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ASSESSING THE EFFECTS OF NATURE ON FUTURE AIR QUALITY: PORTO CASE STUDY

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Abstract: The goal of this work was to investigate the effectiveness of different "green" measures in improving air quality under a future heat wave (medium-term future climate, considering the Representative Concentration Pathway RCP8.5) at Porto urban area. To accomplish this goal the WRF-SLUCM-CHIMERE modelling system was used, and four "green" measures were assessed: i) the introduction of green roofs in areas classified as built-up area; ii) the introduction of "cold" roofs in areas classified as built-up area; iii) the application of "light" surfaces in areas classified as built-up area; and iv) the duplication of existing green areas. The influence of the selected measures on PM10, NO_2 and O_3 concentrations was quantified and compared with a control run simulation scenario (without measures). The results revealed that all the measures are able to mitigate the effects of heat waves by reducing the air temperature between 0.5°C and 1°C (maximum differences for the mean of the episode). Positive and negative effects were found in terms of air quality. The implementation of green roofs and the increase of surfaces albedo promoted an overall increase of PM10 concentrations (between 0.6% and 1.5%) and NO_2 concentrations (between 0.8% and 3.5%), which are closely related to a decrease of vertical mixing in the urban boundary layer. The increase of green urban areas promoted an overall decrease (on average) of both PM10 and NO_2, by around 1% and 3%, respectively. The O_3 levels increased with the increase of urban green areas, mostly located over the Porto urban area. Slight differences were promoted by the implementation of green roofs. For the increase of surfaces albedo, both increases and decreases of O_3 concentrations were observed. The obtained results can be of great importance for stakeholders and decision-makers to deal with climate change impacts.

Key words: *cities air quality, cities climate, resilience, nature-based solutions*

INTRODUCTION

Cities only cover a small fraction of the Earth (approximately 2% of the land surface). Despite that, given the large and ever-increasing fraction of the world's population living in cities, and the disproportionate share of resources used by these urban residents, cities and their inhabitants are key drivers of global environmental change. Urban areas are the major sources of greenhouse gases; while the exact number is debated, overall 70% to 90% of carbon emissions are generated in cities (EEA, 2017). These statistics reveal a straight linkage between cities and climate change. Cities are the main contributor to climate change; however, they are highly vulnerable to climate change effects. Extreme weather events can be especially disruptive to complex urban systems due to the high level of urbanization and demographic growth.

Cities are also the main source of air pollutants and despite the different processes involved in atmospheric pollution and climate change, they are linked in several key ways. Notwithstanding, cities have a unique ability to address global climate change challenges, by applying local measures to deal with specific vulnerabilities and needs (EEA, 2016). Due to the European Research and Innovation policy agenda on Nature-Based Solutions and Re-Naturing Cities, a set of studies have been conducted to investigate the capability of these solutions as adaptation measures. Nature-Based Solutions also called green measures, provide sustainable, cost-effective, multi-purpose and flexible alternatives for various objectives (EC, 2015). A complete literature review of the way of how green measures has been addressed in microscale and macroscale air pollution dispersion models can be found in Tiwari et al. (2019).

The main goal of this study is to investigate and quantify the effectiveness of different green measures in improving air quality under a future heat wave (medium-term future climate), in Porto urban area. Three main urban air pollutants were analysed: particulate matter with an aerodynamic diameter equal or less than 10 µm (PM10), nitrogen dioxide (NO_2) and ozone (O_3). For that, a numerical modelling approach composed by the WRF-SLUCM-CHIMERE was used.

METHODOLOGY

A specific methodology was applied to assess the influence of the application of "green" measures on the air quality of the Porto urban area. Two main steps were performed: i) definition of a modelling setup and ii) selection of green measures. A detailed description is presented in the following sub-sections.

Case study

The Porto urban area is located in the northwest of Portugal and is one of the largest and most densely populated urban area in the country (represents almost 25% of Portugal's urban land use), with near 1.8 million inhabitants (INE, 2011). It was identified as one of the European cities where the urban fringe has grown faster, resulting in a depletion of agricultural land and forests. As result of the high rate of urbanization, Porto stands out as the Portuguese urban area with the least share of green and blue areas (EEA, 2011). The expected changes in the climate (an increase of duration, magnitude and frequency of extreme events) and the air quality trends (exceedances to NO_2 and PM10 air quality standards) (Rafael et al., 2020), associated with the fact that citizens and the urban morphology are not yet prepared to deal with these issues, make this city an interesting and challenging case study to evaluate the potentialities of a "green" strategy.

Numerical Modelling

A modelling system composed by the WRF-CHIMERE models was applied to the study period (24th to 26th of July 2049). The modelling setup was applied for the heat wave episode for the control run (considering the current urban morphology) and for "green" scenarios. The only difference between the control run and the scenarios was the inclusion of designed "green" solutions.

The Weather Research and Forecasting (WRF) model (Skamarock et al., 2008), version 3.7, coupled with the single layer urban canopy model (SLUCM) (Kusaka et al., 2001), was used. The WRF-SLUCM was set up with four domains (see Figure 1). The outer domain (D1), covers Europe and North of Africa and has 173 x 142 horizontal grid cells with a horizontal resolution of 27 km; the nested domain D2 covers the Iberian Peninsula and has 75 × 166 horizontal grid cells with a horizontal resolution of 9 km; D3 covers the Northwest of Portugal and has 121 × 109 horizontal grid cells with a horizontal resolution of 3 km; D4 covers the Porto urban area and has 34 × 34 horizontal grid cells with a horizontal resolution of 1 km. The vertical grid was composed by 30 vertical layers up to the top of the computational domain (50 hPa). The two-way nesting technique was applied for the simulations (Skamarock et al., 2008). The physical parameterizations adopted can be found in Rafael et al. (2020). Information regarding the land use/land cover was taken through a combination between the Corine land cover project 2006 version (CLC2006), with a 3 arc-seconds horizontal resolution, and the Porto Urban Atlas from the European Environmental Agency, with 10 m x 10 m of horizontal resolution, in a complementary approach to better detail Porto urban features. Both land use databases were remapped to the United States Geological Survey (USGS) 33 land use categories.

The meteorological initial and boundary conditions were obtained from the Max Planck Institute Earth System Model – Lower Resolution (MPI ESM-LR) (Giorgetta et al. 2013), with a horizontal resolution of 1.9 degrees and with a temporal resolution of 6-h intervals. The MPI EMS-LR global climate model was chosen since it is considered one of the best models to simulate the climate of Europe (Brands et al. 2013). The Representative Concentration Pathway Scenario RCP8.5 was adopted (Riahi et al., 2007) because it corresponds to the pathway with the highest greenhouse gas emissions, leading to a radiative forcing of 8.5 $W.m^{-2}$ at the end of the century (2100).

CHIMERE v2016a1 was applied directly to the WRF grid. The CHIMERE chemistry-transport model is an open access multi-scale Eulerian chemical transport model (CTM), which applies the integration of the mass continuity equation to estimate the concentrations of several chemical species in each cell of a given grid. The chemical mechanism MELCHIOR-2 was used to simulate the concentration of 44 gaseous species from a set of 120 chemical reactions. The anthropogenic emissions for the year 2015 were obtained from the European Monitoring and Evaluation Programme (EMEP) inventory. The biogenic emissions were calculated using the Model of Emissions of Gases and Aerosols from Nature (MEGAN), part of the CHIMERE model.

”Green” scenarios

Four different “green” scenarios were built using four distinguishable measures: i) the introduction of green roofs in areas classified as built-up area; ii) the introduction of “cold” roofs in areas classified as built-up area; iii) the application of “light” surfaces in areas classified as built-up area; and iv) the duplication of existing green areas. The scenarios were established as follows:

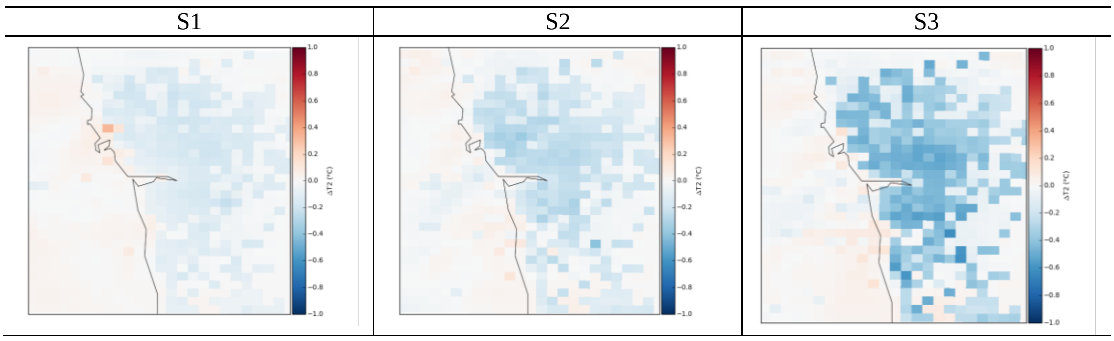
- Scenario 1 (S1) considers that 100% of the urban areas (i.e. the simulation grid cells with USGS land use urban categories as 31, 32 and 33) have green roofs (covered with vegetated surfaces).
- Scenario 2 (S2) considers that 100% of the buildings have white roofs (roofs painted white or covered with white materials). For these grid cells, the roof surface albedo was defined as 80%, which is considered an appropriate value for the albedo of a white-colour newly painted roof.
- Scenario 3 (S3) considers that all built-up surfaces have an albedo of 80% (see S2). This value was defined for the surface albedo of roofs, facades and ground.
- Scenario 4 (S4) considered an increase of Porto green urban areas (parks). To do that, the number of grid points that originally were considered as “green urban area” in the control run was identified. The number of grid points with this classification was then doubled and the land use category was changed to the USGS land use category 3 “Irrigated Cropland and Pasture”.

RESULTS AND DISCUSSION

Based on the methodology previously described, the effects of the “green” measures (scenarios S1 to S4) on the meteorology variables and air quality under a future heat wave in the Porto urban area are displayed and discussed in this section.

Effects on meteorology

Figure 1 shows the temperature mean differences fields for all the analysed scenarios. The results revealed that S1, S2 and S3 scenarios reduce urban temperatures. Since green (S1 scenario) and white roofs (S2 scenario) were applied almost evenly across the urban area, a uniform temperature reduction was obtained thought the study domain. In terms of the effectiveness of the measures in lowering surface temperatures, the results show that the effects of evapotranspiration and the increase of surface moisture availability produced by green roofs are similar to the effects promoted by an albedo increase. S3 scenario showed a more pronounced temperature reduction, which allows to conclude that the higher the proportion of white surfaces coverage is, the higher will be the surface temperature reductions. The differences in the average temperature fields of S1 and S2 scenarios was around -0.5°C, reaching -1°C in S3 scenario. Maximum differences are reached at 12 a.m., with a temperature reduction of -5.7°C for S1 scenario, and of -5.0°C for S2 and S3 scenarios. For the S4 scenario, the mean temperature differences field showed a located pattern, with the temperature differences being located in the vicinity of the added green urban area, the so-called park cool island effect. As a result, the differences in the average surface temperature fields varies between -1°C and +1°C.



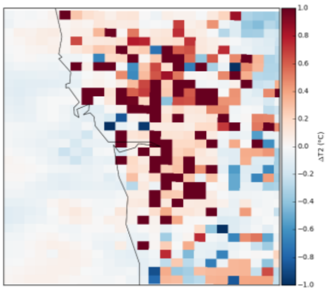
S4	
	S1 – Implementation of green roofs S2 – Implementation of white roofs S3 – Implementation of white surfaces S4 – Implementation of parks

Figure 1. Spatial distribution of the absolute differences between “green” scenarios and control run for temperature at 2 m. The differences are presented for the mean of the modelling period..

Effects on air quality

The analysis of air quality results was made based on the spatial differences between the “green” scenarios and the control run (relative difference) for three time periods (9 a.m., 12 a.m., 6 p.m.), to provide an overview of the day time effects of the studied measures. As an example, the results obtained at 12 a.m. for S4 is presented and discussed in this subsection (see Figure 2).

The S4 scenario showed, on average, a decrease of PM10 concentrations, with the maximum reductions being localised in the urban area. At 12 a.m. maximum decreases of -20 $\mu g \cdot m^{-3}$ was obtained, which corresponds to a relative decrease of -45%. For the mean of the episode, maximum decreases reached -21% (-54 $\mu g \cdot m^{-3}$). This occurs due to the increase of the boundary layer height during this time, which increases the vertical turbulent exchange, promoting the dispersion of PM10. Also, the increase of natural vegetation promotes an increase in the amount of PM10 that is removed by deposition. This happens since plants have a large surface area per unit volume, increasing the probability of deposition compared with the smooth, manufactured surfaces present in urban areas (Rafael et al., 2020). Similarly to PM10, an average decrease of NO_2 concentrations of around -3.4% (for the mean of the episode) was obtained; maximum decreases can reach -26%, corresponding to a reduction of -78 $\mu g \cdot m^{-3}$. As previously discussed for PM10, this decrease is directly related to the increase of the boundary layer height, which promotes the vertical turbulent exchange and therefore the dispersion of NO_2. Due to the link between NO_2 and O_3, these pollutants should be analysed in an integrated way, since the change in NO_2 concentrations, due to a decrease in atmospheric mixing, can evoke a secondary impact on O_3 concentrations via chemical reactions. The results revealed a general increase in O_3 concentrations, especially located in the Porto urban area. Differences lesser than 0.5% were found for the mean of the episode. Due to the chemical coupling of surface O_3 and NO_2, the reduction of NO_2 concentrations promoted by the implementation of green areas (S4) is accompanied by an increase in the atmospheric concentration of O_3.

PM10	NO_2	O3

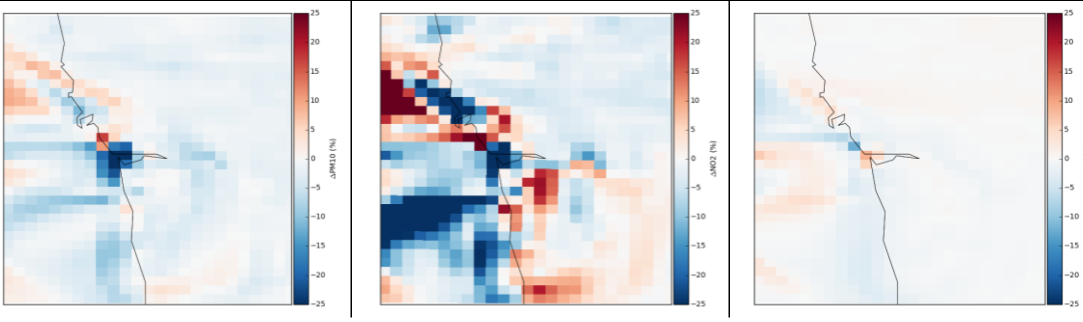


Figure 2. Relative differences (%) between the S4 and the control run for PM10, NO_2 and O_3 concentrations at 12 a.m. (mean over the same hour of the day for all days of the episode).

More details about the model setup and the obtained results can be found in Rafael et al. (2020).

CONCLUSIONS

The modelling results suggest overall benefits for all the analysed measures in the mitigation of heat waves effects, by reducing the air temperature in a range of -0.5°C and -1°C (average differences for the mean of the episode). Regarding the impacts on urban air quality, both positive and negative effects were found. For PM10 and NO_2 air pollutants, the positive effect of reduced temperature is reversed. Model results showed that a temperature reduction has a significant effect on the dynamical structure of the urban boundary layer. A decrease of turbulent kinetic energy due to a lower temperature leads to a lower rate of turbulent mixing and a decrease of the mixing layer height, thus resulting in higher near surface concentrations of these pollutants. For ozone, both positive and negative effects were found, with the spatial distribution of these differences occurring in a negative correlation with the NO_2 differences. This type of results shows that changes in urban planning can influence both climate and air quality of urban areas.

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REFERENCES

EC - European Comission, 2015: Towards an EU Research and Innovation policy agenda for Nature-Based Solutions & Re-Naturing Cities. Final Report of the Horizon 2020 Expert Group on 'Nature-Based Solutions and Re-Naturing Cities'. Luxembourg: Publications Office of the European Union. ISBN 978-92-79-46051-7.

EEA - Environmental European Agency, 2016: Urban adaptation to climate change in Europe 2016 - Transforming cities in a changing climate. EEA Report No 12/2016. Luxembourg: Publications Office of the European Union, 2016. ISBN 978-92-9213-742-7.

EEA - Environmental European Agency, 2017: Air quality in Europe — 2017 report. EEA Report No 13/2017. Luxembourg: Publications Office of the European Union, 2017. ISBN 978-92-9213-921-6.

EEA - European Environment Agency, 2011: The application of models under the European Union's Air Quality Directive: A technical reference guide. Luxembourg: Publications Office of 579 the European Union. ISBN 978-92-9213-223-1.

Giorgetta, M.A., J. Jungclaus, C.H. Reick, S. Legutke, J. Bader, M, Böttinger, V. Brovkin, T. Crueger, M. Esch, F. Fieg, et al., 2013: Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the Coupled Model Intercomparison Project phase 5. *J. adv. model. earth syst.*, **5**, 572–597.

INE (Instituto Nacional de Estatística) – Statistics Portugal, 2011: CENSUS, 2011 - Statistical Data for Portugal [Internet]. Available from: http://censos.ine.pt.

Kusaka, H., H. Kondo, Y. Kikegawa, F. Kimura, 2001: A simple single layer urban canopy model for atmospheric models: comparison with multi-layer and slab models. *Boundary Layer Meteorol.*, **101**, 329-358.

Rafael, S., B. Augusto, A. Ascenso, C. Borrego, A.I. Miranda, 2020: Re-Naturing Cities: Evaluating the effects on future air quality in the city of Porto. *Atmos. Environ*., **222**.

Riahi, K., A. Gruebler, N. Nakicenovi, 2007: Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technol. Forecast. Soc. Change.*, **74**, 887–935.

Skamarock, W.C., J.B. Klemp, J. Dudhia, D.O. Gill, D.M. Barker, X.Y. Huang, W. Wang, J.G. Powers, 2008: A Description of the Advanced Research WRF Version 3. NCAR/TN-475+STR, pp.113.

Tiwari, A., P. Kumar, R. Baldauf, K. Zhang, F. Pilla, S. Sabatino, E. Brattich, B. Pulvirenti, 2019: Considerations for evaluating green infrastructure impacts in microscale and macroscale air pollution dispersion models. *Sci. Total Environ.*, **672**, 410-426.