# CityZen

megaCITY - Zoom for the Environment

Collaborative Project

*7th Framework Programme for Research and Technological Development*

**Cooperation, Theme 6:**

**Environment (including Climate Change)**

Grant Agreement No.: 212095

# Deliverable D4.1.2, type R

## The regional and global impact of selected megacity areas due to changes in population distribution

Due date of deliverable: project month 30

Actual submission date: project month 36

Start date of project: 1 September 2008 Duration: 36 months

Name of lead beneficiary for this deliverable: UiO

Scientist(s) responsible for this deliverable: Frode Stordal, Øivind Hodnebrog

Contributing authors: Frode Stordal, Øivind Hodnebrog, Øyvind Seland, Michael Gauss

| **Project co-funded by the European Commission within the Seventh Framework Programme (2007-2013)** | | |
|---|---|---|
| **Dissemination Level** | | |
| **PU** | Public | X |
| **PP** | Restricted to other programme participants (including the Commission Services) | |
| **RE** | Restricted to a group specified by the consortium (including the Commission Services) | |
| **CO** | Confidential, only for members of the consortium (including the Commission Services) | |

# The regional and global impact of selected megacity areas due to changes in population distribution

Two studies have been performed within CityZen to look specifically at the effect of changes in population distribution. In the absence of detailed migration scenarios for European and/or Chinese population hotspots, we have defined a set of sensitivity studies that could be performed with a coupled meteorology-chemistry model and a couple aerosol-climate model, respectively.

In the first study, conducted by UiO and described in Section 1, different population distributions were realized through varying the resolution of emission data. For instance, a lower resolution of emissions will correspond to a more even distribution of population. The focus in that study was on air pollution and local to regional effects.

The second study, performed by met.no and to be presented in Section 2, distributed emissions over large areas. The focus there was on climate forcing, from regional to global scale. Results from the second study also contributed to deliverable D2.5.1.

## 1 WRF-Chem study

We have used the WRF-Chem model to study impacts of various horizontal resolutions of emissions of ozone precursors on ozone formation over three megacities (Hodnebrog et al., 2011, denoted further as HSB = Hodnebrog, Stordal, Berntsen). In this report we use the results from this work to quantify the impact of various population distributions in the three cities.

In HSB we made calculations for two 3-day summer periods in July and August 2003 for the three megacities; London, Ruhr, and Cairo. In this report we focus on one of the periods, namely August 4-6 which was within the 2003 heat wave over Europe. Simulations were performed with constant WRF model resolution ($9 \times 9$ km$^2$) and with megacity emission resolutions at $9 \times 9$ km$^2$, $27 \times 27$ km$^2$, and $81 \times 81$ km$^2$, by using detailed emission inventories averaged to the appropriate resolution. In order to quantify the megacities' contributions to regional ozone, simulations without megacity emissions were also performed. Comparisons with measurements were made for the London simulations, showing a relatively good representation of the ozone diurnal cycle. In the extreme situation of the European heat wave in August 2003, the ozone values were quite well reproduced by the model, except for an underestimation of the peak daytime ozone values at some stations.

The HSB study investigated impact of megacities on the regional and global environment. In that context the underlying issue was non-linearities in the ozone chemistry, in particular inaccuracies that arise due to non-linear ozone chemistry when megacity emissions are implemented at a typical resolution of global CTMs. Based on several 3-day model simulations performed with the mesoscale numerical weather prediction model WRF-Chem, the HSB results indicate that there are generally small differences in the concentration of large-scale ozone formed from megacities when changing the megacity emission resolution from 9 km × 9 km to 81 km × 81 km (global CTM scale). In the July 2003 time period for London, we found a 12 % higher value of net ozone formed from the megacity when using coarse emissions (81 km × 81 km) compared to fine emission resolution (9 km × 9 km), and this was caused by stronger ozone production outside the megacity region in the coarse emission resolution simulation. Corresponding values for the five other case studies were less than 4-5 % and variable in sign. Thus the effect is moderate but not negligible.

In this report the focus is on distribution of ozone within the megacity itself. Still the complex and non-linear relation between constituents stemming from the various ozone precursor emissions is

the main issue. Results from three experiments are used in this report, as shown in Table 1. In the first experiment, 9X, we have run the model with a resolution of 9 km x 9 km in the megacities, in accordance with how population is currently distributed. In the next experiment, 81X, we mimic that the population is more spread out by assuming constant emissions over 81 km x 81 km grid cells. In this case we average the 9X emissions so that the total emissions are not changed. As we wanted to see the impact of the change in population distribution in relation to the effect of the megacity itself, we conducted a reference experiment, RX, without any emissions in the megacity. In all cases the resolution of the emissions outside the megacity was taken as 81km x 81 km.

### *1.1 Emissions*

The emissions in the three cases are shown in Figure 1. We have included anthropogenic emissions of the ozone precursors CO, $NO_X$, and NMVOC from various emission inventories in the WRF-Chem model (Table 2). The emissions were merged into each of the model domains to ensure that the highest available resolution was used for each model grid box. For the United Kingdom, emissions from the UK National Atmospheric Emissions Inventory were used for the year 2005 (NAEI, 2007), but they were scaled to 2003 based on factors derived from Dore et al. (2007), where yearly estimates of each source category and each species are given. Anthropogenic emissions for the North Rhine-Westphalia (NRW) region have been provided by Landesamt für Natur, Umwelt und Verbraucherschutz (LANUV) through CityZen. The following emission sources were included in the LANUV data set: industry (year 2004), small heating systems (2004) and traffic (2000/2004/2007). The INERIS/EMEP inventory was used for the remaining emission source categories in the NRW region. Also, to ensure consistency, the yearly totals of each of the emission sources in the LANUV inventory were scaled to the corresponding 2003 values of the INERIS/EMEP emissions, but the spatial distribution in the LANUV data set was kept unchanged.

In the framework of CityZen, INERIS downscaled the EMEP emissions (http://www.emep.int) from a 0.5° × 0.5° grid to a horizontal resolution of 0.1° × 0.1° using data from GLOBCOVER (http://ionia1.esrin.esa.int). The two proxies “Crops” and “Artificial areas” in GLOBCOVER were used to regrid the original EMEP inventory for agricultural and other anthropogenic sectors, respectively. In this study, INERIS/EMEP data for the year 2003 were used for the regions of Europe that were outside UK and NRW. For the small region that was outside the INERIS/EMEP coverage, anthropogenic emissions from the RETRO project (http://retro.enes.org) were used for the year 2000.

Apart from the RETRO inventory, emissions of NMVOC were aggregated, implying that a split into different NMVOC species had to be made before inclusion in the WRF-Chem model. Based on UK emissions of the 50 most significant NMVOC species (Dore et al., 2007), source-dependent factors were calculated and applied to each grid cell in the NAEI, LANUV and INERIS/EMEP emissions data. The different NMVOC species were next lumped into the corresponding RADM2 components. After horizontal interpolation to the model grid, the emissions were given a diurnal profile depending on emission source. We have used monthly temporal scaling factors available at the Unified EMEP model web page (http://www.emep.int/OpenSource/) to scale the emission data to July and August based on country, species and emission sector. As the summer months normally are holiday periods in Europe, the scaling leads to lower anthropogenic emissions compared to the yearly averages. Regarding vertical distribution, a profile for each emission sector was assumed according to EMEP (2003).

*Table 1: The model simulations that have been run for each of the three megacities.*

| Acronym | Description of model simulation |
|---|---|
| 9X | Emissions at 9 km × 9 km in megacity, 81 km × 81 km elsewhere |
| 81X | Emissions at 81 km × 81 km in megacity and elsewhere |
| RX | Reference with no emissions in megacity, 81 km × 81 km elsewhere |

*Table 2: Emission inventories used in the simulations (from Hodnebrog et al., 2011).*

| Inventory | Resolution | Coverage |
|---|---|---|
| NAEI | 1 km × 1 km | United Kingdom |
| LANUV | 1 km × 1 km | North Rhine Westphalia (NRW) |
| INERIS / EMEP | 0.1° × 0.1° | Europe (approx.) |
| RETRO | 0.5° × 0.5° | Global |

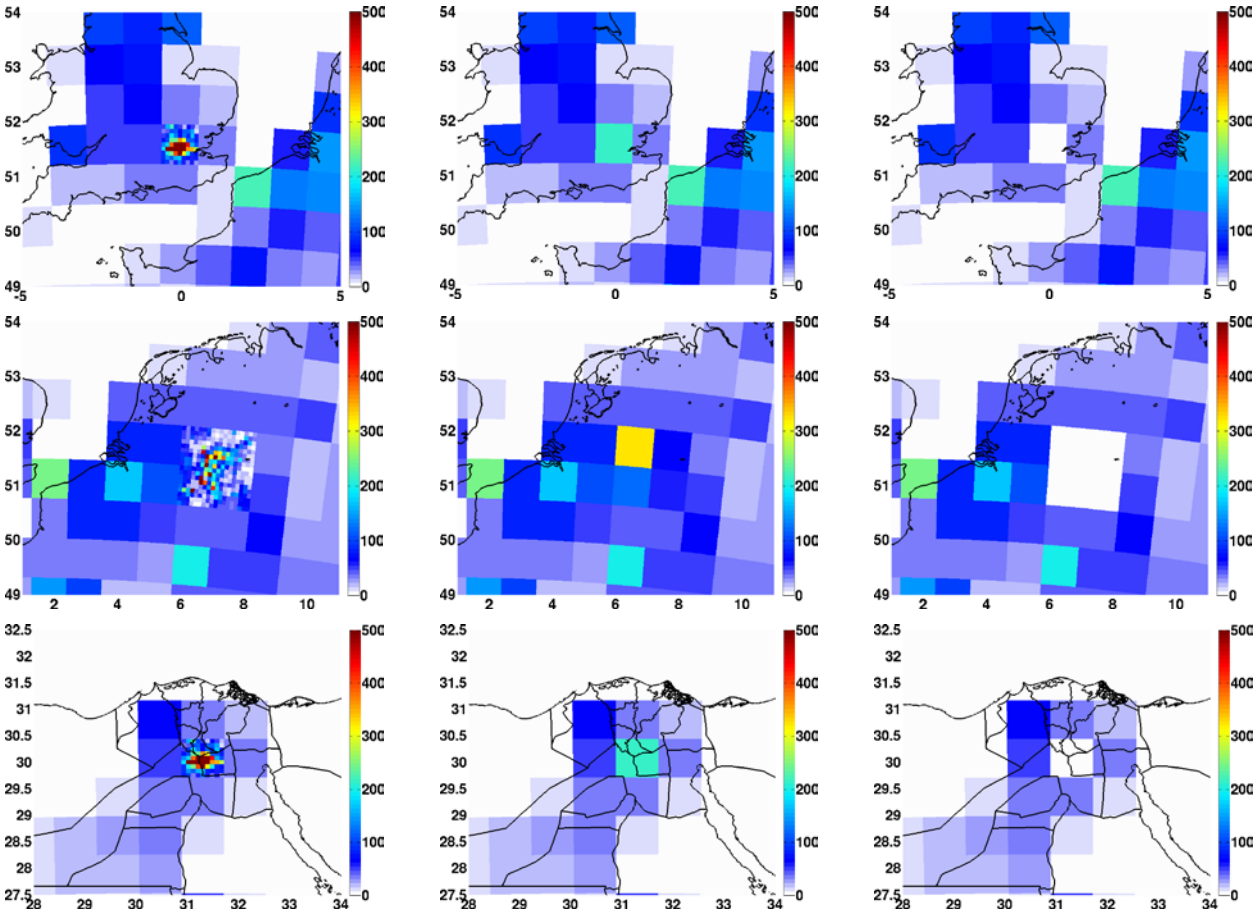

*Figure 1: Emissions of CO (mol km$^{-2}$ hr$^{-1}$) in simulation 9X (left), 81X (middle) and RX (right) shown for London (top), Ruhr (middle), and Cairo with London emissions (bottom).*

### *1.2 Impacts on the CO distribution*

Anthropogenic emissions of CO in Europe are large, and thus we see a strong impact on the concentrations of CO in Europe (Figure 2, two top left column panels). It is worth noticing that only a moderate part of these emissions stem from the restricted regions of London (upper panel) and Ruhr (middle panel) themselves, but more important from the larger European domain. This can be seen in the case of Cairo (bottom panel) where we have assumed London emissions. In that case emissions in the surrounding areas are much smaller than in Europe, so that the CO concentrations in the region are much more moderate than over Europe.

The impact of each of the three megacities is more alike in Europe and around Cairo (centre column panels, Figure 2). In all cases the contributions of the emissions are locally around 30-50 ppb. Ruhr seems to have the most widespread impact, as the emissions in the selected region are larger than in the selected London domain. The main wind direction in the selected time period can easily be seen in these results, with relatively calm anticyclonic winds in Europe and a stronger northerly flow from Cairo towards southern Egypt.

The impact of changing the population distribution is rather large in the three megacity regions (right column panels, Figure 2). The concentration are lower in the core of the megacity emissions, by up to 20 ppb, and higher by a similar amount at the outskirts of the megacities, which is a large impact in view if the 30-50 ppb contributions from the megacity emissions.

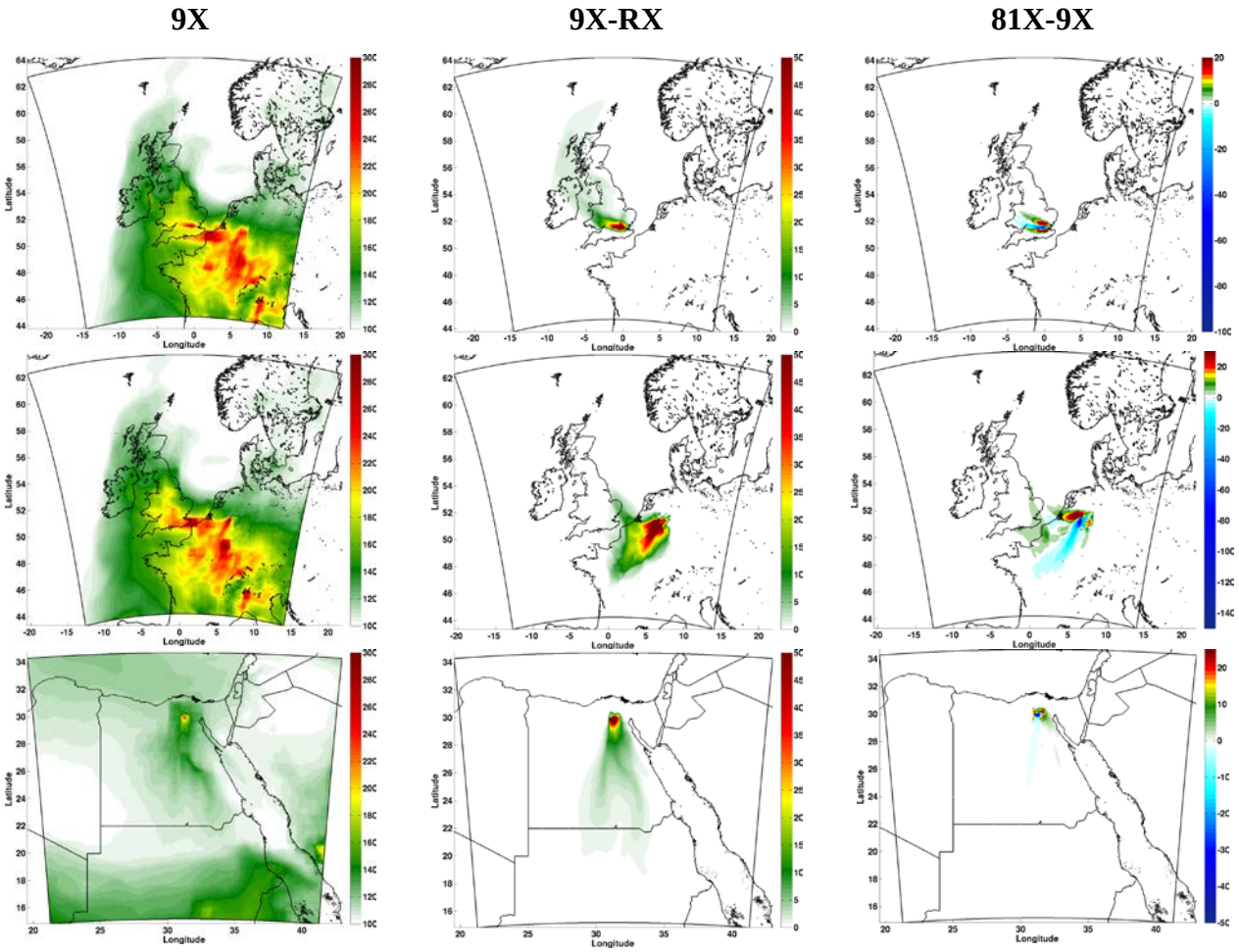


*Figure 2: 3-day averages of near-surface CO (ppb) in simulation 9X (left), simulations 9X-RX (middle), and simulations 81X-9X (right) shown for London (top), the Ruhr (middle), and Cairo with London emissions (bottom). Please note that different scales have been used.*

### *1.3 Impacts on daily ozone maximum*

Anthropogenic emissions of ozone precursors in Europe are large, and as for CO we see a strong impact on the concentrations of ozone in Europe (Figure 3, two top left column panels). We focus here on the daily maximum ozone, which is most critical in the context of the air pollution. As for CO, only a moderate part of these emissions stem from the restricted regions of London (upper panel) and Ruhr (middle panel) themselves. In this extensively studied period there were extremely favourable conditions for ozone formation in Europe (Vautard et al., 2005; Lee et al., 2006), with ozone peak values around 100 ppb, in contrast to the 40-50 ppb background value. As for CO, in the case of Cairo (bottom panel) the extent of elevated ozone is much more limited as ozone precursor emissions in the surrounding areas are much smaller than in Europe.

The impact of the three megacities is more similar in the three cases (centre column panels, Figure 3), with maximum contribution due to the emissions around 10-20 ppb. In the London case, the stable conditions with calm winds cause an accumulation of $NO_X$ emissions, leading to ozone titration (through the reaction $NO+O_3$) due to a high $NO_X$ to NMVOC ratio. Additionally, the plume is later transported over land in the north-westerly direction where large emissions from central England (e.g. Birmingham) lead to high background values of $NO_X$. The wind direction moreover favours transport of air pollutants from the European mainland, which act to further increase the background values over England. Ageing of the plume dilutes the $NO_X$ emissions, also causing net ozone production in combination with VOCs and CO.

The situation is different when looking at ozone impact of emissions from the Ruhr hot spot region. The chemical production of ozone is much larger than for London. This is mainly because a larger region has been defined for the Ruhr, and thereby larger total emissions have been removed in the reference simulations.

Interestingly, the London emissions had a much stronger impact on regional ozone distribution when the emissions were moved to the location of Cairo as a sensitivity test. One of the reasons is more incoming solar radiation in the Cairo domain, leading to more active photochemistry compared to the London simulations. Additionally, the transport of chemical species out of Cairo is fast, leading to rapid dilution of emissions. When this is combined with high temperatures, low background values of chemical species, and a relatively weak dry deposition due to sparse vegetation, the ozone production as a consequence is extremely efficient.

The impact of changing the population distribution is noticeable in the three megacity regions (right column panels, Figure 3). As for CO, the ozone concentration is lower in the core of the megacity emissions and higher at the outskirts of the megacities. The gain and loss of ozone between the two population distributions are up to 3-4 ppb. Thus, in relative terms the impact of redistributing population is more important for CO than for ozone.

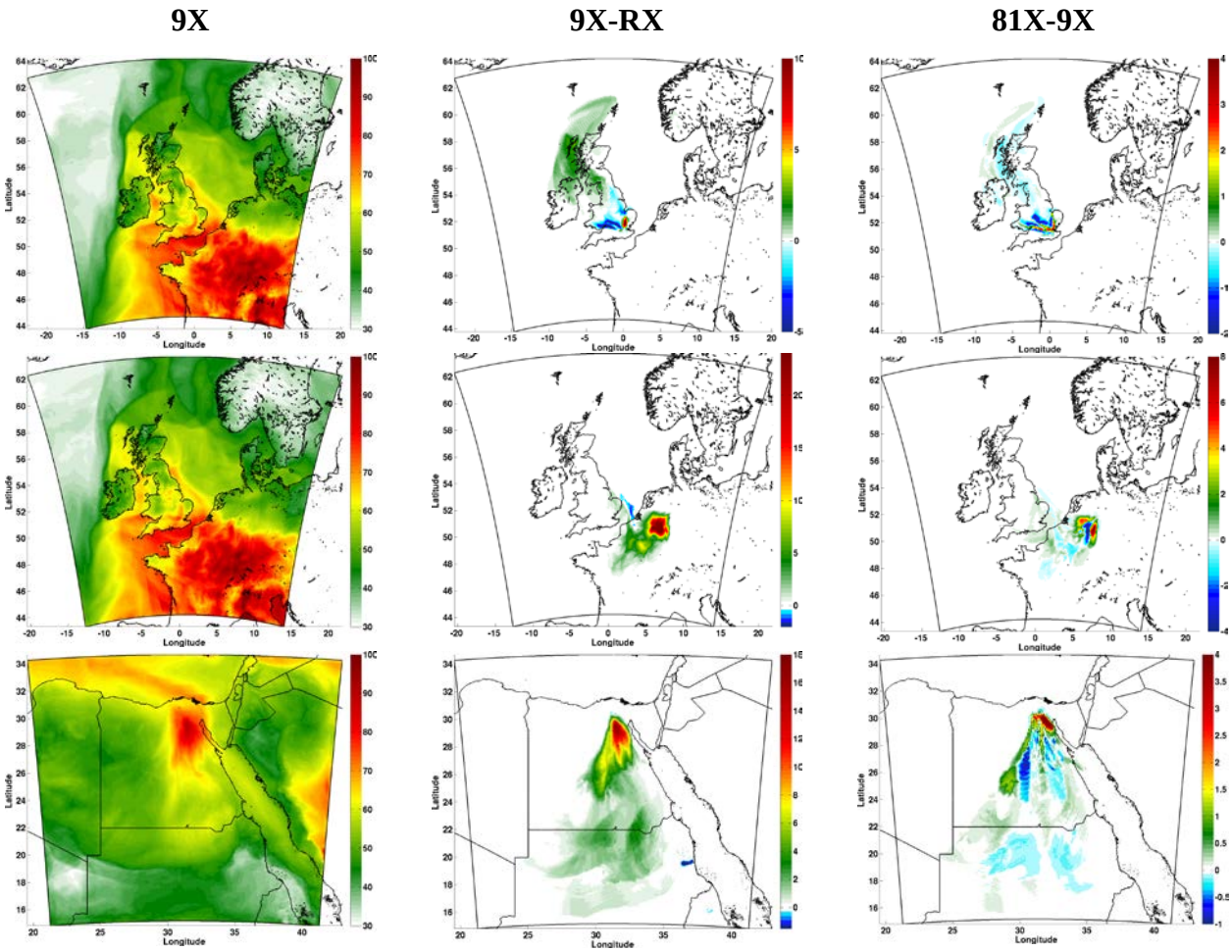


*Figure 3: 3-day averages of daily max near-surface ozone (ppb) in simulation 9X (left), simulations 9X-RX (middle), and simulations 81X-9X (right) shown for London (top), the Ruhr (middle), and Cairo with London emissions (bottom). Please note that different scales have been used.*

# 2 NorESM study

An additional study was made with a climate model in order to look at the effect of population distribution on climate. Global climate models have the advantage of covering the entire globe, but suffer from coarser resolutions which make it difficult to exactly define megacity regions. A sensitivity experiment was thus defined where emissions were distributed over a large, hemispheric scale area, in order to look at non-linearities.

## *2.1 The Norwegian Earth System Model*

NorESM is initially based on CCSM4 from NCAR, including the coupler CPL7 which is the core of the model. The ocean component POP2 has been replaced by a MICOM version based on the ocean model in the Bergen Climate Model (Furevik et al., 2003), and includes an interactive module for carbon (HAMOCC_v5; The Hamburg Ocean Carbon Cycle Model, developed at the Max-Planck-

Institut für Meteorologie in Germany). The land model in NorESM is the original CLM4 of CCSM4, including its own carbon cycle model as well as the SNow, ICe, and Aerosol Radiative (SNICAR) model (Flanner et al, 2007; 2009) which enable calculations of effects on radiation from snow darkening caused by deposited absorbing aerosols. Also, effects of deposition of light-absorbing aerosols on the albedo of snow-covered and bare sea-ice are taken into account in the sea-ice model CICE4 (Holland et al., 2011, manuscript in preparation).

Finally, the atmosphere component of CCSM4, CAM4, has been modified and extended to include updated versions of the aerosol and aerosol-cloud interaction schemes which were originally developed for use in the global atmospheric model CAM-Oslo. The most recent published versions of CAM-Oslo so far are based on CAM3, and are described in detail in Seland et al. (2008), Kirkevåg et al. (2008), Storelvmo et al. (2008), Hoose et al. (2009), and Struthers et al. (2011). The extended CAM4 version used in NorESM, CAM4-Oslo, includes a number of updates relative to CAM-Oslo. Papers on the current state of CAM4-Oslo (Kirkevåg et al., 2011) and NorESM are presently in preparation.

### *2.2 Experimental setup and results*

A sensitivity experiment was performed with the global Norwegian Earth System Model (NorESM) to study the effects of an even distribution of fossil fuel emissions, as opposed to an uneven distribution with heavily urbanized emission hot spots.

All land-based fossil fuel emissions of POM, BC and SO2 between the equator and 60 N except North Africa and the Arabian peninsula south of 30 N were distributed equally over all land-areas within the defined region. The model was initialized from the end of the model year 1988 in a 20$^{th}$ century simulation and was run until 2049 using the RCP8.5 scenario for greenhouse gas concentrations and aerosol emissions.

Despite the large re-distribution of emissions, there are only minor changes in aerosol column burdens and aerosol optical depths. For the model decade 1996-2005 the aerosol optical depth with flat emissions increases by 2 %. The last decade of the simulation 2040-2049 has 2 % lower optical depth than the standard simulation. The shift from a small positive to a small negative number is probably due a shift in the precipitation pattern. During the first decade of the simulation the redistribution of emissions results in reduced emissions in relatively wet source regions (e.g. Europe and North-Eastern United States). During the last decade of the simulation the redistribution of emissions results in higher emissions in wet areas implying higher washout in total and thus a smaller average optical depth. There are no discernable differences in short wave cloud forcing in the two experiments.

As expected from the small change in aerosol optical properties the changes in temperature and precipitation, shown in Figure 4, remain small as well. The global temperature difference in temperature for the model decade 2040-2049 between the perturbation and standard experiments is +0.08 K. The almost uniformly positive sign everywhere may indicate that there is a signal in the data. The strong positive values in the Arctic may be due to polar amplification, but may also be due to a northward shift in black carbon emissions and increased deposition on ice. We find also a slight increase in global precipitation likely caused by the higher temperatures. While there seems to be a tendency toward higher precipitation over continents compared to ocean regions, the period is probably too short to find a signal from natural variability.

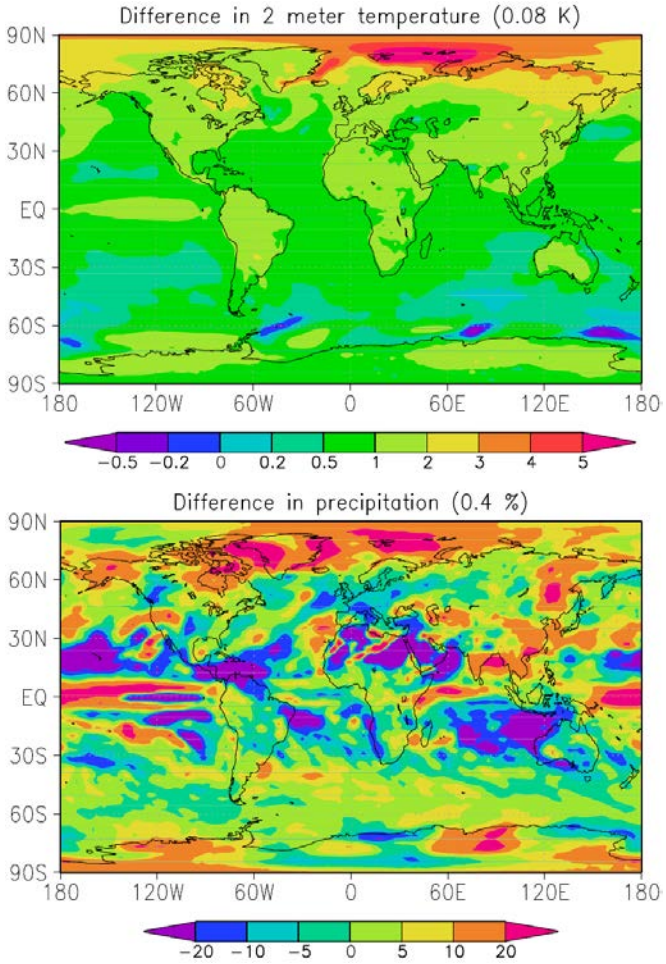


*Figure 4: Difference in temperature (upper panel) and precipitation (lower panel) between model run with re-distributed aerosol emissions and standard emissions for the model decade 2040-2049, scenario RCP8.5.*

## 3 Conclusions

Two calculations have been performed addressing the distribution of population. According to the study focussing on local to regional scales, the impact of making the population distribution more even is noticeable within the megacity regions. As for CO, the ozone concentration is lower in the core of the megacity emissions and higher at the outskirts of the megacities. The gain and loss of ozone between the two population distributions are up to 3-4 ppb. Thus, in relative terms the impact of redistributing population is more important for CO than for ozone. As described by (Hodnebrog et al, 2011) a more even distribution of population may lead to a stronger export of ozone from megacities to the regional scales during summer as ozone production due to NOx becomes more efficient.

The second study which deals with climate impact investigates another process, namely the interaction of aerosols and climate. A more even distribution of emissions here tends to move emissions of aerosols into more arid areas where they have a longer lifetime and thus can lead to cooling. Vice versa, megacities, i.e. an uneven distribution of emissions would have a warming effect. It has to be noted, however, that this is only one of many processes of importance. It is thus planned to repeat a similar study with a fully coupled climate-chemistry model.

# 4 References


Berntsen, T., and I. S. A. Isaksen, 1997: A global 3-D chemical transport model for the troposphere, 1, Model description and CO and Ozone results, J. Geophys. Res., 102(D17), 21239-21280, doi:10.1029/97JD01140.

Dore, C. J., Watterson, J. D., Murrells, T. P., Passant, N. R., Hobson, M. M., Choudrie, S. L., Thistlethwaite, G., Wagner, A., Jackson, J., Li, Y., Bush, T., King, K. R., Norris, J., Coleman, P. J., Walker, C., Stewart, R. A., Goodwin, J. W. L., Tsagatakis, I., Conolly, C., Downes, M. K., Brophy, N., and Hann, M. R., 2007. UK Emissions of Air Pollutants 1970 to 2005, Technical Report.

EMEP, 2003. Transboundary Acidification, Eutrophication and Ground Level Ozone in Europe. Norwegian Meteorological Institute, Report 1/2003.

Flanner, M. G., C. S. Zender, J. T. Randerson, and P. J. Rasch (2007), Present day climate forcing and response from black carbon in snow, J. Geophys. Res., 112, D11202, doi:10.1029/2006JD008003.

Flanner, M. G., C. S. Zender, P. G. Hess, N. M. Mahowald, T. H. Painter, V. Ramanathan, and P. J. Rasch (2009), Springtime warming and reduced snow cover from carbonaceous particles, Atmos. Chem. Phys., 9, 2481-2497.

Furevik, T, Bentsen, M., Drange, H., Kindem, I.K.T., Kvamstø, N.G., and Sorteberg, A., 2003: Description and evaluation of the bergen climate model: ARPEGE coupled with MICOM. *Climate Dynamics*, **21**, 27–51. DOI 10.1007/s00382-003-0317-5.

Hodnebrog, Ø., Stordal, F., and Berntsen, T. K.: Does the resolution of megacity emissions impact large scale ozone?, Atmospheric Environment, In Press, Corrected Proof, 10.1016/j.atmosenv.2011.01.012, 2011.

Holland, M. M., D. A. Bailey, B. P. Briegleb, B. Light, and E. Hunke, 2011, Improved Sea Ice Shortwave Radiation Physics in CCSM4: The Impact of Melt Ponds and Black Carbon. J. of Climate (submitted).

Hoose, C., J. E. Kristjansson, T. Iversen, A. Kirkevåg, Ø. Seland, and A. Gettelman, 2009: Constraining cloud droplet number concentration in GCMs suppresses the aerosol indirect effect.*Geophys. Res. Lett.*, **36**, L12807, doi:10.1029/2009GL038568.

Kirkevåg, A., T. Iversen, Ø. Seland, J.B Debernard,, T. Storelvmo, and J.E. Kristjánsson, 2008: Aerosol-cloud-climate interactions in the climate model CAM-Oslo. *Tellus*, **60A**, 492-512.

Kirkevåg A , Iversen T. , Seland Ø., Struthers H. , Hoose C. and Nilsson D., Aerosols and their radiative effects on climate in CAM4-Oslo/NorESM. The importance of natural aerosols for estimates of anthropogenic impacts, manuscript in preparation.

Lee, J. D., Lewis, A. C., Monks, P. S., Jacob, M., Hamilton, J. F., Hopkins, J. R., Watson, N. M., Saxton, J. E., Ennis, C., Carpenter, L. J., Carslaw, N., Fleming, Z., Bandy, B. J., Oram, D. E., Penkett, S. A., Slemr, J., Norton, E., Rickard, A. R., Whalley, L. K., Heard, D. E., Bloss, W. J., Gravestock, T., Smith, S. C., Stanton, J., Pilling, M. J., and Jenkin, M. E., 2006. Ozone photochemistry and elevated isoprene during the UK heatwave of August 2003. Atmospheric Environment 40 (39), 7598-7613.

National Atmospheric Emissions Inventory, 2007. http://www.naei.co.uk/.

Seland, Ø., T. Iversen, A. Kirkevåg, and T. Storelvmo, 2008: Aerosol-climate interactions in the CAM-Oslo atmospheroc GCM and investigations of associated shortcomings. *Tellus*, **60A**, 459-491.

Storelvmo, T., J. E. Kristjansson, U. Lohmann, T. Iversen, A. Kirkevåg, Ø.Seland, 2008: Modeling the Wegener-Bergeron-Findeisen process – implications for aerosol indirect effects. *Environ. Res. Lett.* 3. 045001. DOI:10.1088/1748-9326/3/4/045001.

Struthers, H., A. M. L. Ekman, P. Glantz, T. Iversen, A. Kirkevåg, E. M. Mårtensson, Ø. Seland, and E. D. Nilsson, 2011: The effect of sea ice loss on sea salt aerosol concentrations and the radiative balance of the Arctic. Atmos. Chem. Phys., 11, 3459-3477.

Vautard, R., Honore, C., Beekmann, M., and Rouil, L., 2005. Simulation of ozone during the August 2003 heat wave and emission control scenarios. Atmospheric Environment 39 (16), 2957-2967.