PROJECT FINAL REPORT

Grant Agreement number: 212095

Project acronym: CityZen

Project title: megaCITY - Zoom for the Environment

Funding Scheme: Collaborative Project
(small or medium-scale focused research project)

Period covered: from 01 Sep 2008 to 31 Aug 2011

Name of the scientific representative of the project's co-ordinator[1], Title and Organisation:

Michael Gauss, Dr., Norwegian Meteorological Institute

Tel: +47 22 96 33 02

Fax: +47 22 96 30 50

E-mail: michael.gauss@met.no

Project website[2] address: http://www.cityzen-project.eu

https://wiki.met.no/cityzen/start

[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement.
[2] The home page of the website should contain the generic European flag and the FP7 logo which are available in electronic format at the Europa website (logo of the European flag: http://europa.eu/abc/symbols/emblem/index_en.htm logo of the 7th FP: http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos). The area of activity of the project should also be mentioned.

Table of Contents

1 Final publishable summary report

1.1 Executive summary

The majority of the world's population is now living in urban areas. In particular the number of megacities (with populations over 10 million) is increasing. Megacities and regional hot spots have developed with anthropogenic emissions and changes in land usage that are likely to have large environmental implications, in terms of air pollution and climate change, both in the regional hot spots themselves and on larger scales.

The CityZen project (megaCITY - Zoom for the ENvironment), funded through the European Union's 7th Framework Programme, involved researchers from 17 institutes in Europe, Africa and Asia, and investigated the air pollution in and around selected megacities and emission hotspots for the last decade and during the 3-year project period using satellite and in-situ observations. Furthermore, a series of different scale models (local-regional-global) was employed to analyze the impacts of emission hot spots on regional and global air quality, the interactions between climate change and air pollution, as well as future scenarios and potential mitigation options. The Eastern Mediterranean, the Po Valley (Italy), the BeNeLux region, and the Pearl River Delta (China) were chosen for intensive case studies. The project was coordinated by the Norwegian Meteorological Institute.

A scientific challenge in this field of research is the multi-scale character of the issue. As megacities have the potential to impact both their local environment but also the regional to global scales, scale-bridging data sets and model systems have to be used.

Observations. CityZen has created extensive sets of satellite observations of gaseous air pollutants, aerosols, and greenhouse gases. Analyses of satellite data for the last 10 to 15 years have revealed different trends for the different regions of the world. Focused ground-based measurements in the selected CityZen regions have been collected and used for air pollution trend analyses, source attribution calculations, and to evaluate regional atmospheric models.

Emission inventories. CityZen has compiled the global MACCity emission data, which provides a two-decade long set of emission data with interannual variability, including anthropogenic and natural sources. Furthermore, fine scale emission data sets have been created for selected hot spots. These include, among others, a recent compilation of Istanbul emissions. Emission scenarios for the future, including various mitigation options, have been provided based on the Global Energy Assessment coordinated at IIASA.

Modelling. The capabilities of modeling different spatial scales in a consistent manner have been improved in CityZen through, e.g., nudging and grid zooming techniques. Numerous model studies have been performed to calculate emission dispersion, chemical transformations, and interactions between air pollution and climate change. Two coordinated model studies using the new emission data sets have specifically looked at 10-year trends (1998-2007) and future development of air pollution, respectively.

The goal of the CityZen project has been to quantify the influence of megacities on air quality and climate, to assess future change under different emission and climate scenarios, and to make suggestions to policy makers as to which mitigation options exist to reduce environmental problems. The results of the project, which have been published through its website (http://www.cityzen-project.eu, to be available for several years after the official end of the project), peer-reviewed articles, brochures, and other dissemination channels, should be useful for scientists as a basis for further research and for policy makers as a scientific basis for air quality legislation and city planning beyond the duration of the project.

1.2 Project context and objectives

Since 2008 the majority of the world's population has been living in urban areas [http://www.unfpa.org/pds/urbanization.htm], many in megacities (with populations over 10 million), and the trend is expected to continue. Megacities and regional hot spots have developed with anthropogenic emissions and changes in land usage that are likely to have large environmental implications both in the regional hot spots themselves and on a larger scale. The pattern in emissions is likely to change with urbanization as a result of changes in lifestyle and economic growth. Rapid economic growth in megacities is often not followed by an equally rapid growth in infrastructure such as road construction or public transportation systems, leading to inefficient traffic flow and enhanced air pollution. The increasing emissions from emerging and evolving megacities as well as changes in the emission patterns increase several environmental problems, in particular in relation to air pollution, climate change, water resources and soil. It has become urgent to deal with this broad problem in a policy context as is affects a large part of the population.

The CityZen project (megaCITY - Zoom for the ENvironment), funded through the European Union's 7th Framework Programme, involves researchers from 17 institutes from Europe, Africa and Asia (Table 1). Air pollution distribution and change are determined in and around selected megacities and emission hotspots for the last decade and during the 3-year project period (2008-2011) using satellite and in-situ observations. A series of different scale models (local-regional-global) is employed in order to analyze the impacts of air pollution hot spots on regional and global air quality, and potential future changes assuming various climate scenarios. The Eastern Mediterranean, the Po Valley (Italy), the BeNeLux region, the Pearl River Delta (China) have been chosen for intensive case studies.

The environmental issues considered in the project have been:

- reduced air quality and health effects from concentrations of major air pollutants;
- ecosystem damage by emissions of sulphur and nitrogen oxides, ammonia and volatile organic compounds;
- transport of the increasing amount of air pollution from megacities to the regional and global scales;
- the influence of air pollution on weather and climate;
- the effects of climate change on the emissions and air quality in megacities and their surroundings.

Relevant to these issues, the following main objectives were defined for CityZen:

- quantify and understand current air pollution distribution and development in and around selected megacities/hot spot regions, including the interaction across the different spatial scales;
- estimate the future impact from emission changes with a focus on the effect of rapid growth in the population of megacities/hot spots and the increasing background of pollutants (ozone, particulate matter PM, and their precursors);
- estimate how megacities/hot spots influence climate change;
- estimate how megacities are responding to climate forcing which can influence transport patterns, chemical oxidation and biogenic emissions (especially biogenic volatile organic compounds BVOC);
- study mitigation options to keep the air pollution load in and around megacities/hot spots within sustainable limits in terms of human health effects and climate impact;
- develop tools to estimate interactions between different spatial scales;
- bring the scientific results and methods developed and applied during the course of the project to semi-operational use; provide technical underpinning of policy work.

Table 1: The partners of CityZen

Partner name	Short name	Country
Meteorologisk institutt (Coordinator)	METNO	Norway
Peking University	PKU	China
LATMOS, Centre National de la Recherche Scientifique	CNRS	France
Institut National de l'Environnement Industriel et des Risques	INERS	France
Institut für Umweltphysik, Universität Bremen	IUP-UB	Germany
Rhenish Institute for Environmental Research at the University of Cologne	FRIUUK	Germany
Forschungszentrum Jülich GmbH	FZJ	Germany
Environmental Chemical Processes Laboratory, University of Crete	ECPL	Greece
Consiglio Nazionale Delle Ricerche – ISAC	CNR-ISAC	Italy
Norsk Institutt for Luftforskning	NILU	Norway
Universitetet i Oslo	UiO	Norway
Institute of Marine Sciences, Middle East Technical University	METU	Turkey
University of Leicester	ULeic	UK
International Institute for Applied Systems Analysis	IIASA	Austria
National Observatory of Athens (NOA)	NOA	Greece
Center for Environmental Hazard Mitigation, Cairo University	CEHM	Egypt
Istanbul Technical University (Subcontractor)	ITU	Turkey

Megacities have effects on both air pollution and climate, they affect different spatial scales (local, regional, global), and studies on their environmental impact require integration across different research topics. With these objectives in mind the various research disciplines and themes pursued during CityZen have been:

- The impact of megacities on air quality (mainly ozone, nitrogen, PM)
    - modeling and observing the megacity signal and trends
    - satellite and ground-based observations, and multi-modeling studies
    - source allocation, anthropogenic versus natural impacts
    - non-linearities in atmospheric chemistry
    - studies for the last 10 to 15 years, the present and the future (until 2050)
    - mitigation options

- The interactions between atmospheric chemistry and climate
    - particle impact on climate
    - effects of climate change on emissions and on air pollution
    - mitigation options, including climate-friendly air quality legislation

- New emission inventories
    - downscaling, interannual variability
    - different policy scenarios for the future, mitigation options

- Crosscutting issue: Scale interactions
    - interactions in between different spatial scales (local – regional – global)
    - harmonization of data sets across different domains and resolutions

Progress has been made within all these themes, as will be described in the following section. While the studies performed within CityZen have built upon previous knowledge and made use, to the extent possible, of already existing data (e.g. emission data and measurement data) and tools, substantial effort has gone into the generation of new emission data and software development. The results and data from CityZen have contributed, and will continue to contribute, to the research on the environmental impact of megacities, in particular regarding air pollution and trends. They will also support air quality policy making in Europe and beyond.

The main results from CityZen will be described briefly in the next section. For a more comprehensive account of the output from the project, the reader is referred to the project website, where links to deliverable reports, periodic reports, and publications are given.

1.3 Main results from CityZen

1.3.1 Current air pollution and trends: Satellite observations

CityZen Objective: Quantify and understand current air pollution distribution and development in and around selected megacities/hot spot regions, including the interaction across the different spatial scales

A large amount of observational data has been collected during CityZen, including both ground-based measurements and space-borne measurements. As the acquirement of satellite data by the IUP-UB constitutes a large and important component of CityZen and since these data have global character they will be treated separately in this dedicated section. The analyses of ground-based measurement data are described in later sections, focusing on the four emission hotspots selected for case studies in CityZen.

1.3.1.1 Background

Air pollution is a global problem and as such should be addressed by using global data sets. Truly global measurements can only be provided by satellites using remote sensing techniques to retrieve information on air composition in general and pollution in the troposphere in particular. Remote sensing of tropospheric constituents can be performed using the specific absorption signatures of molecules such as O_3, NO_2, SO_2, HCHO, CO, CO_2 or CH_4 in observations of backscattered solar light in the UV, visible, and near-infrared spectral ranges. Aerosol optical thickness can also be retrieved from these data by taking advantage of the wavelength-dependent scattering characteristics of these particles.

The first satellite observations of tropospheric NO_2 and other species became possible with the European GOME instrument in 1996. Data on better spatial resolution and for more species have been delivered by the SCIAMACHY instrument on ENVISAT since August 2002, OMI on Aura since August 2004, and GOME-2 on METOP-A since January 2007.

The basic measurement quantity of satellite observations are the spectrally resolved earth-shine radiance and the solar irradiance. From these two spectra, integrated absorber columns along the light path can be determined using absorption spectroscopy. These so called Slant Columns need first to be corrected for the stratospheric contribution, which, in the case of O_3 and NO_2, is large. The resulting Tropospheric Slant Columns are then converted to Tropospheric Vertical Columns by application of an air mass factor which accounts for the length of the light path through the troposphere. It is important to realise that in this rather indirect retrieval, a priori assumptions have to be made which have a significant impact on the results. Also, the quantity retrieved is integrated over the entire troposphere and cannot easily be separated into a boundary layer part (associated to emissions and advection) and a free tropospheric part (linked to convection, long range transport, and transformation processes).

While satellite data provide unprecedented near global spatial coverage on a daily or weekly basis, they still have limited spatial resolution (30 x 60 km^2 in the case of SCIAMACHY) and cannot resolve localised pollution hot-spots or the details of pollution distributions within cities, and even less the effects of street canyons. Therefore, they are best used to investigate the large-scale patterns of pollution and its changes over time which can be well identified in the consistent long-term observations provided by these instruments.

1.3.1.2 Reactive gases and greenhouse gases

Nitrogen dioxide (NO_2) is a key pollutant in the troposphere as it is involved in acidification of rain, ozone production and aerosol formation. In addition, it adversely affects human health and is therefore regulated by environmental legislation. The main anthropogenic sources of NO_2 are NO emissions from fossil fuel combustion, and consequently, high NO_2 levels are mainly found in the industrialised parts of the world with hotspots in urban areas and regions with power plants. As the atmospheric lifetime of NO_2 is short, NO_2 levels quickly decrease with increasing distance from the sources. Satellite derived distributions of NO_2 therefore show clear maxima in Europe, Northern America and Asia. Most of the NO_2 observed from satellite is located in the boundary layer and high values are thus indicative of strong pollution. While in Europe and China, high NO_2 levels are found over large areas, many countries with emerging economies have overall low NO_2 values with a few hotspots linked to large cities. The overall NO_2 amounts in these countries are thus lower; however, exposure of the population living in the polluted cities can still be very high.

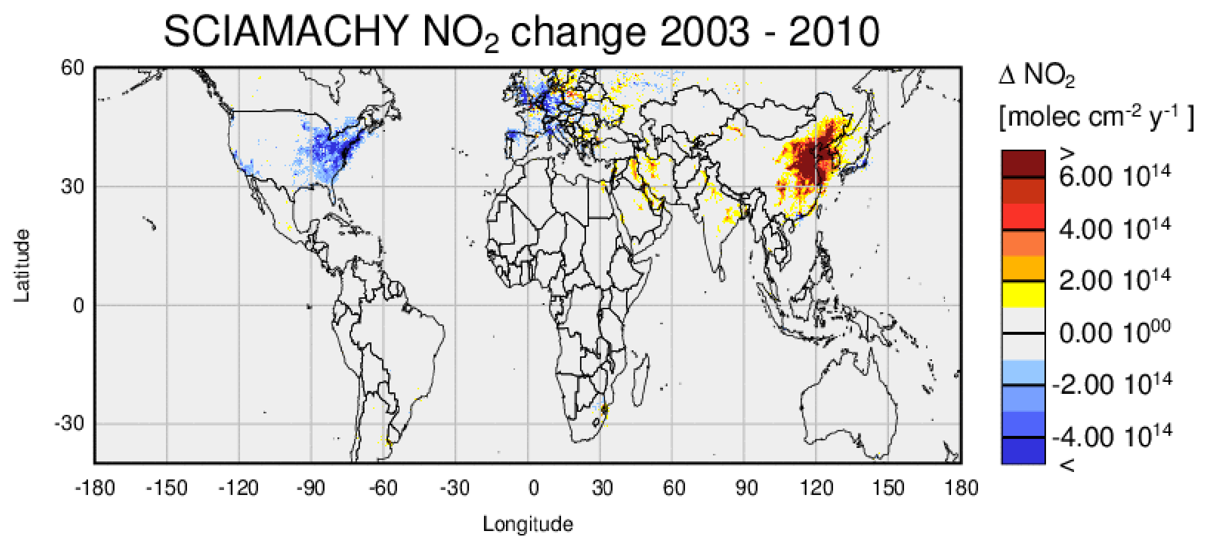

Figure 1: Mean annual change of tropospheric NO_2 derived from SCIAMACHY measurements in the time period 2003 – 2010. Red colors indicate increasing NO_2, blue colors decreasing trends.

Over the last decade, pollution levels have changed rapidly in many parts of the world, driven by economic development, population growth, and improvements in emission reduction technologies. The SCIAMACHY data provide a unique global view of these changes as illustrated in Figure 1, where mean annual changes are shown for the period 2003 – 2010. A number of observations can be made from these data:

1. A very large upward trend is evident over the industrialising parts of China, continuing the development already reported from the GOME observations covering data from 1996 to 2003. This is linked to increases in NOx emissions from intensified use of fossil fuels for energy production and transportation which are so large that they override the effects of significant reductions in specific emissions achieved by the introduction of cleaner technologies. Changes in biomass burning practice could also contribute to the observed changes. Interestingly, the area around Hong-Kong as well as the island of Taiwan show negative trends in NO_2 levels.
2. Large upward trends are also apparent over many large cities in India and the Middle East, but in absolute terms, the NO_2 values and their changes are small compared to China. These upward trends are expected as the use of fossil fuels is increasing in these areas.
3. For many large cities in developing and emerging countries, clear upward trends can be observed albeit at even lower absolute levels and limited to comparatively small areas. In the GOME time-series, this was not detected, presumably because of the much lower spatial resolution of 320 x 40 km^2. While upward trends in pollution levels are expected for these cities, the absolute values are relatively small compared to the severity of the air quality problems in many of these areas.
4. Over the US, a strong downward trend is observed in all polluted areas. This is in contrast to the GOME time-series where the NO_2 trend in the US was less pronounced. This trend is probably explained by the success in denoxification of power plants and a general decrease of NOx emissions from cars. No comparable downward trend is found over Canada or Mexico.
5. Over Japan, there is a continuing downward trend.

6. Over Europe, there is a downward trend but it is not as pronounced as in the GOME time-series. While NOx emissions are thought to have decreased significantly over this time period, the increasing number of Diesel engines has led to a change in NO/NOx ratio that leads to increased NO_2 for a given amount NOx emissions.

Sulphur dioxide (SO_2) which is emitted from fossil fuel combustion, mainly in the form of coal is of large relevance as it is the precursor of sulphuric acid aerosols which are relevant for radiative forcing. Retrievals of SO_2 from SCIAMACHY measurements show clear upward trends over China until about 2007 when flue gas desulphurisation was introduced in power plants, leading to a significant reduction of SO_2 emissions in China until 2010. This is a good example for the rapid results which can be obtained by implementation of emission reduction policies and also how this can be monitored from space. The reduced SO_2 emissions are expected to have a strong impact on aerosol loading and composition in East Asia.

Another species with a clear upward trend observed in SCIAMACHY data over China is formaldehyde (HCHO), an intermediate product of atmospheric oxidation of VOCs. However, this trend stopped in 2009 and it is not clear, if it is mainly the result of anthropogenic emissions of VOCs or if changes in biomass burning or the emissions of biogenic precursors are responsible. Further work is needed to clarify this point.

SCIAMACHY carbon dioxide **SCIAMACHY methane**

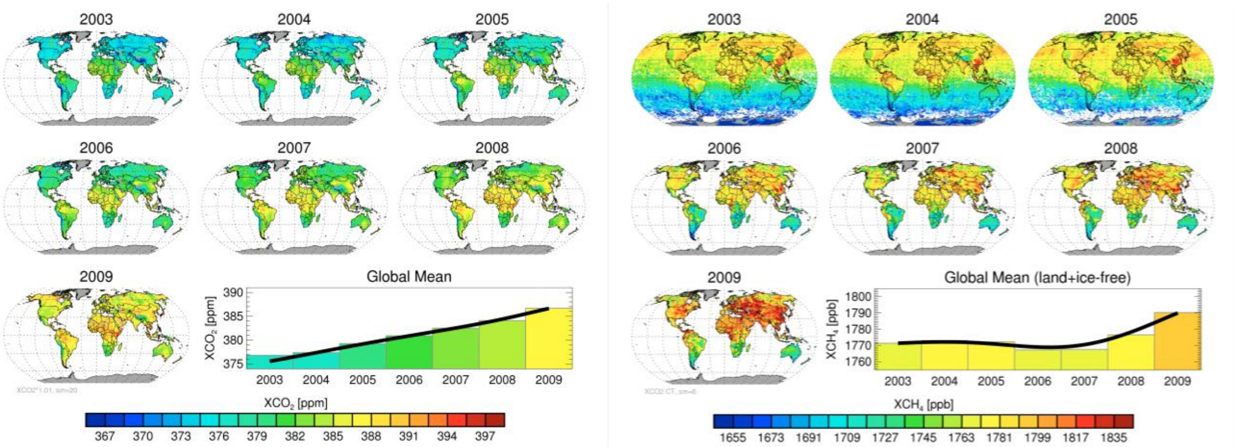

Figure 2: SCIAMACHY retrieved XCO2 (left) and XCH4 (right) columns. A continuing upward trend is found for CO_2 while CH_4 remained relatively constant for a few years before it increased again in 2008 and 2009. See Schneising et al. (2011) for details.

Over the last years, large progress has been made in the retrieval of column amounts of greenhouse gases such as CO_2 and CH_4 from SCIAMACHY measurements (see Figure 2). This allowed for the first time to quantify the inter-hemispheric gradient, the seasonal variation and the inter-annual variation and trend of these species to be derived from satellite data. The absolute accuracy of these retrievals is much better than that of the reactive gases such as NO_2. However, as the atmospheric lifetime of the greenhouse gases is long, pollution leads to relatively small changes in the columns observed locally. A detailed analysis of state of the art CO_2 and CH_4 data sets from SCIAMACHY revealed that any possible pollution signal from megacities is still close to the noise of the measurements and in spite of some indication for enhanced CO_2 values over the BENELUX region, observation of local CO_2

emissions is probably still out of range of current instrumentation. Future instruments with improved spatial resolution and sensitivity such as CARBONSAT are expected to be able to deliver such results.

Within the framework of CityZen data were also retrieved from the IASI instrument on the METOP satellite, which has provided observations since 2008. Up to now, 24 different species were identified, with some of them measurable all the time and at each location (H_2O and isotopes, CO_2, CH_4, O_3, CO, HNO_3, methanol, formic acid), and others observable when specific pollution or fire events or volcanic eruption occur.

1.3.1.3 Aerosols

Aerosols are relevant for the atmospheric radiative balance where they can lead to warming or cooling depending on their composition and vertical distribution. In addition, they pose one of the most serious pollution-related health problems, in particular in cities. Satellite retrievals of aerosols can only provide information on the optical properties such as aerosol optical thickness directly, but aerosol amount and even surface concentrations can be derived if additional assumptions are made.

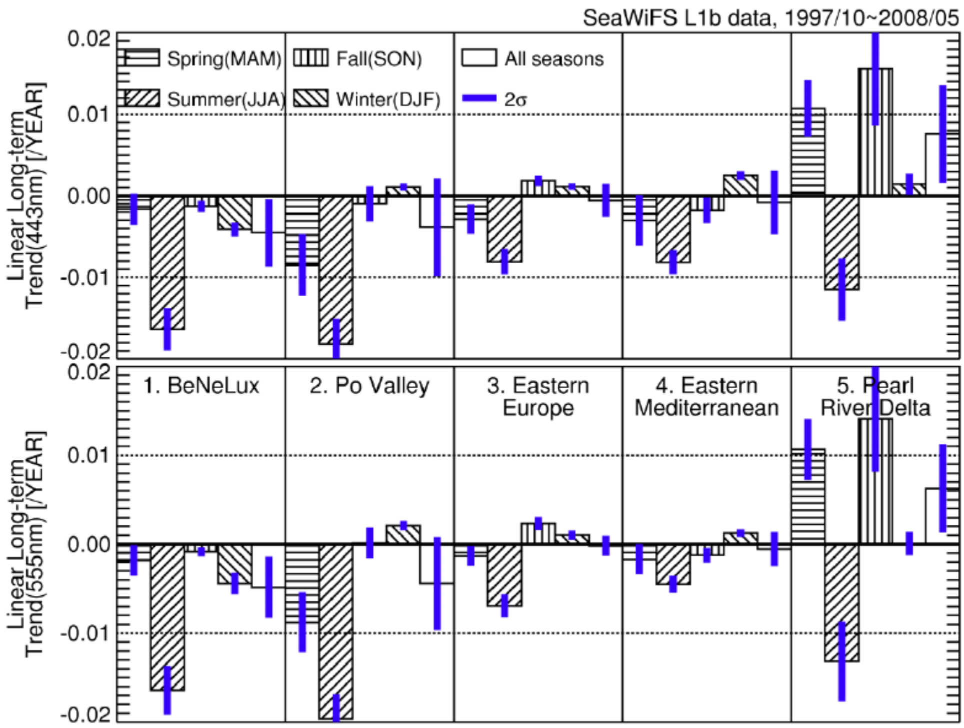

Figure 3: Annual and seasonal trends in aerosol optical thickness retrieved from SeaWiFS data in two wavelength regions over 5 regions from 1997 to 2008. See Yoon et al., 2011 for details.

As aerosols are closely linked to gaseous emissions, either directly for secondary aerosols such as sulphate aerosols or indirectly through common sources such as road traffic, it is expected that their distributions and changes are similar to those shown above for NO_2. In fact, clear downward trends in aerosol loading are retrieved from SeaWiFS observations in the period 1997 – 2008 over the BeneLux area and the Po valley as illustrated in Figure 3. At the same time, large upward trends are reported for the Pearl-River Delta, again in agreement with the results found for NO_2. These results underline the success of pollution abatement laws in Europe and the rapid economic growth in China.

An unexpected result of this study was a large variability in the retrieved aerosol trends as a function of season. Further analysis of the data showed, that this could be related to interference from clouds. Strict cloud screening has to be applied in aerosol retrievals to avoid contamination of the results from clouds within the field of view which would result in very large aerosol amounts. However, as result of the relatively large pixel size of current sensors, cloud contamination cannot be excluded completely, and therefore measurements in the cloudy season (e.g. summer in the Pearl River Delta) have much larger uncertainty than those from other seasons. In addition to these retrieval related impact of clouds, changes in cloud frequency and type can also affect aerosol growth and removal rates introducing further complexity.

1.3.2 Current air pollution and trends: Emissions and Modelling

CityZen Objective: Develop tools to estimate interactions between different spatial scales (megacities to global)

CityZen Objective: Quantify and understand current air pollution distribution and development in and around selected megacities/hot spot regions, including the interaction across the different spatial scales

1.3.2.1 New emission data for the recent past and present

During the early stages of CityZen, Ineris downsclaled EMEP emission data to 10x10 km^2 spatial resolution for use in fine scale regional models. During the second period of CityZen the MACCity yearly global emissions inventory was developed by CNRS and FZJ (Granier et al., 2011), from a linear interpolation of the decadal global ACCMIP data set (*emissions for **A**tmospheric **C**hemistry and **C**limate **M**odel **I**ntercomparison **P**roject*), which had been developed for the IPCC AR5 assessment. It was developed for the period 1850-2100, harmonizing past emissions datasets and incorporating four future scenarios based on the RCPs (*Representative concentration pathways, http://www.iiasa.ac.at/web-apps/tnt/RcpDb/)*. The year 2000 was chosen as the reference year, as it represented a combination of the best information available on existing regional and global inventories when the inventory was built. The MACCity data set is based on the 1990 and 2000 ACCMIP emissions, and the 2005 and 2010 emissions are taken from RCP 8.5. For anthropogenic emissions, a seasonal cycle was first applied sector by sector, the species were then lumped to the 21 MOZART-4 species and finally emissions were interpolated on a yearly basis between the base years 1990, 2000, 2005 and 2010.

With regards to biomass burning emissions, the decadal ACCMIP emissions were extended into a yearly monthly mean emissions of trace species from a combination of the RETRO (Schultz et al., 2008) and the GFED-v2 (van der Werf et al., 2006) inventories. Different sources were used for natural emissions. Biogenic emissions were obtained from the MEGAN model (version 2.1, Guenther et al., 2006) and Volcanic, Oceanic and Soil emissions were obtained from the POET inventory (Granier et al. 2005; Olivier et al. 2003).

Fine scale emission data have also been created for Istanbul on a 2 km spatial resolution (Markakis et al., 2011) and have been extensively used in WRF/CMAQ simulations for the Eastern Mediterranean (Im et al., 2010; Im et al., 2011a and b; Im and Kanakidou, 2011). Fine scale emission data for the Rhine-Ruhr area in Germany were provided by LANUV-NRW (air pollution authority in North Rhine Westphalia), through CityZen partner FRIUUK, and used by UiO in a WRF-Chem model simulation (Hodnebrog et al., 2011).

1.3.2.2 Model development

Megacities affect their environment on very local scales, down to street level, but as strong emission sources they also have global environmental impacts. Conversely, global change will influence megacities, related to both climate change and long-range transport of air pollution. Given the multi-scale character of the effects *of* and *upon* megacities, trade-offs have to be made in modeling. Models having a sufficiently fine resolution for local air pollution studies cannot be run globally, but only for a confined region of the atmosphere (regional or local models). The provision of boundary conditions for these models is not trivial, and effects from the model domain on the areas beyond cannot be taken into account. On the other hand, global models addressing changes in large-scale meteorological parameters and changes in the background concentrations of long-lived air pollutants have too coarse a resolution to be applied to local studies. Although computer power is increasing, this problem cannot be easily solved because the ongoing (and desirable) inclusion of ever more complex physical and chemical processes largely compensates for the increase in available computing power.

In CityZen different approaches have been pursued, including the nudging technique by CNR-ISAC in the BOLCHEM model (Maurizi et al., 2011) and the nesting technique by Ineris in the CHIMERE model (Siour et al., 2011). Nudging has been proposed in CityZen as a bridging method that can couple different models at different scales. Low resolution chemical composition models are forced by high resolution run on critical areas. In the nudging concept applied in BOLCHEM, the concentration in a certain region of the model domain during a low resolution run is forced to the fields obtained from a high resolution run which uses a non-forced low resolution run as boundary conditions. Technically, a term is added to the concentration tendency equation in the model running at low resolution, in order to force the computed concentrations towards the high resolution concentrations obtained from a fine scale model.

The zooming method developed for CHIMERE involved only one model by definition. Local zooms are introduced over a specific area in a continental chemistry transport simulation within a single grid with variable resolution. The method allows bridging the spatial scales from the urban domain (~1km resolution) to the continental domain (~50km resolution). As the CHIMERE grid is regular in latitude and longitude, the resolution is stretched over latitudinal and longitudinal bands. At the intersection of these bands, we obtain a finer grid that is linked in real-time with the larger scale onto the rest of domain. Figure 4 presents a visualization of the zoomed model grid.

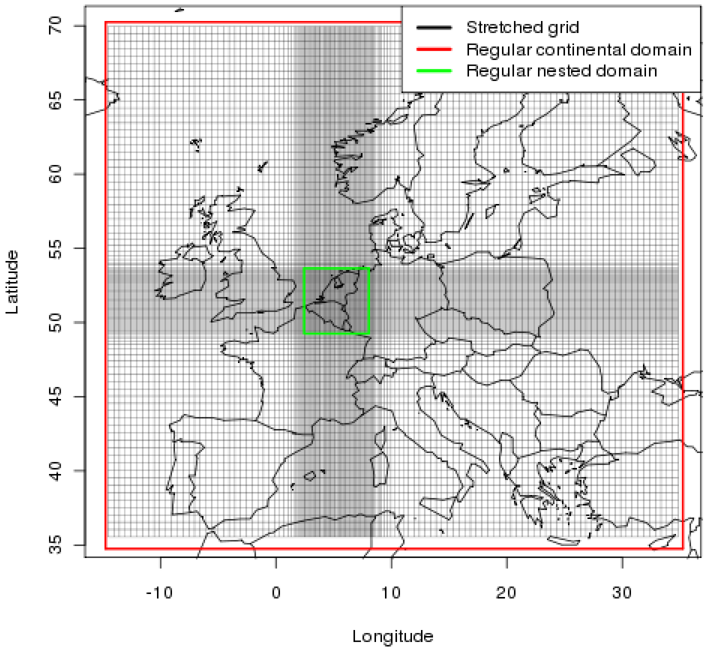

Figure 4: Geometry of the stretched grid implemented in the CHIMERE regional model to bridge urban and regional scales.

1.3.2.3 Coordinated modelling study for the recent past

Several multi-model studies have been performed for CityZen. The largest one was led by Ineris and involved six regional and global chemistry-transport models (Bolchem, Chimere, Emep, Eurad, OsloCTM2 and Mozart) simulating air quality over the past decade in Western European anthropogenic emissions hotspots. Comparisons between models and observations were made to assess the skills of the models to capture the trends in basic atmospheric constituents (NO_2, O_3, and PM_{10}). It was found that the trends of primary constituents are well reproduced by the models (except in some countries – owing to their sensitivity to the emission inventory) although capturing the more moderate trends of secondary species such as ozone is more challenging.

Figure 5 shows, as an example, the modeled trends in surface NO_2. The trends are clear and more robust compared to the trends in ozone (not shown), which are rather small and not significant in many areas. Further details can be found in Colette et al. (2011). The study also found that the magnitude of the emission-driven trend exceeds the natural variability for primary compounds. Emission management strategies have thus had a significant impact over the past 10 years, supporting further emission reduction strategies.

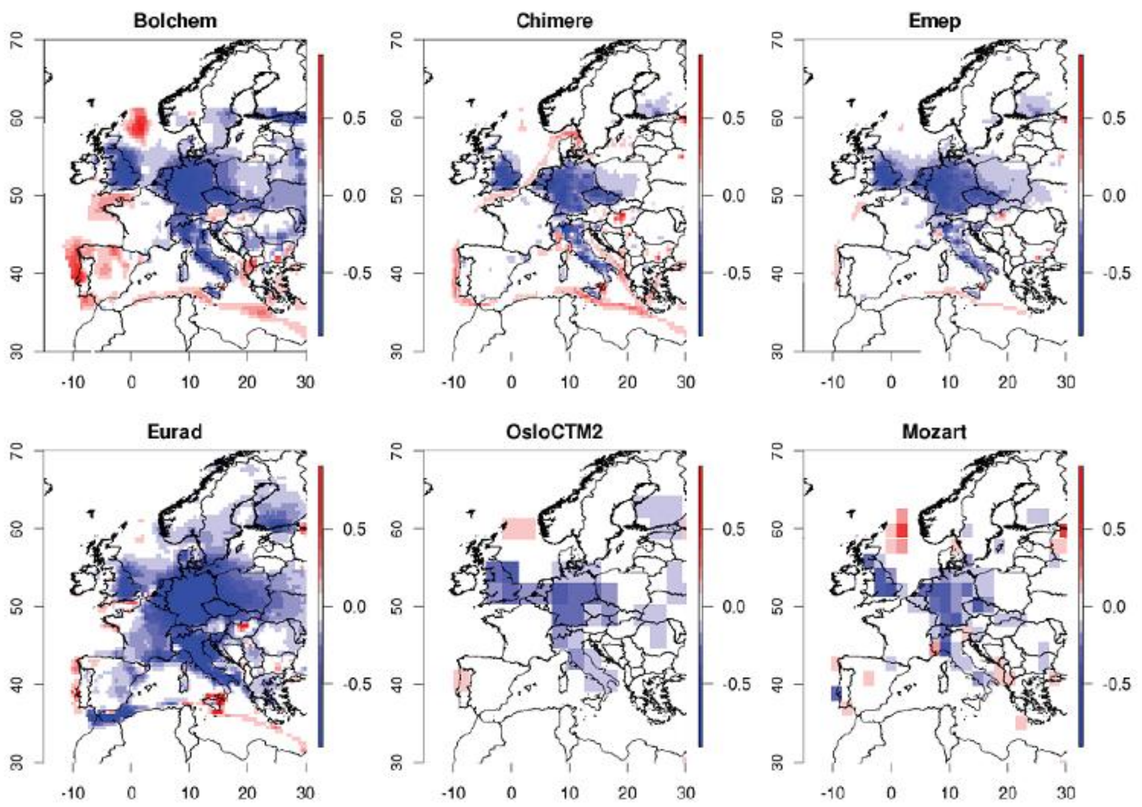

Figure 5: Modelled NO_2 trend (μgm^{-3} yr^{-1}) for each CTM and at each grid point computed on the basis of monthly means of daily means over the 1998–2007 period with a linear least square fit of de-seasonalised values.

1.3.3 The East Mediterranean

CityZen Objective: Quantify and understand current air pollution distribution and development in and around selected megacities/hot spot regions, including the interaction across the different spatial scales

The East Mediterranean region is an air pollution hotspot, located at a cross road of air masses from the surrounding regions that add to locally generated emissions. At the boundaries between the tropics and the mid-latitudes, the region is vulnerable to climate change. The warm and sunny climate of the area favors formation of secondary pollutants, such as ozone, compounding the air pollution problem.

The East Mediterranean region has a high level of air pollution (Kanakidou et al., 2011) owing to:

- Local anthropogenic pollutant emissions from the region's megacities (Istanbul, Athens, Cairo),
- Long range transport from upwind pollution (i.e., anthropogenic emissions from continental regions) or dust sources (i.e., Sahara desert),
- Significant natural emissions originating from within the region (i.e., sea salt, dust, plant emissions),
- Interactions of transported air masses with local/regional emissions.

CityZen has performed observational data analysis and modeling for the region. Mesoscale and global modeling have been used to distinguish and quantify the various impacts on air pollution. New targeted simultaneous observations of aerosol chemical composition have been performed, and the analysis of these data has enabled the identification of the main air pollution sources (Figure 6). The observations have also been used to constraint the Istanbul anthropogenic emissions inventory that has been improved within CityZen through mesoscale model evaluation with observations.

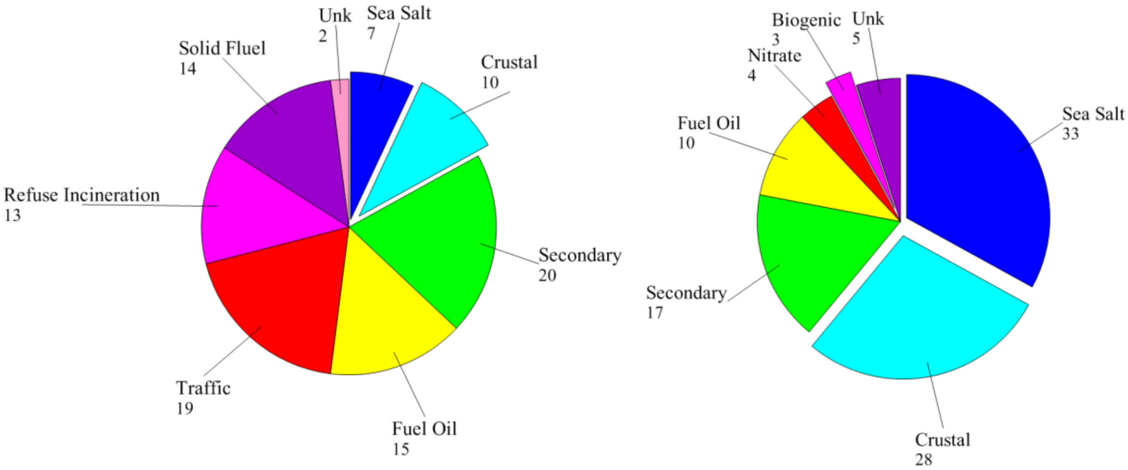

Figure 6: Source contributions for (a) Istanbul-megacity and (b) Erdemli -rural site.

1.3.3.1 Air pollution levels and sources

Impact of forest fire emissions

During the warm season, open fire emissions degrade air quality and affect the regional energy balance. In summer 2007, the large biomass burning events over Greece, with major outflow pattern over the sea, have increased the daily concentrations of elemental (by a factor of 4) and organic carbon (by a factor of 8) levels averaged over the East Mediterranean. Smaller increases have been computed for gaseous pollutants. In summer 2009, open fires occurred upwind of Athens enriching the city’s atmosphere with fine particles reducing solar irradiance up to 70%. The weakening of photochemical activity and the intense emissions of nitrogen oxides from the fires significantly reduced ozone compared to its usual levels in the city (Amiridis et al., 2011).

Contribution of local anthropogenic emissions to air pollution in megacities

Analysis of SCIAMACHY satellite data enabled a first evaluation of the local anthropogenic contribution to the extinction of solar radiation by aerosols over the Greater Athens Area and Greater Cairo Area at 15-30% and 25-50%, respectively (Hatzianastassiou et al., 2009). This contribution maximizes during summer when at Cairo urban sites the contribution of local anthropogenic emissions to PM levels can reach almost 100%. Observations reveal that in the urban cores most fine mode particulate matter of local origin is dominated by organic matter and elemental carbon (up to ~60% ; Theodosi et al., 2011), whereas in downwind locations the inorganic secondary components dominate particulate matter that is composed by larger particles.

Mesoscale simulations show that summertime fine particulate matter in Athens originates by 65% from local anthropogenic emissions, 10% from the regional biogenic emissions and 25% from long-range transport. For Istanbul, these contributions are 75%, 3%, and 22%, respectively (Im and Kanakidou, 2011).

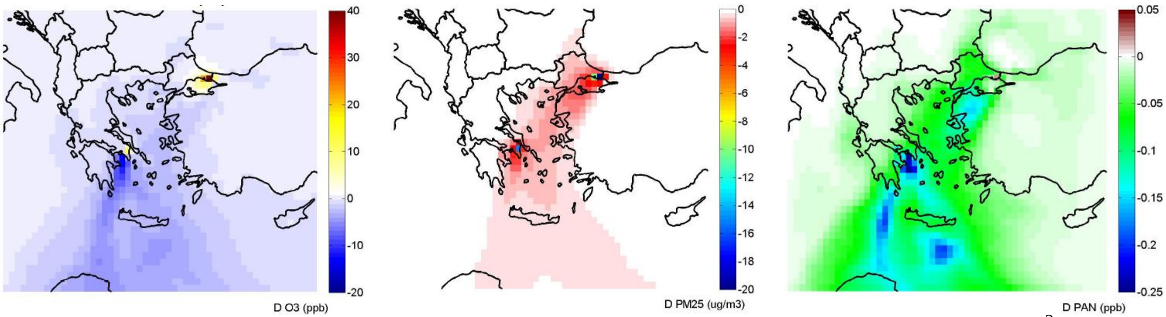

Figure 7: Changes in surface concentrations of (left) ozone (ppbv), (middle) fine particles (ug/m^3) and (right) PAN (ppbv) resulting from omission of anthropogenic emissions from Athens and Istanbul extended areas (Im and Kanakidou, 2011).

Significant contributions to particulate matter originate from natural dust (e.g. from deserts), which is transported into the region and from within in the region itself. This influence is strongest in the southeast of the Mediterranean basin with a decreasing gradient of influence to the northwest. On annual average, observations indicated a regional contribution to Athens particulate matter of 60-70%. Dust from local sources (wind dust and car abrasion) contributes up to 33% to the local aerosol mass in Athens (Theodosi et al., 2011; Gerasopoulos et al., 2011).

During summertime, Istanbul anthropogenic emissions are responsible for about 20% reduction in O_3 inside the extended megacity area itself, whereas they increase O_3 in the suburbs and downwind (Im and Kanakidou, 2011). In contrast, Athens anthropogenic emissions have small impact on ozone in the Athens extended area (~1% increase). This difference is attributed to the elevated regional influence in Athens compared to Istanbul. The significant local influence in Istanbul is seen by the low carbon monoxide to nitrogen oxides molar ratios. High regional ozone is affected by different organic gases to nitrogen oxides ratios and organic gases speciation.

Pollution outflow

Air pollution outflow from megacities deteriorates the air quality of the region and can lead to an increased number of exceedances of the European Union limits for ozone and particulate matter. Istanbul anthropogenic emissions have significant regional impact in the outflow downwind the megacity over the Aegean Sea where in particular secondary air pollutants like ozone and secondary aerosols are increasing (Im and Kanakidou, 2011). They contribute to regional aerosol concentrations (2.4% for fine particles) 5 times more than Athens emissions (0.4%). The opposite holds for gaseous pollutants with Athens emissions contributing more to the regional mean concentrations (0.8% for ozone, 1.5% for carbon monoxide, 3.6% for PAN) than Istanbul emissions (0.6% for ozone, 0.7% for carbon monoxide, 2.4% for PAN).

Interactions between anthropogenic and natural emissions in the region further enhance air pollution, producing ozone, particulate matter or changing the properties of atmospheric particles. For instance, coating by pollutants increases dust solubility and deposition of nutrients. Thus, organic aerosol in the urban sites is primary by 50% whereas downwind it has been chemically modified and is most secondary in nature.

Import/export

Global simulations show that the tropospheric ozone column in the East Mediterranean is largely maintained (> 90%) by emissions from outside the region and long-range transport (Figure 8). This contribution is smaller (~55%) for the shorter lived nitrogen dioxide column and for particulate matter (~40%) when excluding Saharan dust and sea-salt contributions (Myriokefalitakis et al., to be submitted).

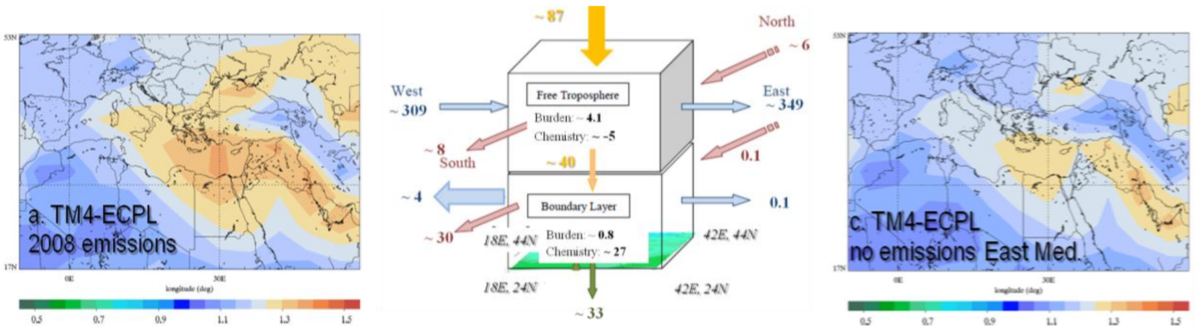

Figure 8: TM4-ECPL global model results: (left) present day tropospheric ozone column over the East Mediterranean (10^{18} molecules/cm^2), (middle) ozone budget in the East Mediterranean (Tg-O_3/yr) for the boundary layer and the free troposphere (Tg-O_3/yr), and (right) tropospheric ozone column over the Mediterranean when all East Mediterranean emissions are zero. The simulations are done for the year 2008 (Myriokefalitakis et al., to be submitted).

Exceedances

Ozone. At urban center and traffic air quality monitoring sites ozone exceedances occurred during summer and were limited (less than 15% of days). At suburban air quality monitoring sites ozone exceedances have been decreasing, but are still problematic 40-50% of days during summer. Urban centers have fewer ozone exceedances because of high primary emissions, particularly of NO, that suppress ozone in the city by reacting with and depleting ozone. However, ozone levels are then typically enhanced downwind of the city.

Particulate Matter. Exceedances are most common during the winter period and least common during summer. A general decreasing trend in pollution has led to less exceedances of the particulate matter limit. At urban air quality monitoring sites exceedances range between 40-70% of days in the region. The occurrence of particulate matter exceedances has fallen from 60% a decade ago to 40% currently at cities where air pollution reduction measures have been adopted (e.g., Athens); the exceedances at suburban sites occur about half as often.

For Istanbul particulate matter exceedances are mainly due to anthropogenic sources (~90%), which is also confirmed by the PMF analysis conducted by Kocak et al. (2011) on observations by Theodosi et al. (2010). By contrast, Athens has elevated background in ozone and particulate matter compared to Istanbul due to its location in the outflow of major pollution sources (for ozone) and due to the importance of Saharan dust events for particulate matter.

1.3.3.2 Trends and future

During the last two decades over the Greater Athens Area, nitrogen oxides, sulfur dioxide and carbon monoxide levels decreased by 42, 75 and 65%, respectively. Similarly, during the last decade over the Greater Istanbul Area, nitrogen oxides, sulfur dioxide and carbon monoxide levels were reduced by 32, 82 and 33%, respectively.

These improvements have been linked to a reduction in primary emissions owing to changes in transportation fuels and industrial emissions controls. These improvements vary between megacities depending on the efficiency of measures adopted and the timing of implementation. However, future increases in emissions (e.g., owing to economic growth, shipping emissions) could counteract the current trend of improvements.

The dominant export pathways from Istanbul and Athens in the recent years (1961-1990) and those in the future (2070-2090) have been compared based on air mass trajectory analysis using climate model simulations that have adopted the A2 IPCC-AR4 future scenarios. The dominant export pathways from these pollution hot spots are expected to remain the same in the future but the frequency of their occurrence will increase, compensated by a decrease in the less frequent pathways. In addition, the dominant winds are expected to be strengthening reducing the minimum travel time needed to reach a specific downwind location (Kindap et al., in preparation). Thus, according to these climate simulations and analysis, the calculated impacts of megacities outflow are expected to increase in a future climate.

Global simulations assuming business as usual increase in the region and the global anthropogenic emissions and present climate, indicate that significant enhancements in the tropospheric ozone column in the region have to be expected if no addition measures are taken to reduce air pollution.

Hypothetical decentralization plans for these urban agglomerations, maintaining the total amount of their anthropogenic emissions constant but homogeneously distributing it over larger "new" extended areas, have been tested with the WRF/MEGAN/CMAQ modeling system for summertime conditions (Im and Kanakidou, 2011). In such case higher ozone concentrations have been simulated inside the urban core (215% and 26% in Istanbul and Athens, respectively). On the opposite, fine particulate matter concentrations would decrease by 67% and 60% in Istanbul and Athens, respectively, whereas they would increase by 10% and 11% in the rural areas of Istanbul and Athens, respectively. The "new" extended area of Athens would experience a reduction in ozone by ~2% whereas Istanbul would experience an increase by ~15%. Overall decreases of fine particulate matter levels by 32% and 9% are calculated over the Istanbul and Athens "new" extended areas. Higher spatial resolution and longer simulations that also include sector-based evaluations are needed to increase the accuracy of the results presented in this study and to evaluate the seasonal responses to these abatement strategies.

Decentralization of present day anthropogenic activities could lead to significant improvements in air pollution in the urban areas decreasing the exceedances and human exposure. Although the re-allocation of the anthropogenic emissions towards rural areas increases the air pollutants levels in these rural areas, and is thus might affect vegetation, the mean pollutant levels in the extended areas are expected to decrease.

1.3.4 The Pearl River Delta

CityZen Objective: Quantify and understand current air pollution distribution and development in and around selected megacities/hot spot regions, including the interaction across the different spatial scales

The Pearl River Delta (PRD) is an area with one of the fastest economic developments in China. Urbanization in the PRD is characterized by city clusters with two megacities (Guangzhou and Hong Kong) and many medium- to small cities that are linked by a dense highway network. The expansion of the economy in this region causes ever higher demands for energy, mobility and communications. As a consequence, coal smog and traffic exhaust together cause serious photochemical smog and particulate pollution problems from urban to regional scales. The potential impact on regional air quality and climate change is a major concern for the national government as well as for the global community. A large number of research activities have been organized to understand air pollution formation and characteristics in this region, and to recommend control policy accordingly. Those activities, especially the "Program of Regional Integrated Experiments of Air Quality over Pearl River Delta (PRIDE-PRD)", have provided a solid basis for the CityZen project to choose the PRD as a hotspot case study for further investigation of the regional air pollution distribution, in-flow and outflow of major pollutants, and science-based control policies by using observational methods and air quality models.

1.3.4.1 Regional O_3 and PM pollution in the Pearl River Delta and control factors

Regional ozone and PM pollution in the PRD

The PRD air quality monitoring network has been in operation since 2006. Data of the network from 2006 to 2010 have been collected and analyzed in the CityZen project. The results show that pollution in the middle and southern PRD was characterized by very high concentrations of O_3, PM_{10}, NO_2, and SO_2. The northeastern PRD, which is upwind of major PRD emission sources, has rather high background concentrations of O_3 and PM_{10}, and pollution episodes have been observed occasionally. Since winds are predominantly northeasterly, high O_3 concentrations are observed frequently in the southwestern PRD. The regional distributions of O_3, PM_{10}, NO_2, and SO_2 have been well reproduced by the atmospheric models CMAQ and CAMx. $PM_{2.5}$ has been measured at several sites of the PRD, providing insight of air pollution in this region. Among the common air pollutants, $PM_{2.5}$ and O_3 are priority pollutants to be addressed in the PRD. In the past several years, the local authority has made great efforts to mitigate air pollution on the regional scale. The monitoring network data show that SO_2 and PM_{10} annual means have decreased, while the NO_2 concentration has been rather stable with a slightly decreasing trend. Although O_3 has increased on the annual mean, O_3 maximum concentrations have been decreasing as well, which means regional secondary pollution might be in the stage of a turnover point.

Ozone-precursor relationship and source apportionment

The relationship between ozone and its precursors is a classic scientific question and needs to be addressed everywhere for policy making. Observational-based models have been used to diagnose the relationship between O_3 and its precursors under conditions constrained by high time resolution data of VOCs, HONO, NOx, O_3 and photolysis rates measured at super-sites in the PRD. In most cases, O_3 is very sensitive to VOCs and has a slight positive correlation with NOx; O_3 production is in the VOC-limited regime and occasionally in a NOx titration regime at the super-sites. A high-order decoupled direct method (DDM) was applied to investigate O_3-precursor sensitivity in the PRD during the PRIDE-PRD campaigns. It showed a NOx-inhibited chemistry along the polluted plumes in central and southern PRD areas, and a NOx-limited condition over larger areas of the western, eastern and northern PRD. To make regional control policy, regional maximum O_3 EKMA curves were calculated by the CMAQ model. In general, regional maximum O_3 was in the VOCs limited regime, a conclusion consistent with the results produced by an observational-based model and CMAQ-DDM.

By applying the Ozone Source Apportionment Technology and the Geographic Ozone Assessment Technology in the CAMx model, ozone contributions from different regions and various emission sources have been quantified. Generally, about 40-50 ppb O_3 in autumn in the upwind areas was from areas outside the PRD, which actually constituted the main source of O_3 in the northeastern PRD and provided probably a rather high regional background in the region (Figure 9). Severe O_3 pollution in the southern PRD is mainly caused by ozone precursor emissions within the PRD. In conclusion, the PRD O_3 comes from two sources: regional (super-regional) background and chemical production within the PRD. Thus to reduce maximum O_3 values, PRD regional control strategy should be the key, whereas concerning the reduction of PRD mean O_3 concentration, super-regional joint control strategy might be necessary.

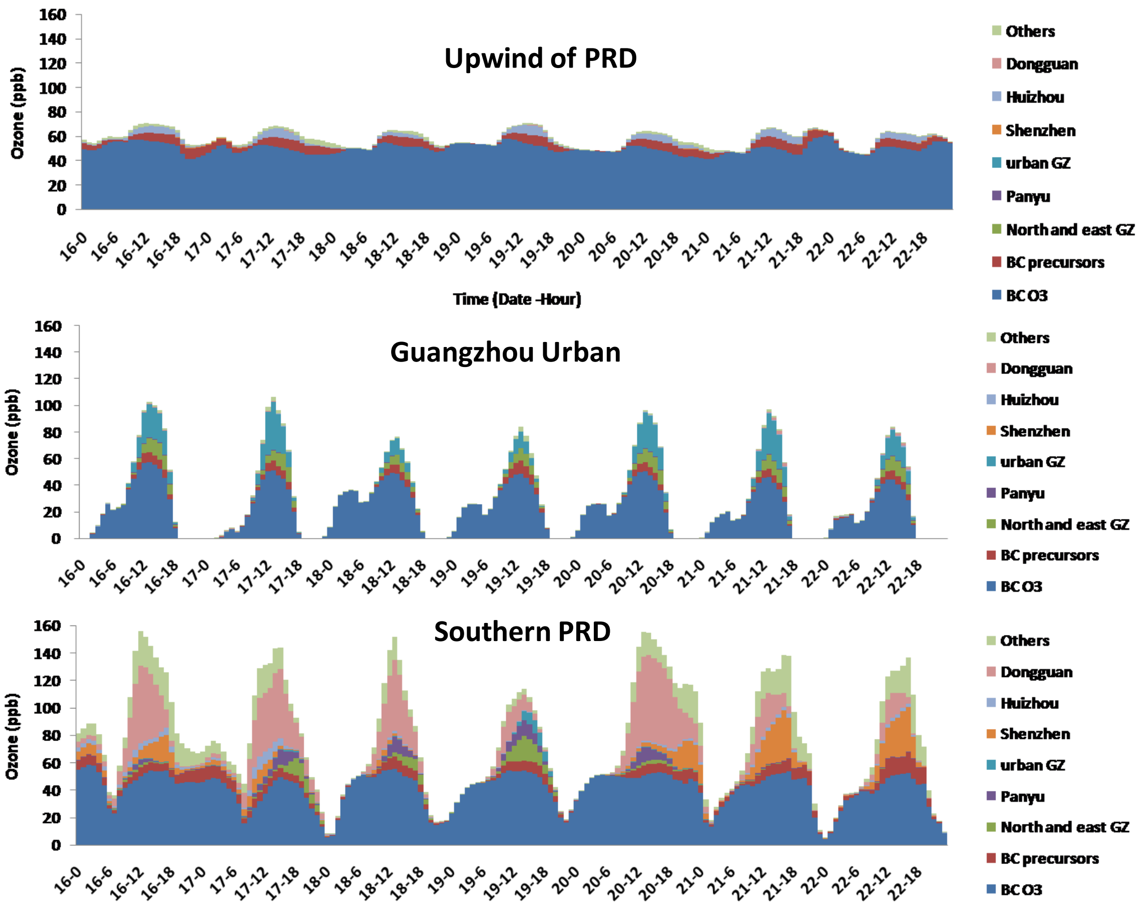

Figure 9: Ozone source apportionment in the PRD during 20-26 Oct, 2004.

$PM_{2.5}$ speciation and optical properties

Analysis of fine particle speciation indicates that SO_4^{2-}, NO_3^-, NH_4^+ and POM (primary organic matter) are major chemical components in the PRD regional $PM_{2.5}$, while the crustal contribution is below 10%. The analysis of AMS mass spectra by positive matrix factorization (PMF) methods identified three sources of submicron organic aerosol: hydrocarbon-like organic, low volatility oxygenated organic, and semi-volatile oxygenated organic aerosol. The results of the PMF together with the EC tracer method revealed that primary organic aerosol constituted ~34-47% to the organic aerosol (OA) mass, while secondary organic aerosol (SOA) constituted ~53-66% to the OA mass in the PRD during summer. This result, in combination with SO_4^{2-}, NO_3^- and NH_4^+, implies that secondary pollution is the main source of $PM_{2.5}$ mass in the PRD.

Aerosol data during the PRIDE-PRD 2006 campaign were further analyzed by the aerosol numerical optical closure method. The measured scattering coefficient σ_{sp}, absorption coefficient σ_{ap}, and ambient extinction coefficient σ_{ext}(RH) agreed well with calculations from Mie theory based on measured aerosol size distribution, theoretically refractive index, and RH (relative humidity). Compared to the dry condition, σ_{ext}(RH) on average increased by ~51% and atmospheric visibility deceased by ~35% under ambient condition (Figure 10). In addition, the influence of RH on the aerosol asymmetry factor and up-scatter fraction was investigated. At 80% RH, the aerosol direct radiative forcing increased by about 280% compared to that at dry condition and on average, it increased by about 100% during the campaign under ambient condition. It can be inferred that the aerosol water content is a key factor and cannot be ignored in assessing the role of aerosols in visibility impairment and radiative forcing, especially in the high RH region.

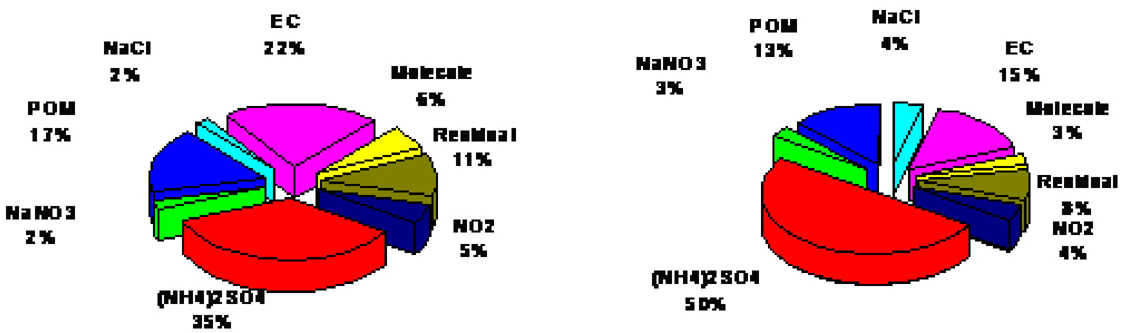

Figure 10: Contributions of the major chemical species to the atmospheric extinction coefficient under dry and ambient conditions.

1.3.4.2 Import/export fluxes of major pollutants between PRD and its surrounding areas

Budget of main pollutants in the PRD

The CMAQ model has been used, together with process analysis methods, to probe import/export fluxes of major pollutants in the PRD region. Figure 11 shows that emissions are the dominant source for all primary pollutants in the PRD, and significant O_3 and PM_{10} production occurs from April to November. Export is the dominant sink for most pollutants except PM_{10}, for which the export has similar magnitude as deposition processes. To quantify local or super-regional contributions to the PRD regional air pollution, a scenario of zero PRD emission has been used and compared to the base case. Import makes a significant contribution to PRD air pollution, for instance 42% for PM_{10}, 25% for SO_2 and 10% for NO_2.

O_3 shows different behaviour in the zero-emission scenario, as its concentration increases by 10%, showing its non-linear relationship to PRD emissions. Still, according to the O_3 source apportionment in the CAMx model, super-regional transport provides rather high background O_3 concentrations of up to 40 ppb in the PRD. These results imply that super-regional pollution control is necessary for improving the PRD air quality, although the PRD is a net pollution export area according to budget analyses.

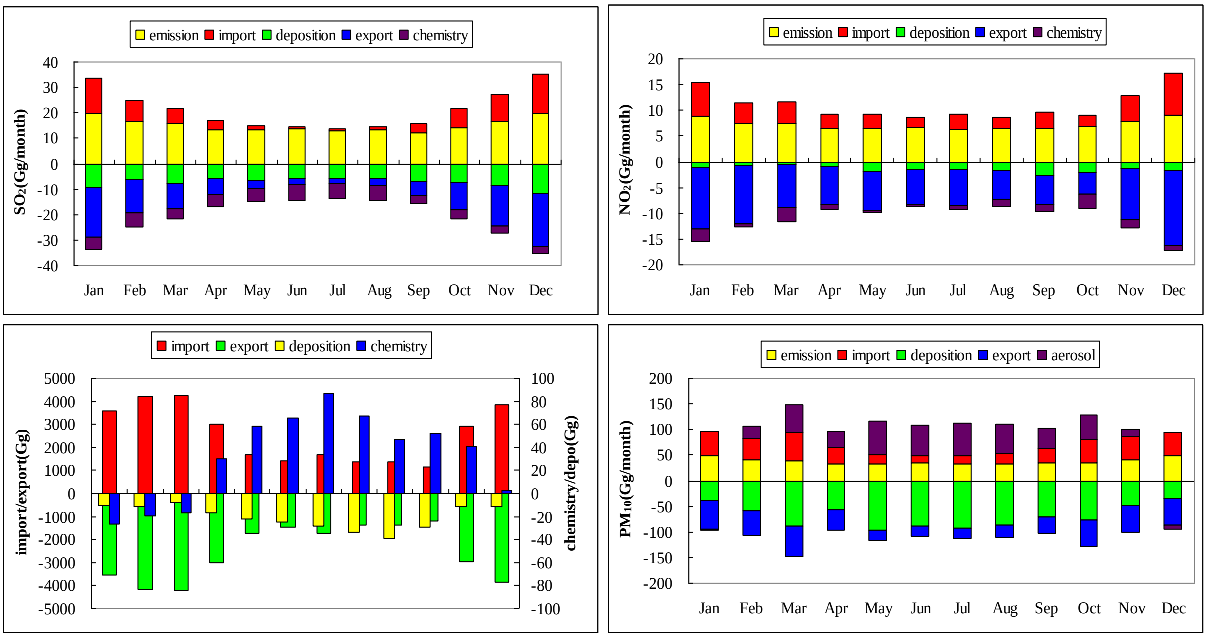

Figure 11: Budget of main pollutants in the PRD calculated by CMAQ.

Deposition fields of ozone and PM in the PRD region

Deposition (dry and wet) is an important sink for most pollutants. For ozone in the PRD, dry deposition is several orders of magnitude higher than wet deposition. O_3 deposition in summer and autumn is much higher than in other seasons. In summer, although the Asian monsoon leads to the lowest O_3 concentration, strong turbulence results in the highest deposition of the year. In autumn, higher deposition is also found due to high O_3 concentrations and the significant downward flux. Dry deposition of PM_{10} shows no significant seasonal variation. PM_{10} wet deposition in the PRD shows significant seasonal variations, well correlated with PM_{10} concentration, precipitation rates and cloud processes. Compared to dry deposition, the wet deposition is a more effective way to clean particulate matter in the atmosphere.

The inter-regional effect of the PRD emission

Figure 12 shows the percentage of air quality change due to PRD emissions. The influence of PRD emissions depends on the dominant wind direction in all months. April is a monsoon transition period in the PRD region when weak southerly wind dominates, with occasionally strong northerly winds. The footprint extends further toward the southwest of the PRD region than toward the northeast direction. In October, the footprint covers vast areas in the west and the south of the PRD region. Easterly wind is responsible for the footprint covering the Guangxi and Yunnan provinces. The strong vertical transport of PM_{10} and the easterly wind causes the large footprint area for PM_{10}, while the footprint for SO_2 can be attributed to emissions from large point sources and relatively minor wet removal in October.

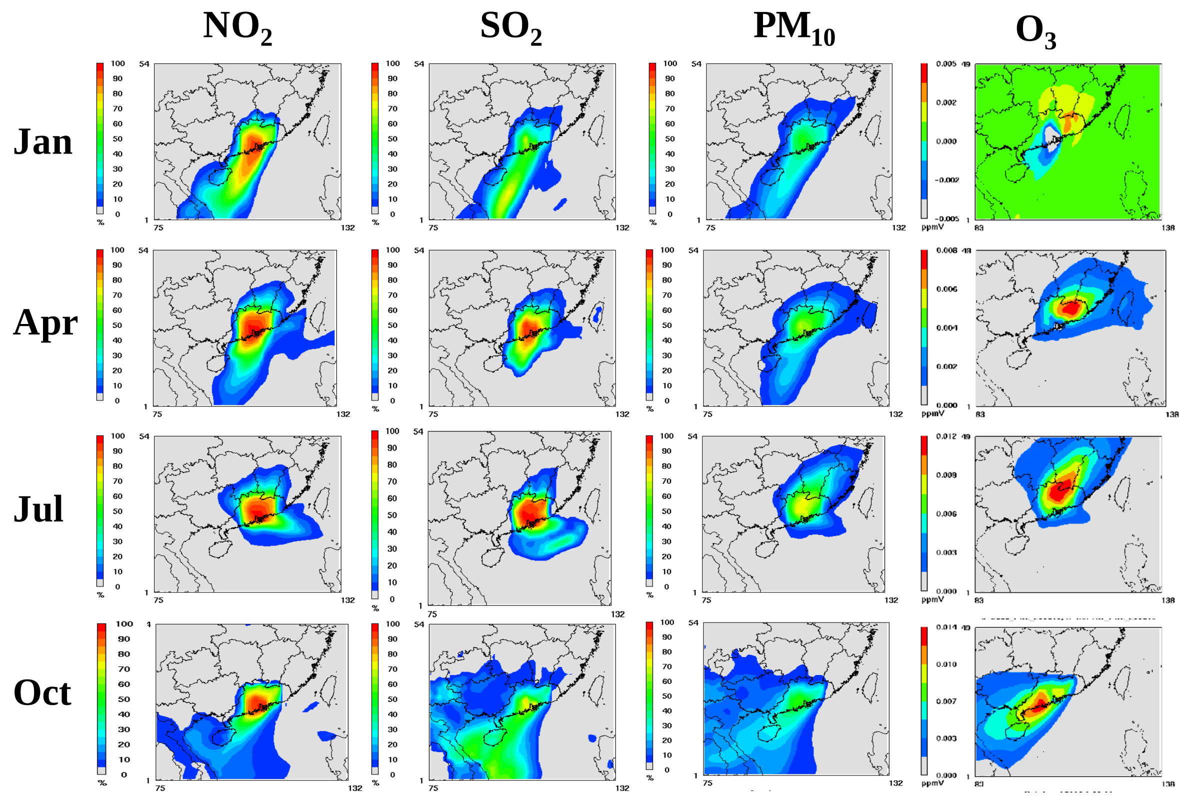

Figure 12: Percentage of air quality change due to the PRD emission.

1.3.5 Focus on the Po Valley

CityZen Objective: Quantify and understand current air pollution distribution and development in and around selected megacities/hot spot regions, including the interaction across the different spatial scales

The highly urbanized Po Valley area in Northern Italy is subject to a critical combination of intense emissions related to road traffic, urban heating and industrial sources, and a peculiar meteo-climatic situation, characterised by low winds and, in general, poor vertical mixing.

Many specific investigations have been made to assess the state of air quality in the Po Valley. A synthetic picture of the overall situation can be derived from the data of the stations available from AirBase (http://www.eea.europa.eu/data-and-maps/data/airbase-the-european-air-quality-database-2). Regarding the PM_{10} concentration averaged over the entire basin (defined as the small Po valley area, according to CityZen conventions) for year 2007, the median value ranges from 17 µg/m^3 in summer to 24 µg/m^3 in the other seasons for rural stations, and from 19 µg/m^3 in summer to 47 µg/m^3 during winter for urban stations. For about half of the days in that year the average concentration was larger than the threshold value.

The same year has been used to assess the skill of the model to simulate observed concentrations. Results of this investigation concerning O_3 and PM_{10} are reported in a synthetic way using Taylor diagrams (Figure 13). The diagram allows to compare the model with observations: the perfect model would have its symbol on the x axis, with relative standard deviation and correlation both equal to 1. The more the symbols depart from that point, the worse is the model performance.

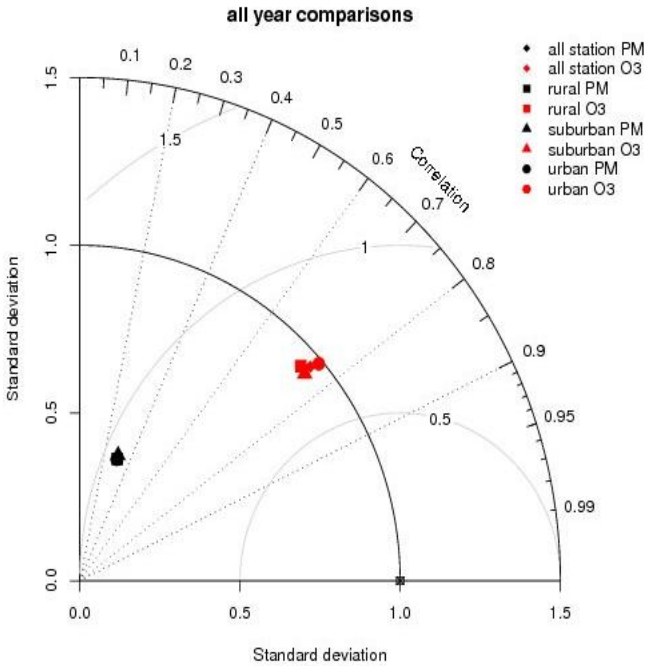

Figure 13: Taylor diagram of the PM and O3 comparisons relative to the entire 2007 and for the different station types. The O3 comparisons are significantly better than the PM comparisons for all the station types.

A seasonal analysis (not shown) reveals that PM data during winter compares better with the model than in the other seasons and it does not depend significantly on the station type. For ozone the model simulation is in better agreement with the data during fall, where the correlation is higher. One interesting feature to notice is the spread of the points relative to different station types. In the PM comparison the spread is higher during the summer while for the ozone the spread is higher in winter. This is coincidental to the fact that these seasons are those characterized by a respective concentration minimum for the two species.

Beyond correlations and average values, it is also relevant to compare the frequency distributions for measured and simulated PM (Figures 14 and 15). The much larger distribution of values from the data with respect to the model is evident, especially in winter, which indicates the larger variability of the data with respect to the model, being much more critical during the winter season.

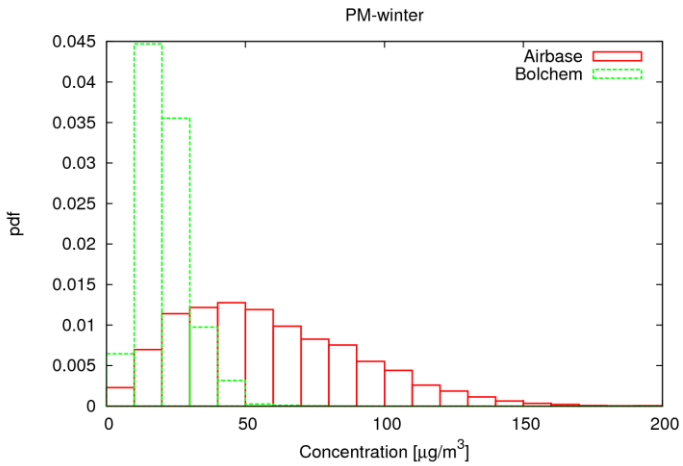

Figure 14: Normalised histogram of PM10 concentration, for the winter season and for all stations. Red: data; green: model.

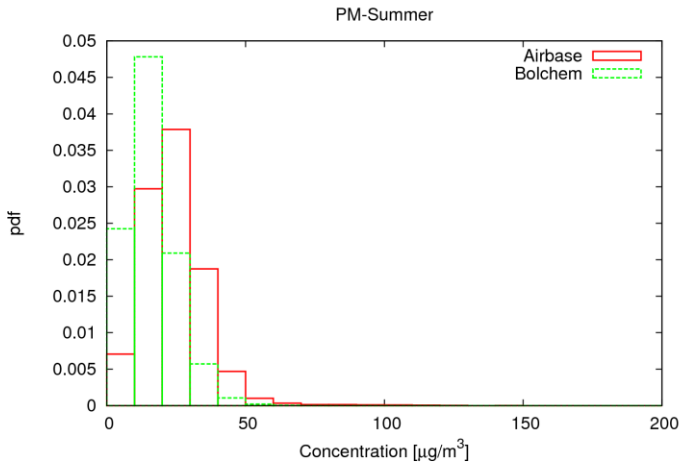

Figure 15: Normalised histogram of PM10 concentration, for the summer season and all stations. Red: data; green: model.

A further focus of the current research on large cities is whether they act as sources or sinks of pollutants, with reference to the surrounding areas. Quite obviously, as these hot spots are characterised by intense emissions, during pronounced advection the plume of pollutants from the hot spot affects the downwind areas. This phenomenon can occur quite systematically for large industrial regions such as the BeNeLux area. The situation may be different for areas like the Po Valley, as shown by the tracer numerical experiment performed for the year 2007. In this experiment, a tracer emitted only from outside the Po Valley (tracer 'o') contributes to the concentration in the Valley, and its concentration is compared with the concentration of a tracer, with the same characteristics, emitted only inside the Valley (tracer 'i'). In Figure 16 the ratio of the total mass of tracer 'i' in a layer 60 m thick at the ground and the total mass of tracer 'o' is shown.

It is evident that now there are cases in which the contribution from outside overcomes the contribution from internal emissions (about 15% of the cases). A broad correspondence is seen between occurrences of dominant transport from outside both in the entire column and near the ground.

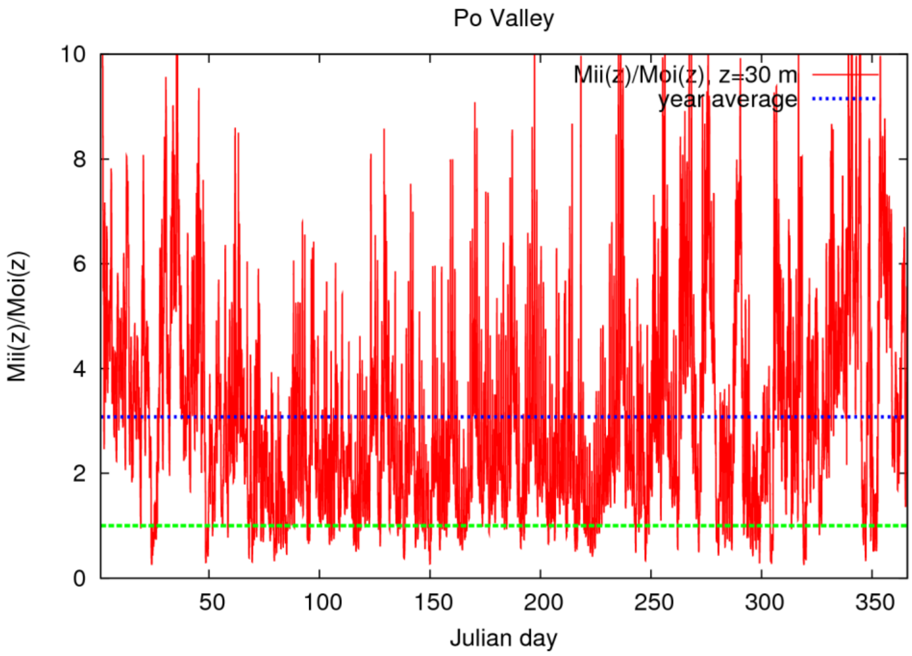

Figure 16: Time series of the ratio Mii/Moi in the layer near the surface. The green line indicates the unit value, the blue line the average value.

1.3.6 Focus on the BeNeLux/Rhine-Ruhr

CityZen Objective: Quantify and understand current air pollution distribution and development in and around selected megacities/hot spot regions, including the interaction across the different spatial scales

The Benelux/Rhine-Ruhr area is a strongly industrialized region located in Central Europe with a high population density and about 40 Million inhabitants. High emissions due to traffic and industrial activities make Benelux/Rhine-Ruhr a hot spot area with respect to air pollution in Europe.

Decadal simulations performed with the EURAD model have been used to compare model results with observations and to calculate fluxes of air pollutants. Figure 17 shows the annual mean of model results compared with measurements within North-Rhine-Westphalia for NO_2. It can be seen that the observations show a tendency to overestimate NO_2 annual means in the second half of the decade. This might be due to an underestimation of direct emitted NO_2 which is expected to increase within the decade and beyond. Further inspections of this hypothesis had been carried out as a follow up project in cooperation with the North Rhine Westphalia State Agency for Nature, Environment and Consumer Production (LANUV-NRW) to quantify the impact of increased direct NO_2-emissions. It could be shown that a moderate increase of the direct NO_2-emissions from 10% to 20% of the NOx-Emissions lead to an increase of 1 – 2 µg/m^3 of the annual average (about 5%).

The increase of the NO_2/NOx ratio for the emissions from road traffic during the decade, implies that even a decrease of NOx-emissions might not necessarily lead to a decrease of NO2-emissions due to road traffic. Consequently the NO2-concentrations remain more or less on the same level with some small interannual variations which might be due to changing meteorological conditions.

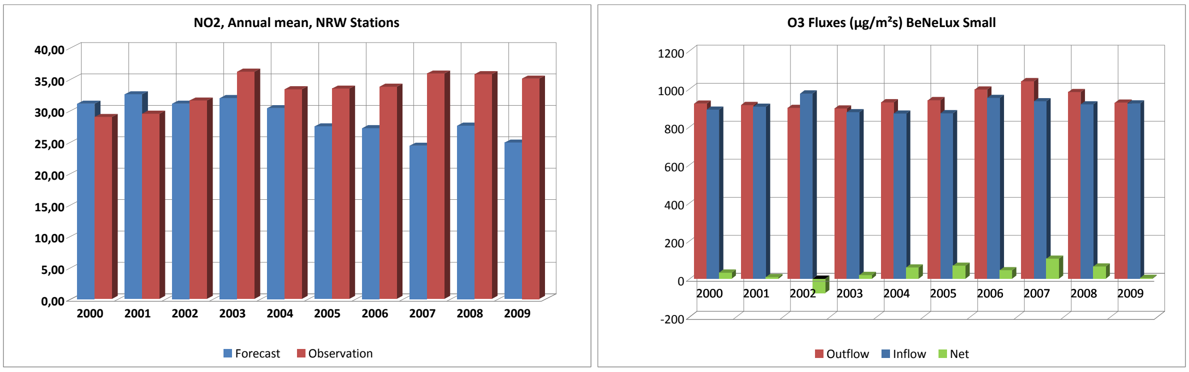

Figure 17: Annual average of NO_2 during the decade 2000 – 2009, observation vs. model results (left) and net ozone flux for the BeNeLux area showing that BeNeLux is a source region for all years except 2002 according the model calculations.

Agreement between observed and modelled values for PM10 (Figure 18, left) is better than for NO2. A clear trend during the decade cannot be seen, even though the last three years show the lowest values of the decade – in contrast to NO_2. Observed values are higher than the modelled results, except for the first year 2000.

Regarding ozone (Figure 18, right), observed values are always lower than the modelled concentrations (in contrast to NO_2 and PM10). A clear trend cannot be seen neither in observations nor in simulated values. Forecast and simulation show the highest averaged values in the years 2003 and 2006. Both years are characterized by high pressure episodes in summer leading to photochemical episodes in central Europe.

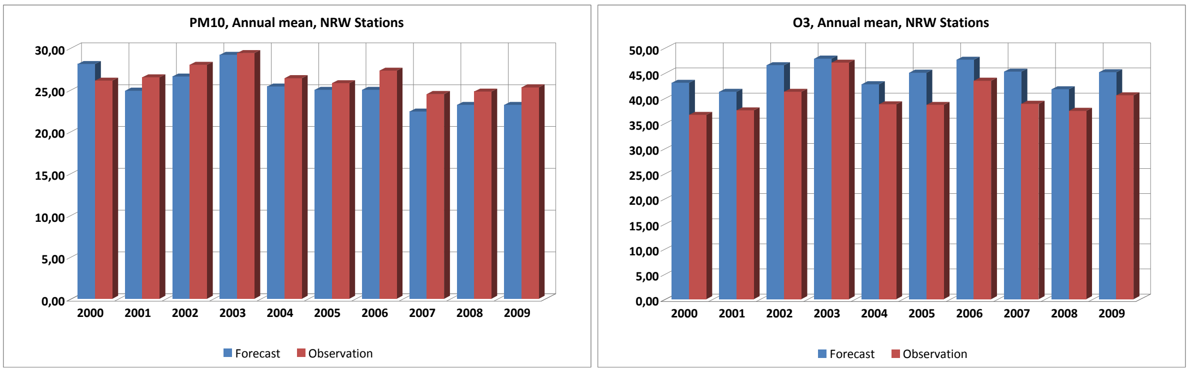

Figure 18: Annual mean of PM_{10} (left) and ozone (right) for the decade 2000-2009. Comparison of observed values (red) and modelled data (blue). Units: µg/m^3).

1.3.7 Focus on London

CityZen Objective: Quantify and understand current air pollution distribution and development in and around selected megacities/hot spot regions, including the interaction across the different spatial scales

Although not geographically a part of the initially selected hotspot areas, London was subject of several studies performed during CityZen, to be described in this section.

Detailed information on the UK Automatic Urban and Rural Network monitoring sites can be found at http://www.bv-aurnsiteinfo.co.uk/default.asp. For the CityZen study performed by ULeic, focusing on the megacity of London NO_2, NO, CO, and ozone data were included from 17 urban roadside, urban center, suburban, and urban background sites in Greater London. In addition, ozone data from 20 sites in southeast England were included. The majority of these sites were rural and urban background sites. The change in concentration of total VOCs (this includes 24 non-methane hydrocarbons) for the two sites with VOC data (Marylebone Road and Eltham) are shown in Figure 19. A comparison of all NO_2 and NO data for the 17 sites in greater London is shown in Figure 20.

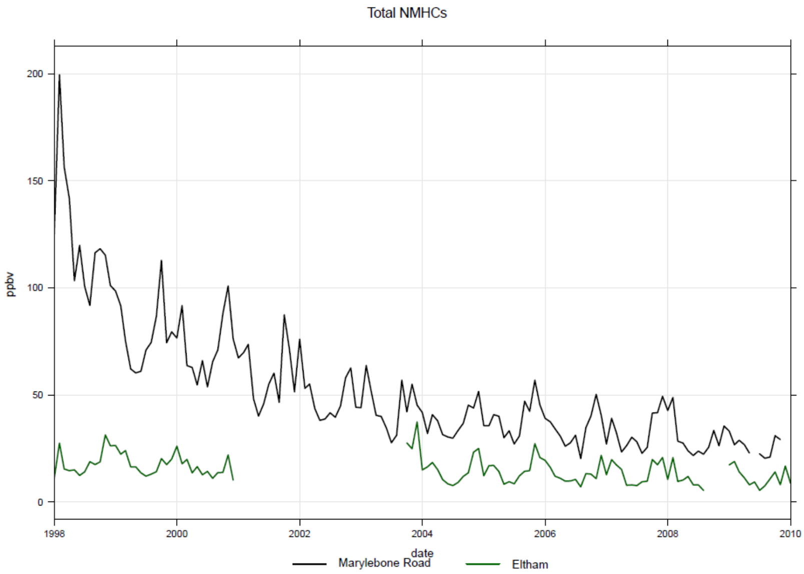

Figure 19: Monthly average total volatile organic compound (VOC) concentrations for Marylebone Road (urban roadside) and Eltham (suburban background).

Among all of the London sites, the observed trends in NO_2 were decreasing at all sites, with the exception of the urban roadside site at Marylebone Road. Nitrogen dioxide annual average (geometric mean) concentrations ranged from 24 ug m^{-3} to 85 ug m^{-3} in 1998 and from 15 ug m^{-3} to 94 ug m^{-3} in 2009 for Greater London. The NO_2 decreases ranged from -5.1% per year to -1.0% per year. Overall, if considered as one continuous 12 year period, the NO_2 concentration increased by +2.0% per year at Marylebone Road. However, a noticeable change in the trend took place in early 2003, which corresponds to the implementation of the congestion charging scheme and other traffic congestion and emissions reduction measures. The additional measures implemented, which were not limited to the congestion charging zone but incorporated all of Greater London, included additional bus lanes, the use of larger buses, particle traps on diesel buses, increased bus frequency, and changes to traffic light phases (Atkinson et al., 2009). If analyzed as two separate time periods (before 2003 and after 2003), the trend is very different. For the period from 1998 to 2003 NO_2 at Marylebone Road was decreasing at a rate of -4.1% per year (99.9% significance level), whereas from 2003 to 2010 a 0% per year trend in NO_2 was observed, but the trend was not significant. This would indicate that while the implemented changes may have positively influenced (reduced emissions) other species such as particulate matter, the impact on NO_2 actually reversed a decreasing trend at Marylebone Road. These results are in agreement with a study quantifying the changes due to the congestion charging scheme for the two years before and after its implementation, which observed increases in NO_2 and O_3 after implementation from monitors within the Congestion Charging Zone (CCZ) (Atkinson et al., 2009). The Marylebone Road monitoring station is on the boundary of the CCZ. No other sites have evidence of such a trend reversal.

Nitrogen oxide data showed decreasing trends at all sites in Greater London, which ranged from -20% per year (Bromley, roadside) to -3.0% per year (Bexley, suburban and Westminster, urban background). The largest per year decreases were observed among the roadside sites.

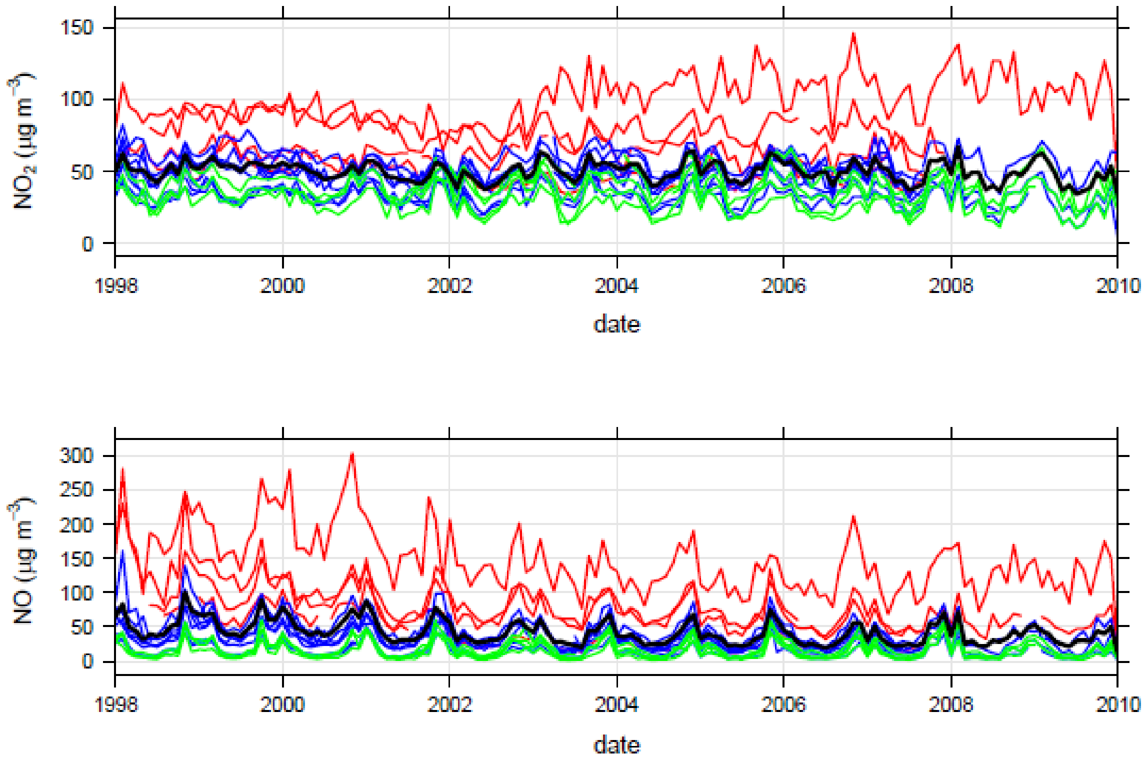

Figure 20: Monthly average concentrations of nitrogen dioxide and nitrogen oxide for the 17 sites in Greater London. Red lines are urban roadside sites, blue lines are urban center and suburban sites, green lines are urban background sites, and the thick black line shows the average of all London data.

Similar analyses have been made for carbon monoxide and volatile organic compounds (VOC) both showing decreasing trends during the investigated time period.

Ozone trends within London showed increasing trends ranging from +2.0% per year to +3.9% per year. The highest increases in London were among the urban background sites. The overall average trend for all London ozone data was +1% per year. These results agree with recent findings from Bigi and Harrison (2010) who found that ozone showed a steady increase from 1996-2008 at North Kensington in London, unfortunately the trend was not quantified, so the rate of increase could not be compared. Ozone trends for sites surrounding London in Southeast England were also quantified. The majority of these sites were rural and urban background sites, with a few exceptions. These trends ranged from -3% per year to +3% per year. All of the surrounding sites that showed statistically significant increasing trends in ozone were in the predominant downwind region (to the northeast) from London.

Trends in atmospheric concentration are generally decreasing for ozone precursor species (NO_2, NO, VOCs, CO), with roadside trends typically showing larger reductions with respect to other types of monitoring sites throughout London (except for NO_2 at Marylebone Road). While concentrations of ozone precursors are decreasing throughout London, the subsequent trends in ozone in London and in the downwind regions of London are not showing corresponding decreases. However, there are many other factors in ozone formation, such as long-range transport and the contribution of hemispheric background ozone that must be considered, and this must be investigated further.

1.3.8 Climate-chemistry interactions

CityZen Objective: Estimate how megacities/hot spots influence climate change

CityZen Objective: Estimate how megacities are responding to climate forcing which can influence transport patterns, chemical oxidation and biogenic emissions (especially biogenic volatile organic compounds BVOC)

Megacity areas are global emission hot spots. Due to the high population densities and the associated concentration of emissions from anthropogenic activities – in particular fossil fuel combustion – emission flux densities for CO_2, gas-phase air pollutants and aerosols are much larger in megacity regions than elsewhere. Aerosol and aerosol precursor emissions in particular will interfere with the radiation budget through direct (scattering and absorption) and indirect (influences on clouds) effects. This could have important consequences for the regional and, potentially, even global climate. On the other hand, the space consumed by megacities is comparatively small, so that on average over larger regions, the megacity impacts on temperatures, clouds or precipitation may barely be noticeable. Climate change will also change the chemistry of the atmosphere so that the air pollution response to emission changes might be different under different climate scenarios. Within CityZen, these relations were investigated in a series of model studies performed with global chemistry climate and chemistry transport models.

1.3.8.1 Megacity impact on climate

In order to analyse the potential megacity impacts on climate, one first needs to specify how "megacities" shall be represented in the global model simulation. In CityZen we adopted a year 2030 population mask by Vadim Chirkov, IIASA, and labelled each grid box with more than 150 inhabitants per km^2 in 2030 a "megacity grid box". This led to a megacity distribution where large parts of Southern and Eastern Asia were identified as megacities (Figure 21). While this pattern may not fully reflect reality, it turns out to be quite useful for a model sensitivity study, because it combines effects from large perturbations (over Asia) with effects from small perturbations (such as over Europe).

Two decadal simulations with sea surface temperatures from the decade 2030-2040 were carried out with the ECHAM5-HAM aerosol climate model. The base case run "MC on" used best estimate emissions for 2030 in all grid cells, while the "MC off" simulation had no urban emissions in the grid cells designated as megacities. Figure 22 (left) shows the total radiative forcing difference between the "MC on" and "MC off" simulations and thus gives an indication about the importance of megacity aerosol emissions on the climate system. Net reductions of the surface shortwave irradiance of up to -23 Wm^{-2} are found over the Ganges region and over China. At the top of the atmosphere, megacity emissions exert a much smaller influence which is predominantly positive (up to +3.1 Wm^{-2} over China). Among the other world regions with megacity emissions, only Africa yields a noticeable impact on the radiative balance. Here, TOA (top of atmosphere) forcing is enhanced by up to 1 Wm^{-2} while surface radiation is reduced by up to -3.1 Wm^{-2}. The radiative forcing changes for Europe are shown in Figure 22 (right). The small signal of megacity emission in Europe leads to a slight cooling effect over western Europe and the North Atlantic while it exacerbates warming in the Mediterranean region. Note that the simulation does include indirect aerosol effects so that this net radiation change includes the changes in cloud properties. For Europe, the simulations indicate an increase in cloud droplet number concentrations due to megacity emissions (Figure 23) as it should be expected when the aerosol load in the atmosphere is increased and more but smaller cloud droplets are formed.

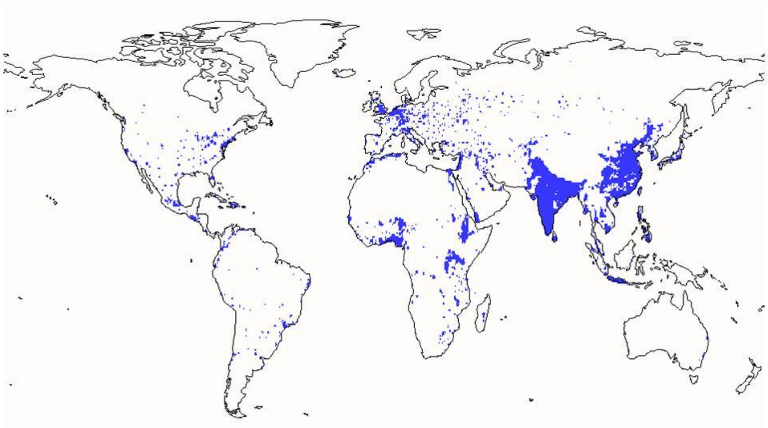

Figure 21: Distribution of megacities in the ECHAM5-HAM simulation to investigate the impact of future megacities on climate.

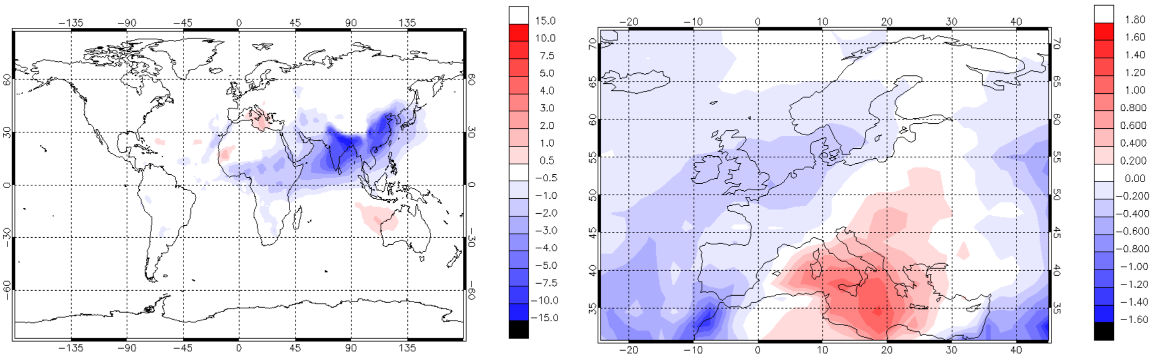

Figure 22: Instantaneous direct radiative forcing due to aerosols from megacities at the surface. Shown here is the difference between the deacadal annual mean values from the ECHAM5-HAM base case simulation and a sensitivity run without megacity emissions. Units: Wm^{-2}. Note the different scales.

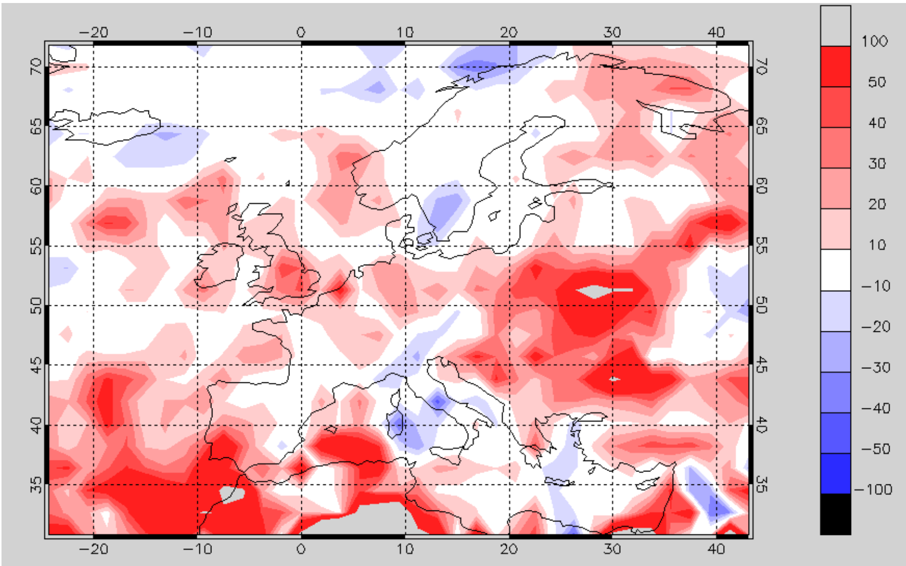

Figure 23: Change in the cloud droplet number concentration at the surface over Europe due to the influence of megacity emissions. Units: %.

1.3.8.2 Climate impact on megacities

Future simulations

Couplings between air pollution and climate change were studied by several model systems in CityZen. The most common approach was to drive comprehensive chemical transport models with climate data from general circulation models provided for present and future time slices. The effects of climate change and emission changes until the year 2050 were studied separately and combined. UiO has run the OsloCTM2 model with climate data provided by FZJ and the ECHAM5 model, while METNO has used the EMEP/MSC-W model, driven by climate data for present and future time slices from the HIRHAM model, to calculate the response on ozone and particulate matter to changes in climate and emissions.

An example of the METNO results for ozone is shown in Figure 24. Ozone tends to increase during the first half of this century in the Mediterranean area, when only climate change is taken into account. However, an overall decrease is modeled when projected emission reductions are implemented in addition. Exceptions are seen within some confined, heavily polluted areas, e.g. Southern England. Similar calculations have been made for CityZen for the year 2030 time frame. The results are similar to the 2050 results, although the signal from climate change is weaker.

Figures 25 and 26 display the UiO results. CO concentrations were found to generally decrease in cloudier regions with higher humidity, while they tended to increase in regions that would become drier in the future (Figure 25). The signal from the anticipated emission changes is stronger than the climate signal and would lead to reduced CO concentrations in many world regions due to air pollution abatement measures (see also Stordal and Hodnebrog, 2011b). Daily maximum surface ozone concentrations are also more sensitive to precursor emission changes (notably of NOx) than to the relatively modest climate change that is predicted for the 2040s. However, enhanced ozone concentrations due to climate change are predicted to outweigh potential negative trends due to emission reductions in warm and dry regions such as the central Mediterranean region (Figure 26). The Oslo CTM2 simulations suggest that the climate impact exacerbates the expected surface ozone pollution in India and that it neutralizes potential ozone reductions that could be achieved in China as a result of strict pollution control measures.

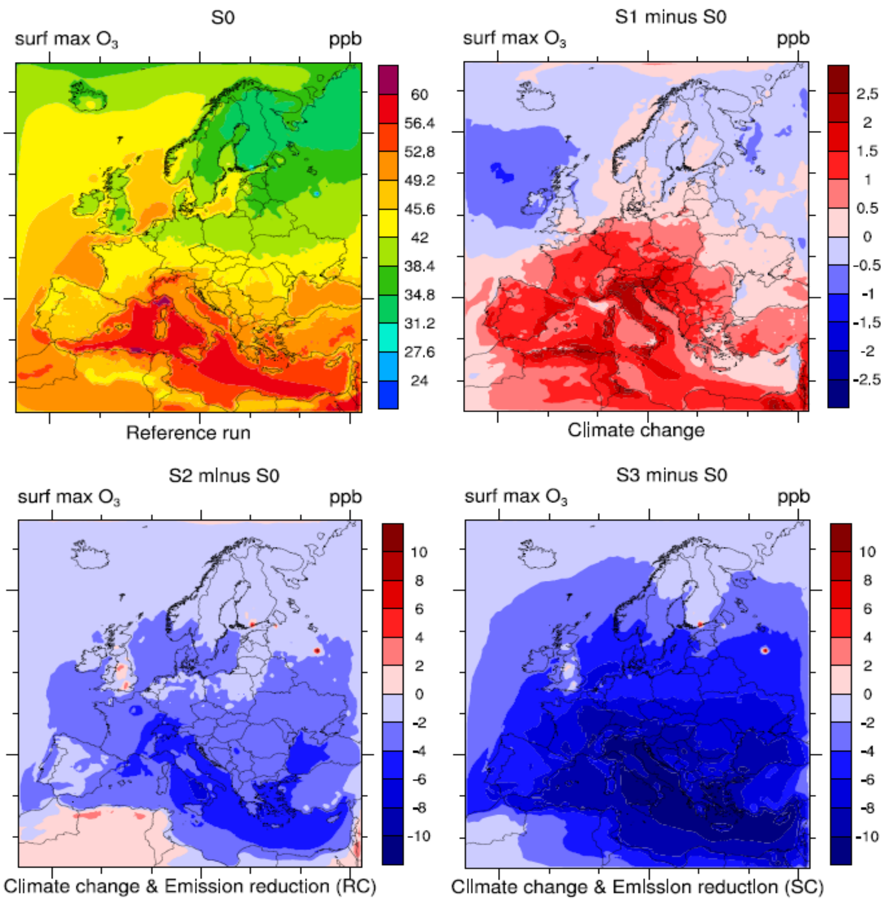

Figure 24: Upper left: Daily maximum near-surface ozone, averaged over the 11-year period 2000 to 2010, as modeled by the EMEP/MSC-W model. The three other plots show modeled changes in daily maximum surface ozone. Upper right: effect of climate change from 2000s to 2040s, lower left: effect of climate change and emission change - current legislation scenario, and lower right: effect of climate change and emission change – stringent climate policy. Units: ppb. The future emission scenarios, based on the Global Energy Assessment, were provided by IIASA (see section 1.3.9).

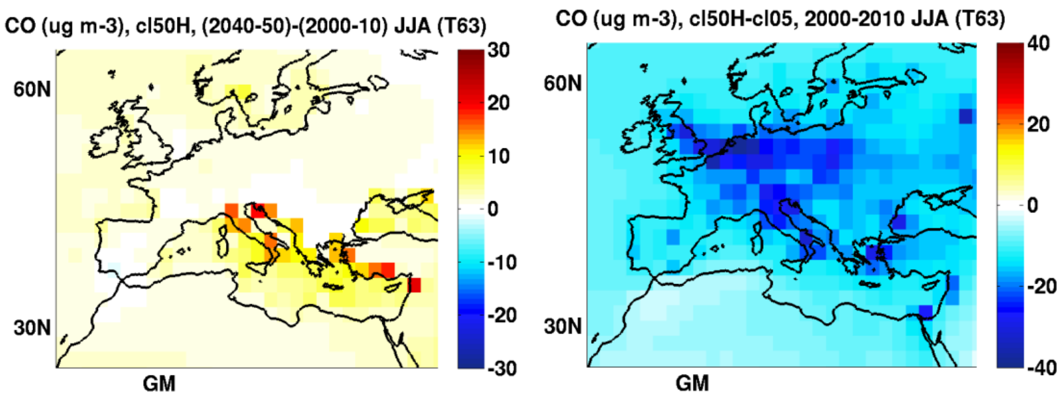

Figure 25: Changes in surface CO concentrations over Europe, left: as a result of climate change (2040-2000), and right: as a result of projected emission changes from the HIGH-CLE emission scenario (see section 1.3.9).

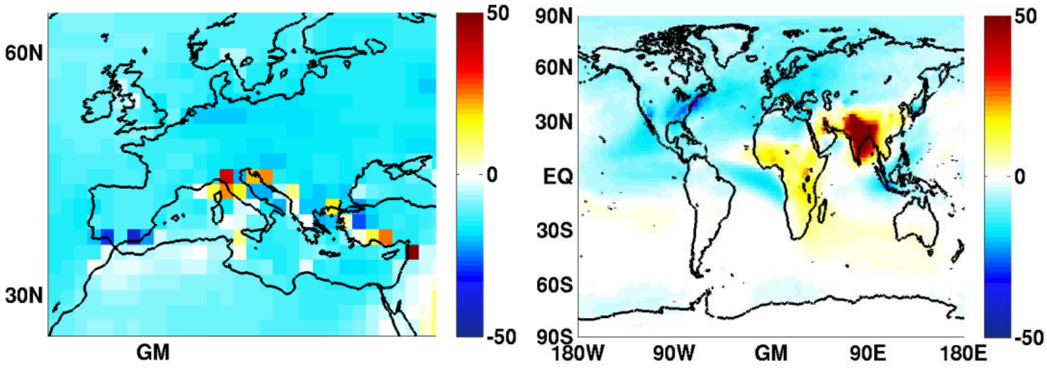

Figure 26: Combined climate- and emission-induced changes on surface ozone over Europe (left) and globally (right).

Climate variability

The impact of climate variability on air quality in Europe was investigated with the ECHAM5-MOZ tropospheric chemistry climate model (Richter and Schultz, 2011). Two simulations were performed for the period 1989-2008, one of them using meteorological reanalysis data and the other one using prescribed sea surface temperatures and sea ice fields only. Emissions were taken from the ACCMIP inventory (Lamarque et al., 2010), to which CityZen contributed both with respect to the planning of the inventory structure and with a historic time series of biomass burning emissions following Schultz et al., 2008. Both simulations yielded very similar mean distributions of surface temperatures and ozone concentrations over Europe (Figure 27). The largest ozone differences were found in Southern Scandinavia, western Russia and in the Mediterranean (up to 5 ppb). In contrast to the very similar average distributions, the interannual variability of ozone differs markedly between the two simulations (Figure 28). In the simulation with assimilated meteorology, the variability is generally larger and there is an extended region with high variability in eastern Europe which is absent from the simulation based on sea surface temperatures and sea ice fields. The differences in the ozone variability patterns correspond well with the differences in the 2 m temperature variability (Richter and Schultz, 2011) suggesting a positive correlation between surface ozone concentrations and temperature (cf. Rasmussen et al., 2011). However, when we look at extreme events (heat wave episodes), these are more pronounced in the run driven with sea surface temperatures, yet the maximum ozone concentrations are found in the simulation with assimilated meteorology.

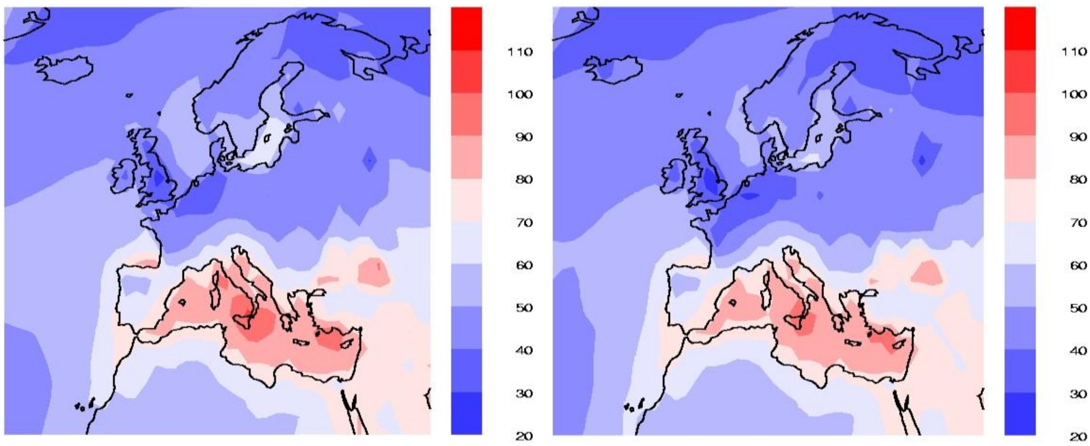

Figure 27: Multi-annual mean summertime surface ozone concentrations over Europe from the ECHAM5-MOZ simulations with assimilated meteorology (left) and with prescribed sea surface temperatures and sea ice fields (right).

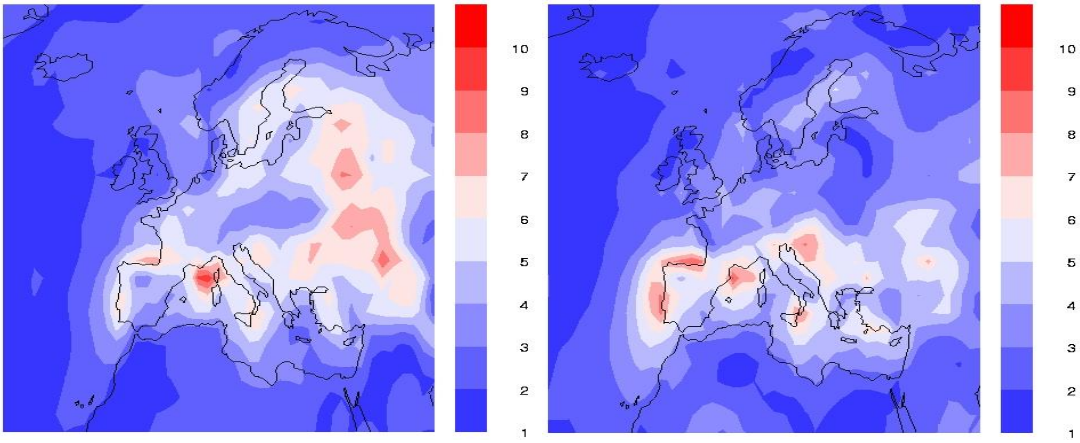

Figure 28: Summertime surface ozone variability (standard deviation) from the two ECHAM5-MOZ simulations with assimilated meteorology (left) and with prescribed sea surface temperatures and sea ice fields (right).

Case studies for the East Mediterranean situation

Im et al. (2011a) have shown for the East Mediterranean region that, with increasing temperatures, average summer ozone levels are expected to be enhanced by 0.9 (±0.1) ppbv per degree increase owing to more natural emissions from plants which are expected to increase by 9% (±3%) per degree. For Istanbul, a smaller increase of 0.4±0.1 ppb ozone per degree is calculated, which is about half of the domain-averaged increase. In a warmer climate, lesser increases are expected for secondary organic aerosol and nitrate aerosols, while sulfate aerosols are expected to decrease in future summers with warmer temperatures (Im et al., 2011b). The temperature impact on particulate matter increases via its effect on other meteorological fields. The risk of open fires is also expected to increase in a warmer climate.

Hodnebrog et al. (2011) have looked at the hot summer of 2007 in southeast Europe, using two regional atmospheric chemistry models; WRF-Chem and EMEP MSC-W. The region was struck by three heat waves in 2007, and by a number of forest fire episodes, greatly affecting air pollution levels. The plume from the Greek forest fires in August 2007 is clearly seen in satellite observations of CO and NO_2 columns, showing extreme levels of CO in and downwind of the fires. Model simulations reflect the location and influence of the fires relatively well, but the modelled magnitude of CO in the plume core is too low, presumably due to underestimation of CO in the emission inventories. Biogenic VOC emissions reacting with anthropogenic NOx emissions are calculated to contribute significantly to the levels of ozone in the region, but the magnitude and geographical distribution depend strongly on the model and biogenic emission module used. During the July and August heat waves, ozone levels increased substantially due to a combination of forest fire emissions and the effect of high temperatures. It was found that the largest temperature impact on ozone had been through the temperature dependence of the biogenic emissions, closely followed by the effect of decreased dry deposition. The impact of high temperatures on the ozone chemistry was much lower. One of the conclusions of the study is that forest fire emissions, and the temperature effect on biogenic emissions and dry deposition, will potentially lead to substantial ozone increases in a warmer climate.

1.3.9 Future mitigation options

CityZen Objective: Estimate the future impact from emission changes with a focus on the effect of rapid growth in the population of megacities/hot spots and the increasing background of pollutants (concentrate on ozone O3, particulate matter PM, and their precursors)

CityZen Objective: study mitigation options to keep the air pollution load in and around megacities/hot spots within sustainable limits in terms of human health effects and climate impact

1.3.9.1 New emission data for the future

IIASA provided CityZen with global gridded emission data for the time period 2005 to 2050 for different scenarios. These scenarios relied on the energy projections developed within the Global Energy Assessment (GEA) coordinated at IIASA (http://www.iiasa.ac.at/Research/ENE/GEA/index_gea.html), where the IIASA MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) model was used (Messner and Struberger, 1995), while air quality legislation assumptions (CLE) until 2030 originated from the GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) model (Amann et al., 2011). The following scenarios were provided:

1) No policy change ('GEA Frozen')

This scenario assumes that there is no change in future air pollution policies after 2005 which implies that the combustion technologies and abatement measures penetration remains at the level of 2005 for the entire modelling period. Furthermore, no climate change policies are implemented, thus assuming no feedback on energy demand from such policies. There is also no implementation of policies on energy access, although increasing economic growth leads to a slowly declining use of dirty solid fuels for cooking and heating in developing regions. As a result pollution levels in this scenario are the highest among the considered scenarios.

2) Current legislation AQ Policy ('GEA high CLE')

This scenario is identical to the FLE case described above in terms of energy structure and has no specific policies on climate change and energy access. However, it assumes full implementation of all current and planned air pollution legislation world-wide until 2030.

3) Current legislation AQ+Climate Policy ('GEA low CLE')

This scenario assumes implementation of a stringent climate policy corresponding to a 2 degree global temperature target. In addition, it assumes a moderate energy access policy corresponding to microfinance and 20% fuel subsidy well as full implementation of all current and planned air quality legislation until 2030, similar to the reference case described above.

4) Very ambitious AQ+Climate Policy

This scenario varies from the above one in that it assumes global implementation of extremely stringent pollution policies (SLE) until 2030. These stringent air quality control strategies assume fast implementation of low emission measures in all sectors.

Beyond developing the above scenarios, an estimated impact of “climate friendly air pollution measures” on further (beyond CLE) reductions of air pollutants was provided. These measures were based on the so-called ‘Low GWP’ scenario which incorporates a set of air pollutant emission reduction measures that were selected on the basis of reducing global warming potential (GWP), the "climate-friendly air quality measures". A brief characterization of identified measure categories is given in Table 2. A full implementation of these measures by 2030 would lead to significant reductions of short-lived climate forcers (SLCF) emissions relative to current emissions or to the 2030 emissions in the reference scenario, and also reduce a high proportion of the emissions relative to the potential offered by full implementation of all 2000 measures in the GAINS model.

Table 2: Identified measures to reduce radiative forcing from short-lived substances; ‘LowGWP’ case

Measure	Sector
Diesel particle filters for road and off-road vehicles	Transport
Replacing coal by coal briquettes in cooking and heating stoves	Residential
Pellet stoves and boilers, using fuel made from recycled wood waste or sawdust, to replace current wood burning technologies in the residential sector in industrialized countries	
Introduction of clean-burning biomass stoves for cooking and heating in developing countries	
Replacing traditional brick kilns with vertical shaft kilns	Industry
Replacing traditional coke ovens with modern recovery ovens, including the improvement of end-of-pipe abatement measures in developing countries	

1.3.9.2 Coordinated modelling study for the future

In order to investigate future air quality, anthropogenic emissions scenarios developed by IIASA were investigated by the all the modelling groups in a coordinated manner. Six atmospheric chemistry modelling groups covering different scales were involved. The methodology followed the framework used for the 10 years hindcast (Section 1.3.2.3). Using common meteorological fields representative of the current (early 21st century) conditions we could isolate the impact of changes in anthropogenic emissions on the modelled concentrations of atmospheric pollutants.

The strengths of this work include:

- Use of realistic emission scenarios (as opposed to sensitivity studies), similar in their design and development to IPCC projections, yet more appropriate for air pollution studies.
- Use of a variety of chemistry transport models, including both global and regional-scale models so that an ensemble representative of a range of scales could be derived, hence providing a better insight into model uncertainty.
- Comparability with a hindcast multi-model initiative using the same models (Colette et al., 2011), so that the representativeness of this subset of numerical tools is well documented.
- Simulation of a 10-year period to offer more robust statistics.
- Presentation of the results in an “exposure-based” framework, with indicators specifically de-signed for health and ecosystem exposure assessment.

We find that overall O_3 and PM_{10} concentrations decrease in 2030 compared to 2005 with a stronger improvement for the scenario including climate policy enforcement in addition to the cur-rent air quality legislation. However, for some models and scenarios a relative increase of O_3 remains in areas saturated in nitrogen oxides (Figure 29). Nevertheless exposure indicators weighted by the population density or landuse fraction unambiguously show the overall improvement in terms of total pollution cumulated over sensitive areas (Table 3).

By offering a quantification of the difference in terms of modelled concentrations of the main pollutant between a business-as-usual scenario and a projection where a climate policy is enforced, we offer a first insight into the impact of mitigation strategies on future air quality.

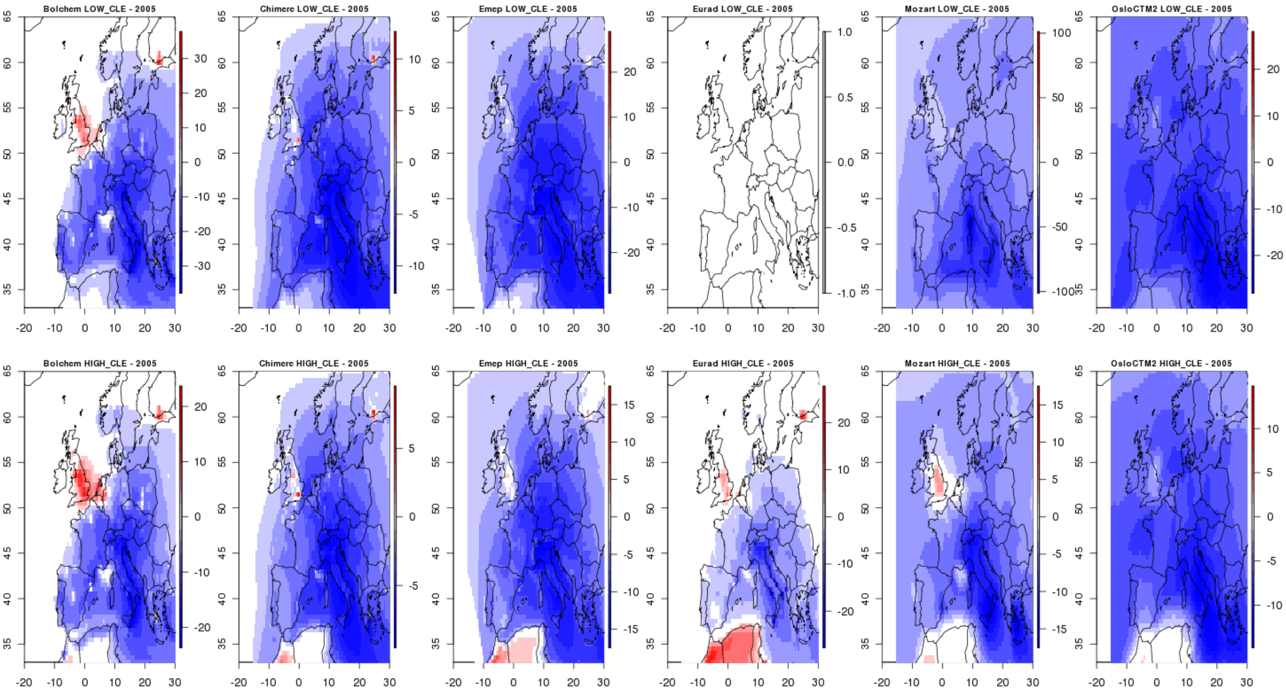

Figure 29: Difference between modelled summertime (JJA) O3 concentrations (µg/m3) at the surface with the 2030_LOW_CLE scenario (top row) and 2030_HIGH_CLE (bottom row) compared to the reference (2005) for each model: from left to right: Bolchem, Chimere, Emep, Eurad, Mozart and OsloCTM2.

	Scenario	Europe	Benelux	Po Valley
SOMO35	HIGH_CLE	17.7 (10.2)	17.4 (4.31)	27.9 (11.9)
	LOW_CLE	43.3 (13.6)	50.4 (23.5)	51.4 (14.1)
MTDM	HIGH_CLE	11.1 (5.34)	15.6 (6.31)	19.3 (8.8)
	LOW_CLE	20.5 (7.63)	24.4 (8.33)	38.5 (29.1)
AOTc	HIGH_CLE	39.5 (11.7)	45.6 (9.15)	46.2 (11.3)
	LOW_CLE	68.5 (21.7)	73.5 (9.15)	72.2 (18.5)
AOTf	HIGH_CLE	30.8 (13.5)	40.9 (9.44)	43.3 (13.2)
	LOW_CLE	62.4 (18.5)	69.6 (14.9)	71.4 (16.7)
PM10_avg	HIGH_CLE	32.7 (4.27)	39.9 (3.55)	45.6 (4.05)
	LOW_CLE	42.7 (5.56)	61 (20)	60.1 (8)

Table 3: Change of the air quality exposure indicators (weighted by the population or the landuse) expressed as a percentage of reduction compared to the reference (2005). We provide the mean of percentages estimated by each of the CTM and the standard deviation between the estimates of each model is given in brackets.

1.3.10 References

Amann M., et al., 2011: Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications, *Environmental Modelling & Software*, doi:10.1016/j.envsoft.2011.07.012, Article in press.

Amiridis, V., et al., 2011: Impact of the 2009 Attica wild fires on the air quality in urban Athens, *Atmos. Environ.*, doi: 10.1016/j.atmosenv.2011.07.056.

Atkinson, R.W., et al., 2009: The impact of the congestion charging scheme on ambient pollution concentrations in London. *Atmos. Environ.*, 43, 5493-5500.

Bigi, A., and Harrison, R.M., 2010: Analysis of the air pollution climate at a central urban background site, *Atmos. Environ.*, 44, 2004-2012.

Colette, A., et al., 2011: Air quality trends in Europe over the past decade: a first multi-model assessment, *Atmos. Chem. Phys.*, 11, 11657-11678.

Gerasopoulos, E., et al., 2011: Three-year ground based measurements of aerosol optical depth over the Eastern Mediterranean: the urban environment of Athens, *Atmos. Chem. Phys.*, 11, 2145-2159, doi:10.5194/acp-11-2145-2011.

Granier, C. et al., 2011: Evolution of anthropogenic and biomass burning emissions of air pollutants at global and regional scales during the 1980-2010 period, *Climatic Change*, DOI 10.1007/s10584-011-0154-1, 2011.

Granier, C., et al., 2005: POET, a database of surface emissions of ozone precursors. Available on the internet at http://ether.ipsl.jussieu.fr/eccad.

Guenther, A., et al., 2006: Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and Aerosols from Nature), *Atmos. Chem Phys.*, 6, 3181-3210.

Hatzianastassiou, N., et al., 2009: Natural versus anthropogenic aerosols in the eastern Mediterranean basin derived from multi-year TOMS and MODIS satellite data, *J. Geophys. Res.*, 114, D24202, doi:10.1029/2009JD011982.

Hodnebrog, Ø., et al., 2011: A model study of the Eastern Mediterranean ozone levels during the hot summer of 2007, *Atmos. Phys. Chem.*, submitted.

Im U., et al., 2010: Study of a winter PM episode in Istanbul using high resolution WRF/CMAQ modeling system, *Atmos. Environ.*, 44, 3085-3094.

Im, U., and Kanakidou, M., 2011: Summertime impacts of Eastern Mediterranean megacity emissions on air quality, *Atmos. Chem. Phys. Discuss.*, 11, 26657-26690.

Im, U., et al., 2011a: The impact of temperature changes on summer time ozone and its precursors in the Eastern Mediterranean, *Atmos. Chem. Phys.*, 11, 3847-3864, doi:10.5194/acp-11-3847-2011, 2011a.

Im, U., et al., 2011b: Summertime aerosol chemical composition in the Eastern Mediterranean and its sensitivity to temperature: A modeling case study, *Atmos. Environ.*, submitted.

Kanakidou, M., et al., 2011: Megacities as hot spots of air pollution in the East Mediterranean, *Atmos. Environ.*, 45 (6), 1223-1235.

Koçak, M., et al., 2011: Particulate matter (PM_{10}) in Istanbul: Origin, source areas and potential impact on surrounding regions. *Atmos. Environ.*, 45, 6891-6900.

Lamarque, J.-F., et al., 2010: Historical (1850-2000) gridded anthropogenic and biomass burning emissions of ozone and aerosol precursors: methodology and application, *Atmos. Chem. Phys.*, 10, 7017–7039, doi:10.5194/acp-10-7017-2010.

Markakis K., et al., 2011: Compilation of a GIS based high spatially and temporally resolved emission inventory for the Greater Istanbul Area, *Air Pollution Research*, doi:10.5094/APR.2012.011, article in press.

Maurizi, A., et al., 2011: Nudging technique for scale bridging in air quality/climate atmospheric composition modelling, *Atmos. Chem. Phys. Discuss.*, 11, 17177-17199.

Messner, S., and Strubegger, M., 1995: User's Guide for MESSAGE III, WP-95-69, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Olivier, J., et al., 2003: Present and future emissions of atmospheric compounds, *POET report #2*. EU report EV K2-1999-00011.

Rasmussen, D. J., et al., 2011: Surface ozone-temperature relationships in the eastern US: A monthly climatology for evaluating chemistry-climate models, *Atmos. Environ.*, in press.

Richter, C. and M. G. Schultz, 2011: Impact of emission changes on climate, in: CITYZEN Climate Impact Studies, Report 116 in the series “Energie und Umwelt” of the Forschungszentrum Jülich.

Schneising, O., et al., 2011: Long-term analysis of carbon dioxide and methane column-averaged mole fractions retrieved from SCIAMACHY, *Atmos. Chem. Phys.*, 11, 2881-2892, 2011.

Schultz, M.G., et al., 2008: Global Wildland Fire Emissions from 1960 to 2000, Global Biogeochem. Cyc., 22, GB2002,doi:10.1029/2007GB003031.

Siour, G., et al., 2011: Bridging the scales in an eulerian air quality model to assess megacity export of pollution, 2011, *Environmental Modelling & Software*, submitted.

Stordal, F. and Ø. Hodnebrog, 2011a: Climate induced changes in air quality and chemical composition on different scales, in: CITYZEN Climate Impact Studies, Report 116 in the series “Energie und Umwelt” of the Forschungszentrum Jülich.

Stordal, F. and Ø. Hodnebrog, 2011b: Implications for mitigation strategies on air pollution under climate change, in: CITYZEN Climate Impact Studies, Report 116 in the series “Energie und Umwelt” of the Forschungszentrum Jülich.

Theodosi, C., et al., 2010: Aerosol chemical composition over Istanbul, *Science of the Total Environment*, 408, p. 2482–2491.

Theodosi, C., et al., 2011: Mass and chemical composition of size-segregated aerosols (PM1, PM2.5, PM10) over Athens, Greece: local versus regional sources, *Atmos. Chem. Phys. Discuss.*, 11, 7659-7691.

van der Werf, G. R., et al., 2006: Interannual variability in global biomass burning emissions from 1997 to 2004, *Atmos. Chem. Phys.*, 6, 3423-3441.

1.4 Potential impact

CityZen has significantly advanced scientific tools, gathered a substantial amount of scientific data, and published more than thirty papers in the peer reviewed literature, with more being in preparation. It is hoped that our results will be useful for our colleagues in the scientific community for further studies, but also provide a scientific basis for policy makers for legislative decisions to improve air quality and to limit climate change.

The dissemination of results has occurred not only through scientific publications and presentations at conferences but also through a policy brochure and policy briefs. Many of the CityZen partners are in continuous contact to policy. For instance, METNO hosts the EMEP centre MSC-W, which reports to the UN LRTAP convention on a regular basis, Ineris reports continuously to the French Ministry of Ecology, and FRIUUK and CNR-ISAC are in close contact with their local authorities in the Rhine/Ruhr area and the Po Valley, respectively.

The impact and the means to strengthen the impact of the results from the project will be further described in this section.

1.4.1 Impact on science and policy

CityZen Objective: bring the scientific results and methods developed and applied during the course of the project to semi-operational use; provide technical underpinning of policy work.

The CityZen project has brought together a consortium of multidisciplinary European, African and Asian teams, several of them representing leader laboratories in the selected subjects. Thus, the project has contributed to the further integration of the European science in a global context. The outcome of the project will benefit science and policy with regard to air pollution control and climate change prevention.

The observational and modeling studies conducted within CityZen have resulted in a better understanding and in better tools to assess air pollution and to design air quality control policies. The four work packages, making up this FP7-project, have provided improvements of input data, modeling tools and observational methods. The development, validation and subsequent application of the new tools, useable under different circumstances and for different areas inside and outside the EU will contribute to more effective measures to prevent increased air pollution and climate change.

Concerning national activities, the project has strengthened the links between the partner laboratories. At international level, the project has established a strong European collaboration in basic and in applied research. This concerns not only the countries of the partner laboratories, but also the institutions of other member countries, which have established collaboration in air pollution and climate research with the partners that have participated in this project.

An important strategic objective of this project has been that the data on air pollution, emissions, and climate change, as well as the new diagnostic methods would be disseminated among partner institutes and air pollution authorities inside and outside the EU. Since the air pollution problem is global, and decisions on air pollution control policy are taken both at international (EU) and on national levels, the dissemination work needs to be carried out at both national and international levels to guarantee results that will be exploitable in the EU and beyond. This dissemination process is still ongoing. The writing of policy briefs is one important output based on the final results of CityZen and will be described in more detail in section 1.4.2. The involvement of several CityZen scientists in the ongoing support of the ongoing EU air quality policy review is another important activity, which, based on CityZen results will continue well beyond the lifetime of the project.

The co-ordination of the evaluation of the actual available knowledge in Europe has already resulted in a better knowledge. The further improvement based on new observational methods and models to study air pollution and climate change, and interactions and the development of new diagnostic tools will support European decision makers.

1.4.1.1 CityZen in China: Science-based control policies for regional pollution in the Pearl River Delta

PKU has conducted a research program on regional air pollution in the PRD for years, in terms of both fundamental research and policy supporting. These activities have been sponsored by the Chinese Ministry of Science and Technology and the Guangdong province, and have been partially supported by the CityZen project as well. Important scientific findings were demonstrated through scientific workshops, policy suggestions and control strategy/plan led by PKU, most of which have been adopted by authorities. PRD air pollution prevention goes towards a regional non-linear and multi-pollutant control strategy, and relevant capacity has been built up gradually. The Guangzhou Asian Games in 2010 provided a case study to verify these regional control policies, strategies and infrastructures. In the process, the CityZen project and its science team have provided tremendous support, such as the EMEP expertise, modelling and measurement techniques.

PRD regional air pollution control policy

Regional photochemical smog and gray haze are recognized as priority problems for the PRD air quality. The Guangdong environmental protection bureau (GD-EPB) has developed a multi-pollutant control strategy and mitigation target. GD-EPB has issued the PRD regional air pollution prevention regulation in 2009, and started the PRD clean air initiative in 2010. Meanwhile, under the support by the 3C-STAR project, PRD regional 3-D regional air quality monitoring and ensemble forecasting system was in pilot operation.

The 16th Asian Games Air quality Assurance

The 16th Asian Games was hold in Guangzhou of China during November 12-27, 2010. PKU took lead in organizing a science team to design the air quality assurance plan. Regional multi-pollutants control strategy was used as guideline for control scenarios design. Five key source categories were defined by analysis of an emission inventory; regional sensitive sources were determined by the ensemble model system, and control measures for various sources were recommended based on available technology and policy. The assurance plan was adopted and implemented by GD-EPB and Guangzhou EPB. In the end, air quality met the requirement set by the Asian Games organizing committee, see Figure 30, even though November is normally a polluted month.

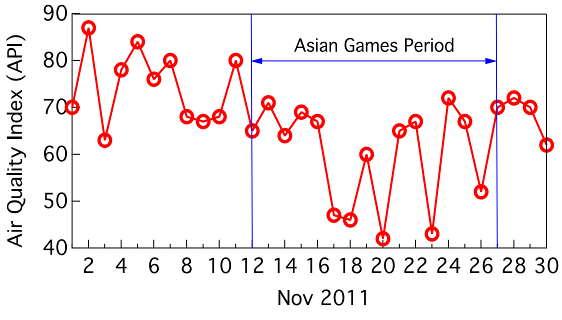

Figure 30: Observed air pollution index in November 2010 (left); and blue sky on the opening day of the Asian Games (right).

1.4.1.2 Science-based control policies for regional pollution in the Rhine-Ruhr area

Parts of the work carried out by FRIUUK in CityZen have been used by the North Rhine Westphalia State Agency for Nature, Environment and Consumer Production (LANUV-NRW) for the planning of air quality improvement in North-Rhine-Westphalia including aspects of the notification process for the air quality directives of the European Commission (2008/50/EC). Publications usually are in German and available as reports for specific projects of LANUV-NRW. Results from the EURAD model have been delivered to LANUV on a 5 km grid basis for NRW and on a 25 km basis for Germany. These results have been distributed further by LANUV-NRW for decision making within urban administrations and on a national basis (national environmental agency, UBA), and presented on international meetings (e.g. EIONET, Bordeaux, October 2011).

Specific investigations have focused on:

- The impact of neighboring states on the air quality in North-Rhine-Westphalia (Belgium, Netherlands)
- Air quality projections for the year 2015
- The effect of changed NO_2/NOx ratio on air quality (in particular NOx, PMx and ozone) as mentioned above as example

1.4.2 Dissemination

CityZen Objective: bring the scientific results and methods developed and applied during the course of the project to semi-operational use; provide technical underpinning of policy work.

The dissemination of CityZen results has occurred (and will continue to occur) through the CityZen web sites, peer-reviewed publications, reports, presentations, press releases, and other channels. Results from CityZen will feed into the ACCENT-Plus Ozone and Methane synthesis and to the forthcoming EU report to support the review of European Air Quality policy. The CityZen project has built bridges to some parts of the policy community and those connections will be improved in future projects and the lessons learned here will help to inform dissemination activities of future projects.

As an important outreach activity dedicated to policy use in the near future, all partners of the CityZen project have been asked to identify the main policy messages from their research within CityZen. The messages have been compiled into five policy briefs, concise leaflets (see Figure 31) to be disseminated among policy makers and stakeholders, and focusing on different CityZen research topics:

- Ozone
- Particulate Matter
- Observations
- Eastern Mediterranean

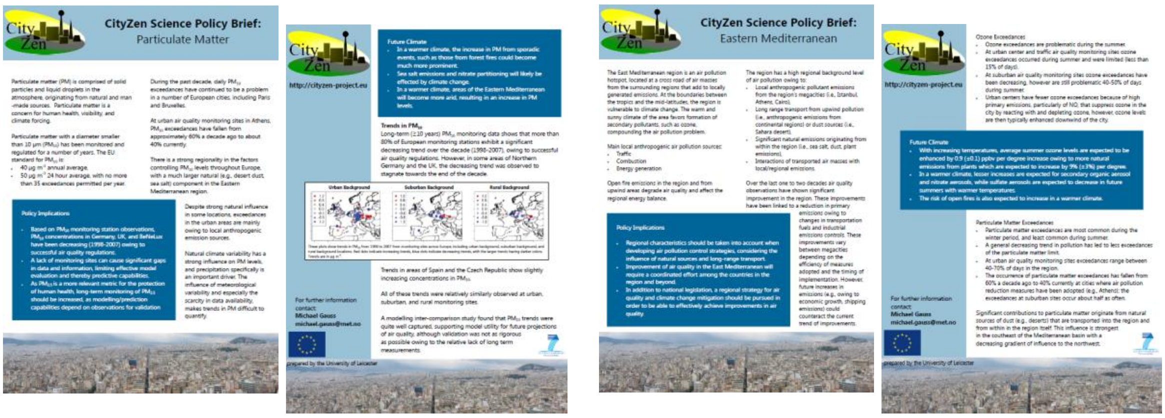

Figure 31: Facsimiles of two of the five policy flyers, which are created for CityZen by ULeic, based on input from the CityZen consortium.

This condensed information is also intended to feed into the review of European Air quality legislation to be concluded in 2013. The briefs encompass the major scientifically relevant conclusions and identify the following implications for policy:

Ozone

- Emission reduction measures have proved to be efficient for ozone precursors, and should be continued.
- Sustained, long term monitoring of ozone and ozone precursors in urban and rural locations is crucial to understanding the effect of regulations to improve air quality.
- Trends in ozone have been small over the last decade, owing to the complexity of ozone as a pollutant that is formed in the atmosphere rather than directly emitted, which makes it more sensitive to meteorological variability and chemical processes.

Particulate Matter

- Based on PM_{10} monitoring station observations, PM_{10} concentrations in Germany, UK, and BeNeLux have been decreasing (1998-2007) owing to successful air quality regulations.
- A lack of monitoring sites can cause significant gaps in data and information, limiting effective model evaluation and thereby predictive capabilities.
- As $PM_{2.5}$ is a more relevant metric for the protection of human health, long-term monitoring of $PM_{2.5}$ should be increased, as modelling/prediction capabilities depend on observations for validation.

Observations

- Air quality networks remain the backbone of pollution observations.
- Weaknesses in the instrumentation used and stations established need to be addressed, e.g., interference by other species and spatial coverage of networks.
- Emerging observation technologies using remote sensing from the ground should be evaluated for possible inclusion into national and European observation networks.
- Satellite observations already provide useful information on pollutant distributions and patterns on regional scales. As resolution in space and time improve further,

integration of satellite data into pollution observation strategies becomes increasingly important.

Eastern Mediterranean

- Regional characteristics should be taken into account when developing air pollution control strategies, considering the influence of natural sources and long-range transport.
- Improvement of air quality in the East Mediterranean will require a coordinated effort among the countries in the region and beyond.
- In addition to national legislation, a regional strategy for air quality and climate change mitigation should be pursued in order to be able to effectively achieve improvements in air quality.

1.5 Project website and contact details

Project website address: http://www.cityzen-project.eu

The project website will be accessible for several years after the official end of CityZen.

Coordinator: Norwegian Meteorological Institute, PO 43 Blindern, 0313 Oslo, Norway

Scientific representative of the coordinator: Dr. Michael Gauss
phone: +47 22 96 33 02, fax: +47 22 96 33 80, e-mail: michael.gauss@met.no

Administrative representative of the coordinator: Per Helmer Skaali
phone +47 22 96 33 18, fax: +47 22 96 33 80, e-mail: per.helmer.skaali@met.no

2 Use and dissemination of foreground

This section is provided by met.no through the Research Participant Portal.

3 Report on societal implications

This section is provided by met.no through the Research Participant Portal.