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Estimating future air-quality due to climate change: the Athens case study

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Abstract. The aim of this study is to investigate the development of an empirical-statistical model in order to examine the potential impact of increasing future temperatures on ozone exceedance days in the Greater Athens Area. It is based on the concept that temperature is a capable predictor for the ozone concentrations and that in a future climate change world, the likelihood of ozone pollution episodes may increase.

1 Introduction

It has become widely recognized that climate change could affect air quality, through the assumption that air quality is strongly dependent on weather systems and therefore sensitive to climate change. A thorough review of recent studies and methods used to provide estimates of the climate change effect on air quality can be found in Jacob and Winner (2009). In their study, one of the methods used seeks to determine predictive relationships between air pollution concentrations and individual meteorological parameters. A major task of research in the above framework has been dedicated to the systematic study of surface ozone correlations with meteorological variables identifying temperature, morning solar radiation, number of days since the last frontal passage, humidity and the frequency of summertime mid latitude cyclones as the closest associated with ozone (Ordóñez et al., 2005; Wise and Comrie, 2005; Camalier et al., 2007; Leibensperger et al., 2008). The ozone-temperature relationship has been studied over the years indicating that temperature is strongly associated with ozone concentrations and therefore can be used as a predictor for ozone concentrations. In particular, the strong correlation of ozone with temperature is associated with surface air ventilation, since high temperatures occur under the presence of light winds, high levels of isolation and stagnant circulation conditions (Jacob et al., 1993; Sillman and Samson, 1995). In addition, the correlation of ozone with temperature also depends on local ozone production chemistry such as thermal decomposition of PAN, on the temperature dependent biogenic emissions such as isoprene as well as to correlations of temperature with anthropogenic emissions (NO_x and VOC) (Sillman and Samson, 1995). Recently, Bloomer et al. (2009) defined as a climate penalty factor the ozone temperature slope in the rural eastern US, suggesting that the present day empirical relation between ozone and temperature, although not including non linear effects on ozone production as in state of the art 3-D photochemical models, if combined with future temperature projections could provide estimates of the future air-quality.

In addition, one of the main conclusions of the 2003 European Environmental Agency's report (EEA, 2003) after the European summer heatwave episode (Beniston, 2004; Schär et al., 2004) is that the potential summer temperature increase in Europe, due to climate change, could lead to more frequent exceedances of the ozone information threshold (hourly average concentrations of 180 $\mu g\,m^{-3}$) (EU Directive, 2002/3/EC, 2002) at the current emission levels. Although uncertainty exists, current climate change modelling studies in Europe suggest that higher temperatures like those occurred in 2003 could become the norm in the mid of the current century (Fischer and Schär, 2010; Giannakopoulos et al., 2009). As a result temperature becomes of particular interest as a predictor of ozone quality in Europe due to the ozone temperature relationship. The aim of this study is to investigate the development of an empirical-statistical model in order to examine the potential impact of increasing future temperatures on ozone exceedance days in the Greater Athens Area (GAA) using daily maximum temperatures and hourly ozone observations from two measuring stations within the GAA domain as well as daily maximum temperatures from a regional climate model.

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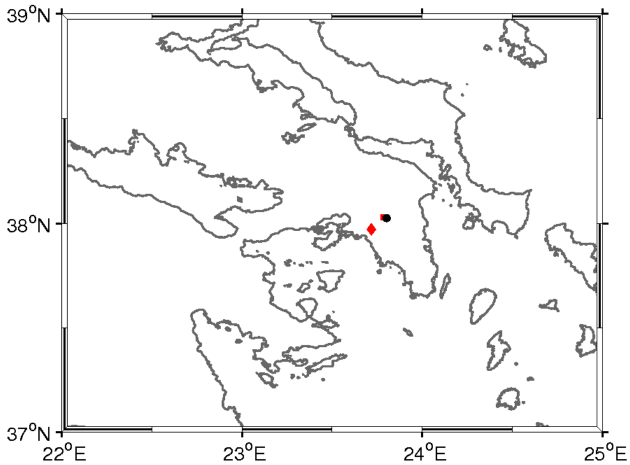

Figure 1. Greater Athens Area including the locations of the Marousi ozone station (red square), the NOA temperature station (red diamond) as well as the location of the RCM closest grid point to the ozone station location (black circle).

2 Data sources and methodology

2.1 Surface ozone and temperature observations-model data

Hourly ozone concentrations data from the suburban station of Marousi, located at the North-East of the urban core of Athens (Fig. 1), are retrieved from the Greek Ministry of Environment, Energy and Climate Change database for the 1990–1999 period. For the purpose of this study the observations are filtered choosing the daily maximum 8-h average that is calculating 8-h moving averages, indexed by the first hour, for each 8-h interval with at least 6 h of data. Local daily maximum surface temperatures are taken from the National Observatory of Athens station (NOA) located about 10 km to the South-West of the ozone station location. We extract 2 periods of daily maximum temperatures (Table 1). The period 1961–1990 is extracted for validation purposes with the regional climate model RACMO2, while a second shorter period is also extracted to correspond with the years range used in the ozone site. In addition, daily maximum temperatures, from the RACMO2 regional climate model, developed at KNMI in the Netherlands (Lenderink et al., 2003, 2007) are used. RACMO2 simulations are dynamically downscaled regional climate simulations of 25 km ($0.22° \times 0.22°$) horizontal resolution using initial and boundary conditions from the General Circulation Model (GCM) ECHAM5. For the purposes of our study 3 simulated periods of the closest grid point to the ozone station location are considered. The control period (1961–1990) for evaluating the model behavior in comparison with the observed maximum temperatures and two future projections for the periods 2021–2050 and 2071–2100. The two future period simulations of the model are based on the IPCC SRES A1B scenario (Nakicenovic et al., 2000).

Table 1. List of the data used in the analysis.

Data used in the analysis	lon	lat	year range
Ozone (Marousi)	23.78	38.03	1990–1999
Observed T_{max} (NOA)	23.71	37.97	1990–1999
			1961–1990
RCM T_{max}	23.80	38.02	1961–1990
			2021–2050
			2071–2100

2.2 Methods of analysis

To investigate the relationship of ozone exceedance days (defined here as days with maximum 8-h average ≥60 ppb) (EU Directive 2008/50/EC, 2008) with daily maximum temperature, we construct the probability distribution of ozone exceedance days. This is performed by calculating the number of ozone exccedance days in temperature bins of 1 °C divided by the total number of days whose temperature fell in that bin (Lin et al., 2001). By computing these probabilities we utililize the hypothesis that the total derivative of ozone with daily maximum temperature includes the partial derivatives of ozone with temperature-sensitive variables such as stagnation, chemistry, biogenic emissions, clear skies, weak winds (Mickley et al., 2004). In addition, the threshold temperature associated with the appearance of ozone exceedance days is derived which is applied with the future model simulations.

Subsequently we construct our empirical-statistical model by calculating the probability distribution of maximum 8-h average ozone concentration with daily maximum temperature, using bins of 1 °C above the pre-calculated temperature threshold and bins of 5 ppb for ozone concentration. If m are the number of ozone bins and n the number of temperature bins above the temperature threshold, we can derive an $\mathbf{m}\times\mathbf{n}$ matrix where each n bin describes the contribution of each temperature bin to the ozone m bins in terms of probabilities. The sum of the probabilities in each ozone m bin is the total contribution of temperatures in ozone at the same bin.

Finally the calculated probabilities of the present day from the observational dataset are used to estimate the probability distributions of the future model projections.

3 Results

3.1 Relationship of ozone exceedance days with temperature

The maximum 8-h average ozone concentration values range between 4 and 143 ppb while 28% of the days exhibit maximum 8-h average concentration above 60 ppb. The daily maximum temperature varies from 1.4 to 42 °C. The correlation coefficient between the two variables is 0.66 with the confidence limits of the 95% confidence interval calculated

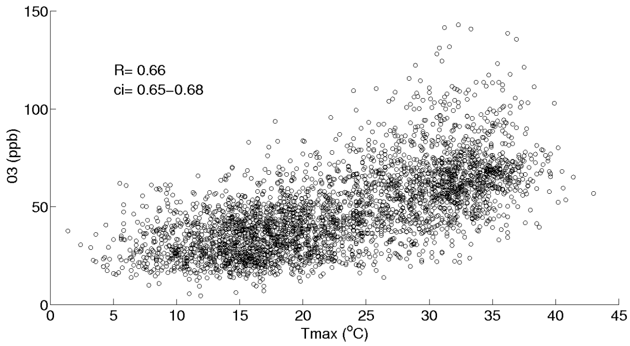

Figure 2. Correlation coefficient *R* and limits of the 95% confidence interval, *ci*, as calculated by bootstrap between maximum 8-h average ozone concentration and daily maximum temperature.

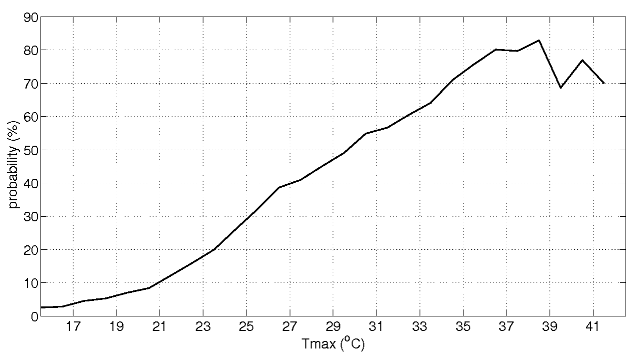

Figure 3. Probability that the daily maximum 8-h average ozone will exceed 60 ppb for a given daily maximum temperature (T_{max}) for the Marousi ozone station. Values are plotted at the mid-point temperature of the 1 °C temperature bin.

by bootstrap (Efron, 1987) varying from 0.65 to 0.68 (Fig. 2). The high values of maximum 8-h average ozone are mainly attributed to O_3 precursors, due to the traffic. The station is located downwind of the urban core, when the atmospheric conditions favor the development of sea breeze circulation over the Athens basin and it is also sited close to the forestry area of Parnitha (Bossioli et al., 2007, 2009).

From Fig. 3 it is evident that the probability of ozone exceedance days with daily maximum temperature increases over the temperature range 17 to 38 °C mainly due to high activity of photo-chemical processes. On the contrary the decline of the ozone exccedance days probability when temperature is above 38 °C can be attributed to the high sensitivity of isoprene emissions to temperature. More specifically, isoprene emissions tend to increase with temperature until a certain temperature and then decline due to the impact of high temperatures in physiological processes (Guenther et al., 1993). Due to the variability of isoprene emissions to different tree species it is found that temperatures responsible of isoprene emission decrease vary from 35 to 44 °C (Singsaas and Sharkey, 2000). Finally, the ozone exceedance days re-

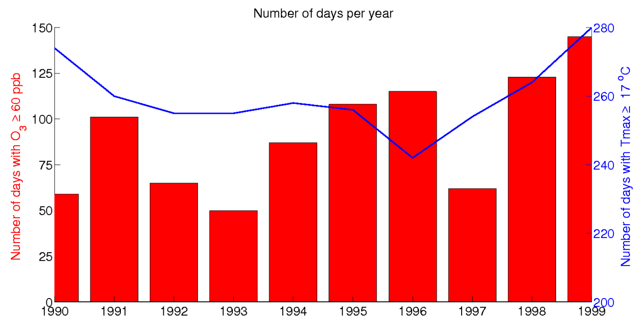

Figure 4. Number of days where daily maximum 8-h average ozone exceed 60 (red bars) and number of days where Tmax is above 17 °C (blue line) for the 1990–1999 period.

lationship with daily maximum temperature above 17 °C is reinforced by examining the number of ozone exceedance days with the number of days where temperature is above the aforementioned temperature threshold per year respectively (Fig. 4). From the figure it is apparent that the number of ozone exceedance days varies from about 50 to about 150 days.

3.2 Estimation of the future ozone exceedance days

Before presenting the results for the future simulations, the RACMO2 performance and accuracy was evaluated on an annual basis with the observed daily maximum temperature for the "recent past" period (1961–1990), using correlation coefficient and the corresponding confidence intervals for the 95-percentile as they are derived from the bootstrap percentile method. A statistically significant correlation coefficient of 0.839 (0.835–0.844) was found between the two timeseries. The analysis of the daily differences of the model and observations indicated that the model is capable of reproducing the temperature seasonal cycle. Furthermore, the 2021–2050 average annual maximum temperature in the GAA is higher by 1.5 °C than the control period whereas for the 2071–2100 the difference reaches 3.7 °C.

In Fig. 5 the probability distributions of ozone with temperature above 17 °C are shown. These distributions were calculated for the 3 periods and under the assumption of no changes in emissions for both the future periods. In general the future projections of the probability distributions follow the shape pattern of the observed. Another common feature of the two future distributions is that both indicate lower probabilities compared to the observed in the lower and higher centiles of the selected average 8-h maximum daily concentrations whereas higher than the observed probabilities are evident in the average centiles for both periods. The latter two results are in line with findings of previous climate change-air quality interactions studies (Vautard and Hauglustaine, 2007). Nevertheless, the 2021–2050 period distributions indicate smaller differences than the 2071–2100

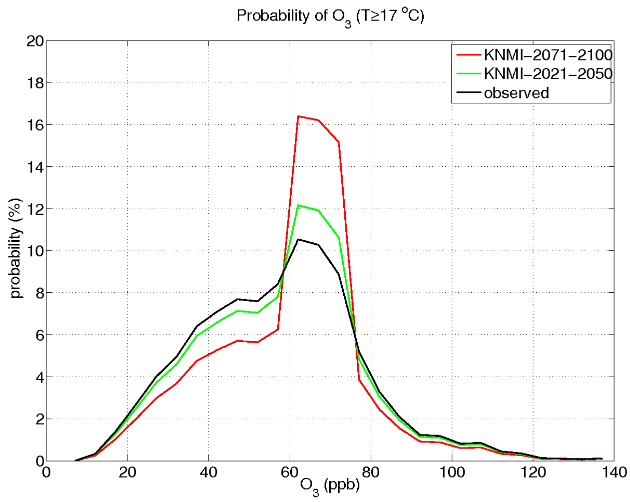

Figure 5. Ozone probability distributions for temperature above 17 °C, for three periods, the observed (1990–1999) (black), the 2021–2050 (green) and the 2071–2100 (red). Values are plotted at the mid-point concentration of the 5ppb ozone concentration bin.

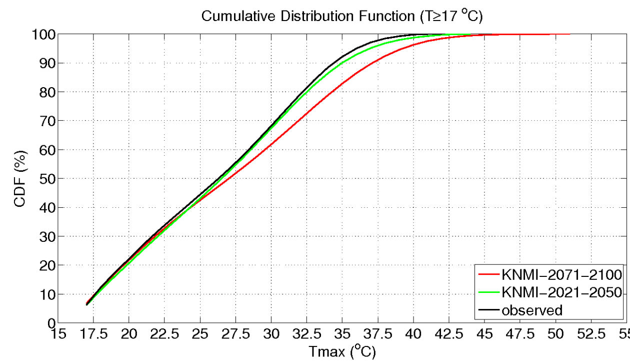

Figure 6. Cumulative distributions functions of temperature above 17 °C for the three periods, the observed (1990–1999) (black), the 2021–2050 (green) and the 2071–2100 (red).

distributions compared to the observed, due to the smaller differences in the daily maximum temperatures. As far as the number of ozone exceedance days is concerned, the results of the empirical-statistical model indicate an increase, compared to the corresponding observed distribution. In particular for the 2021–2050 simulation the percentage increase is about 8% which leads to about 7 extra ozone exceedance days per year. For the end of the 21st century (2071–2100) the percentage increase is higher, about 30% which leads to about a month (∼27 days) extra ozone exceedance days per year. Since our empirical-statistical model is temperature sensitive the cumulative distributions functions of temperature above the threshold temperature for the three periods are also examined (Fig. 6). It is evident, that there is about a 70% probability that daily maximum temperatures for the first future period are not significant higher than the observed in the 17–32 °C temperature range, whereas for the 2071–2100 the probability is only about 40% and for a smaller temperature range (17–25 °C). Thus, the increases in the number of ozone exceedance days for both future periods could be explained in a similar way from the differences between the two future periods and the observed in the higher temperature centiles. More specifically, it is very likely that the difference will be less than 0.65 °C and less than 2.86 °C between the 2021–2050 period and the observed and the between the 2071–2100 and the observed period respectively. Comparison of the results of the ozone exccedance days, especially for the near future period 2021–2050, with results from recently published studies using coupled climate-chemical models at the regional scale in Europe is encouraging for our statistical results. For instance, Forkel and Knoche (2007) using a varied-resolution climate-chemical model system emission scenario, found that the impact of climate change on its own could lead to an increase of about 16 extra ozone exceedance days in Central Europe in the 2030s compared to the 1990s.

4 Summary

This study describes the development and application of an empirical-statistical model to provide estimates of the future ozone exceedance days under the impact of climate change. It is based on the concept that daily maximum temperature is closely associated with the average 8-h maximum ozone concentrations. Our results indicate that a probable increase in the higher centiles of temperature less than 0.65 °C in the 2021–2050 and less than 2.86 °C in the 2071–2100 period compared to the observed could lead to an increase in the ozone exccedance days of about 8 and about 30 extra ozone exccedance days per year respectively. Finally, although it can be used as a quick indicator of ozone sensitivity to climate change it demonstrates two caveats. Primarily it assumes constant emissions of ozone precursors and secondly it may not capture the exceedance days seasonality (variability).

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