Atmospheric Environment 190 (2018) 317–330

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Impacts of green infrastructures on aerodynamic flow and air quality in Porto's urban area

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ARTICLE INFO

Keywords:
Air quality
CFD modelling
Resilience measures
Road traffic emissions

ABSTRACT

Air pollution is an environmental and social issue at different spatial scales, especially in a climate change context, with an expected decrease of air quality. Despite the technological evolution of the last decades in the transport sector, road traffic emissions are still one major source of air pollution at the city level. The main goal of this study was to evaluate the influence of a set of resilience measures, based on nature-based solutions, in the wind flow and in the dispersion of air pollutants, in a built-up area in Portugal. For that, two pollutants were analysed (NO_X and PM10) and four scenarios were developed: i) a baseline scenario, ii) an urban green scenario, iii) a green roof scenario, and iv) a "grey" scenario (without trees). Two models were used, namely the Weather Research and Forecasting model (WRF) and the CFD model VADIS (pollutant dispersion in the atmosphere under variable wind conditions). The WRF model was used to initialize the CFD model, while the last was one used to perform the set of numerical simulations, on hourly basis. The implementation of a green urban area promoted a reduction of air pollutants concentrations, of about 16% [PM10] and 19% [NOx] in the overall domain; while the application of green roofs showed an increase of concentrations (reaching 60% during specific time periods). Overall the results showed that a strategic placement of vegetation in cities has the potential to make an important contribution to the improvement of air quality and sustainability of urban environments.

1. Introduction

Air pollution in urban environments with dense population has become an important research issue in the past decades, which led to the enforcement of several studies of the airflow and dispersion patterns in cities (Borrego et al., 2003; Buccolieri et al., 2011; Amorim et al., 2013; Salmon et al., 2013). In Europe, the atmospheric pollutants emissions have decreased substantially over the last years, resulting in an improved air quality across the region. However, air pollutants concentrations are still too high in many European cities, showing exceedances of air quality standards still occur, and so air quality problems persist (EEA, 2016).

More recently, the interaction among climate change, air pollutant emissions and atmospheric concentrations has been considered a crucial research field. As Markakis et al. (2014) denote, the impact of climate change on air quality at the local scale is still a current research challenge since much has still to be explored in order to understand and accurately predict the changes in pollutant levels under future climatic conditions and at different spatial scales. This is especially relevant since there is consistent research that projects an increase of the atmospheric concentrations under climate change scenarios (Lacressonnière et al., 2014). In this sense, it is crucial that cities are able to absorb the impacts related to climate change and poor air quality. The inclusion of green infrastructures, such as green roofs, urban green areas, green walls, have been pointed as low-cost and easily applicable strategies to deal with extreme weather events (Carvalho et al., 2017; Rafael et al., 2017), as well as to improve air quality and mitigate air pollution (EC, 2015; EEA, 2011).

Roadside vegetation barriers have been widely evaluated as a potential mitigation strategy for near-road air pollution (Tong et al., 2016). Those studies revealed that the aerodynamic effects of trees on near-road air quality, that are primarily governed by two physical mechanisms, dispersion and deposition, are more important than the chemical effects (i.e. uptake) (Nowak et al., 2006) and, dispersion appears to be more important than deposition (Jeanjean et al., 2016; Steffens et al., 2012). In fact, modelling studies have shown a modest impact of vegetation on air pollutants deposition with less than a few percent reduction (Nowak et al., 2006; Tallis et al., 2011; Selmi et al., 2016). Also, previous findings shows that there is a large variability about the effectiveness of road-side vegetation barriers on reducing air pollution. For example, Vos et al. (2013) investigate the role of roadside urban vegetation on the local air quality, and have been concluded that

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https://doi.org/10.1016/j.atmosenv.2018.07.044
Received 28 April 2018; Received in revised form 14 July 2018; Accepted 25 July 2018
Available online 26 July 2018
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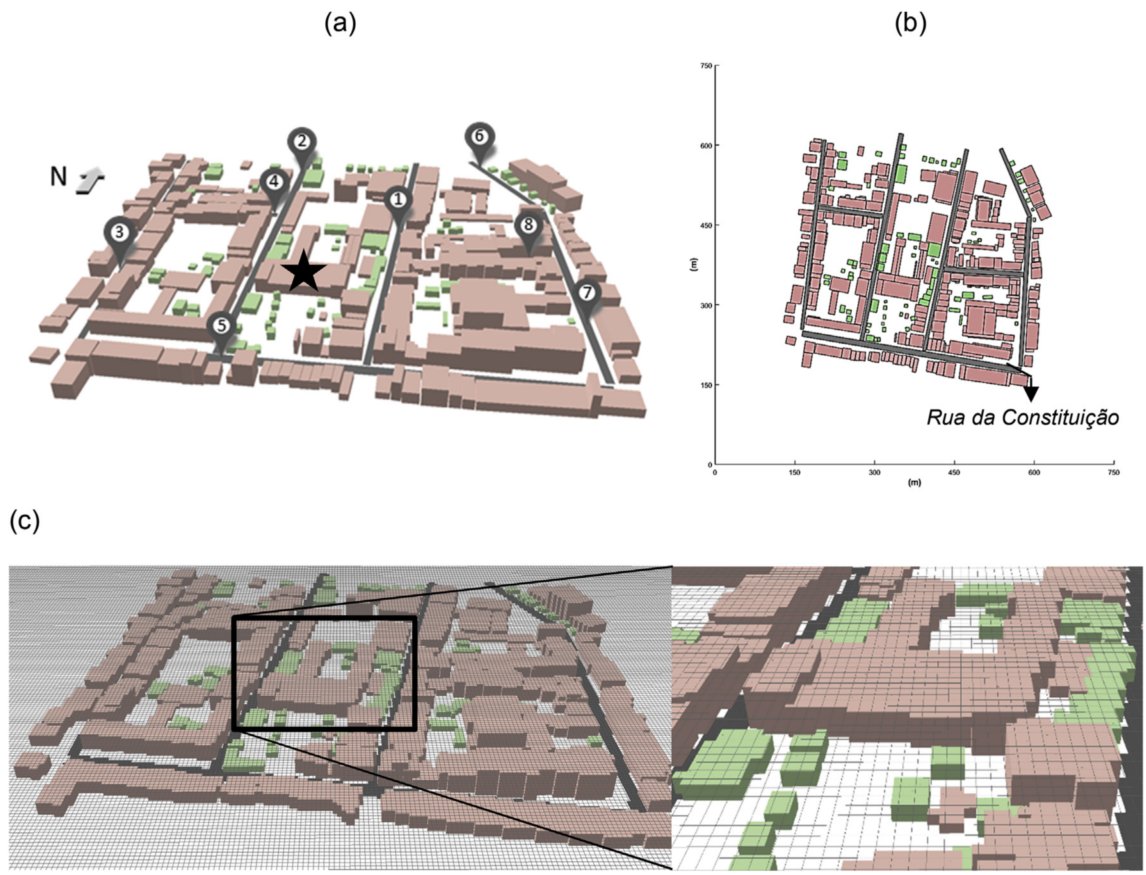


Fig. 1. 3D (a) and 2D (b) study domain showing the set of buildings (in pink), trees (in green) and roads (in grey, numbered from 1 to 8) (images on the top). The black star indicates the location of a meteorological station (wind velocity). Computational grid domain (with a horizontal and vertical resolution of 3-m) is also showed (c). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

roadside urban vegetation leads to increased pollutant concentrations. This is explained with the fact that in the presence of trees or other types of vegetation, the ventilation process, responsible for the dilution of traffic emitted pollutants, is reduced. Despite of this conclusion, the authors also mentioned that the fact that roadside trees negatively affect the local air quality does not mean that trees in urban backyards, urban parks or traffic free streets have a similar effect (Vos et al., 2013). In fact, the benefits of vegetation on air quality is demonstrated in studies such as Amorim et al. (2013), Tong et al. (2016) or Lee et al. (2018). Thus, previous findings are inconsistent potentially due to the high variability associated with local microclimate, vegetation characteristics and design options.

This certain level of uncertainty related to the street scale mitigating capacity of urban trees, creates a knowledge gap regarding the application of green infrastructures to improve local air quality at city scale, which is a critical issue for policy makers. Inspired in this need, two research questions were formulated: (i) Can green infrastructures be used to an effective improvement of local air quality in a complex city morphology? and (ii) Which are the best design options to improve local air quality?

To address these questions, a set of numerical simulations, at street level, have been performed to assess the aerodynamic effect of different resilience measures, based on green infrastructures, in the flow (wind velocity) and dispersion (air pollutant concentrations) processes. A complex built-up area in the city of Porto, Portugal, was selected as case study. A modelling system composed of the WRF-VADIS models (mesoscale-Computational Fluid Dynamics (CFD)) was used. An urban canopy parameterization scheme was used in the WRF simulation to better simulate urban meteorological conditions. The work was focused on the main pollutants emitted by the road traffic, namely nitrogen oxides (NO_X) and particulate matter with an aerodynamic diameter less than 10 µm (PM10). These are also the most critical air pollutants in the study area, which frequently exceeded the annual limit value for NO_2 and the daily limit value for PM10 (Monteiro et al., 2007; Borrego et al., 2012; Miranda et al., 2016).

Although similar studies (Buccolieri et al., 2011; Wania et al., 2012; Vos et al., 2013) have been already published, from a scientific point of view the current study differs in the following sense: (i) provides a holistic approach to deal with air quality problems, by adapting the concept of resilience to air pollution and evaluating the ability of a city to tackle air pollution issues through green urban planning; (ii) focus on multiple and traffic related pollutants; previous studies are often limited to a single and non-traffic specific pollutant such as PM10; (iii) applies a quite recent methodology to perform air flow and dispersion analyses in cities, by using a CFD model with initial conditions given by mesoscale models; Tewari et al. (2010) and Miao et al. (2013) demonstrated that by using outputs from the Weather Research and Forecast (WRF) model as the initial and boundary conditions, the CFD model capability applied over an urban area can be improved; and (iv) different types of urban designs; instead of roadside trees the study is focused on urban parks and green roofs implementation.

This paper is presented as follows: section 2 describes the modelling setup methodology including a brief description of the applied models and their configuration for the simulations. Also in section 2 the case study is characterized and the green resilience scenarios are defined. A comparative analysis between the different scenarios, as well as a model validation, are presented in section 3. Summary and conclusions follow in section 4.

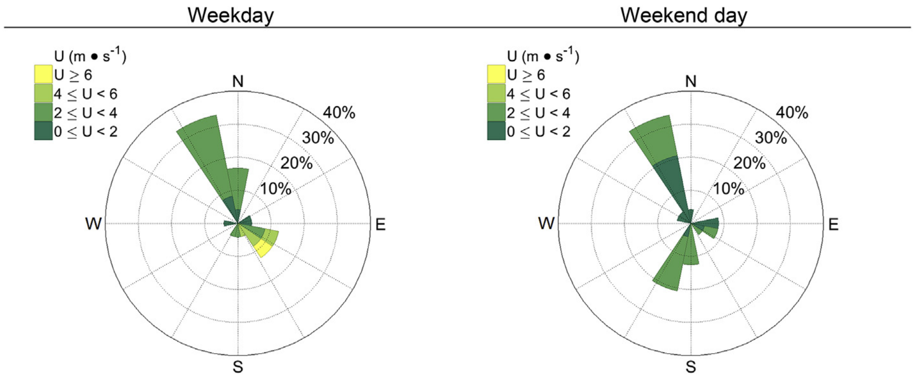


Fig. 2. Wind roses at the inlet boundaries of the study area, for the week and weekend day periods.

2. Data and method

2.1. Case study description

The study area is located at approximately 3-km north (N) of the Porto city centre (Portugal), and is a typical built-up neighbourhood in the city. The area consists of residential, commercial and recreational areas with a few sparse green areas; the majority of the area is covered by impervious surfaces (90%). In the vicinity of the site, both residential and commercial areas are characterized by high buildings (around 6 floors). The area comprises of important traffic thoroughfares bounded by the presence of a complex array of buildings (Fig. 1). The existence of a meteorological station located inside the study area allows the evaluation of wind velocity simulations.

A week (23rd September 2014) and weekend day (28th September 2014) were selected to characterize distinct emission dispersion behaviours. The selected periods correspond to neutral stability conditions, in agreement with the numerical approach adopted in this study. Fig. 2 shows the wind rose for the study periods. The data show that wind direction was predominantly from Northwest (more than 30%) for both days. The wind velocity oscillates between the days and the hours; the weekday shows an average wind velocity of 3 $m\,s^{-1}$, reaching a maximum value of 6.6 $m\,s^{-1}$ (at 3 p.m.). At the weekend day the average wind velocity was of 2.2 $m\,s^{-1}$, reaching 3.8 $m\,s^{-1}$ (at 2 p.m.).

The main road in the study domain is the *Rua da Constituição* (numbered as 5 in Fig. 1) with a total of two traffic lanes. Seven other streets perpendicular to the main road were also considered. Traffic flow data, for both study periods, were acquired using automatic devices in the study area. For the roads in which no data were available, empirical rates expressing the relation with the traffic in the surrounding roads were applied. These empirical rates were obtained according the findings of previous studies that assessed road traffic emissions in Portuguese urban areas (Bandeira et al., 2011; Sá et al., 2015; Duque et al., 2016). Fig. 3 shows the daily fluctuation of traffic volumes. The traffic flow data show a well-defined traffic dynamic, that is different into the week and weekend days. At the weekday, the peak periods occur at the early morning, between 7 and 9 a.m. (the maximum daily traffic is reached at 8 a.m.), and at the beginning of the night between 7-8 p.m. (around 74% of the daily traffic). The off-peak periods mostly occur at the night between 10 p.m. and 6 a.m. (daily traffic less than 25%). This is a typical behaviour of the traffic flow for a large city downtown. At the weekend day, the peak periods occur later; at 12 a.m. and 1 p.m. during the day and between 11 p.m. and 3 a.m. during the night. On average, the daily traffic volume at the weekend is around 15% less than those that is observed at the weekday. For both days, and even during off-peak periods, a low volume ratio is maintained for all the domain.

To characterize the state of the study area in terms of road traffic emissions, hourly averaged air pollutant emissions were defined for

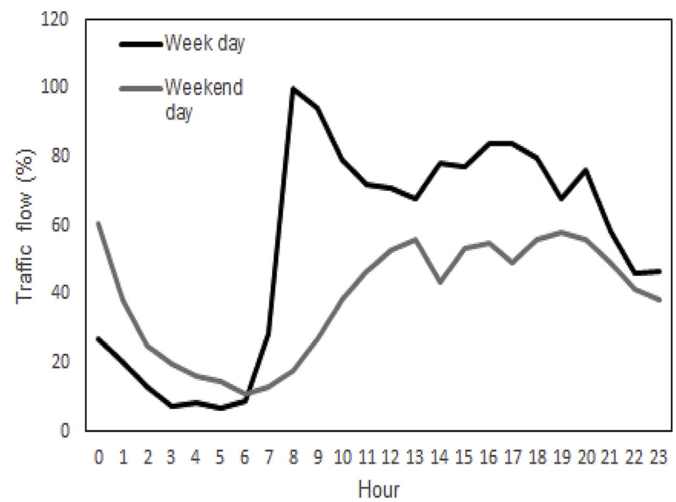


Fig. 3. Typical daily traffic volume profile for both study periods (in percentage).

each road by applying the Transport Emission Model for Line Sources (TREM) (Borrego et al., 2003). TREM is based on the MEET/COST methodology, with its main objective being the estimation of road traffic emissions with high temporal and spatial resolution to be used in air quality modelling. Although the average-speed approach for the emission factors implemented in the model follows the European guidelines (EMEP/EEA, 2010) the way transport activity data are considered for the emission inventory is conceptually different. Roads are assumed as line sources and emissions induced by vehicles are estimated individually for each road segment considering detailed information on traffic flow. The model also considers the vehicle speed for each road segment (approximately 50 $km\,h^{-1}$ in this particular urban case), the road gradient, the fleet composition and the characteristics of the vehicles (such as age of vehicles, engine type, capacity and technology, vehicle weight, and fuel consumption [e.g. diesel, gasoline, LPG]). Due to the flat terrain of the study area (below 2%), a road grade with a zero-degree slope was assumed for emissions estimation. TREM system applies an aggregation of vehicles by categories (e.g. passengers, light duty vehicles, heavy-duty vehicles, buses, motorcycles, and new technology vehicles, such as hybrid and electric cars). A total of 350 vehicles classes were considered, based on the vehicles characteristics. Fleet data of the percentage of vehicles in each class were obtained from regional databases (INE, 2011; ACAP, 2015). According to these databases, around 74.5% of the vehicle fleet are classified as passenger's cars, 16% as light duty vehicles, 1.7% as heavy-duty vehicles and 7.4% as motorcycles. Simulations were performed on hourly temporal frame for NO_X and PM10.

As expected, the emissions follows the behaviour of the daily traffic

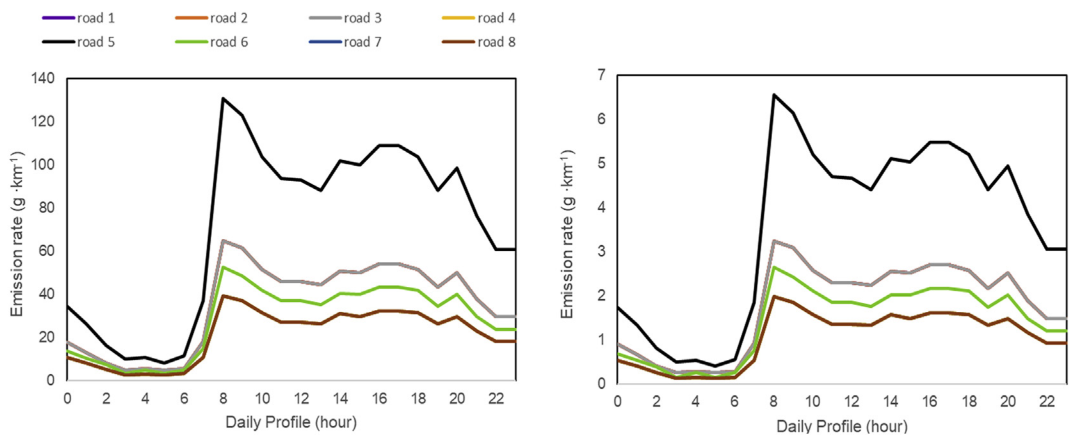


Fig. 4. Daily emissions, in grams per kilometer, of (a) NOx and (b) PM10 for all the roads sources of the study domain (numbered from 1 to 8; the main road, *Rua da Constituição*, is numbered as 5) for the weekday period. Total emissions are showed for each road source.

volume profile. Fig. 4 shows the PM10 and NOx emissions daily profile for the weekday (total emission of the road source), for all the road sources considered in the analysis (roads were numbered from 1 to 8). NO_X emissions varies in a range of 2.6–131 g km^{-1}, depending of the road and the period of day. Maximum values are obtained for the main road of the study domain, *Rua da Constituição*, at peak hours (8–9 a.m. and 7-8 p.m. with values of 131 and 104 g km^{-1}, respectively). The emission of the remaining roads represent 5%–20% of the emissions of the main road. Similar behaviour were obtained for PM10 emissions, with values varying in a range of 0.1–6.6 g km^{-1}. The emissions magnitude are in accordance with the values obtained on urban roads in other Portuguese urban areas (Borrego et al., 2016; Dias et al., 2018).

To accomplish the study goal, by assessing the aerodynamic effect of green infrastructures on the dispersion of road traffic air pollutants concentration within the study area the modelling system composed of the WRF-CFD models was applied. The WRF model was used to provide the wind speed (velocity components) at the reference height (at 10 m of height) as inflow conditions to the CFD model, which recalculates flow fields for the area of interest. A grid cell nearest to the location of CFD domains (at north-northwest, according to the predominant wind direction) was selected and used for this purpose. The meteorological data, on hourly basis, were provided for the days selected for the CFD modelling application. The model setup (section 2.2.) and the resilience scenarios developed (section 2.3.) are fully described in the following sections.

2.2. Model setup

2.2.1. Mesoscale model

The WRF model, version 3.7.1, was set up with four domains (Fig. 5). The outer domain (D1), covering Europe and North of Africa, has 173 × 142 horizontal grid cells with horizontal resolution of 27 km; the nested domain D2 covers the Iberian Peninsula and has a 175 × 166 horizontal grid cells with a horizontal resolution of 9 km; and D3 covers the Northwest of Portugal and has 121 × 109 horizontal grid cells with a horizontal resolution of 3 km. The inner domain (D4) has 34 × 34 horizontal grid cells with horizontal resolution of 1 km, covering the Porto urban area. The vertical grid was composed of 30 vertical layers up to the top of the computational domain (50 hPa). The two-way nesting technique (Skamarock et al., 2008) was applied for the simulations.

The meteorological initial and boundary conditions were initialized with ERA-Interim data from the European Centre for Medium-Range Weather Forecasts (ECMWF) global analysis (horizontal resolution of 1° x 1°) with a temporal resolution of 6-h intervals. The sea surface temperatures and the soil moisture were also initialized using the ECMWF data. Information regarding the land use/land cover was taken from the Corine land cover project (Büttner et al., 2006) 2006 version (CLC 2006), with a 3 arc-seconds horizontal resolution, remapped to the United States Geological Survey (USGS) 24 land use categories, following the methodology proposed by Pineda et al. (2004). The physics parameterizations were selected based on recommendations included in Wang et al. (2014), as well as on validation and sensitivity studies previously performed over Portugal (Carvalho et al., 2006; Monteiro et al., 2015, 2016). The physical options for the inner domain included: the Dudhia shortwave radiation scheme (Dudhia, 1989) and the RRTM (Rapid Radiative Transfer Model) longwave radiation scheme (Mlawer et al., 1997); the Yonsei University (YSU) Planetary Boundary Layer scheme (Hong et al., 2006), and the WRF single moment 5-class scheme (Hong et al., 2004).

In order to better represent the physical processes involved in an urban environment (exchange of heat, momentum and water vapour) the Noah land surface scheme with a single layer urban canopy model (UCM) was also used. The UCM has a simplified urban geometry. Some of its features include, shadowing from buildings, reflection of short and longwave radiation, wind profile in the canopy layer and multi-layer heat transfer equation for roof, wall and road surfaces (Kusaka et al., 2001; Kusaka and Kimura, 2004).

2.2.2. CFD model

2.2.2.1. Model description. The Computational Fluid Dynamics (CFD) model, VADIS (pollutant dispersion in the atmosphere under variable wind conditions) was applied to the study area (Fig. 1) within the Porto urban area (D4). VADIS was developed as a tool to estimate the dispersion of atmospheric pollutants in complex urban areas due to the traffic road emissions and to estimate local hot-spots (Borrego et al., 2003; Rodrigues et al., 2018). VADIS has the capability to support multi-obstacle (buildings and trees) and multi-source description as well as, time varying flow fields and time varying emissions, allowing the evaluation of short-term local concentrations in urban morphologies (Amorim et al., 2013).

The VADIS structure consists of two coupled distinct modules. The FLOW is a Eulerian module able to simulate the turbulent flow dynamics under stationary conditions within the atmospheric boundary layer. This module uses the numerical solution of the Reynolds Averaged Navier-Stokes equations and the one-and-a-half order $k-\varepsilon$ turbulence model to calculate the wind, turbulent viscosity, pressure, turbulence kinetic energy and temperature 3D fields. In this module two different grids are used: i) a cartographic grid, used to include the information related to the obstacles (buildings and vegetation) and the emission sources location (e.g. roads) and dimension; and ii) the Eulerian grid, used to calculate the wind field. The wind grid is overlaid to the cartographic one and rotates according to the wind direction. The mean velocity profile is calculated from the logarithmic profile

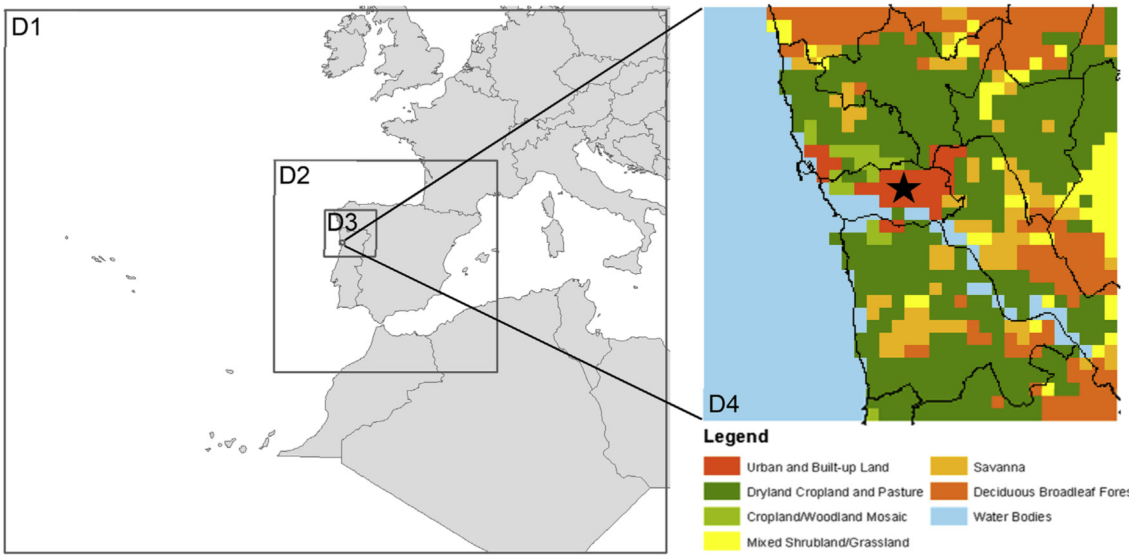


Fig. 5. Configuration of the WRF model domains. Horizontal resolution of the coarse domain is 27 km with 173 × 142 horizontal grid cells (D1). The inner domain have a horizontal resolution of 1 km with 34 × 34 horizontal grid cells (D4). The black star shows the location of the study area (classified as Urban or Built-up Land, according to the United States Geological Survey (USGS) 24 land use categories).

corresponding to the upwind terrain via the roughness length, through the Richards and Hoxey (1993) equations. The grids dimension and number of cells in each axis must be defined as a compromise between the required resolution and accuracy, and the computational demand. The DISPER module applies the Lagrangian approach to the computation of the 3D pollutant concentration field using the 3D wind field previously estimated by FLOW. This approach assumes that the spatial and temporal dispersion of the mass of pollutant emitted is represented by a large number of numerical particles arbitrarily released in the flow. In each time step, each particle displacement is calculated by the sum of a deterministic component obtained from the velocity field, the stochastic component related with the local turbulence translated by the Langevin stochastic theory and the influence of the fluctuation forces, represent by the Langevin equation (Lee and Naesslund, 1998). Initially, the wind field is calculated considering the stationary conditions (FLOW module) and then the model calculated the displacement of these numerical particles over the cartographic grid (DISPER module). As output, VADIS provides the three wind velocity components, the turbulent viscosity, the turbulent kinetic energy, the turbulent dissipation, the temperature and the pollutant concentration in each grid cell for the entire cartographic grid.

The VADIS model also includes the Urban Vegetation (URVE) module. This module was developed to calculate the perturbations induced by vegetation elements on the flow dynamics and dispersion patterns, to better understand the aerodynamic effects of trees. The main concept behind the simulation of the tree-airflow interactions (mathematically representation of the aerodynamics behind the interaction of leaves and branches with the 3D wind flow) is the extension of the standard mean flow and turbulence equations with additional source terms for momentum (equation (1)), turbulent kinetic energy (equation (2)) and its dissipation (equation (3)), neglecting viscous drag relative to form (or pressure) drag.

$$S_u = -C_d LAD|U|u_i \tag{1}$$

where, C_d is the mechanical drag coefficient, set to 0.6 as recommended by Ghasemian et al. (2017), LAD denotes the leaf area density and |U| is the magnitude of the wind speed vector.

S_k denotes the production of turbulence by the action of vegetation elements.

$$S_k = -C_d LAD(\beta_p |U|^3 - \beta_d |U|k) \tag{2}$$

where, β_p is set to 1 and indicates the fraction of the mean flow kinetic energy converted to wake-generated turbulent energy by canopy drag. β_d is set to 4 and denotes the fraction of turbulent energy dissipated by "short-circuiting'" of the Kolmogorov cascade (Kaimal and Finnigan, 1994; Poggi et al., 2004) and β_d |U|k point out the dissipation of the generated wakes (Raupach and Shaw, 1982). Then, S_k represent the sum of the source and sink of turbulent kinetic energy due to the effect of vegetation elements.

The numerical formulation of S_ε is similar to the formulation of S_k.

$$S_\varepsilon = -C_d LAD\left(c_{\varepsilon 4}\beta_p |U|^3 \frac{\varepsilon}{k} - c_{\varepsilon 5}\beta_d |U|\varepsilon\right) \tag{3}$$

where $c_{\varepsilon 4}$ and $c_{\varepsilon 5}$ are both equal to 1.5 (Amorim et al., 2013).

Consequently, the dispersion of the emitted air pollutants is conditioned by vegetation trough this disturbed wind flow. The magnitude of this perturbation depends on the conjoint influence of the characteristics of the vegetation itself (e.g., location, size) and of the flow conditions (e.g., velocity, direction, turbulence). A more complete description of VADIS can be found on Borrego et al. (2003, 2004) and Amorim et al. (2013).

VADIS performance has been evaluated and improved through the years. The simulation results were evaluated with measured data from meteorological and air quality stations (Borrego et al., 2003, 2004; Amorim et al., 2013), as well as with physical measurements conducted in wind tunnel (Richards et al., 2006). The model performance was also evaluated through comparison with other numerical models (i.e. the FLUENT model [Vardoulakis et al., 2011; Amorim et al., 2013]). All of these works shows the VADIS's capability to simulate different air pollutant concentrations, at different study areas, with a good agreement between modelled results and measured values (e.g., a mean BIAS of $-29.03\,\mu g\,m^{-3}$, a normalised mean square error (NMSE) of 0.04 and a correlation factor of 0.86 were obtained for CO concentration simulation). A recent study conducted by Rodrigues et al. (2018), compared physical and numerical simulations for a reference scenario (characterizing a built-up urban area) and an urban green scenario, for a set of wind speeds and directions, using the validation metrics proposed by Chang and Hanna (2005). The results revealed that VADIS and wind tunnel measurements are in a good agreement, based on the acceptance criteria purposed by Chang and Hanna (2005) (a value less than 1.5 for the NMSE and a fraction of the simulated values within a factor of two of the measured values in the wind tunnel (FAC2) comprised between

0.5 and 2). A NMSE ranging between 0.3 and 1 (depending of the inflow conditions) were obtained for the reference scenario, while in the urban green scenario the obtained NMSE ranged from 0.1 to 0.7. The factor FAC2 varied between 0.9 and 1.7 in the reference scenario, and between 0.6 and 1.2 in the urban green scenario. The obtained statistic metrics confirm the ability of the VADIS model to simulate the perturbation exerted by the green infrastructures on the turbulent flow dynamics.

2.2.2.2. Computational domain. The numerical simulations were performed following the best practice guidelines proposed by the COST Action 732 (Franke et al., 2007). In this sense, for the simulation of urban flows with multiple buildings, the vertical, horizontal and downwind extensions of the computational domain were defined with a minimum of $5H_{max}$, where H_{max} represents the height of the tallest building. The CFD simulations were performed for a domain of 753 × 753 × 126 m^3 (L x W x H), with a grid resolution of 3 m × 3 m x 3 m, which totalize a number of 2 646 042 cells. A minimum of 10 cells per building height and between buildings in the horizontal plane was used in the area of interest (Franke et al., 2007). A grid-sensitivity analysis was previously conducted to select the mesh resolution. A total number of 3 grids has been used for the analysis: i) coarse grid, 73 125 cells; ii) basic grid, 562 500 cells; and iii) fine grid, 2 646 042 cells. The grids were compared based on the wind velocity along different locations across the study domain. From this analysis, it was concluded that the coarse grid predicted higher wind flows than those predicted by basic and fine grids across all wind vertical profile. The differences are more noteworthy between the coarse and fine grids at pedestrian level (in a range of +0.5 to +1.4 m s^{-1} in the coarse grid). Similar behaviour was found for turbulence (higher values in the coarse grid, in a range of 0.3–5.7 $m^2 s^{-2}$). Comparison between modelled and measured data was also performed. The results showed a bias increasing from the fine to the coarse grid. For brevity, the results are not included in this paper. Thus, it is argued that the fine grid is suitable to be used the current study.

The complexity of the urban objects (buildings and trees) present in both domains was streamlined by assembling adjacent individual volumes with similar characteristics. In the specific case of trees, the set of elements were defined as parallelepipeds positioned at a given distance above ground, representing the average trunk and branches heights. The generation of the urban objects (3D buildings, trees and roads) were virtually defined in VADIS using the geometry pre-processors developed, based on the coordinates of the objects (Fig. 1). The computational domain are composed of hexahedral cells arranged in a horizontal and vertically structured meshing scheme. A brief description of the study area (baseline scenario) is given in Table 1.

Regarding boundary conditions a typical surface roughness length value for an urban area with medium height was considered, defined as 1.5 m (Grimmond and Oke, 1999). At ground and buildings surfaces no-slip conditions were imposed. The standard wall functions proposed by Launder and Spalding (1974) were used. In the near-wall region the logarithmic law-of-the-wall for the mean velocity was applied, while the production of k and its dissipation rate, ε, at the wall-adjacent were computed on the basis of the local equilibrium hypothesis. Wall roughness effects were modelled applying the law-of-the-wall modified for roughness. The assembled tree volumes were defined in the model as porous elements, in which transport equations were solved. Based on the work of Lalic and Mihailovic (2004), an average Leaf Area Density (LAD) of 1 $m^2 m^{-3}$ was considered. The emission sources (8 roads in total) were defined as line sources, and created as fluid zones.

2.3. Resilience scenarios

The concept of resilience has been widely used in the most recent research to denote the need of cities to increase the capability to tolerate or absorb the impacts related to climate change (i.e. heat waves). In this study, two resilience measures were selected based on consistently reported benefits and multifunctionality: green areas and green roofs. To assess the influence of these measures on wind flow and air pollutants dispersion four scenarios were defined, including: i) a baseline scenario, with the current characteristics, both in terms of wind flow and air pollutants concentration, of the case study; ii) an urban green area scenario, which consists of the implementation of an urban green area in the centre of the domain (by replacing the current buildings); iii) a green roof scenario, which consists of the application of green roofs in a specific area of the domain; the area was selected to allow a direct comparison between the urban green area and green roofs implementation; and iv) a “grey” scenario, which consists of the removal of the current vegetation; this scenario was defined to assess the importance of the vegetation in the atmospheric dispersion and air quality.

The domain dimension, the mesh resolution, the boundary conditions and the air pollutant emissions were kept constant for all the scenarios. Table 2 shows the general characteristics of the computational domains for each scenario. The computational domains for the grey and the green scenarios are displayed in Fig. 6.

3. Results and discussion

Given the described methodology (section 2), the capability of VADIS to simulate the wind flow was evaluated (section 3.1), since most of the resilience measures under study will influence the flow pattern. Then, the influence of resilience measures on air pollutants concentration was assessed in terms of behaviour and magnitude (section 3.2).

3.1. Flow validation and baseline characterization

The performance and accuracy of the model was evaluated in terms of wind flow through the application of the BOOT software (Chang and Hanna, 2005). The following parameters were calculated: mean bias (MB), normalised mean square error (NMSE), Pearson correlation coefficient (r), and factor of two (FAC2). Results are shown in Fig. 7c. Additionally, time series for both week and weekend day were analysed to assess the ability of VADIS to represent the daily wind velocity variability (Fig. 7 a, b). The measured data were provided by the meteorological station located inside the domain (see section 2).

The temporal variation of the mean hourly values of measured/modelled wind velocity shows a good agreement, for both study periods. The statistical parameters also indicates a good performance of VADIS, with a correlation between the measured and modelled data of 0.77 and a NMSE lower (0.10) than the maximum of 1.5 defined by the

Table 1
General description of the computational domain (baseline scenario) (Ld and Wd represent the total length and width of the domain, including the open belt around the built-up area. Letter N indicates number).

Domain	Mesh			Buildings		Trees			Roads
Ld x Wd (m)	Type (−)	Resolution (m)	N cells (−)	N sets (−)	Height range (m)	N sets (−)	Crown height (m)	Total height (m)	N sets (−)
753 × 753	Regular	3	251 × 251	298	3.0–25.0	72	1.0–6.0	2.0–9.0	8

Table 2
General description of the computational domains used to simulate the different resilience scenarios.

		"Grey" scenario	Urban Green Area	Green roofs
Buildings	N sets	298	278	298
	Height range (m)	3.0–25.0	3.0–25.0	3.0–25.0
Trees	N sets	0	92	92
	Crown height (m)	0	1.0–6.0	1.0–6.0
	Total height (m)	0	2.0–20.0	1.0[a]– 9.0[b]
Roads	N sets	8	8	8

[a] Height of green roofs.
[b] Maximum height of trees.

acceptance criteria of Chang and Hanna (2005). FAC2 also shows a value that is in accordance with the acceptance criteria (higher than 0.5). Overall the model exhibits a tendency to underestimate the wind velocity, with a negative MBE of 0.34 m s^{-1}. These results are in accordance with the data obtained in previous works (Borrego et al., 2003, 2004; Amorim et al., 2013) and gives the confidence to apply the model for the different resilience scenarios.

Since two distinguish periods, in terms of both emissions and meteorological conditions, a comparison of the influence of these factors on air pollutants concentration is provided (Fig. 8). This analysis was done on hourly base and considering a spatial average of the domain. The results reveal that both pollutants have a similar profile. The concentration profiles follow the behaviour of the traffic flow, as expected, with the higher concentrations obtained at the weekday and for the peak periods of road traffic (maximum concentrations are obtained at 10 a.m. with values of around 10 and 40 μg m^{-3} for PM10 and NO_X, respectively, which is a result of a combined effect of low wind velocity and higher emissions). At the off-peak periods the concentrations are very similar for both days, despite the differences in the traffic flow (as previously mentioned, at the weekend the traffic flow is 15% less than the observed at the weekday). This behaviour is related to the low wind velocity registered in this period at the weekend day (around 2.2 m s^{-1}, which compared with the weekday correspond to a reduction of the wind velocity in the range of 14–51%) that does not promote the air pollutants dispersion. A low dispersion implies that air pollutants are retaining near the emitting source, increasing the levels of air pollutants concentration. Values of around 3 and 2 μg m^{-3}, are obtained for PM10 and NO_X, respectively, for the off-peak period (22 p.m.–7 a.m. and 12 a.m.–18 p.m.).

The modelled concentrations are considerably lower than the limit values of the European legislation, namely, the limit hourly value for NO_2 (200 μg m^{-3}), the limit daily value for PM10 (50 μg m^{-3}). These results are in accordance with the average values measured in an air quality monitoring station (classified as traffic station according the dominant emission source) located near the study domain. The measured values, on hourly base, were the following: 18.5 μg m^{-3} of PM10 and 64.2 μg m^{-3} of NO_X.

3.2. Resilience scenarios analysis

The effects of the resilience measures on the air pollutants dispersion were investigated considering as reference the baseline domain. Two different approaches were used to provide this analysis: i) mapping of the hourly concentrations for both pollutants and for each scenario (Figs. 9 and 10) to understand the spatial variability of the air pollutants concentration according to the configuration of the urban elements (buildings and vegetation); for this analysis two different periods of the weekday were selected (9 a.m. and 8 p.m.) based on the higher emissions and the different wind conditions; and ii) time evolution of the hourly mean for both pollutants, based on a spatial average of the domain, to quantitatively assess the influence of resilience measures.

For both pollutants, at the baseline scenario the higher concentration values occur in *Rua da Constituição* and in the adjacent pedestrian area, as a result of the conjoint influence of higher road traffic emissions and the wind flow direction (winds blow from northwest at 9 a.m. and from northeast at 8 p.m.). It can be observed that when the wind blows from northwest (i.e. 9 a.m.) the air pollutants are retained in leeward side of the street canyon (buildings on the lower left side of the domain – west side of *Rua da Constituição*) increasing the air pollutants concentration in this area; this is a result of the influence of the 3D configuration of buildings over the wind flow. This behaviour is originated by the oblique roof-level incoming winds that induce a counterclockwise swirling flow along the canyon (Amorim et al., 2013). As a

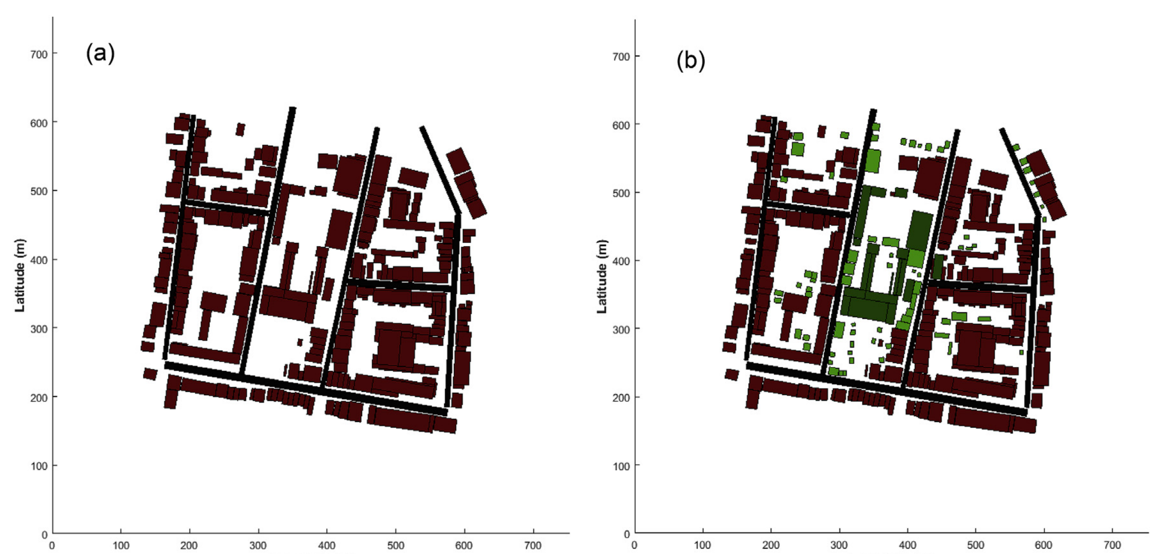
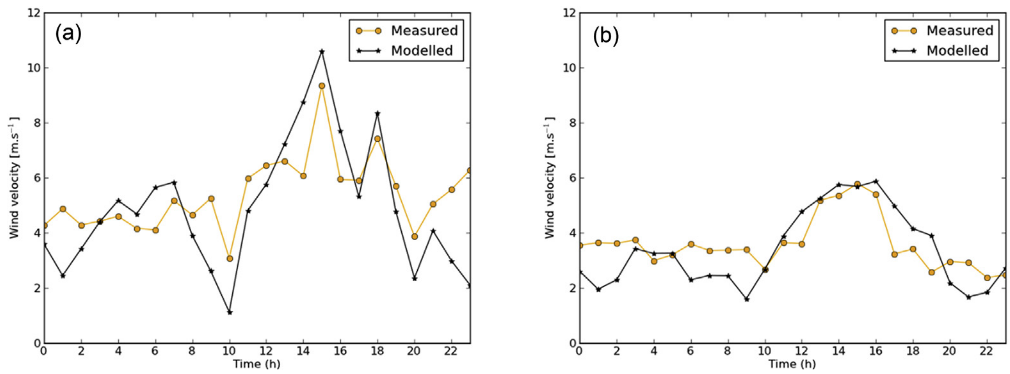


Fig. 6. 2D computational domains generated by the VADIS model for the resilience scenarios: (a) "grey" scenario (without trees) and (b) both urban green area and green roofs scenarios. The dark red shows the set of buildings, the light green shows the trees, the black shows the roads, and the dark green shows the intervention area for the implementation of both green roofs and urban green area. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



(c)

	Statistical Parameters			
	MB ($m \cdot s^{-1}$)	NMSE (-)	r (-)	FAC2 (-)
Model acceptance criteria	-	<1.5	-	>0.5
Wind velocity simulation	-0.34	0.10	0.767	0.917

Fig. 7. Time evolution of the hourly values of wind velocity ($m{\cdot}s^{-1}$) measured in the meteorological station and simulated for the same location, for both study periods: (a) weekday; (b) weekend day. (c) Statistical parameters for the assessment of modelling performance relative to the measurements. A total of 48 values (hours) were used to perform this analysis.

result, this vertical airflow transports the pollutant emitted near the ground level by traffic towards the leeward of the street canyon, where the pollutants are trapped by the decreased vertical exchange rate of air with the above roof-level atmosphere. It is also clear that this behaviour does not occur in east side of the *Rua da Constituição* since the dispersion of air pollutants is channelled through the existent open space between buildings.

Additionally, it was observed, for the great majority of the hourly simulations, that the effects induced by the vegetated canopy on the wind flow lead to the formation of hot-spots around trees, in specific areas, with an increase of air pollutants concentration. The magnitude of these effects are mostly dependent on the orientation of the incoming wind in relation to the positioning of the emission sources, buildings and trees. Thereby, can be inferred that the effect of trees on air quality is extremely spatially dependent, mostly because the heterogeneous positioning of trees that induces complex wind flow patterns. These results are in accordance with the findings of previous studies which have shown that the aerodynamic effect of trees would end up trapping road emissions (Gromke et al., 2008; Buccolieri et al., 2011; Wania et al., 2012). Other studies have found that the alignment of trees with the incoming wind enhance the ventilation, promoting air pollutants dispersion (Amorim et al., 2013; Abhijith and Gokhale, 2015). In fact, this can be seen in the results obtained by 8 p.m., which show a reduction of both number and magnitude of hot-spots around trees when compared with the data for 9 a.m. (reduction of around 50%). This is only a result of wind orientation since the wind velocity is the same for both time periods ($1.6\,m\,s^{-1}$). It can be concluded that the street canyon trees have the ability to be beneficial for air quality, depending on the prevailing wind direction, wind speed, street canyon and surrounding buildings geometry.

When the set of buildings in the central part of the domain are replaced by a green urban area, the results show a reduction, in comparison with the baseline scenario, of the air pollutants concentration of around 16% (changing in a range of 4.7% and 19% along the day) and 19% (changing in a range of 5.8% and 24%) for PM10 and NO_X, respectively, in the overall domain. The urban green scenario assumes the replacement of a non-porous material (buildings) by a porous (trees), which is an approach distinguish from the previous works that assessed the influence of trees on urban environments. As result, the decrease of air pollutants concentration is due to an increase in the turbulence

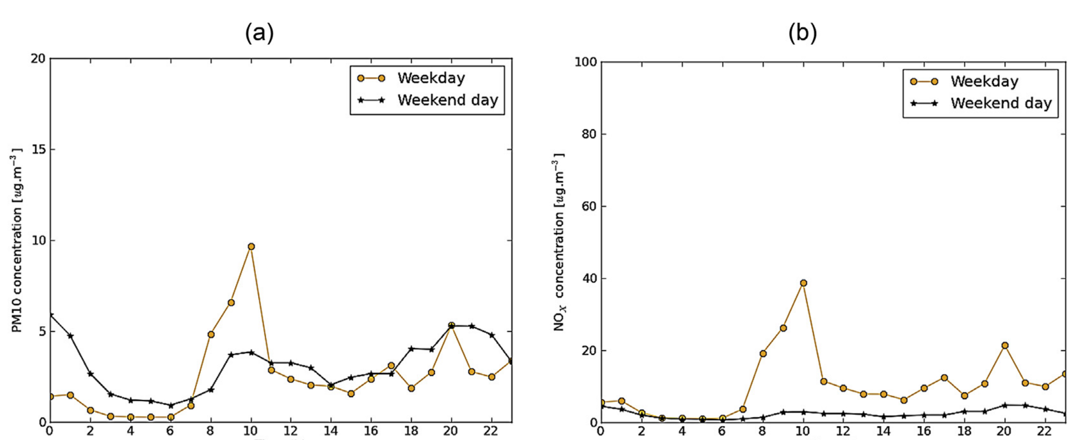


Fig. 8. Time evolution of the mean hourly modelled values of (a) PM10 and (b) NO_X concentrations ($\mu g{\cdot}m^{-3}$), spatially averaged for the entire domain (baseline scenario) for the week (orange line) and weekend days (black line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

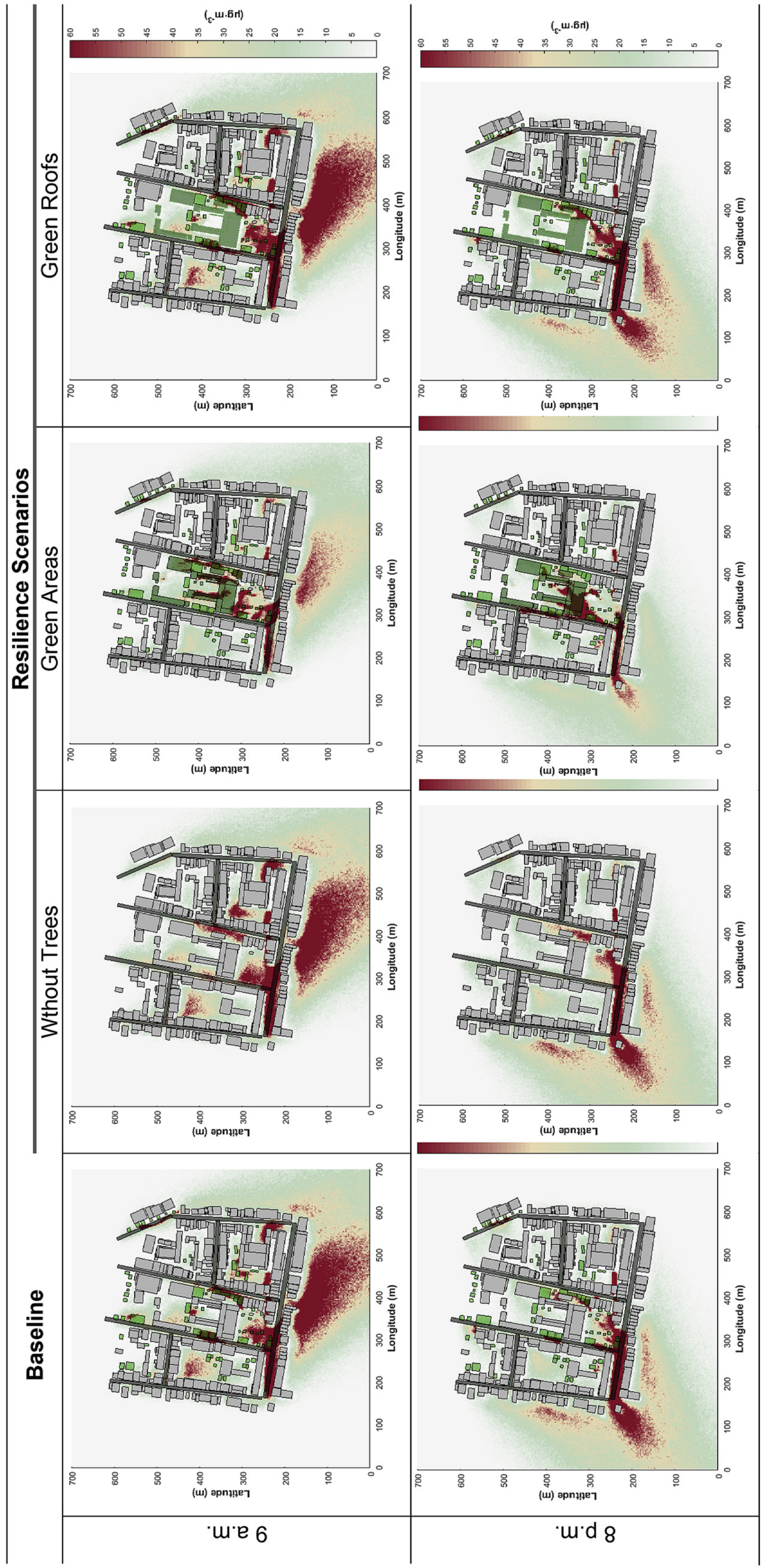


Fig. 9. PM concentration field for the scenarios under study for 3 m high horizontal streamlines. Contours refer to the period of 9 a.m. (with a wind velocity of 1.6 m s^{-1} and a wind direction of 330°) and 8 p.m. (with a wind velocity of 1.6 m s^{-1} and a wind direction of 57°) for the weekday.

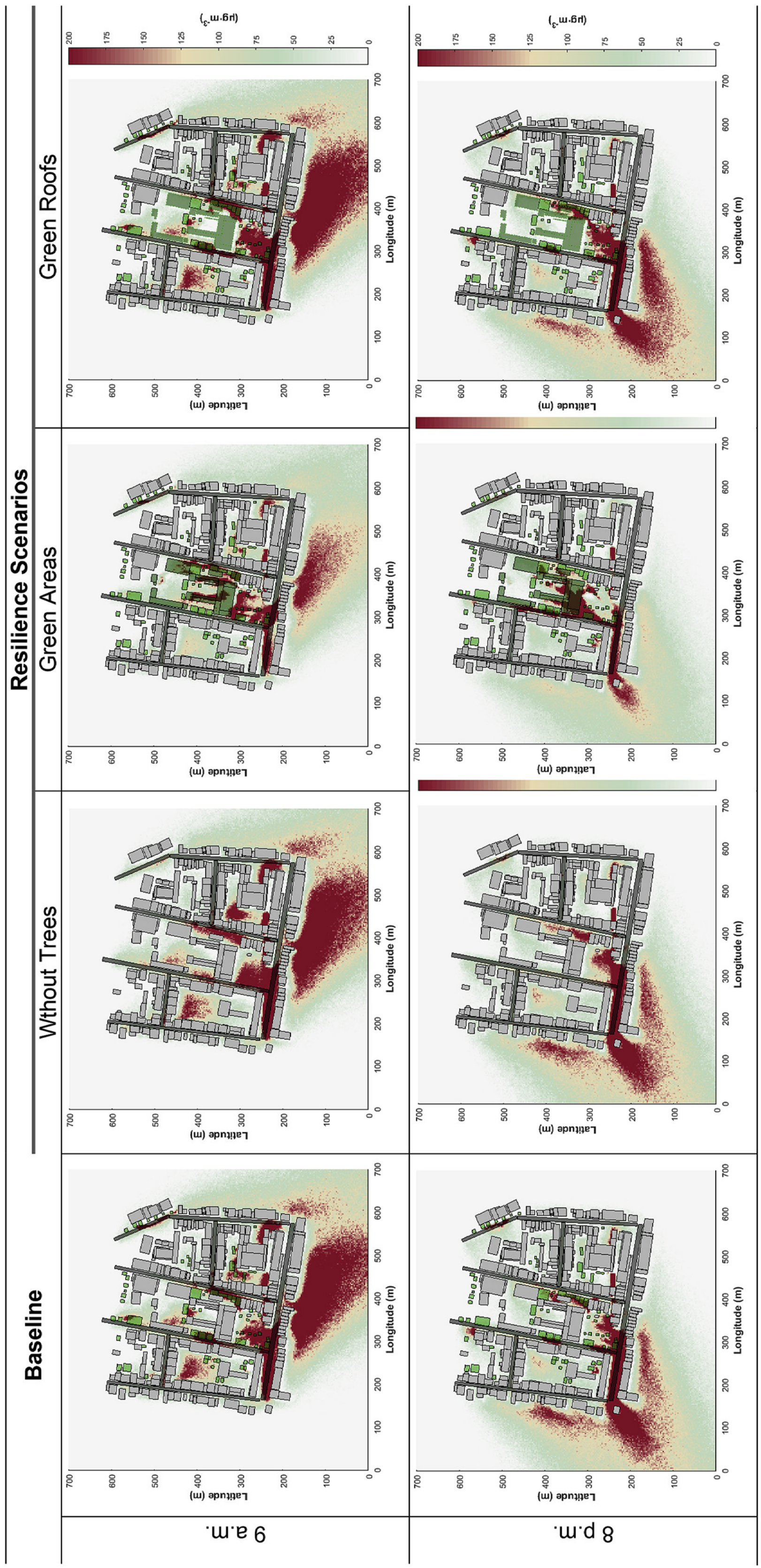


Fig. 10. NO_X concentration field for the scenarios under study for 3 m high horizontal streamlines. Contours refer to the period of 9 a.m. (with a wind velocity of 1.6 m s^{-1} and a wind direction of 330°) and 8 p.m. (with a wind velocity of 1.6 m s^{-1} and a wind direction of 57°) for the weekday.

production (Jeanjean et al., 2016) related to the increase of wind velocity (around $+1$ m s^{-1}, on average, when compared with the baseline; maximum difference of $+2$ m s^{-1} is obtained at 3 p.m.). It can also be seen that despite the general improvement of air quality (decreasing of air pollutants concentration), the implementation of an urban green area lead to the formation of additional hot-spots due to the rearrangement of vertical flow structures. Therefore, the higher concentrations within the green urban area are a consequence of: i) air recirculation induced by the building's walls and trees; and ii) the decrease of wind velocity at these spots (reduction of around 40%, when compared with the baseline; a maximum difference of -60% is obtained at 10 a.m.), which then decreases the dispersion. Additionally, it was concluded that for a wind speed equal or lesser than 1 m s^{-1}, no turbulent dispersion occurs under laminar conditions and the trees in the green urban area are shown to increase air pollutants concentrations in this area. Overall, the implementation of green urban areas promotes the improvement of air quality in their surroundings for several pollutants and thus, reduces the related effects on human health. A suggestion of this work is that, in general, for cities with average wind speeds greater than 1.5 m s^{-1} a high vegetation cover improves air pollutants dispersion in an urban environment (great number of trees, better benefits).

Notwithstanding the obtained results, the implementation of green urban areas in a particular area requires a previous assessment of its effectiveness, since several studies have been showing that implementation of trees increases air pollution levels by reducing the wind flow (e.g., Gromke and Blocken, 2015; Amorim et al., 2013; Vos et al., 2013). Most of these studies were focused on the influence of trees as barriers along road-avenues. Other studies that assessed the influence of avenue-like tree planting found that in-canyon air quality is considerably altered, with an increase of pollutant concentration at the leeward wall and a moderate decrease near the windward wall (Buccolieri et al., 2009; Gromke and Ruck, 2007, 2009). These studies confirm previous findings that have showed that the influence of trees is highly dependent of the urban design and local meteorological conditions. In addition to these factors, the cover management of trees (vegetation design), the species used and related LAD (tree species with high LAD are the best to enhance the aerodynamic dispersion (Jeanjean et al., 2016) should also be taken into account by urban planners.

Regarding the green roof scenario, the results does not show an improvement of air quality. This is mostly due to the fact that horizontal flow is weaker with green roofs (around 40% less when compared with baseline scenario). Overall, for most of the hourly simulations, the air pollutants concentration in terms of dispersion pattern is the same than the obtained for the baseline scenario (at 3-m above the ground). However, the magnitude of the air pollutants concentration is higher in specific areas when compared with the baseline scenario. Despite these findings, some studies have found a positive effect of green roofs on pollutant dispersion near roads (Berardi et al., 2014; Speak et al., 2012). Speak et al. (2012) found that while not as effective as street trees, due to lower surface roughness lengths and increased distance from sources, green roofs can be considered to reduce urban air pollution because their construction does not require major upheaval of the urban built environment, as tree-planting schemes often do. Another possible way to consider the benefits of green roofs on air quality improvement is by taking into account their capability to enhance buildings energy saving and to decrease the Urban Heat Island (UHI). As UHI increases radiant temperature and cooling loads of buildings, the effectiveness of green roofs in reducing the heat island will indirectly result in reducing energy consumption (Santamouris, 2014). Many studies mention that the decrease of energy consumption through green roofs would indirectly reduce the level of pollution (i.e. Sarrat et al., 2006; Stathopoulou et al., 2008). Should also be noted that, since the green roofs change the local temperature, they will influence the thermal stability of the atmosphere, and so, the magnitude and behaviour of air pollutants dispersion changes according to the stability conditions of the atmosphere (neutral, stable or unstable conditions).

The air pollutants concentration patterns in the "grey" scenario (without trees), highlights the importance of traffic flow, prevailing wind velocities and street geometry in determining pollutant concentrations within street canyons. The obtained results show that in the leeward side (of the *Rua da Constituição*) the concentrations are 10% [NO_X] and 9% [PM10] higher when compared with the baseline. Comparing the leeward and windward sides for these conditions, the results indicate that concentrations are 1.4 times higher in the leeward side, for both pollutants; a maximum difference of 2.6 times higher is obtained at 10 a.m. for PM and NO_X. These findings are in accordance with modelling and field's studies that consistently reported that on the leeward side, pollutants concentrations are 2–3 or more times higher than those on the windward side of the street canyon (Vardoulakis et al., 2002, 2003; Salmond and Mckendry, 2009; Xie et al., 2009). It can also be seen that the hot-spots observed in the baseline around the trees does not occur in the "grey scenario", confirming that these hot-spots are a result of the influence of vegetation canopy in wind flow. Overall, the results here obtained indicate that the absence of vegetation does not benefit the urban air quality.

Fig. 11 shows the time evolution of the mean hourly values for PM10 and NO_X, and for the set of the modelled scenarios. This analysis allows a quantitative comparison of the effects of the resilience

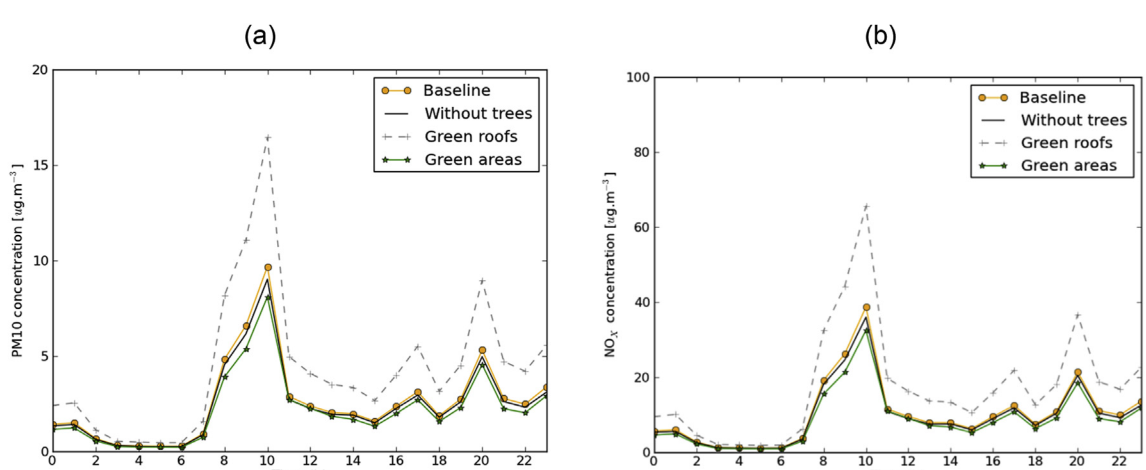


Fig. 11. Comparative analysis of the time evolution of the mean hourly modelled values of (a) PM10 and (b) NO_X concentrations (μg·m^{-3}) for the scenarios under study and for the weekday, in a spatial average of the domain.

scenarios in the air pollutants concentration values and was performed based on the average concentration values for all the cells of the domain. Therefore, the results represent the average behaviour of the study area, giving an idea of how resilience measures might influence the air quality of this region as a whole.

It is observed that the implementation of green roofs is the worst scenario in terms of PM10 and NO_X concentration values. In fact, for the majority of the simulation period, in particularly at 10 a.m., 5 p.m. and 20 p.m. green roofs result in 60% increase of pollutants concentration in relation to the baseline scenario (related to peaks of road traffic and wind flow). As previously mentioned, this is mainly due to the changes promoted by the presence of vegetation in the wind flow, namely the influence in the vertical exchange rates of polluted air with the above roof-level atmosphere. It is interesting to realise that, despite the vegetation are implemented in a high level (building roof), it has a great influence at the pedestrian height (3 m in this case) for both wind flow and pollutants dispersion.

The inclusion of an urban green area is the scenario showing more benefits for air quality, with a general reduction of pollutants concentrations. The greater benefits are obtained along the periods 7–8 a.m. and 8-9 p.m., with a reduction of air pollutants concentration of around 20%. This is quite important since the identified periods correspond to road traffic peaks where the people are most exposed to air pollution, whether people are driving, walking on the street or at home. These benefits on air quality are also important under a climate change scenario, because NO_X and PM10 concentrations (annual means) will increase in the study region, even if emissions remain at current levels (Sá et al., 2016). PM10 is the pollutant with higher reduction of concentration. Beyond the air quality benefits, vegetation provides a set of ecosystem services namely: i) environmental, mostly related to its ability to abate the effects of climate change; ii) economic, for example, through the creation of local job opportunities; and iii) social, since having areas where the people can socialize and be in liaison with nature improves health and well-being.

The "grey" scenario shows a slight reduction (around 5%) for both pollutants concentration, mostly related with the dissipation of the hotspots promoted by trees, which are characterized by higher air pollutants concentration. These results should be carefully analysed because of the potential fake notion of air quality improvement in the absence of vegetation. As previously mentioned, in the "grey" scenario an increase of the air pollutants concentration is observed near the emitting source, especially in the leeward side of the street canyon.

3.3. Limitations of the study and further research

It is of great importance to take into account the broader context of the obtained results and conclusions. The scope of this work is limited to the role of green infrastructures on the local air quality at a city level, at neutral meteorological conditions. The analysis of the spatial distribution of air pollutants concentrations, confirms the earlier findings of Tallis et al. (2011), Amorim et al. (2013), Tong et al. (2016) and Lee et al. (2018), showing the benefits in terms of air quality improvement, of increasing the vegetation rates at the city level, when the city morphology and wind conditions are taken into consideration, although there may be some level of uncertainty associated to these modelling results.

The uncertainty of results are mostly related with three issues. First, a CFD model is used in the analysis and, as implied by the word, a model is merely a model of reality. As such, its use induces a certain level of uncertainty. As already mentioned, the VADIS model have been validated through time. In a more similar context of the air quality impact of vegetation, Rodrigues et al. (2018) showed a good agreement between measurement data (based on wind tunnel measurements, which can be considered as a different type of model) and VADIS results. Despite of that, additional validation of the VADIS model is needed in order to validate the results presented in this work. The problem, also identified by Vos et al. (2013), is that no suitable validation dataset is available for comparison. To our best knowledge, no real life measurement campaign that studies the effect of vegetation on the local air quality in an urban environment has been published. Second, there are uncertainties associated with parameters such as LAD value, drag coefficient and meteorological conditions. This means that, depending on the magnitude of variation of these parameters, the impact of the concentration reduction could vary. Third, there is a level of uncertainty related with emissions estimation, since the characterization of vehicle fleet composition was obtained using statistical information.

In order to handle this uncertainty, it is important to interpret the results of the model simulations in an appropriate way. Therefore, specific results in the simulation, such as the percentage of concentration reduction may not be generalized. By doing so, the modelling results presented in this work have a valuable role: by combining the best available knowledge within the modelling community, it was possible to make a fair prediction of what will be the effect of green infrastructures on the local air quality. However, further studies should be conducted to enrich these findings, namely: i) a sensitivity analysis on the effects of vegetation type, such as trees height, planting distance and LAD; ii) an exposure analysis, to assess the capability of green infrastructures in reduce the human exposure to air pollution. These scientific knowledge will be of great interest for city planners.

4. Conclusions

Nowadays, air quality problems still persist, especially in cities, where most of the European population lives. To make a sustainable and resilient city to air pollution is a growing need, particularly in the current context of climate change. It is crucial the implementation of options that go further than the typical technological measures. This work aimed to assess the influence of different resilience measures, based on green infrastructures, in the flow and dispersion of air pollutants (NO_X, PM10) in a typical built-up area in Portugal. The WRF-CFD modelling setup was applied to quantitatively evaluate how the urban morphology and the green infrastructures affect the wind field and the pollutant distribution within the study area. Two separated periods were analysed and a set of scenarios were developed for this purpose.

The model performance (wind flow) was assessed for the current conditions (baseline scenario), showing a good capability of the CFD to simulate the wind patterns, with a Pearson correlation factor of 0.77 and a NMSE of 1.0, which is substantially lower than the threshold of 1.5 defined by modelling acceptance criteria. The analysis of resilience scenarios showed that green infrastructures have a role to play at city scale.

The results showed that the implementation of a green urban area leaded to an overall improvement of air quality, with a general decrease of both air pollutants concentration values of around 16%, mostly related to an enhanced ventilation and dispersion capacity of the street canyon. However, at some hot-spots, the air pollutants concentration increased due to lower wind velocities and the formation of additional recirculation areas. The implementation of green roofs showed an increase pollutants concentration, at specific areas, due to a decrease of the horizontal flow. This increment promoted an overall degradation of air quality in the study area, compared with the baseline scenario. The "grey" scenario (absence of vegetation) showed that local air quality is strongly dependent on the linkages between the traffic flow, meteorological conditions, the 3D configuration of the street canyon, and the presence of trees. Overall, the results indicate that, the absence of vegetation does not benefit the urban air quality. For all scenarios, the results showed that the change of the wind direction can strongly affect the dispersion patterns of pollutants (and concentrations), which was a more sensitive factor than the wind speed.

For the set of the analysed scenarios, the implementation of a green urban area is the best option for air quality improvement. Notwithstanding the overall benefits, it should be noted that in many city areas, space constrains mean that there are only limited opportunities for increasing vegetation extent (especially tree density) within the existing urban fabric. This fact combined with the formation of hot-spots within the trees, shows the importance of using CFD tools in the urban planning process with the goal of optimising the benefits of green infrastructures on the improvement of air quality, human comfort and health. While the general trends presented in this study provide insights regarding the benefits of green infrastructures, further works are required to investigate whether the findings in this study holds for other building configurations and other real urban morphologies, as well as, to other climate conditions.

Acknowledgements

The authors acknowledge the financial support of CLICURB project (EXCL/AAG-MAA/0383/2012), supported in the scope of the European Funds through COMPETE and by National Funds through the Portuguese Science Foundation (FCT) within project PEst-C/MAR/LA0017/2013, and to COST Action FP1204 "Green Infrastructure Approach: linking environmental with social aspects in studying and managing urban forests" (GreenInUrbs). An acknowledgement to Professor Casimiro Pio and his team for providing the meteorological measured data used in this work. We also extend an acknowledgement to the Portuguese 'Ministério da Educação e Ciência' for the PhD grant of Sandra Rafael (SFRH/BD/103184/2014) and the Portuguese Foundation for Science and Technology (FCT) through the financial support to CESAM (national (UID/AMB/50017/2013) and FEDER funds, within the PT2020 Partnership Agreement and Compete 2020).

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