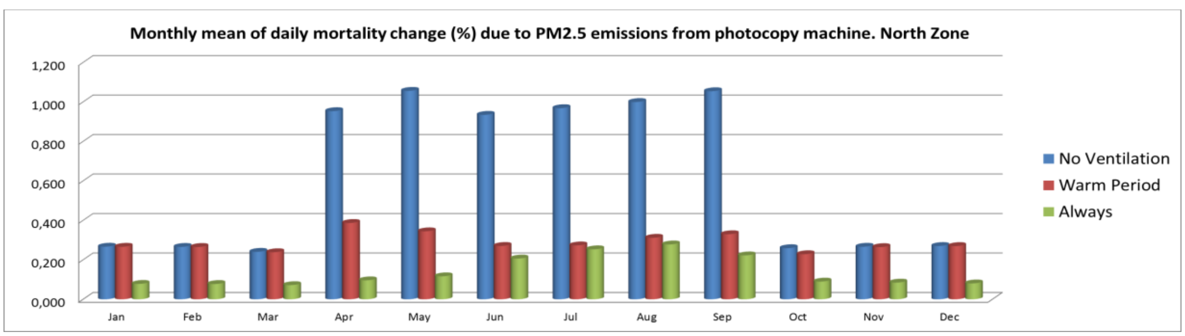

Figure 5: *Monthly mean of daily change (%) due to PM2.5 emissions from photocopy machine in the North zone.*

Figure 5 confirms that the best way of ventilation is always to keep the windows open. We can also observe a very important result: if we do not ventilate, the temperature of the interior will increase during the summer, which will cause a greater operation of the air conditioning system and this in part will cause the concentrations of PM2.5 to increase in the area, causing a very high increase in mortality during these months of about 1%.

Figure 6 shows the monthly mean of daily mortality change (%) due to ventilation modes respect no ventilation (windows are always closed) in the North zone.

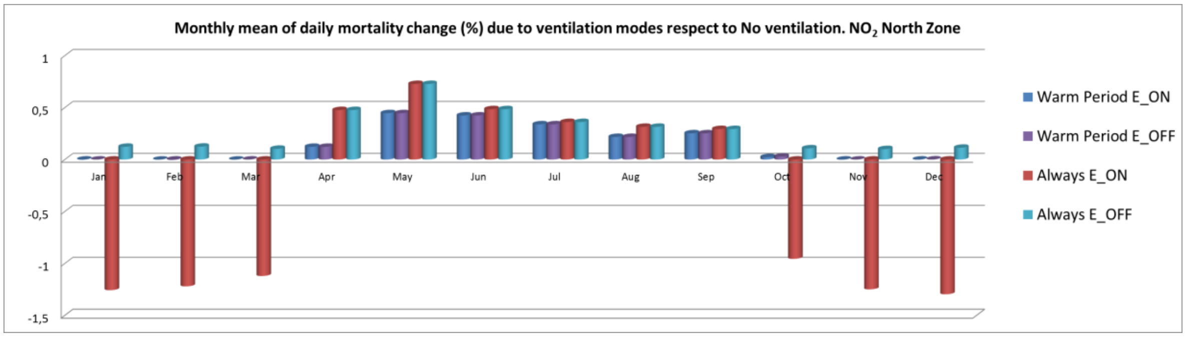

Figure 6: *Monthly mean of daily mortality change (%) due to ventilation modes respect no ventilation. North zone*

Figure 6 shows that in case of emissions, in this case the source of NO2 only emits out of the warm period, continuous ventilation reduces mortality by up to 1%. However, when there are no emissions, during the summer months when the windows are open, the penetration of pollutants from the outside causes a slight increase in mortality for the occupants of the area.

Figure 7 represents the monthly mean of daily hospital admissions change (%) by respiratory causes by differences between outdoor and indoor exposure. The indoor concentrations correspond with the North zone.

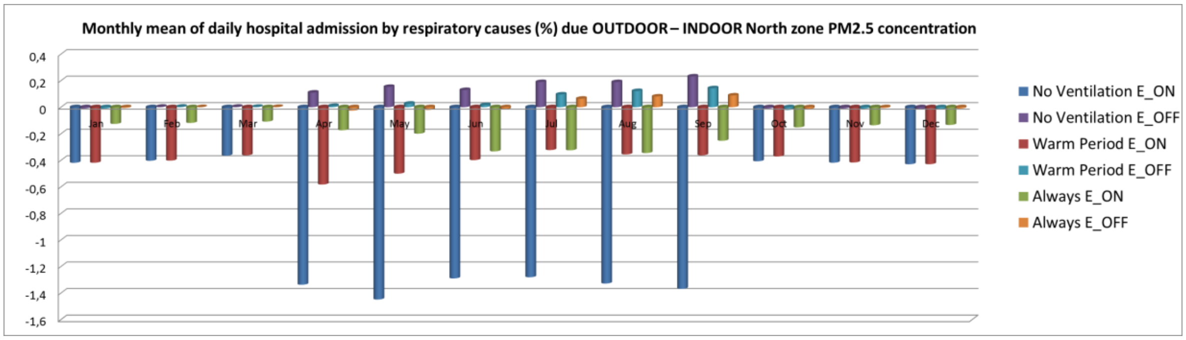

Figure 7: *Monthly mean of daily hospital admissions change (%) by respiratory causes by differences between outdoor and indoor exposure.*

Clearly, exposure to indoor concentrations is worse than to outdoor concentrations with increases in daily hospital admission of up to 1.4% in the non-ventilation scenario. Only in the absence of any type of emission would hospital admissions be slightly reduced by being inside the office.

5. Conclusions

An outdoor air quality modelling system has been implemented. The system includes an emission model (EMIMO) and a pollutant transport and meteorological-chemistry model (WRF/Chem). EMIMO-WRF/Chem has been evaluated. Model results concentrations have been compared to measured data provided by 47 monitoring sites for year 2016. EMIMO-WRF/Chem fulfils all criteria for correlation, bias, standard deviation and RMSEu < 1 (100% of satiations) for PM25 and NO2, so it can be used for applications. The evaluation of the performance has been very satisfactory. Indoor pollution simulation has been run for a office building located in the Madrid city center for year 2016. The EMIMO-WRF/Chem has been used to provide outdoor pollution and meteorological inputs to the indoor air quality/energy model Energyplus with high spatial (1 km) and temporal (1 hour) resolution. A Short term health impact assessment has been done comparing three ventilation modes and two emission scenarios (ON, OFF) to know the health impacts (mortality and morbidity) for the people working in the office.

Open the windows all year demands ≈4 times more of gas for heating the office with light decrease of electricity demand for cooling. Open windows during warm periods (T>21.1ºC) doesn´t produce increments of energy demand. People in the zone (North) where the emitting sources are located would experience a mortality and morbidity of 2.5 times more than in the non-emitting zones. Window ventilation in the warm period reduces mortality and morbidity by 2 times. If the windows were opened all year, there would be a 4.5 times lower risk of death or hospital admissions, although this would lead to an increase in energy. When the emitting sources are active, ventilation (windows) improves health and if there are no active sources, the health of the building occupants is slightly deteriorated by the outdoor pollution. The health impacts of emitting sources are highest in the warm months due to the operation of the air conditioning system. The health impact of indoor emission sources is higher than the outdoor pollution. If there were no sources of emissions, the health of its occupants would be better than that of people living outside. The main limitation of this study is to consider prototype buildings, in future work is intended to simulate real buildings for which it will be necessary to advance in the research of emissions in indoor environments.

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