Statistical Approach to Estimate the Impact of Climate Change in Daily Ozone Concentrations

Pedro Garrett Lopes[1], Mário Pulquerio[2], Elsa Casimiro[3]

Abstract — Short-term exposure to ozone is a public health concern worldwide. Tropospheric ozone is a secondary air pollutant, formed primarily through a complex series of photochemical reactions between nitrogen oxides and reactive hydrocarbons. Hot days with clear skies favour ozone production. Hence a warmer climate is likely to increase ozone ambient concentration and consequently the impact of ozone related health effects.

In this paper we present a statistical model that was developed using an additive mixed modelling approach to estimate daily ozone concentrations based on ground level climate variables, ozone precursors and synoptic atmosphere variables from the National Centre of Environmental Prediction. Two future scenarios (A2a and B2a) of daily ozone concentrations were obtained using the global circulation model (GCM) HadCM3 taking also into account local per capita ozone precursor's emissions and population growth for each scenario.

Keywords — Climate Change, Generalized Additive Mixed Modelling, Ozone.

1 INTRODUCTION

There is a significant volume of studies providing evidence that short-term exposure to urban air pollution is a public health concern worldwide. The impact of a changing atmosphere will affect pollutant chemical reactions, transportation and dilution rates, consequently affecting local and regional air quality. Urban pollutants most likely to be affected by climate change are ozone and particulate matter. However, additional research is needed to better understand possible impacts of climate change on air pollution and subsequently on health [1].

Ozone is a secondary pollutant formed by a series of chemical reactions involving solar radiation, nitrogen oxides (NOx) and volatile organic compounds (VOCs). As a result of higher levels of ozone precursors, tropospheric ozone concentrations have increased in urban areas, mostly due to transport vehicles emissions, and globally by about 35% since preindustrial period [2].

Several studies using dynamical regional scale models for Europe, United States and China indicate that ozone concentrations are likely to increase during the 21st century due to climate change [3], [4], [5], [6]. Results from Matthias et al. 2009 using a statistical downscaling approach for Western Europe also showed that the overall 8h ozone mean increases by 2.5–6.5 and 6.1–10.9 µg m^{-3} in various scenario periods, 2051–2060 and 2091 –2100 respectively.

Statistical downscaling methods are well known for being a faster and non-computer intensive way to assess the impact of climate change at the local level when compared with the dynamical downscaling approach. Nevertheless, both downscaling methods should be complementary.

As demonstrated by Ordóñez et al. 2005, the link between high temperatures and ozone concentrations makes Mediterranean countries like Portugal particularly vulnerable to high ozone levels. In Lisbon, capital of Portugal, studies also indicate an inverse relation between ozone and nitrogen dioxide demonstrating the influence of traffic in ozone levels. Exceedances of the information threshold (180 µgm^{-3} - one hour) are common during higher temperatures, especially between July and August. However, highest monthly average of ozone concentrations in Lisbon occurs in April and May [9].

We present in this study a novel statistical approach using local and synoptic climatological variables and NO_2 emissions to assess the impact of climate change in ozone concentrations for the municipality of Lisbon. The Global Circulation Model HadCM3 and socio-economic scenarios for the A2a and B2a SRES were used to assess the

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impact of climate change in ozone levels taking also into account the contribution of local per-capita emissions for the 2050's and 2080's.

2 METHODS

The study area is the city of Lisbon, the capital of Portugal. It is the largest urban area in Portugal with a population of about 0.5 million. Frequent exceedances of EU directive targets for air quality occur.

2.1 Environmental and Health Data

Daily maximum temperature and daily minimum temperature for Lisbon (2002-2009) were obtained at the European Climate Assessment & Dataset (ECA&D). Data, for the following meteorological station: Name: 177 LISBOA GEOFISICA; WMO: 08535; Latitude: 38:43:00; Longitude: -09:09:00; Height: 77m, located in Lisbon city center were used. Large scale synoptic climate was collected from the NCEP/NCAR Reanalysis 1 acquired at the NOAA National Center for Environmental Prediction website. This data set was interpolated to the same grid as the Global Circulation Model HadCM3 using a bilinear interpolation method. The central grid point with latitude: 40.00 ° and longitude: -7.50 ° was used to extract the necessary variables.

Hourly nitrogen dioxide (NO2) and ozone (O3) concentrations were obtained from the Portuguese Environmental Agency from four monitoring stations (Restelo, Beato, Entrecampos and Olivais) located within the Lisbon municipality. For each monitoring station several daily statistics were calculated based on the hourly dataset of the two pollutants: daily mean, maximum, 50th percentile, 95th percentile, 98th percentile and 8 hours mean concentrations. Only days with more than 75% of the hourly observations were considered and the calculated daily statistics from all monitoring stations were averaged to better represent the air quality of the study area.

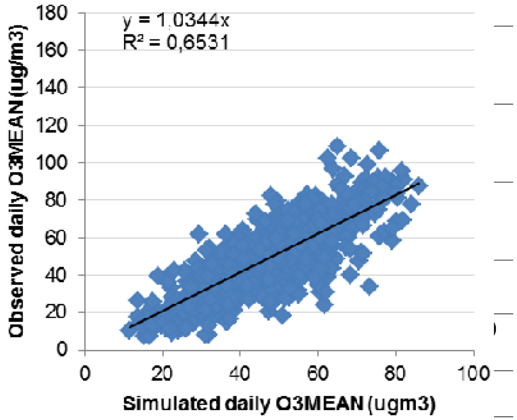
2.2 Statistical Analysis

Gaussian additive mixed modeling with thin plate regression splines and with an exponential variance function structure was chosen to build an O3 regression model [19, [11], [12]. The R software version 2.6.0 was used for statistical analysis with the "mgcv" package version 1.3-27 [13], [14].

Model calibration and validation were made for two different time periods, 2002 to 2007 and 2008 to 2009 respectively. Model selection was done taking into account the Akaike Information Criterion (AIC)[15] and model variables were chosen based on the p-value at the 0.05 confidence level. Table 1 presents the analysed variables.

TABLE 1. OZONE PREDICTORS.

	Daily Stats	Pressure levels
Temperature	mean/max/min	
Cloud forcing net		



To accommodate seasonality in the model four other variables were created: "TIME" counts the total number of days; "DAY YEAR" represents the Julian day for each year; "SEASON" to represent each season; and "MONTH" to represent each month.

2.3 Climate Change Scenarios (A2a and B2a)

To estimate O3 concentrations until the end of XXI century NCEP predictors were replaced with the GCM HadCM3 [16]. Local climate was downscaled, using the same GCM, with the SDSM (Statistical DownScaling Model) tool, a hybrid of stochastic weather generator with transfer function methods [17]. In this case, large-scale circulation patterns and atmospheric moisture variables were used to condition local scale weather parameters obtaining daily maximum and minimum temperature for the "Lisboa Geofísica" meteorological station [18].

Two future O3 scenarios (A2a and B2a) were developed taking into account population growth and per capita NO2 emissions for the study area. These results were based on the work developed by Vuuren et al, 2006 where they estimate population growth and the per capita NO2 urban emissions for each scenario. The methodology was implemented considering 2005 as the reference year in terms of number of habitants in the Lisbon municipality. The estimated urban NO2 per capita emissions were multiplied by the population with a time step of five years until 2099. Each percentage difference was added to observed daily NO2 concentrations taking as reference the years from 2003 to 2007.

3 RESULTS AND DISCUSSION

From all ozone variables tested only the dependent variables daily mean ozone (O3MEAN), daily 95th percentile (O3P95) and daily maximum (O3MAX) gave robust results. For these dependent variables a seasonal model was chosen using maximum temperature in the exponential variance function and the following covariates: Maximum Temperature, Geopotential Height at 500 hPa, Net Shortwave Radiation Flux and NO2 daily mean. For the O3P95 model, the covariate Mean Sea Level Pressure was also added. All variables were selected at 0.05 confidence level.

3.1 Model Validation and Results

Model validation was made for the 2008 to 2009 period. Figure 1, 2 and 3 shows the trendline, with an intercept in zero, between the observed ozone concentrations and the simulations for above mentioned daily statistics in that period.

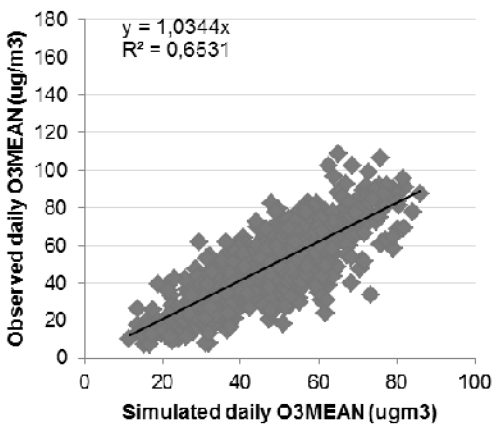


Fig 1. – Daily ozone mean versus simulated results for the validation period of 2008 to 2009.

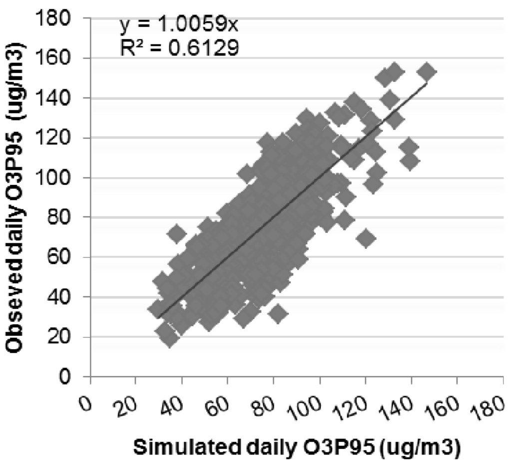


Fig 2. – Daily ozone 95th percentile versus simulated results for the validation period of 2008 to 2009.

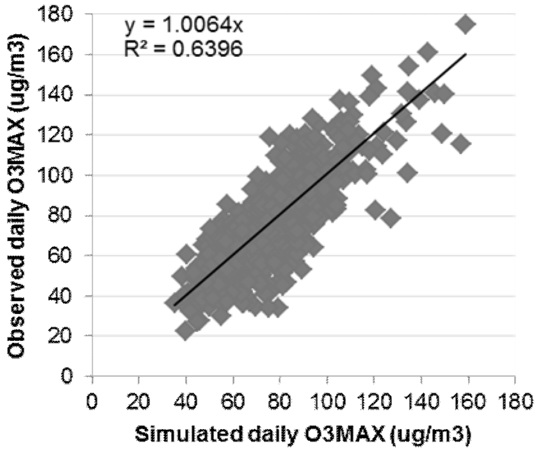


Fig 3. – Daily maximum ozone versus simulated results for the validation period of 2008 to 2009.

Results show the coefficient of determination, R^2, varying from 61% to 65% showing a good agreement between the simulations and observations.

To test model performance representing ozone seasonality the monthly average of the daily values of ozone for the validations period (2008 to 2009) were plotted as showed in figure 4, 5 and 6.

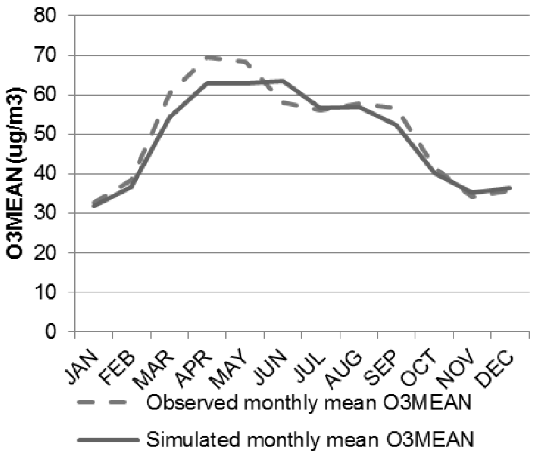


Fig 4. Monthly mean of daily ozone mean versus simulated results for the validation period of 2008 to 2009.

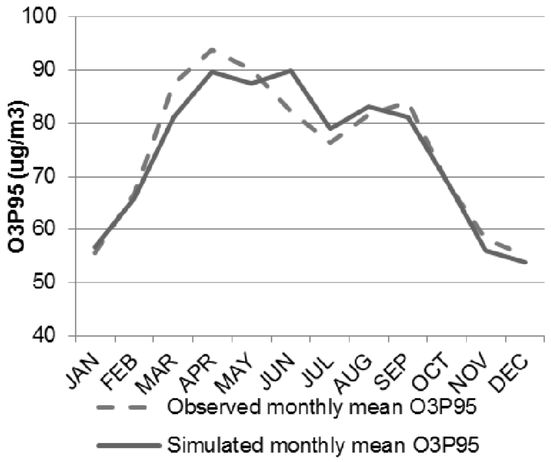


Fig 5. Monthly mean of daily ozone 95th Percentile versus simulated results for the validation period of 2008 to 2009.

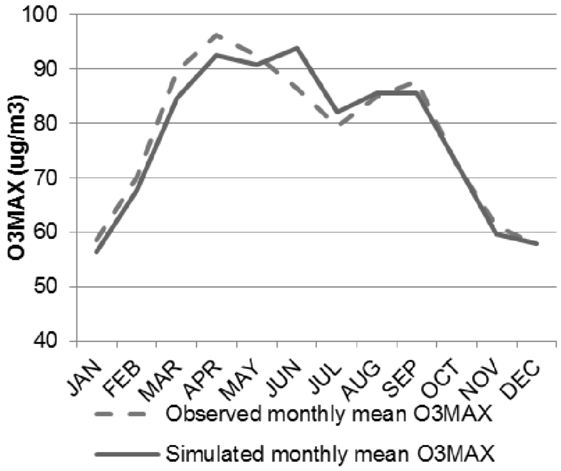


Fig 6. Monthly mean of daily ozone maximum versus simulated results for the validation period of 2008 to 2009.

Results show that globally the simulations are capturing ozone annual seasonality very close to the observed concentrations. A slightly underestimation during spring and a small overestimation in June is found for all three models.

3.2 Emissions Scenarios

Figure 7 and 8 shows the evolution for each population scenario in the municipality of Lisbon and their per capita emissions in tons of CO_2 equivalent.

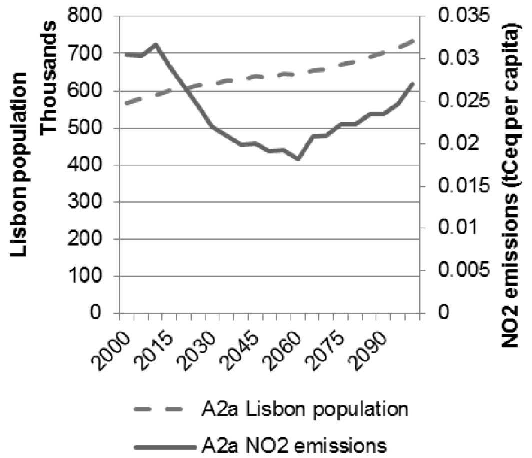


Fig 7. Population growth and per-capita NO2 emissions for the A2a scenario.

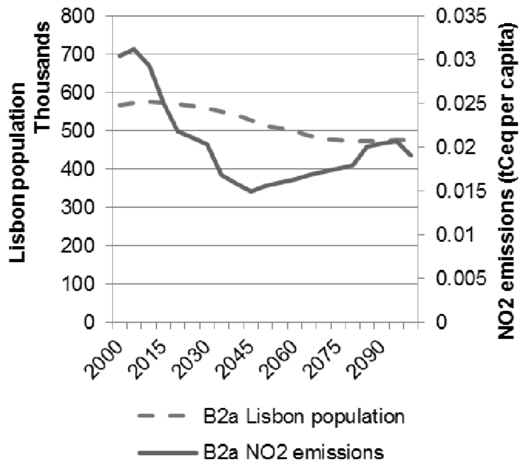


Fig 8. Population growth and per-capita NO2 emissions for the B2a scenario.

Figure 7 shows that in the A2a scenario NO_2 per-capita emissions will decrease until mid-century, increasing again until 2100. In this scenario the Lisbon population will be constantly increasing. As showed in figure 8 for the B2a scenario NO_2 per-capita emissions will be lower than the A2a scenario for the mid-century increasing again at a lower rate than the A2a scenario until 2100. For the B2a scenario population will decrease from almost six hundred thousand to five hundred thousand until the end of the century.

The increase percentage of total NO_2 emissions was added for the baseline period (from 2003 to 2007), using a time step of five years.

3.3 Ozone Scenarios

After incorporating the NO2 concentrations, the downscaled temperature and the HadCM3 GCM synoptic variables as the new covariates it was possible to run all models until 2099. Since all

results had similar trends only maximum ozone concentrations in both A2a and B2a scenarios are showed.
Figure 9 and 10 shows the number of events per threshold taking as reference the period between 2007 to 2008 for both scenarios for the mid and end-century.

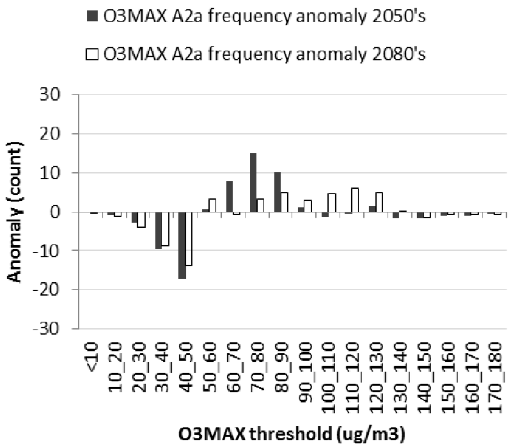


Fig 9. Maximum daily Ozone frequency anomaly, related to the 2002 to 2007 period, for the A2a scenario for the mid and end-century.

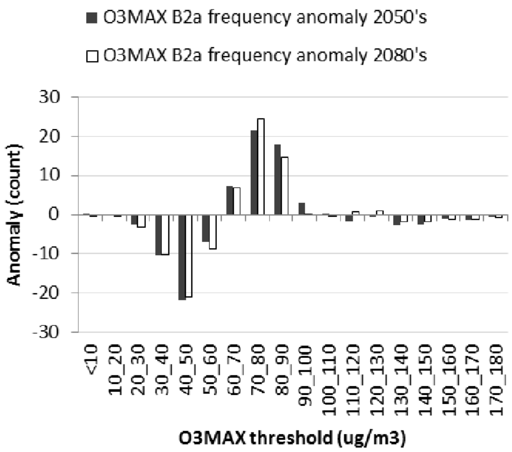


Fig 10. Maximum daily Ozone frequency anomaly, related to the 2002 to 2007 period, for the B2a scenario for the mid and end-century.

Results show an overall increasing tendency in the number of events per year between 70 and 90µg m^{-3}. In the A2a scenario for the end of the century an increase in the number of events with higher concentrations, between 90 and 130 µg m^{-3}, is also verified. In both scenarios this increase is accompanied by a decrease in the number of events bellow 50-60 µg m^{-3}.

Ozone seasonality is another important factor to check overall tendencies both in the short and long term. Figure 11 and 12 show the results of the annual seasonality considering periods of thirty years for the A2a and B2a scenario and the 2002-2007 baseline period.

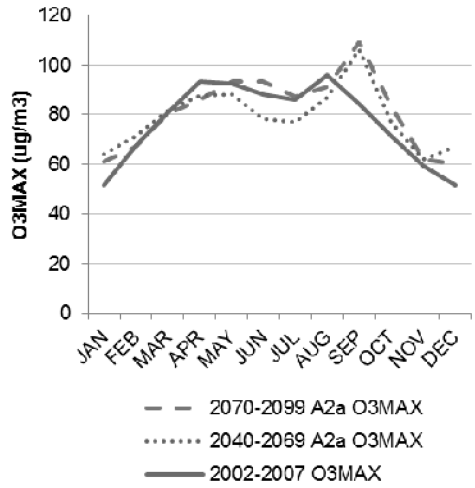


Fig 11. O3MAX annual seasonality for the A2a scenario.

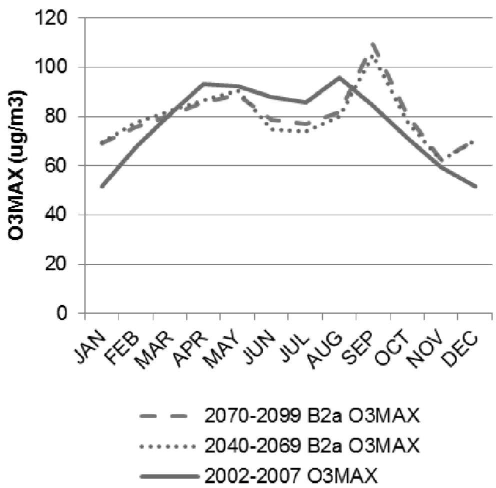


Fig 12. O3MAX annual seasonality for the B2a scenario.

Results show, in both scenarios, a shift in the location of the bimodal seasonal peak: the spring peak is shifting from March to May or even July considering the results for the A2 scenario in the end of the century and the summer peak is changing from August to September. The summer peak also presents higher annual ozone concentrations when compared with the reference period. Lower concentrations between March and August are also observed, except for the A2a scenario by the end of the century, where the concentration in June and July are slightly higher.

4 Conclusion

Model validation of ozone showed similar trends when compared with the daily and monthly observations, describing not only extreme values but also its seasonality. Results showed the coefficient of determination, R^2, varying from 61% to 65% showing a good agreement between the simulations and observations.

An overall increasing tendency in the average number of events per year between 70 and 90 µg m^{-3} of daily maximum ozone is observed in both scenarios. Results also show that in the A2a scenario the average number of events between 90 and 130 µg m^{-3} for the end of the 21^{st} century is higher when compared to the 2002-2007 reference period.

Both scenarios show a shift in the location of the bimodal seasonal peak. In the A2a scenario the spring peak shifts from March to May or even July in the end of the century. In both scenarios the summer peak changes from August to September representing in all scenarios the month with higher averaged ozone levels. Lower concentrations between March and August are also observed, except for the A2a scenario by the end of the century, where the concentration in June and July are also slightly higher.

For future work it's important to perform a sensitivity analyses to better understand the influence of each covariate in the final results in terms of frequency of events and seasonality. Generally is possible to observe that higher frequency of high ozone concentrations in the A2a scenario for the end of the century can possibly be due to high NO_2 emissions. This raises the importance on how local emissions can affect human health.

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