Hindawi Publishing Corporation
Advances in Meteorology
Volume 2012, Article ID 240894, 12 pages
doi:10.1155/2012/240894

Research Article

Modeling Effects of Climate Change on Air Quality and Population Exposure in Urban Planning Scenarios

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Received 15 March 2012; Revised 29 June 2012; Accepted 11 July 2012

Academic Editor: Eugene Rozanov

We employ a nested system of global and regional climate models, linked to regional and urban air quality chemical transport models utilizing detailed inventories of present and future emissions, to study the relative impact of climate change and changing air pollutant emissions on air quality and population exposure in Stockholm, Sweden. We show that climate change only marginally affects air quality over the 20-year period studied. An exposure assessment reveals that the population of Stockholm can expect considerably lower NO_2 exposure in the future, mainly due to reduced local NOx emissions. Ozone exposure will decrease only slightly, due to a combination of increased concentrations in the city centre and decreasing concentrations in the suburban areas. The increase in ozone concentration is a consequence of decreased local NOx emissions, which reduces the titration of the long-range transported ozone. Finally, we evaluate the consequences of a planned road transit project on future air quality in Stockholm. The construction of a very large bypass road (including one of the largest motorway road tunnels in Europe) will only marginally influence total population exposure, this since the improved air quality in the city centre will be complemented by deteriorated air quality in suburban, residential areas.

1. Introduction

Worldwide air pollution cause more than 2 million premature deaths annually [1]. A majority of the world's population today live in cities. One of the most challenging tasks of city planning is to cope with demands for efficient transport systems of the increasing urban population without risking adverse health impacts through poor air quality. The European air pollution directive states that if a proposed plan will lead to exceedances of air quality limit values, it should not be implemented. Estimates of future air quality are based on air quality dispersion models using assumptions of future air pollutant emissions. Future air quality is, however, not only a matter of emissions. City planners need also to consider climate change in order to fully assess the impacts on the environment (water and air quality), local climate (heat waves, storm water, and river flooding events), and the effects on population health. This requires much higher spatial resolution than available from global climate modeling [2]. Downscaling of global climate models to local scales has been done to assess effects on land use [3], agricultural potential [4], rain events, runoff, and local meteorology [5]. The effect of climate change on European air quality levels has been investigated in earlier studies, for example, [6, 7], but larger effects can be expected over urban areas and during pollution episodes [8]. Studies that address climate change effects on urban air quality and population exposure are only recently published. Mahmud et al. [9] assessed future exposure levels of particulate matter in California.

In this work we investigate the role of climate change on future urban air quality and compare it with the effects of changing emissions in Europe and locally in a specific urban area, namely, Stockholm, Sweden. We compare the future year 2030 pollution levels in the urban background air with current levels (ca. year 2010). We also assess the effects of different traffic solutions on future urban air quality. The impact on air quality and population exposure of a road transit scenario, in which a new bypass highway is constructed, is compared to that of a reference scenario

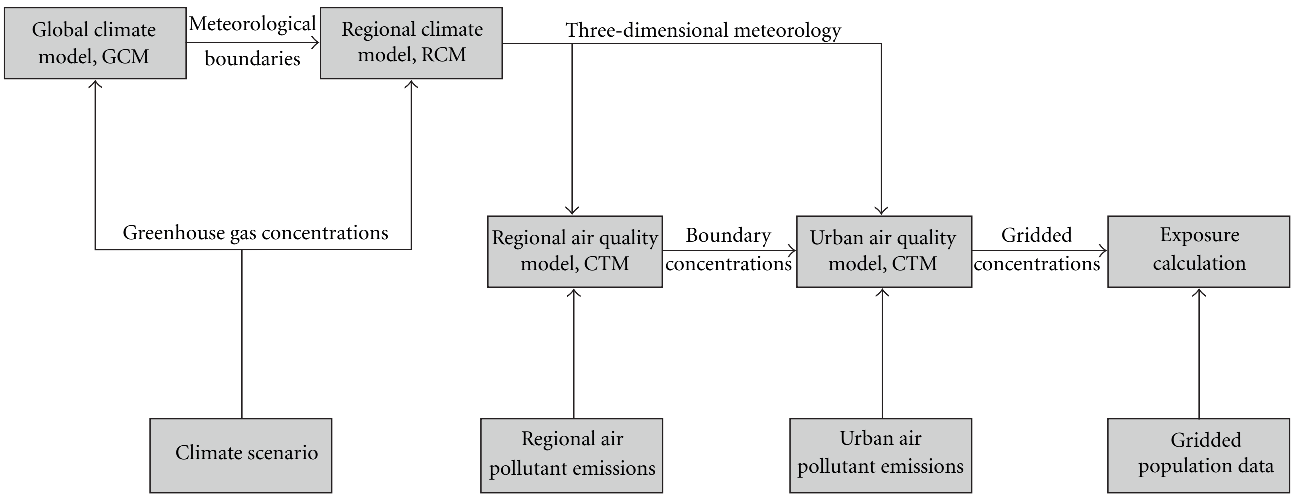


Figure 1: Conceptual overview of the model chain used in the present study. The global climate models (*ECHAM5 A1B-r3* and *HadCM3 A1B-ref*) utilizing the A1B climate scenario are being regionally downscaled by the Rossby centre regional climate model, RCA3. The regional and urban air quality models (MATCH) are driven by the same three-dimensional meteorology but forced by different emissions estimates, the urban air quality model takes boundary concentrations from the European-scale air quality model. The calculated near-surface concentrations from the urban scale air quality simulation are finally coupled to gridded population data to produce population exposure in the urban domain.

where no new roads are created. The comparison is made for year 2030 when the road project should be completed.

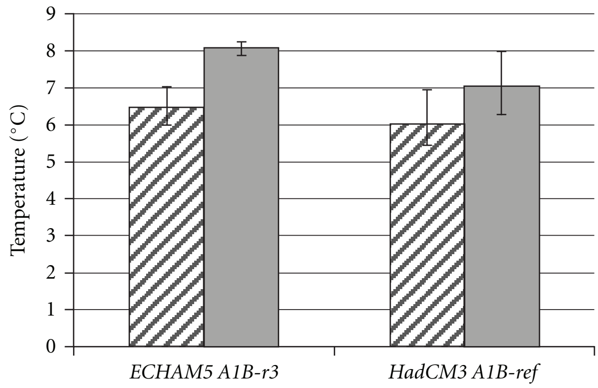
2. Methods

Figure 1 gives an overview on how different input and model results are coupled in the present study. Below we explicitly discuss some of the more important steps in our analysis of future air quality and population exposure in Stockholm.

2.1. Climate Scenarios. To assess the present and future climate in Stockholm we make use of European climate data provided by the Rossby Centre [5]. The Rossby Centre has completed a suite of regional climate simulations (climate downscaling), which provide more details over Europe than the global climate models (GCMs). The regional climate simulations address a range of uncertainties regarding projections of future climate in Europe through studying different climate scenarios (i.e., greenhouse gas concentrations), utilizing different global climate models as drivers of the regional climate model (RCM), taking into account different initial states and different climate sensitivities of the global climate models. The largest spread in the regional climate projections originates from varying the driving GCM. For our air quality simulations we will use climate downscaling of two different GCMs (*ECHAM5 A1B-r3* and *HadCM3 A1B-ref*, cf. Kjellström et al. [5]) to cover some of the inherent uncertainty in predicting the future climate. Three-dimensional regional climate data is available at model levels every 3 or 6 hours for use in the air quality models.

As an illustration of the expected climate change and intermodel differences, Figure 2 shows annual-average temperature and precipitation in Stockholm for the years used as present (2009–2011) and future (2029–2031) climate. We note that both *ECHAM5 A1B-r3* and *HadCM3 A1B-ref* feature a clear increase in local temperature, while precipitation changes only little (*ECHAM5 A1B-r3*) or increases slightly (*HadCM3 A1B-ref*); both tendencies are in line with the long-term future trend towards a warmer and wetter climate in Scandinavia reported by Kjellström et al. [5]. The short averaging times—only three years—and the limited timespan of only 20 years, result in natural year-to-year variations obscuring the long-term trends in climate. The change in wind speed is not significant in any of the two climate downscaling.

2.2. Air Quality on the European Scale. To simulate present and future air quality over Europe, we use a regional chemistry transport model (CTM)—MATCH [10, 11] driven by meteorology (precipitation updated every 3 hours, all other parameters every 6 hours) from the regional climate model, time varying emissions of air pollutants from RCP4.5 [12], and with seasonally varying tracer concentrations at the lateral and top boundaries. The boundaries were identical during the present and the future period; for numerical values, see Andersson et al. [11]. The pan-European air quality simulations operate on the same horizontal grid as the regional climate model covering Europe with 50 km resolution but using 15 model levels up to ~6 km. The set-up was recently evaluated [13], and it was concluded that the CTM simulations using climate model output were able to capture the major features of the observed distribution of surface O_3 over Europe, although the spatial correlation is lower compared to results obtained using meteorological data constrained by observations. Further details of the set-up can be found in Andersson and Engardt [7]. The RCP4.5 emissions are available on a global 0.5°× 0.5° grid every 10 years from 1960 to 2100. The RCP4.5 scenario assumes that



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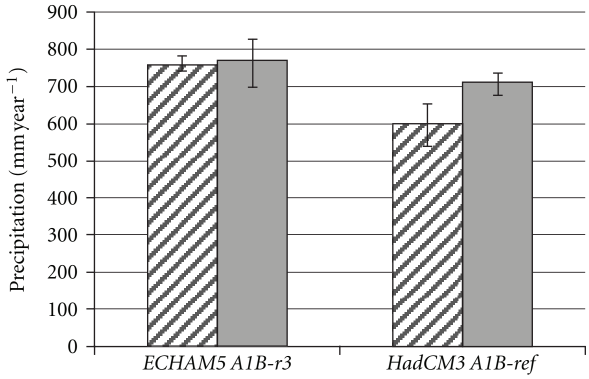

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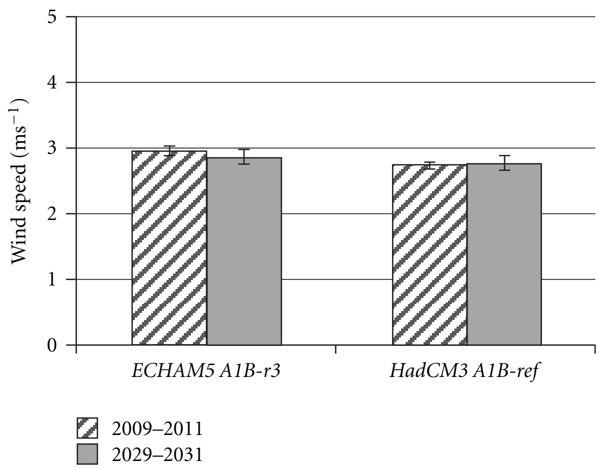


(c)

Figure 2: Three-year-averages of 2 m temperature (a), precipitation (b), and wind speed (c) at Torkel Knutssonsgatan in city center of Stockholm for the period 2009–2011 (striped) and 2029–2031 (grey). Error bars indicate maximum and minimum annual average for the 3 years.

Table 1: Local ($2 \times 2\,\text{km}^2$ grid over Stockholm) and European emissions for present situation (year 2010) and for two alternative future (year 2030) scenarios.

Substance	Present 2010 (tons/year)	Reference 2030 (compared to Present)	Road transit project 2030 (compared to Present)
Local NO_x	15 511	58.9%	59.1%
Local PM_{10}	3 879	113%	114%
Europe NO_x	26×10^6	81%	81%

all nations mitigate their emissions in response to a shared price system for greenhouse gases where different gases are priced according to their global warming potential [12]. With this driving mechanism, substantial reductions in European NOx emissions are projected between 2010 and 2030, from 26 Tg year^{-1} in 2010 to 21 Tg year^{-1} in 2030, cf. Table 1.

2.3. Air Quality Downscaling over Stockholm. The Stockholm air quality downscaling is performed by operating a high-resolution set-up of MATCH forced with interpolated meteorology from the regional climate model; the methodology follows Gidhagen et al. [14]. The urban air quality simulations take boundary concentrations—including top boundary—every three hour from the pan-European set-up of MATCH. For assessing future NO_2, and O_3 levels the urban downscaling was performed over a $102 \times 102\,\text{km}^2$ region which includes the Stockholm Metropolitan area and also the city of Uppsala north of Stockholm (Figure 3). The horizontal resolution is 2 km, and the vertical resolution identical to the European set-up, with the lowest model layer being 60 m thick. The PM_{10}, NO_2 and O_3 exposure assessment was made through a downscaling over a smaller $36 \times 30\,\text{km}^2$ domain with 1 km spatial resolution (domain also indicated in Figure 3). For PM_{10} we do not present total concentrations since the European scale model only simulates the tendencies for secondary inorganic aerosols and does not project what will happen in the future with important part of the PM mass such as organic aerosols and sea salt. However, since the downscaling over Stockholm involves primary PM and we have access to a high-quality emission inventories for both present and future periods, we can project the changes in PM exposure for different emission scenarios within Stockholm.

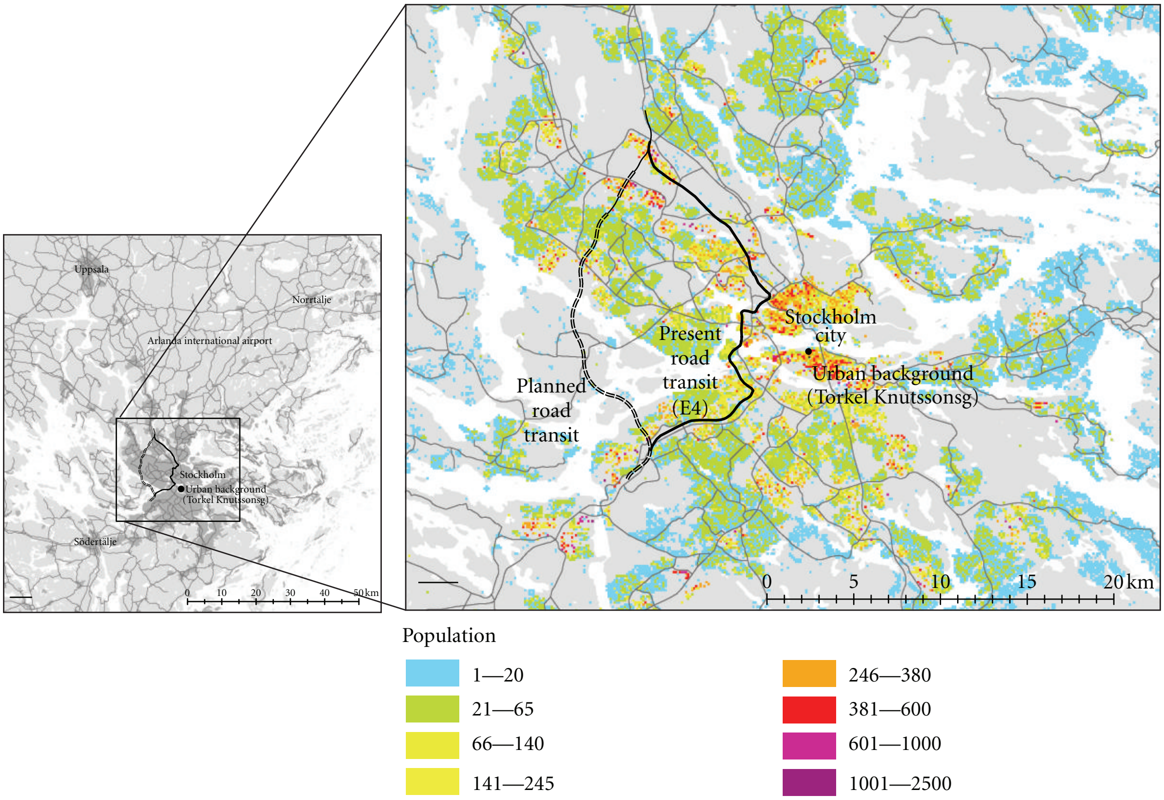


Figure 3: Map showing the air quality downscaling modeling domain ($102 \times 102\,\mathrm{km}^2$, left) and the local domain ($36 \times 30\,\mathrm{km}^2$, right) used for population exposure assessment. The locations of present and planned road transit are indicated with solid and broken lines, respectively. The location of the urban background monitoring station is indicated with a filled circle. The colors indicate population density (number of people in $100 \times 100\,\mathrm{m}^2$ squares). Thin black lines are roads. White and grey areas indicate water and land.

2.4. Urban Emissions. A detailed local emission database is administered and updated annually. It includes the two counties of Stockholm and Uppsala, covering an area with some 30 municipalities and ca. 2 million inhabitants [15]. The estimates of total traffic volumes are primarily based on *in situ* measurements. Such measurements are of different kinds: regular automatic traffic counting by the local traffic and street authorities within municipalities, automatic traffic counting on main roads by the Swedish National Road Administration, and manual surveys of traffic volumes. Variations of vehicle compositions and temporal variation of the traffic volumes are described for different road types. Present and future vehicle fleet composition and vehicle exhaust emission factors are based on the Swedish application of the ARTEMIS model [16]. In addition to the vehicle exhaust emissions there are large nontailpipe emissions of particulate matter due to wear of road surfaces, brakes, and tires. In Stockholm the nontailpipe emissions dominate and emission factors are estimated based on local measurements [17, 18].

The local air pollution emissions in the Stockholm subregions are described for three different situations: (a) current (2010) situation, (b) a future (2030) scenario with a new transit road, and (c) a future (2030) scenario without the bypass. The transit road is mainly an underground road tunnel (21 km). Emissions are described for all important sectors but the difference in emissions in the three situations is only due to differences in road traffic emissions. Traffic prognoses for the future scenarios are obtained from a national traffic forecast model system called SAMPERS [19]; a travel demand forecasting tool. SAMPERS is based on travel enquiries and describes the transports using cars, public transport, cycling, and walking depending on the distances, destination, availability of different transportation systems and so forth. It also includes a model that considers peoples willingness to pay in order to account for taxes, for example, the congestion tax in central Stockholm [20]. Traffic forecasts are based on assumptions on future developments and involve many uncertainties. Likely the largest uncertainty is due to input data, such as assumptions on future economic development, salaries, car ownership, and so forth [21]. The uncertainties of the SAMPERS model itself (due to the model, not due to input data assumptions) have been evaluated using a bootstrap method [22]. Beser Hugosson [22] found a 95-percent confidence interval to be ±8% to ±11% of the total traffic volume on the road links studied. But the uncertainties in the difference in travel demand between two traffic scenarios have not been assessed. Some of the uncertainties in input data (e.g., economic development) are likely to be less important for the difference in traffic volumes in the two future scenarios, since such input will be the same in the two future scenarios.

The two scenarios with and without the transit road have the same land-use (e.g., with respect to locations of residential areas). With the bypass road the existing congestion tax zone is extended and includes a tax on the highway-ring around the inner city. This additional tax extension is not included in the scenario without the bypass road, the motivation being that there must be a way to bypass Stockholm without having to pay a tax. The decrease in local NOx emissions between the two periods, as estimated from the planned renewal of traffic fleet and stricter vehicle emission limits, is expected to be around 40% (cf. Table 1).

2.5. Population Exposure. While assessing the environmental consequences of future urban planning scenarios, population exposure can be used as a complement to a pure comparison of air pollution concentrations. In this study we produce exposures using a $100 \times 100\,\mathrm{m}^2$ resolution population density grid (Figure 3), based on home addresses for the year of 2008 provided by Statistics Sweden. The exposure output is a population-weighted average exposure level for each scenario, together with tables indicating how many people that are exposed to a certain pollution level, and statistics on how many Stockholm citizens that will experience an improved or deteriorated air quality outside their residence as a consequence of a certain future scenario.

The 2008 population data was used to assess exposure both for present and future scenarios (future population projections with a comparable spatial precision do not exist). It is clear that the number of people exposed will be underestimated in future scenarios as population will grow. The merit of population weighted averages is that they take into account both the distribution of pollution levels and the location of densely populated areas. If population will grow without major redistribution between residential areas, then population weighted pollution averages will not change significantly with increasing population. The exposure calculation uses simulated concentrations on a $1 \times 1\,\mathrm{km}^2$ grid representing outdoor urban background concentrations, that is, no correction is made for indoor concentration levels being different.

2.6. Measurement Methods and Sites. NO/NO_2 and O_3 were measured in the urban background site (Torkel Knutssonsgatan) in the city centre of Stockholm (Figure 3). Torkel Knutssonsgatan monitoring station is located at roof-top level (25 m, close to the middle of the lowest model layer of MATCH, 30 m) not directly affected by nearby emissions [14, 20, 23]. Continuous measurement of O_3 is based on its absorption of ultraviolet (UV) light, with an absorption maximum of 254 nm (Environment S A, Model 42M). NO and NO_2 was measured by chemiluminescence (Environment S.A., Model AC31M).

3. Results and Discussion

3.1. Present and Future Air Quality. Simulations of air quality were made for a $102 \times 102\,\mathrm{km}^2$ domain that includes the Stockholm Metropolitan area as well as Uppsala, the fourth largest city in Sweden. The different combinations of meteorology, European emissions, and local emissions are summarized in Table 1. The assessment of how future air quality will evolve is focused on urban background levels in the central parts of Stockholm, as represented by Stockholm's main urban air quality monitoring station, Torkel Knutssonsgatan.

Figure 4 shows the spatial distributions of three-year average O_3 and NO_2 concentrations for the present conditions (i); for the future situation with current emissions but future climate (ii); the Reference scenario 2030 with future emissions both in Europe and in Stockholm, but without the transit road (iv). While climate change alone has a very small effect on NO_2 and O_3 concentrations, emission reductions significantly decrease future concentrations of both pollutants over the modeling domain. During both present and future periods NO_2 concentrations are highest in Stockholm, close to Arlanda international airport, and in the city of Uppsala; major roads and sea lanes are also visible. O_3 is anti-correlated with NO_2 and features the lowest concentrations in central Stockholm and the highest concentrations over the eastern, sea-dominated, part of the domain. The spatial pattern reflects relatively higher local traffic emissions of NO_X in central Stockholm and the associated O_3-NO chemistry.

Figures 5 and 6 show three-year average concentrations at the urban background monitoring station (its location shown in Figure 3), where the simulated levels for present conditions are compared to measured concentrations. The figures also show the concentrations resulting from the two different climate scenarios as meteorological driver (*ECHAM5 A1B-r3* or *HadCM3 A1B-ref*), all other input kept the same. In total four different experiments were evaluated (cf. Table 2):

(i) The present situation (2009–2011) using European emissions valid for 2010 as well as local Stockholm emissions for 2010.

(ii) The climate change effect on air quality in Stockholm is assessed through retaining all emissions at their 2010 level, but using the climate around 2030 for both the regional and local air quality simulations.

(iii) The climate change effect together with the European emission reductions as given by the RCP4.5 scenario, but retaining local Stockholm emissions at the 2010 level. This experiment illustrate the expected evolution of pollution levels in the long-range incoming air.

(iv) Climate change, time-varying European emissions according to RCP4.5 and also a local Stockholm emission scenario projected for 2030.

Figure 5 shows that the simulated average concentrations of O_3 for the present situation (i) are within the variability of the measured levels both for the *ECHAM5 A1B-r3* and *HadCM3 A1B-ref* simulation, but *HadCM3 A1B-ref* predict 8% higher concentrations compared to *ECHAM5 A1B-r3*. The simulated 8-hour daily maximum concentrations are lower than observed concentrations, indicating that the

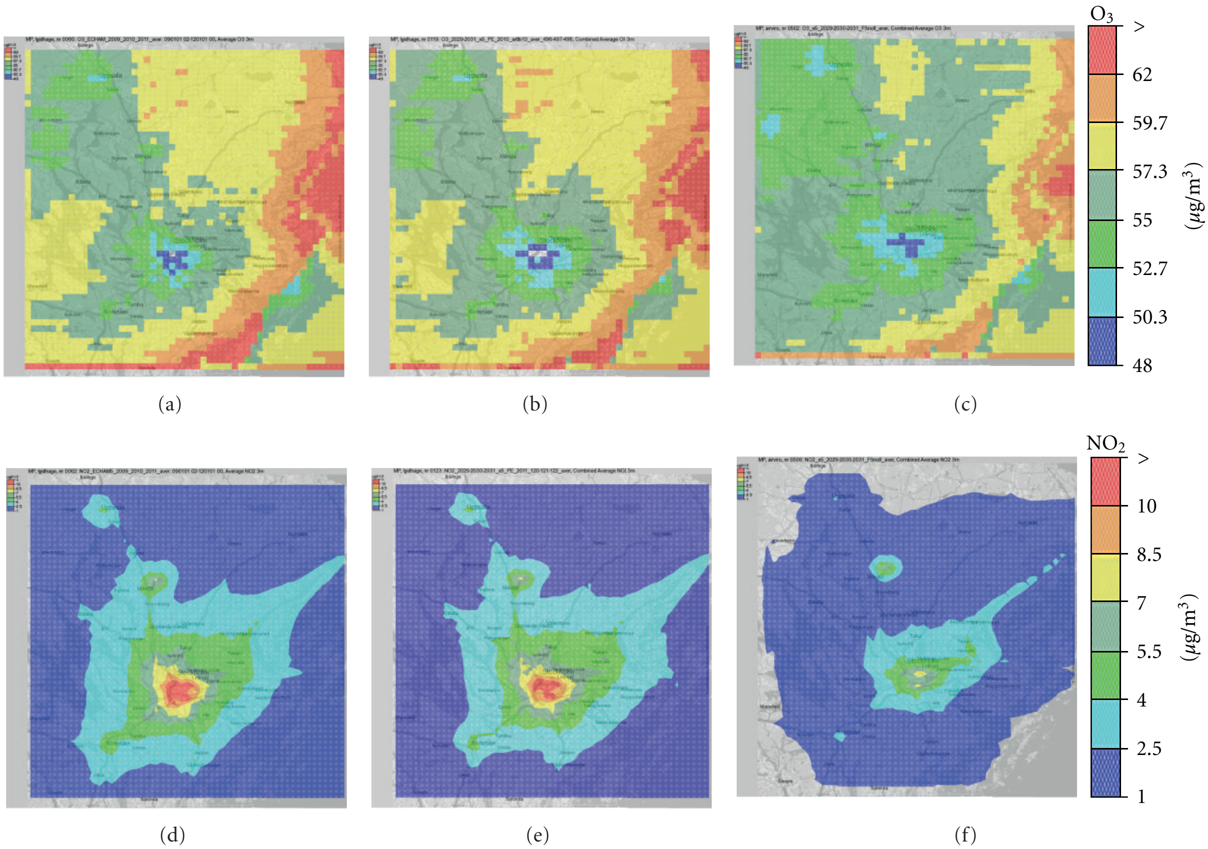


Figure 4: Simulated three-year-average O_3 (top) and NO_2 (bottom) concentrations in 2009–2011 (case i, left), 2029–2031 (case ii, middle), and 2029–2031 (case iv, right) in the downscaled area over the Stockholm region, based on *ECHAM5 A1B-r3* climate and RCP4.5 emissions in Europe.

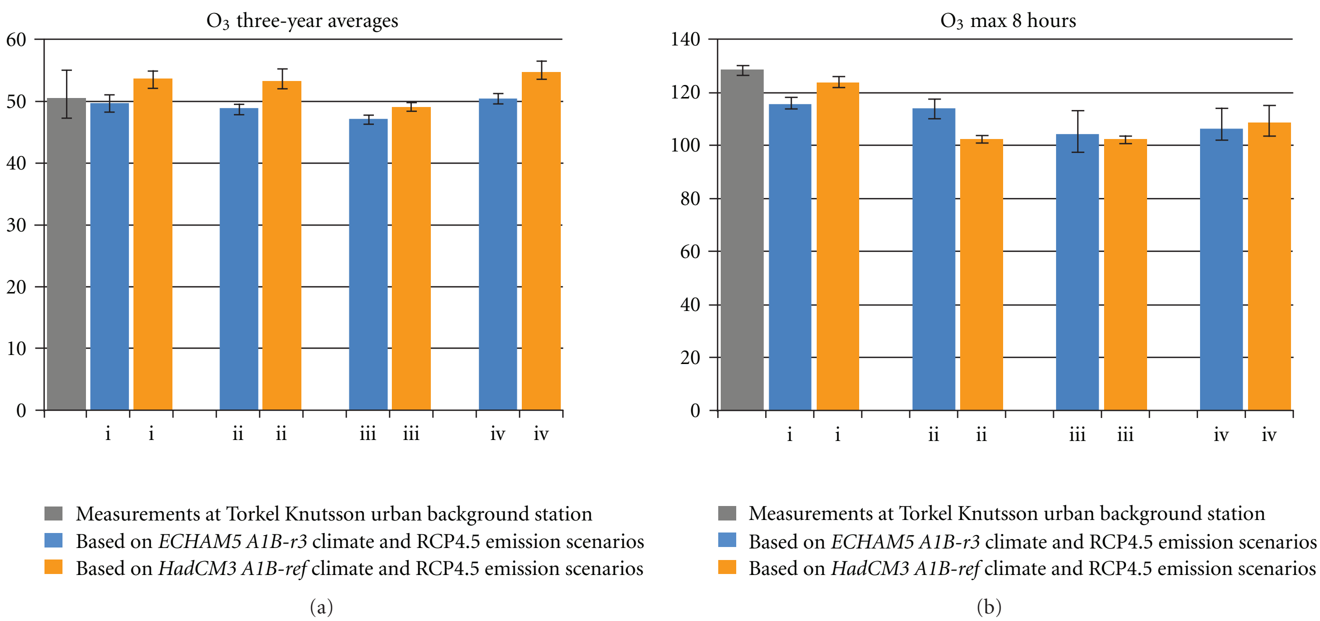
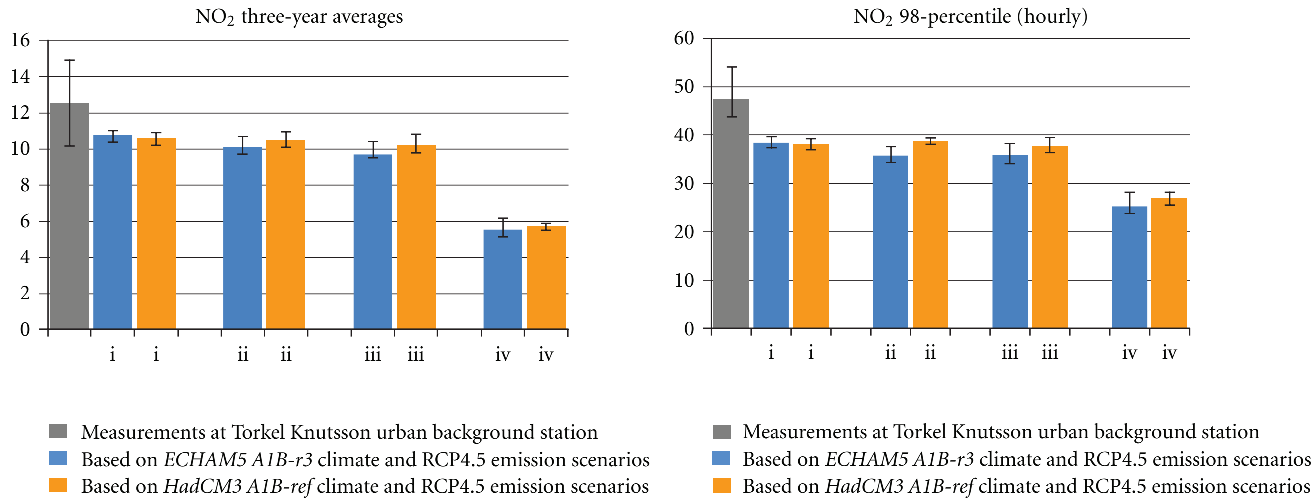


Figure 5: Observed and simulated levels of O_3 diurnal mean (a) and maximum 8-hour levels (b) at Torkel Knutssonsgatan (city centre of Stockholm), for present conditions (i) and simulated projections of future levels with only climate change effect (ii), including also emission changes in Europe (iii), and adding local emission changes in Stockholm (iv), see Table 2 for explanations. Error bars indicate lowest and highest annual average value of the three years. Unit: $\mu g m^{-3}$. Simulated concentrations are bilinearly interpolated to the location of the monitor location.



(a) (b)

Figure 6: Observed and simulated levels of NO_2 diurnal mean (a) and 98-percentile of hourly levels (b) at Torkel Knutssonsgatan (city centre of Stockholm), for present conditions (i) and simulated projections of future levels with only climate change effect (ii), including also emission changes in Europe (iii) and adding local emission changes in Stockholm (iv), see Table 2 for explanations. Error bars indicate lowest and highest annual average value of the three years. Unit: $\mu\,\mathrm{g\,m^{-3}}$. Simulated concentrations are bilinearly interpolated to the location of the monitor location.

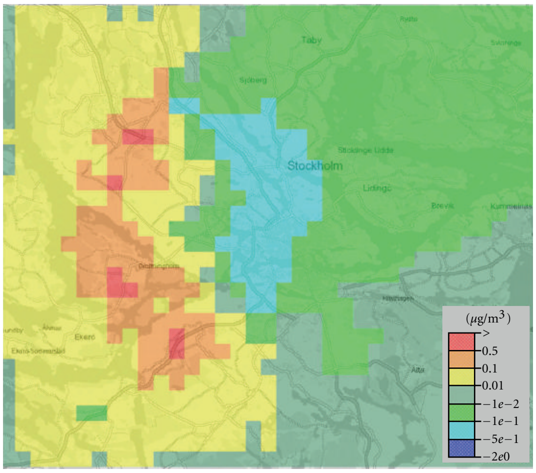
Table 2: Model simulations performed for the large metropolitan area with $2 \times 2\,\mathrm{km}^2$ spatial resolution. Present and future meteorology represent 3 full years centered around 2010 and 2030, receptively. Data generated by the RCA3 model forced with *ECHAM5 A1B-r3* and *HadCM3 A1B-ref* on the boundaries.

Case	Simulation scenario	European emissions	Local Stockholm emissions
(*i*)	Present meteorology Present European emissions Present Stockholm emissions	RCP4.5 at 2010	database 2010
(*ii*)	Future meteorology Present European emissions Present Stockholm emissions	RCP4.5 at 2010	database 2010
(*iii*)	Future meteorology Future European emissions Present Stockholm emissions	RCP4.5 at 2030	database 2010
(*iv*)	Future meteorology Future European emissions Future Stockholm emissions	RCP4.5 at 2030	Reference 2030

climate and air quality simulations representing present conditions underestimate the extreme O_3 concentrations. This tendency also holds for comparison of simulated and measured NO_2 concentrations as shown in Figure 6. The average simulated levels are within the inter-annual variability of the measured concentrations, but for the 98-percentile of the hourly values, the calculations underestimate the concentrations both in the *ECHAM5 A1B-r3* and *HadCM3 A1B-ref* simulations of the present situation. A multimodel study where the *ECHAM5 A1B-r3* climate scenario was used for an evaluation against measured ozone levels across Europe during 1997–2003 also showed that the MATCH model gives a good estimate of average ozone levels but an underestimation of summertime extreme values [24].

The simulation with changed climate but present (2010) European air pollution emissions (ii) demonstrate that the effect of climate change is minor on the average concentrations, this applies both to O_3 (Figure 5) and NO_2 (Figure 6). A larger impact is seen on the average 8-hour daily maximum O_3 concentrations, which reflects the potentially larger impact of climate change on the extreme values of O_3. A weak decreasing trend in background O_3 concentration in northern Europe from 2000–2009 to 2040–2049 was also detected in a recent multimodel study [24] on the impact of climate change on European surface O_3 concentrations.

The reduction of European NO_x emissions (as well as other O_3 precursors according to RCP4.5 [12]), case iii, results in slightly reduced average ozone concentrations. This



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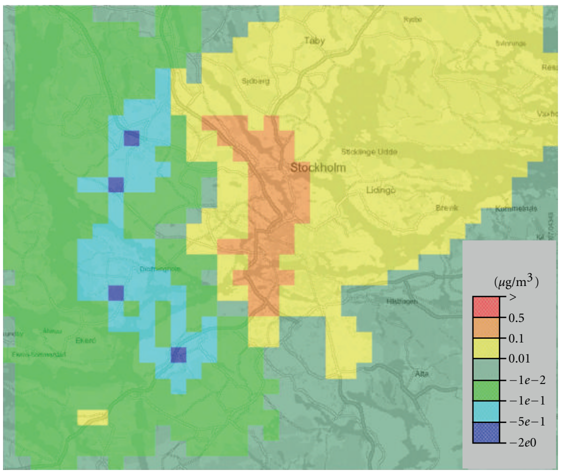

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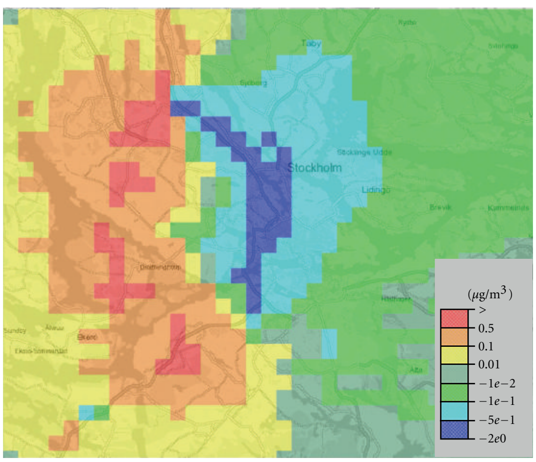


(c)

Figure 7: Differences in simulated NO_2 (a), O_3 (b), and PM_{10} (c) between the 2030 Road project and Reference average concentrations. Unit: $\mu\,\mathrm{g\,m^{-3}}$.

Table 3: Population-weighted average exposure given for a total population of 1 463 780 persons living inside the modeling domain. Model simulations performed for the smaller Stockholm domain with $1 \times 1\,\mathrm{km}^2$ spatial resolution. Air quality simulations were made for the single year 2010 and 2030, with RCA3 downscaled *ECHAM5 A1B-r3* meteorology and time varying RCP4.5 emissions over Europe. Unit: $\mu\,\mathrm{g\,m^{-3}}$.

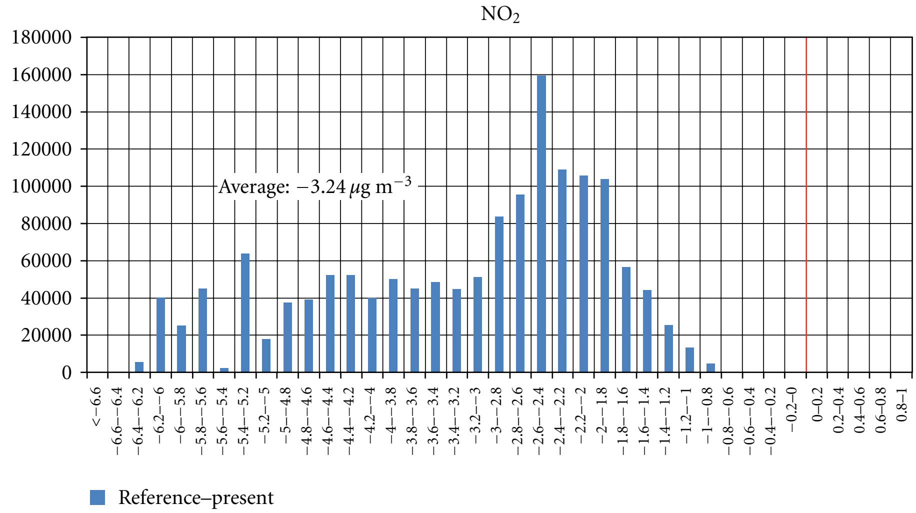
Simulation scenario	Local Stockholm emissions	Population weighted exposure	
		NO_2	O_3
Present conditions	database 2010	6.85	54.13
Future: Reference	Reference 2030	3.62	53.05
Future: Road project	Road transit project 2030	3.60	53.06

is valid for both climate scenarios, but with *HadCM3 A1B-ref* forcing there is a stronger reduction of O_3 in Stockholm during the studied period. For NO_2 average values the impact of reduced European NO_x emissions is small and comparable with the climate change-only effect. Extreme NO_2 values are also not significantly affected by the emission reduction in Europe; a consequence of the strong influence of local NO_x emissions, which in this case are kept constant at the year 2010 level.

The last simulation, case iv, (see also Figure 4) includes the combined effect of climate change and changes in European as well as local emissions. For NO_2 this results in a significant reduction (halving the average levels). This scenario, where local NO_x emissions are reduced with 40%, results in increased ozone levels in the city centre compared to present levels.

3.2. Population Exposure. Simulations for the exposure calculations were made with $1 \times 1\,\mathrm{km}^2$ spatial resolution over the smaller domain covering $36 \times 30\,\mathrm{km}^2$, which has a population of close to 1.5 million distributed as shown in Figure 3. This experiment utilized the *ECHAM5 A1B-r3* meteorology with European air pollutant emissions valid for either 2010 or 2030. The objective was to quantify and compare, on one hand, the present and the future air pollutions levels and, on the other hand, assess the expected differences in future air quality resulting from two different traffic solutions.

The general characteristics of how NO_2 and O_3 concentrations develop between present and future (Reference scenario without road project) were shown for the larger modeling domain in Figure 4. Figure 7 shows the difference in one-year average NO_2, O_3, and PM_{10} concentrations between the two future scenarios (with and without the bypass road). Even though the total local emissions of NO_x and PM_{10} are similar for the two local 2030-scenarios (see Table 1), there are considerable changes in emissions in certain areas. Since most of the new transit road will be constructed as an underground highway tunnel, the location



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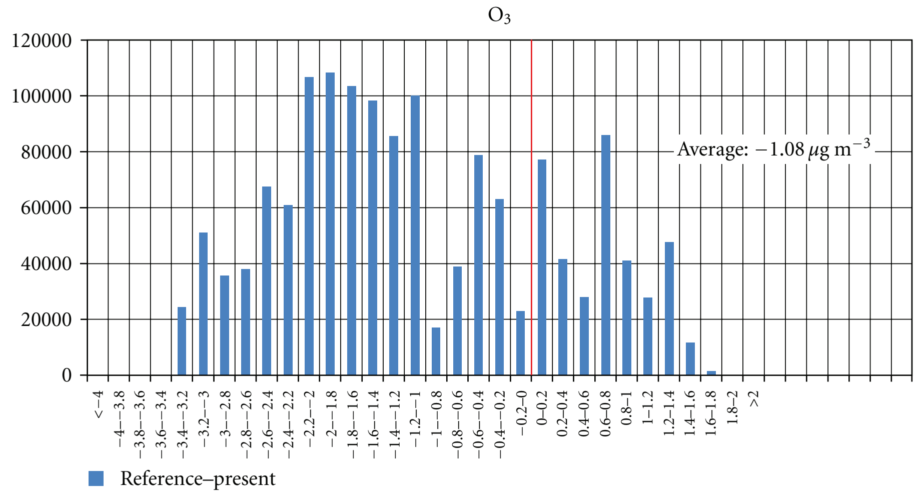


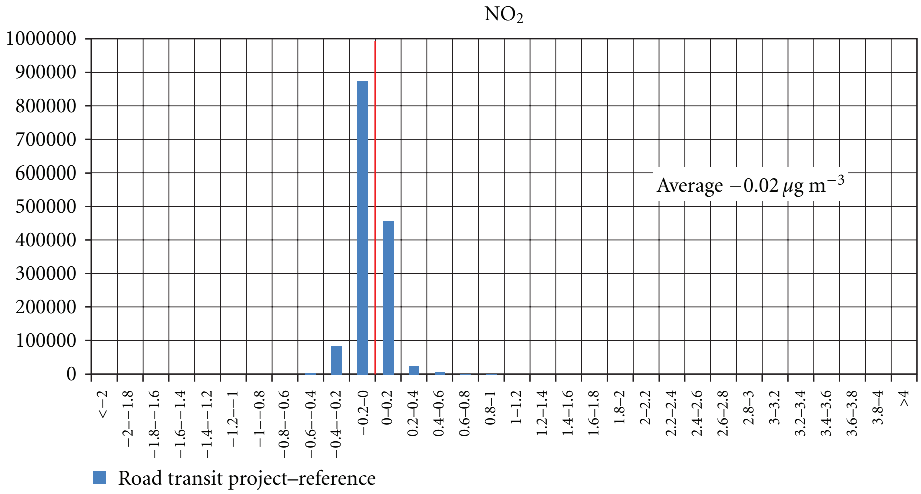
(b)

FIGURE 8: Differences in the number of inhabitants exposed to NO_2 (a) and O_3 (b) concentration levels "Reference" (2030)—"Present" (2010). The red vertical line indicates zero difference. All simulations made with *ECHAM5 A1B-r3* and RCP4.5 time varying emissions. Unit x axis: $\mu\,\mathrm{gm}^{-3}$.

of the emissions will be very different compared to a situation with a highway on the ground. Most emissions from the tunnel will be ventilated in 10 to 20 meter high towers, with some emissions occurring at tunnel exits at ground surface level. The Figure 7 concentration differences indicate the locations of the pointwise emissions from the underground highway's ventilation towers.

The main difference between the two alternatives is that there will be much less traffic emissions close to the city centre with the new transit road, but this is accompanied with a negative impact on the air quality (NO_2 and PM_{10}) west of the city centre. Figure 7 also illustrate how ozone levels are anticorrelated with traffic-induced air pollution. It should be noted that concentration differences are small, for NO_2 and O_3 rarely exceeding $0.5\,\mu\,\mathrm{gm}^{-3}$. For PM_{10} we can see a somewhat larger effect where large parts of the city centre concentrations are lowered 0.5–2.0 $\mu\mathrm{g\,m}^{-3}$.

Table 3 summarizes the population-weighted concentrations for NO_2 and O_3. For both pollutants population-weighted exposure will decrease from 2010 to 2030; for NO_2 the exposure reduction is almost 50%. The reason is, as discussed earlier, the expected strong reductions in local road traffic emissions. For ozone it is the lower concentrations in incoming, background, air that will result in a reduction of the average population weighted exposure level. Figure 8 shows that all residents can expect lower NO_2 concentrations outside their homes in 2030 compared to present situation. However, despite the overall reduced population-weighted ozone concentration, some 25% of the population will experience higher ozone levels in the future. The reason is the decreased amount of NO available in the city-centre for destroying O_3 in the future. Table 3 also shows that the average population-weighted exposure for the two future scenarios are only marginally different, although



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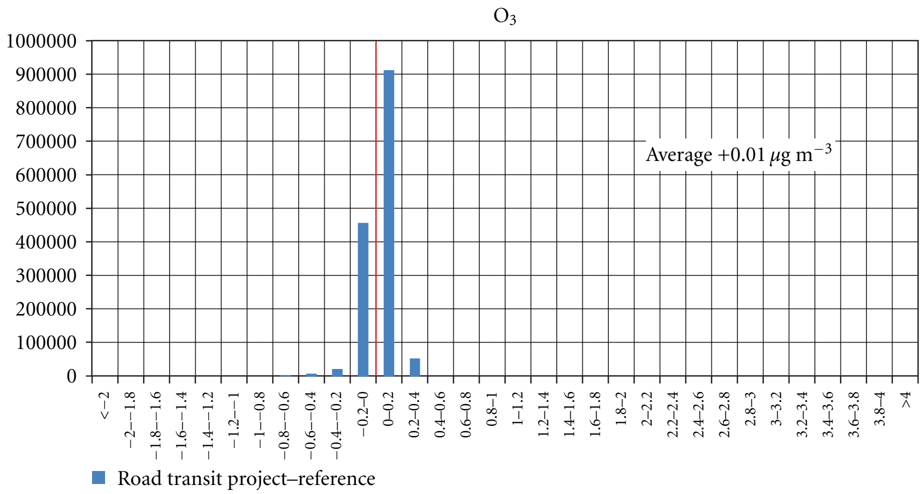

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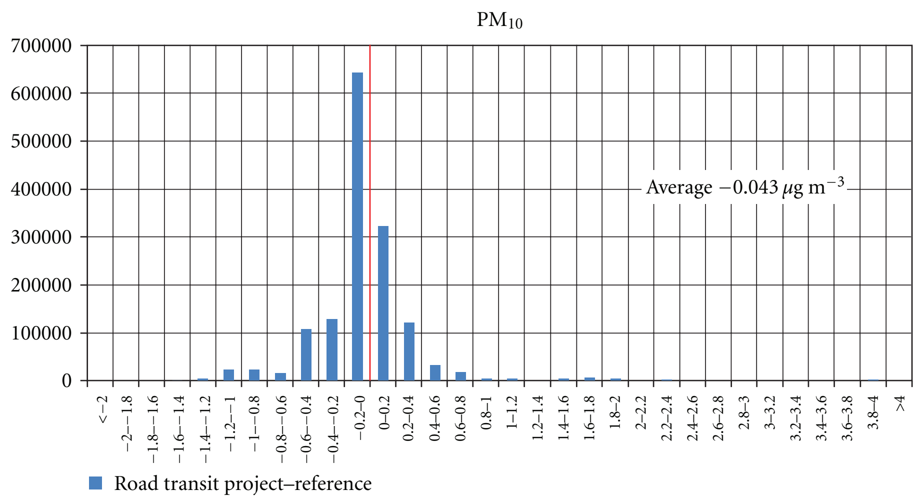

(c)

Figure 9: Differences in the number of inhabitants exposed to NO_2 (a), O_3 (b), and PM_{10}, (c) concentration levels between "Road transit project"—"Reference", both scenarios valid for 2030. The red vertical line indicates zero difference. All simulations made with *ECHAM5 A1B-r3* and RCP4.5 time varying emissions. Unit x axis: $\mu\,\mathrm{gm}^{-3}$.

they for individuals may imply a considerable difference. Figure 9 shows differences in population exposure of NO_2, O_3, and PM_{10} between the two future scenarios, with and without the planned road transit. With the realization of the road transit project, a majority of people will experience a minor reduction in NO_2 concentrations compared with the situation with present roads, but at the same time a minor increase in ozone concentrations. The PM_{10} level differences are similar to those of NO_2 (the same traffic source), but the local impact is stronger since local emission are not expected to decrease. Figure 9 illustrates that the bypass is not an effective action to lower air pollution exposure in Stockholm. Even if there is a small average reduction of population-weighted PM_{10} exposure of $0.04\,\mu\mathrm{g\,m}^{-3}$, there will be a population share of more than 100 000 persons that will experience an exposure increase of 0.2–0.4 $\mu\mathrm{g\,m}^{-3}$ and more than 10 000 persons will experience exposure increases $>1.5\,\mu\mathrm{g\,m}^{-3}$.

As described in Section 2, the simulation of future long-range concentrations of PM_{10} are not fully described in our modeling-system, which means that we can only discuss changes caused by local scenarios. A recent study from California [9] found that climate change will contribute to a small decrease in future PM_{10} levels, comparing the conditions year 2000 to those simulated for 2050. The net change over this period was however smaller than the inter-annual variations and mostly driven by an increase in average wind speed (more dilution of local sources). They could also see that higher temperatures will increase the formation of secondary inorganic aerosols. Climate change conditions in Stockholm are different from California, so a similar assessment in Stockholm is definitively of interest (Sweden is also much influenced by primary PM emissions in Europe, so that future levels will depend a lot on the rate of emission reductions).

Mahmud et al. [9] also reported more stagnation periods in the future that also contributed to higher extreme values in local (traffic and wood combustion) PM. From our assessment of NO_2 extreme values (Figure 6)—which should respond in a similar way as PM10 to stagnation conditions-responding to the sole effect of climate change, we cannot see any trend towards higher values in the future. Note, however, that we have only simulated three years, which is a too short period to conclude on extreme values.

4. Conclusions

In this study we have used regional downscaling of two different global climate models (*ECHAM5 A1B-r3* and *HadCM3 A1B-ref*) together with the RCP4.5 air pollution emission data to assess the importance of changing climate and changing emissions for the concentrations of O_3 and NO_2 in the urban area of Stockholm in 2030. Comparison of simulations for present situation (mean values for the period 2009–2011) shows acceptable agreement with measurements in the urban background for both climate realisations. The effect of a changing climate is small. Decreased future emissions of O_3 precursors in Europe will reduce O_3 production in Europe, but this effect is partly compensated for by increased hemispheric background concentrations of O_3 [13], leading to only modest changes in O_3 affecting the urban area of Stockholm.

The exposure assessment revealed that all residents can expect considerably lower NO_2 exposure in the future. Ozone exposure will change only marginally, partly due to decreased concentrations in the suburban areas and increased concentrations in the city centre.

We have also shown that a very large road transit project (involving the construction of one of the largest motorway road tunnels in Europe) will only marginally influence population exposure, since the improved air quality in the city centre will be complemented by deteriorated air quality in other residential areas.

Acknowledgments

This work has been cofunded by SUDPLAN: Sustainable Urban Development Planner for Climate Change Adaptation, European Framework Program 7, ICT-2009-6.4 ICT for Environmental Services and Climate Change Adaptation of the Information and Communication Technologies program, Project no. 247708.

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