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Urban SIS
D441.3.5 Urban air quality ECV and impact indicator data for present and future climate

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Introduction

The goal of UrbanSIS is to develop and demonstrate a method to downscale climate and impact indicators to the urban scale, delivering the information with a space/time resolution and format that makes it useful for consultants, urban planners, engineers and scientists dealing with intense rainfall, heat waves, and air pollution hazards. Within the project, WP3 targets the downscaling of climate, air quality and hydrology parameters over three selected urban landscapes: Stockholm, Bologna, and Amsterdam/Rotterdam. Simulations were carried out for selected time periods representing historical conditions taken as reference for validation purposes (see reports D441.5.1 to D441.5.3 for more details) and climate scenarios.

The current deliverable (D441.3.5) addresses specifically the air quality downscaling over two 5-year time periods representing present and future climate. Together with the downscaling of urban climate (D441.3.4) and hydrology (D441.3.6) it completes the delivery of 1 km resolution sectoral ECVs and impact indicators, in addition to the set of results delivered for the historical conditions (previously reported in deliverables D441.3.1 to D441.3.3).

The downscaling modelling chain consists of three numerical models as depicted in Figure 1: the climate model HCLIM-AROME, the air quality model MATCH and the hydrological model HYPE. For the climate scenarios, the meteorological boundary and initial conditions are provided by the global climate model EC-Earth. Similarly to the historical runs, emission data is provided to MATCH through freely available pan-European inventories on the regional scale and by national services on the finer resolution. Essential Climate Variables (ECVs) and Sectoral Impact Indicators driven by the outputs of the models are available on-line in the UrbanSIS portal (http://urbansis.climate.copernicus.eu/).

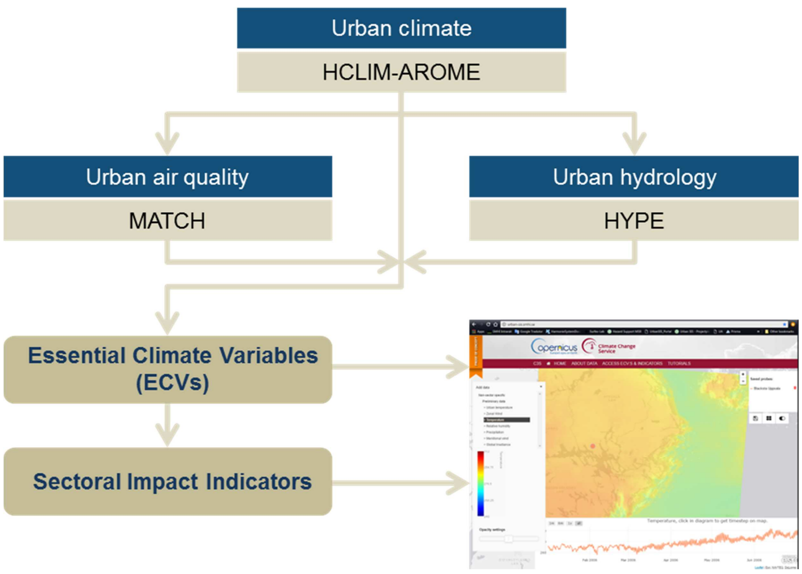

Figure 1 – General flowchart representing the dynamical downscaling approach applied in UrbanSIS for the simulation of the selected climate scenarios. More detailed information about each model will be given in the following sections and in the accompanying reports D441.3.4 and D441.3.6.

Sections 1 and 2 of this report summarize relevant information about the main characteristics of the MATCH model, specific assumptions and developments, computational domain, and input/output data, while highlighting specific differences relating the application to the historical period. More details about the models and the numerical techniques applied can be found in the literature listed at the end of the document. Climate-related ECVs and indicators are listed in section 4, followed by an analysis of downscaled climate data. Finally, the last section of the report intends to share some experiences from the air quality downscaling within Urban SIS that can be useful for the end-users exploiting the data or for those willing to replicate this method in other European cities, in agreement with the proof-of-concept nature of this project.

1. Air quality model used for downscaling

The MATCH model is the tool applied for describing the concentrations of the atmospheric pollutants of interest for the Copernicus service of future climate scenarios. Except for minor adjustments, when needed, the model setup was kept constant through all the applications in order to determine the changes in concentrations between the historical simulations (see D2.1 and D441.3.2), the present climate conditions and the future climate scenario. The model was applied over a domain covering Western Europe (MATCH-pan-E) and the obtained concentration 4D fields were used for the subsequent downscaling with MATCH-local to higher resolution domains for three cities chosen from different climate regions over Europe, Stockholm (Sweden), Amsterdam/Rotterdam (The Netherlands) and Bologna (Italy).

The main differences in the MATCH model application are driven by the changes on the meteorological forcings: the UERRA reanalysis for the historical period, obtained with the regional numerical weather prediction model HARMONIE-AROME (see D441.3.1), and the meteorological fields obtained by the regional model HARMONIE in climate mode – HCLIM-AROME (see D441.3.4) in present and future climate conditions; and also by the emissions estimations in a new future.

The MATCH model, the initial and boundary conditions, and how it was applied in present and future climate scenarios are described in sections 1 and 2 of the present report.

1.1 Introduction

MATCH (Multiple-Scale Atmospheric Transport and Chemistry Modeling System) is a state-of-the-art, off-line, chemical transport model developed at the Swedish Meteorological and Hydrological Institute (SMHI). It takes four-dimensional (x,y,z, and time) meteorological fields from an external climate or weather forecast model and uses this meteorology to transport air pollutants with the mean wind and through turbulent mixing. The diurnal variations of physical and meteorological parameters (e.g. solar radiation, temperature, humidity) are also controlling the chemical reactions and emissions/depositions taking place at the surface-atmosphere interface. The model describes the chemistry and physical processes of an array of gaseous and particulate species. A general description of MATCH can be found in Robertson et al. (1999). The photochemical scheme is outlined in Langner et al. (1998) and Andersson et al. (2007). A recent summary and evaluation of the system's description of particulate matter can be found in Lacressonnière et al. (2017) and references therein.

In addition to meteorological forcing MATCH also needs other input data, such as temporally and spatially varying emissions and boundary concentrations of all species of interest, as shown in Figure 2. In the following sections we will focus on the various inputs to the model and touch upon some of the developments done in the present project.

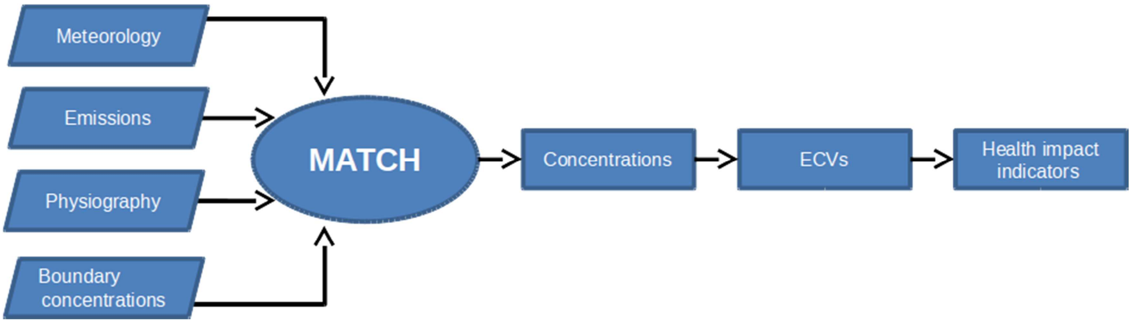

Figure 2 – Schematic structure of the data flow into and out of the off-line model MATCH.

1.2 Boundary layer parameterizations

In order to describe the surface exchange process and the vertical mixing within the boundary layer (the layer of the atmosphere closest to the ground; typically 100-2500 m in thickness, i.e. the lowest 2-15 model levels in MATCH), the time varying turbulent fluxes inside this layer must be described and quantified. The turbulence acts on scales from 100 m down to the thermal vibration of air molecules and the grid resolution does not allow for explicit description of the turbulent fluxes. Instead, we have to rely on parameterizations based on the forcing from physiography and the resolved meteorological variables (e.g. temperature, wind, humidity etc.) to derive the impact from mixing on grid cell average concentrations. Basic parameters needed to describe the turbulent mixing are listed in Table 1.

Table 1 – Boundary layer parameters.

Abbreviation	Explanation	Unit	Comment
T2m	2 m temperature	K	
Q2m	Water vapor mixing ratio	g kg^{-1}	
Ts	Surface temperature	K	Most important here is the water surface temperature
u* (*)	Friction velocity scale	m s^{-1}	A measure of the stress the atmosphere experience from the surface
w* (*)	Turbulent velocity scale	m s^{-1}	A measure of the vertical turbulence intensity
Ri (*)	Richardson number	-	A measure of the ratio of heat and momentum gradients
F_{bv} (*)	Brunt-Vaisala frequency	s^{-1}	Wave frequency in a stable stratified layer
Zi (*)	Boundary layer height	m	The height of the turbulent layer close to the surface: 10-2500 m
L (*)	Monin-Obukhov length	m	A measure of the stability
K_Z (*)	Vertical exchange coefficient	m^2 s^{-1}	Intensity of the vertical turbulent mixing
TKE	Turbulent kinetic energy	m^2 s^{-2}	A profile of turbulent intensity provided from the weather model HCLIM–AROME

(*) Derived (i.e. calculated from other fields) variables, others are read from HCLIM-AROME output files.

The turbulent mixing in MATCH is described by the vertical exchange coefficient, K_Z. It represents the intensity of the vertical turbulent mixing, and ranges between 1 and 150 m^2 s^{-1}. The larger the value the more efficient is the turbulence to transport air pollutants vertically. In the standard MATCH configuration the variables w*, L, Zi, etc. (see Table 1) are calculated on the basis of the similarity theory. This is also the scheme used for the pan-European application of MATCH.

As in the historical application, the turbulent kinetic energy, TKE, was taken as input variable, converted into K_Z by taking the square root of TKE and scale it with a length-scale defined from the Richardson number (Ri).

1.3 Precipitation

The HCLIM-AROME model provides precipitation amounts on ground level, as well as precipitation intensities on model levels. The surface precipitation amounts are accumulated values over the forecast length and MATCH chops up the precipitation amounts to hourly integrated values. In order to get around spin-up problems, the forecasted values (that also include cloud cover and humidity) are taken as the difference between the +12 and +6 hour forecasts. The lessons learned from the previous attempts to directly use the model level specific precipitation intensities did not match the ground precipitation amounts given in HARMONIE-AROME output. Moreover, the model level precipitation intensities are instantaneous and do not necessarily represent the integrated precipitation of the latest hour. In order to make use of the vertical precipitation information the distribution of the ground precipitation vertically by means of the model level data was done in the historical and climate runs.

2. Input to the air quality downscaling

2.1 Time period of simulation

Five representative years in the present climate scenario and 5 representative years in the future climate scenario were selected with the goal of combining cold/wet, cold/dry, warm/wet, warm/dry, and 'normal' seasons. The selected years are shown in Table 2.

Table 2 – Years selected for the different regions.

	Normal	**Cold/Wet**	**Cold/Dry**	**Warm/Wet**	**Warm/Dry**
Stockholm					
Present climate	2009	1995	1994	2005	1985
Future climate	2032	2053	2046	2035	2064
Amsterdam					
Present climate	2005	2000	1996	2010	2007
Future climate	2053	2038	2034	2035	2049
Bologna					
Present climate	2005	1987	1996	2010	2006
Future climate	2050	2037	2053	2063	2044

The selection was based on HARMONIE regional climate model (HCLIM-ALARO) runs carried out in the GLOBAQUA project (http://www.globaqua-project.eu). Boundary conditions for HCLIM-ALARO were provided by the global climate model EC-Earth. The spatial resolution of HCLIM-ALARO was ca. 20 km. The time period covered by the regional climate simulations was 30 years in present climate (1980-2010) and 35 years in future climate conditions (2030-2065). Future emissions scenario considered was RCP8.5. A description of the methodology for the selection of five years that represent present and future climate scenarios can be found in report D441.3.4.

2.2 Computational domains

2.2.1 Urban air quality domain

All climate, air quality and hydrology ECVs and Sectoral Impact Indicators for each respective city are provided on a common 110×110 km^2 grid with 1 km resolution. The selection of the size, location and resolution of this area was a compromise between computational time and data amount on the one hand and the wish for as large and representative domain as possible on the other hand. The 1x1 km^2 grid size matches the spatial resolution of the emissions data usually available for urban areas, while delivering a good representation of the surface spatial gradients. The meteorological downscalings had to be performed on a much larger area than the cities in order to be meaningful. In a too small domain the effects of local topography and land use would never have the chance to develop. Furthermore, is it advisable to exclude data close to the lateral rims of the local meteorological model as non-realistic boundary effects typically occur.

The urban air quality simulations were performed on a 120×120 km^2 grid with 1 km resolution both in the historical and climate scenarios (present and future); the configuration and underlying physiographic data were kept constant. Figure 3 shows the extent of the three urban air quality downscaling domains together with each city's respective 110×110 km^2 UrbanSIS area, where 10 grid cells next to the boundaries are ignored, regarding the explanation above. The urban air quality simulations were performed on the geometry of the urban meteorological model but only utilizing data from a subset of its horizontal coverage. The vertical extent of the urban domain typically extended to 550 hPa (ca 5 km above surface). The vertical resolution and number of layers were reduced by a factor of two in the air quality model compared to the meteorological model by averaging all meteorological parameters over every two layers starting from the ground and extending throughout the model atmosphere.

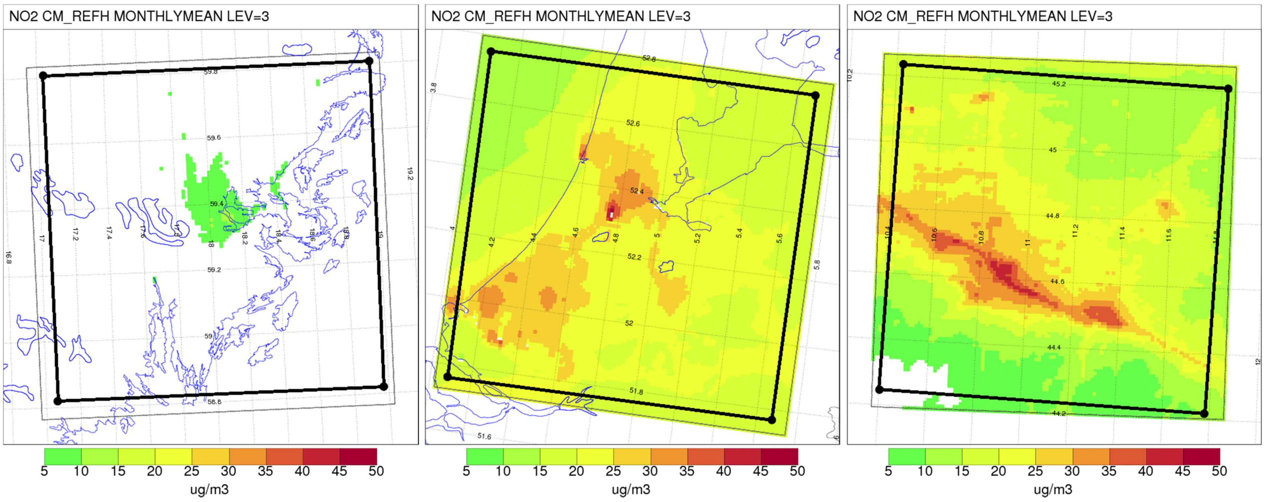

Figure 3 – Monthly mean NO_2 concentration in the three urban domains during February 2014. Left: Stockholm; Middle: Amsterdam; Right: Bologna. The extent of the 110×110 km^2 UrbanSIS areas is indicated by the fat line in the respective maps. Note the identical color scale in all panels.

2.2.2 Nesting of domains

To accurately model air quality in a city it is of utmost importance to also consider the flux of air pollutants into the domain from sources outside the city. In UrbanSIS this was achieved by running a series of nested meteorological and air quality models, all simulating the same period but with varying coverage and resolution. Figure 4 outlines the principles of the nesting, which can be imagined as a series of Russian "Matryoshka" dolls where each finer domain fits into a coarser resolution outer one. An important feature is that although all set-ups run on rectangular domains they may be shifted or tilted with respect to each other due to varying geographical projections.

The MATCH air quality downscaling over the urban domain covers a smaller area than the high-resolution urban meteorological model but utilizes the same geometry and resolution, which means that HCLIM-AROME 1 km × 1 km meteorology is not interpolated prior to usage in the air quality model, similarly to the historical application with the UERRA European reanalysis (see D2.1). This choice leads to the necessity of interpolating the local emissions and land-use data.

The above described model design was used as much as possible in the climate simulations in order to get only the signal of differences in future climate and emissions into the simulated atmospheric constituents concentrations of interest. However, the regional climate model HCLIM-ALARO was operated in a closer horizontal resolution of the MATCH model over Europe, with a grid resolution of 20 km x 20 km. Also, in the climate runs at the urban scale the meteorological fields resulting from the HCLIM-AROME simulations were not previously interpolated.

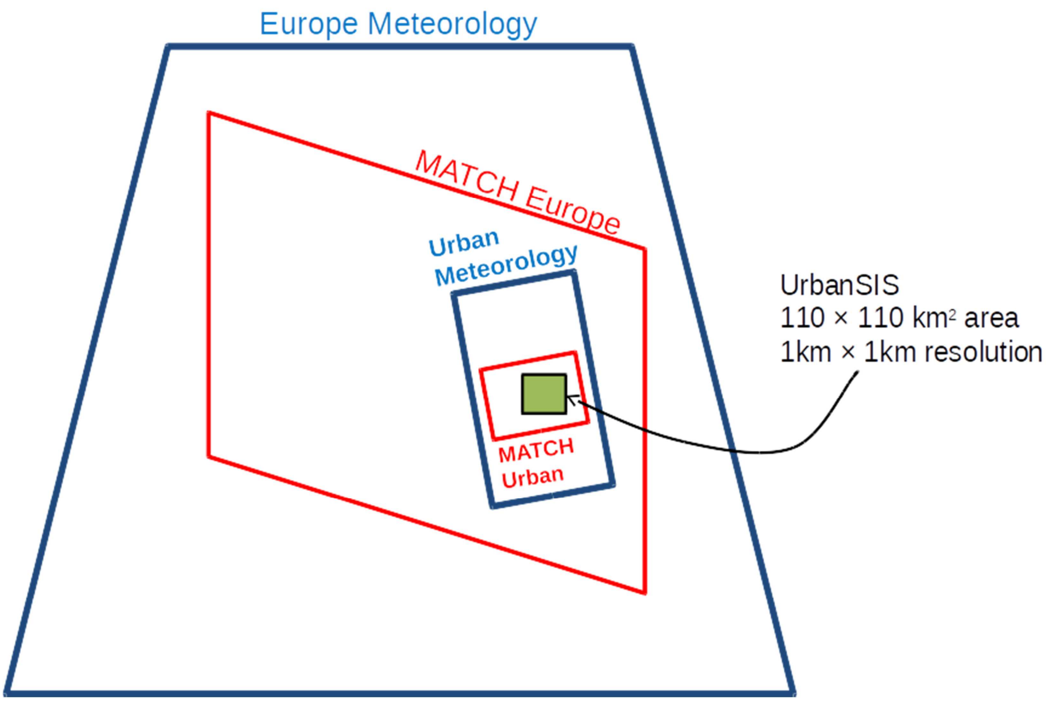

Figure 4 – Nesting of domains in UrbanSIS. The figure is not to scale. The European Meteorological fields produced by HCLIM-ALARO are on a 20 km × 20 km resolution. MATCH-pan-E operates on 0.2° × 0.2° (ca. 22 km × 22 km) resolution, while the urban meteorological (produced by HCLIM-AROME) and air quality applications both run on 1 km × 1 km resolution.

2.3 Boundary conditions: tracer concentrations

The boundary forcing to the MATCH-local domains are derived differently according to the application: historical, present, or future climate scenarios. As depicted in Figure 2, the MATCH model needs 4 types of boundary conditions.

No assumption on physiography (described in section 2.4) changes between present and future climate scenario was made. Emissions assumptions are explained in section 2.5. Here meteorological forcing and chemical boundary conditions imposed to MATCH-local are further explained for the climate scenarios simulations.

Figure 5 shows the horizontal extent of MATCH Europe, MATCH-pan-E, which was used to get the boundary concentrations imposed in all urban downscalings. The three-dimensional boundary concentrations are interpolated horizontally and vertically to accurately describe the influx of air pollutants every 1 hour.

The chemical boundary forcings produced this way, along with the meteorological fields downscaled over each of the local cities, and the emission fluxes, are taken into account in the mass conservation equations of each MATCH pollutant species to produce the historical concentration fields used in the indicators calculation.

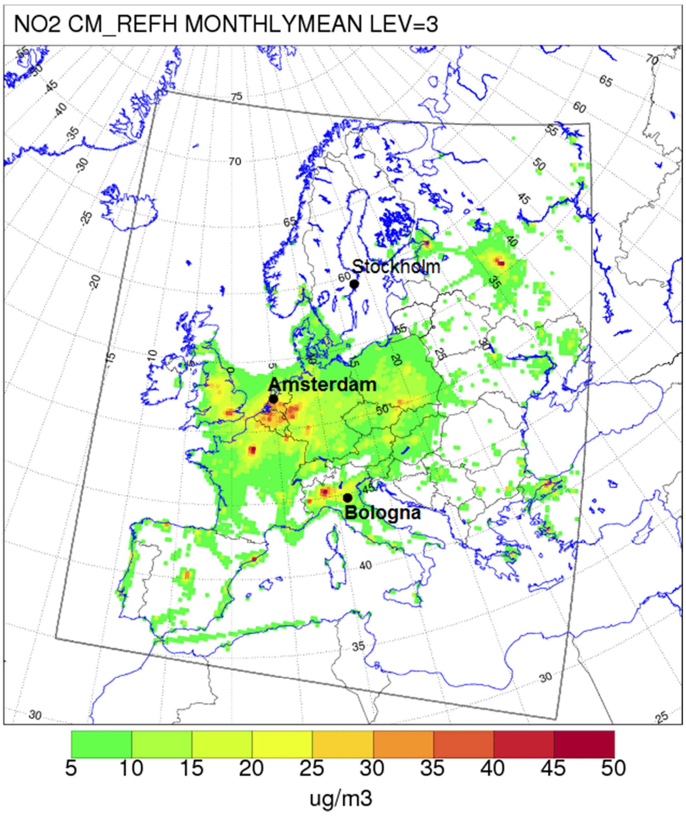

Figure 5 – Monthly mean NO_2 concentration in the European MATCH domain during February 2012. The extent of the pan-European domain and the locations of the three downscaled cities are indicated on the map.

To derive the climate scenarios, the MATCH-local chemical boundary conditions were calculated based on the meteorological inputs resulting from the HCLIM-ALARO model in present and future climate conditions (over the pan-E domain). The MACC emissions database constrained the amount of pollutants injected into the European domain in present conditions, whereas the ECLIPSE V5a global emissions (Stohl et al., 2015) are driving the pollutants mass influx future scenario.

To obtain the considered air quality indicators over the three metropolitan areas, the kinetics, deposition and advection of each respective concentration fields were obtained by MATCH-local considering together the above described chemical boundary conditions, the meteorological fields downscalled with the HCLIM-AROME regional model over the 1 km x 1 km grid resolution representing the urban domains. The urban emissions considered are described in section 2.5.

2.4 Surface description

Embedded in the meteorological data are physiography fields that MATCH uses both for the diagnostics of the near-surface mixing and for the calculation of the deposition and emission of different chemical species. Different species have different dry deposition velocities to different surfaces and MATCH discriminates between five deposition classes (see Table 3). A number of land-types also emit biological precursors (isoprene and monoterpenes) that are important for the chemistry and physical processing of gases and particulate matter. These classes are defined in Simpson et al. (2012) and listed in Table 3 below. For the European scale MATCH simulation we use the surface data described in Simpson et al. (2012), while for the urban dowscalings we use the data from the AROME dataset that originates from the SURFEX package. The different tiles that come out from this are sometimes a bit exotic and different from site to site. In order to have a common ground we lump the various tiles in AROME/SURFEX to the surface and vegetation types shown in Table 3. This leads to much higher resolution in the land-cover seen by MATCH although all classes are not used.

Table 3 – List of surface types used in MATCH.

Surface type, used for BVOC emissions	**Deposition class in MATCH**
WATER	WATER
URBAN	URBAN
MED_BRDLF	FOREST
TEMP_DECID	FOREST
TEMP_CONIF	FOREST
MED_NDLLF	FOREST
GRASS	LOWVEG
MED_CROP	LOWVEG
WETLAND	LOWVEG
SEMI_NATURAL	LOWVEG
TUNDRA	LOWVEG
MED_SCRUB	LOWVEG
ROOT_CROP	LOWVEG
TEMP_CROP	LOWVEG
ICE_GLACIER	NOVEG
DESERT_BARREN	NOVEG

2.5 Emissions

The chain of models leading to air quality downscalings of air pollutants in different cities of Europe utilizes local emissions for the city of concern, as well as pan-European emissions used for determining the background concentrations of air pollutants. The present set-up of MATCH needs anthropogenic emissions of a number of pollutants, as listed in Table 4 below. Based on land-cover and meteorological forcing the model also performs on-line calculations of the emissions of isoprene and monoterpenes mainly important for particle formation or as precursors for ozone (O_3), cf. the discussion on the surface description above.

In MATCH it is possible to read hourly resolved emissions or take monthly or annual two-dimensional fields which are scaled by sector-specific coefficients to mimic a typical seasonal-, weekly- and daily cycle of emissions. The sectors are the SNAP categorization (Selected Nomenclature for reporting of Air Pollutants) used by e.g. the EMEP model (see Simpson et al., 2012). In the present study we used annual mean data on SNAP sectors for Bologna, Amsterdam, Stockholm and the pan-European application (the MACC dataset). All simulated historical period, and present climate scenario conditions used the same emissions data (see Table 5 below). The information about SNAP-sectors is also used to release the emissions from different sectors at different heights. The emissions from traffic and agriculture (SNAP 7 and 10) are, for example, typically released closer to the surface than emissions from combustion in energy and transformation industries (SNAP 1).

Regarding the future climate scenario, ECLIPSE V5a global emissions (http://www.iiasa.ac.at/web/home/research/researchPrograms/air/ECLIPSEv5a.html) were used for the MATCH-pan-E simulations. No hypotheses were made for changes in the monthly and daily anthropogenic emission profiles within MATCH-pan-E, so the historical ones were also used in the simulations of future times. The ECLIPSE V5a global emissions were interpolated to the European grid, changing the original projection along a reclassification of the original ECLIPSE activity sectors into the SNAP sectors, according to Table 6.

Table 4 – List of anthropogenic emissions.

Species	Comment
NO_x	Split into NO and NO_2
SO_2	Split into SO_2 and sulfate
CO	
NMVOC	Split into 10 NMVOCs with different O_3 forming potential
NH_3	
PM2.5	PM less than 2.5 µm
PMcoarse	PM bigger than 2.5 µm but less than 10 µm

Table 5 – Specifics of emissions used for the different domains in the historical and present climate simulations.

Model domain	Emission year	Type of data
Stockholm	2010	Annual average field, 10 SNAP-sectors
Amsterdam	2013	Annual average field, 10 SNAP-sectors
Bologna	2010	Annual average field, 10 SNAP-sectors
Europe	2011	Annual average field, 10 SNAP-sectors

Table 6 – Correspondence between ECLIPSE and SNAP activity sectors.

ECLIPSE – sector	SNAP -sector	SNAP – sector code number
Power plants, energy conversion, extraction	Combustion in energy and transformation industries	1
Residential and commercial	Non-industrial combustion plants	2
Industry (combustion and processing)	Combustion in manufacturing industry	3
	Production processes	4
Agriculture (waste burning on fields)	Extraction and distribution of fossil fuels and geothermal energy	5
Solvents	Solvent use and other use	6
Surface transportation	Road transport emissions	7
Shipping emissions	Other mobile sources and machinery	8
Waste	Waste treatment and disposal	9
Agriculture (animals, rice, soil)	Agriculture	10

For each urban application the given emission input was considered according to the local partner. Over Bologna the local emission inventory was derived from the GAINS – Italy model (http://gains-it.bologna.enea.it/gains/) for the year 2030.

Amsterdam/Rotterdam adjusted the actual emissions also for 2030 based on the established and planned Dutch National energetic policy (Smeets et al., 2016). Over the city of Stockholm the focus was on searching for impacts on air quality driven by future traffic planning to be implemented. The total emissions amounts over each one of the simulated domains are presented in Table 7, while the percentage of change between present emissions and future scenarios are depicted in Figure 6.

Table 7 – Total amount emitted (ktons/year) by the considered pollutants in the three urban domains.

Pollutant	Present			Future		
	Amsterdam	Bologna	Stockholm	Amsterdam	Bologna	Stockholm
CO	352	360	48	352	376	39
NH3	41	89	1	36	75	1
NMVOC	324	191	7	337	151	6
NOx	158	180	11	91	148	9
PM10	13	27	6	10	21	5
PM2.5	7	22	4	6	17	3
PMcoarse	10	5	2	8	4	2
SO2	27	26	3	26	24	3

Every city has its own underlying local emissions scenarios but in general there is a convergence for a decreasing of the total amounts of the pollutants in each metropolitan area. Increases compared to present conditions are expected for a few cases: CO in Bologna, NH_3 over Stockholm and NMVOC in Amsterdam.

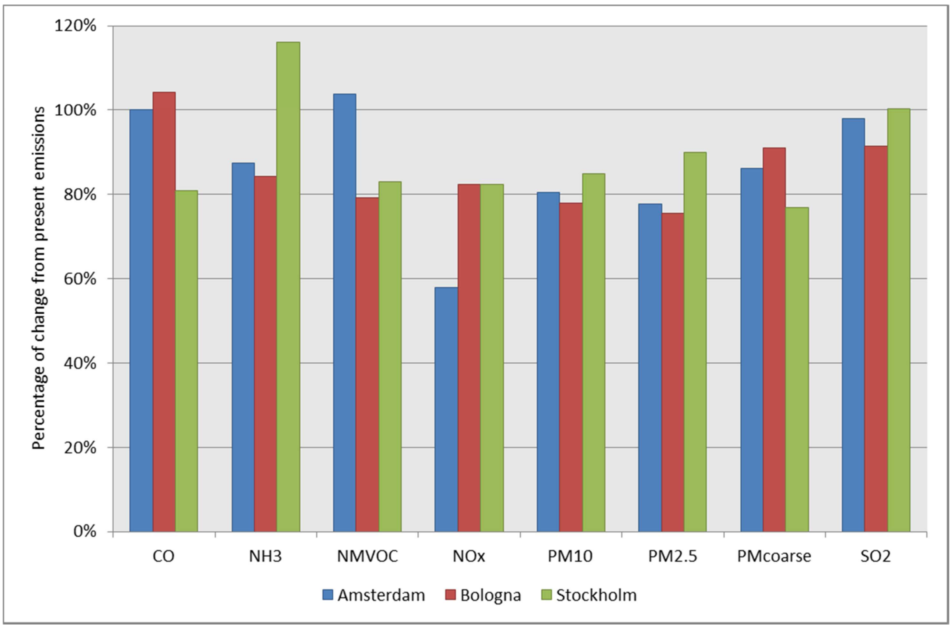

Figure 6 – Percentage of the amount of emission changes between present and future conditions, over the three urban domains.

3. Post-processing of model output

3.1 Transformation of gridded time series to NetCDF

The gridded time series data from MATCH has been converted from GRIB to netCDF format using Python and the netcdf4-python library (Unidata, https://unidata.github.io/netcdf4-python/). For each timestep the horizontal grid is re-projected into a local geographical projection (different for each city) and then a smaller grid (110x110 cells) is cut-out and stored in a netCDF file (one for each parameter).

The resulting time-series files in netCDF format have then been used as input for the calculation of ECVs and indicators.

3.2 Statistical post-processing of air quality ECVs

The statistical post-processing of air quality variables is made using the same methods and software as for the meteorological and hydrological ECVs. They have been calculated using the Climate Data Operators (CDO) software, version 1.8 (CDO 2017: Climate Data Operators, https://code.zmaw.de/projects/cdo/). For each air quality parameter, the following statistical processing is performed: mean; yearly mean; yearly max; yearly min; monthly mean; monthly max; monthly min; annual monthly mean; annual monthly max; annual monthly min; mean of yearly min; and mean of yearly max.

Note though that some combinations of parameters and statistical operators are not shown in the final results, since they are not meaningful. One such combination is yearly minimum of concentration.

3.3 Calculation of air quality indicators

Most of the indicators have been calculated using the same software as for the ECVs, the Climate Data Operators (CDO) software, version 1.8 (CDO 2017: Climate Data Operators, https://code.zmaw.de/projects/cdo/). While CDO has a large number of functions related to climate implemented, some of these differ in definition from those used in UrbanSIS, while others are not available in CDO. In such cases, the indicator has been calculated directly using Python and the netcdf4-python library (Unidata, https://unidata.github.io/netcdf4-python/), together with the NumPy library (van der Walt et al., 2011).

4. Summary of delivered air quality data

4.1 Air quality ECVs

Table 8 lists the ECVs related to air quality, defined in agreement with the requirements detailed in deliverable D4.2.

Table 8 – Summary of air quality ECVs.

ECV name	Unit
O_3 concentration	$\mu g\ m^{-3}$
NO_2 concentration	$\mu g\ m^{-3}$
PM10 concentration	$\mu g\ m^{-3}$
PM2.5 concentration	$\mu g\ m^{-3}$

4.2 Air quality impact indicators

Table 9 lists the indicators related to air quality. These are described in detail in report D4.3.

Table 9 – List of air quality indicators. Threshold values defined based on WHO guidelines and EU limit values. For more details see deliverable 4.3.

Sector	Type	Indicator	Aggregation	Unit	Threshold
Health	Air pollutant concentration	99.8th percentile of hourly NO_2 concentration	yearly	$\mu g\ m^{-3}$	200 $\mu g\ m^{-3}$
		Yearly average NO_2 concentration	yearly	$\mu g\ m^{-3}$	40 $\mu g\ m^{-3}$
		Yearly average PM2.5 concentrations	yearly	$\mu g\ m^{-3}$	25 $\mu g\ m^{-3}$
		Yearly average PM10 concentrations	yearly	$\mu g\ m^{-3}$	40 $\mu g\ m^{-3}$
		90th percentile of daily average PM10 concentrations	daily	$\mu g\ m^{-3}$	50 $\mu g\ m^{-3}$
		93.15th percentile of daily max of 8-hour running averages of ozone concentration	yearly	$\mu g\ m^{-3}$	120 $\mu g\ m^{-3}$
		SOMO35	yearly	days $\mu g\ m^{-3}$	35 ppb
	Air pollution exposure	Persons exposed to NO_2 conc. > AQ EU hourly limit value	yearly	persons	200 $\mu g\ m^{-3}$
		Persons exposed to NO2 conc. > AQ EU yearly limit value	yearly	persons	40 $\mu g\ m^{-3}$
		Persons exposed to PM2.5 conc > AQ EU hourly limit value	yearly	persons	25 $\mu g\ m^{-3}$
		Persons exposed to PM10 conc. > AQ EU hourly limit value	yearly	persons	40 $\mu g\ m^{-3}$

		Persons exposed to PM10 conc. > EU daily limit value	yearly	persons	50 µg m^{-3}
		Persons exposed to O_3 conc. > EU daily target values	yearly	persons	120 µg m^{-3}
		Persons exposed to O_3 conc. > WHO guidelines	yearly	persons	100 µg m^{-3}
		Persons exposed to PM2.5 concentrations > WHO yearly limit value	yearly	persons	10 µg m^{-3}
		Persons exposed to PM10 concentrations > WHO recommended yearly limit value	yearly	persons	20 µg m^{-3}
		Persons exposed to NO2 concentrations > WHO recommended yearly limit value	yearly	persons	20 µg m^{-3}
	Annual deaths due to long-term exposure	Mortality, all-cause, long-term NO_2 and PM2.5 exposure	yearly	deaths $year^{-1}$	
		Annual deaths per 100,000 inhabitants due to long-term NO_2 and PM2.5 exposure	yearly	deaths 100,000 $inhab^{-1}$	
		Mortality, all-cause, long-term NO_2 exposure	yearly	deaths $year^{-1}$	
		Annual deaths per 100,000 inhabitants due to long-term NO_2 exposure	yearly	deaths 100,000 $inhab^{-1}$	
		Mortality, all-cause, long-term PM2.5 exposure	yearly	deaths $year^{-1}$	
		Annual deaths per 100,000 inhabitants due to long-term PM2.5 exposure	yearly	deaths 100,000 $inhab^{-1}$	
	Annual deaths due to short-term exposure	Annual deaths due to O_3 short term exposure	yearly	deaths $year^{-1}$	
		Annual deaths per 100,000 inhabitants due to short term exposure	yearly	deaths 100,000 $inhab^{-1}$	

5. Analysis of downscaled air quality data for the scenarios

The influence of both changing climate and the emissions estimations over the urban domains may be studied in different ways through extracting the results available in the Urban SIS portal. Here we exemplify with a comparison of the concentration time series of NO_2 and PM2.5 for Bologna. The concentrations of these two pollutants are connected with socio economic activities producing enhanced concentrations near the location where they were emitted. Their hourly time series concentrations were extracted for the three five-year periods simulated, historical, present and future climate scenarios over two sites inside the Bologna domain: Giardini Margherita and San Pietro di Capofiume, classified as urban and regional background air quality stations, respectively.
The extracted time series were averaged according to the hour of the day, days of the week, months, and hourly by day of the week using the Openair R package software. The graphs for these averages (with the 95 % confidence intervals of the mean in shade) on NO_2 concentrations at the above mentioned locations are depicted in Figure 7 and Figure 8, whereas Figure 9 and Figure 10 display the same kind of information for PM2.5.

The MATCH results during the historical period were previous assessed in the deliverable D441.5.2. The validation of the air quality variables showed errors expected for the simulated pollutants, process scale and model resolution. Moreover, the historical and present climate simulations display similar patterns and comparable magnitudes in their concentrations, which give confidence on the MATCH results for future climate scenarios. The smaller differences encountered may be attributed to two main reasons, the way the meteorological numerical prediction model was applied in the historical period (as in the numerical forecast mode) and in future climate (as a regional climate model), and the criteria imposed to the years simulated in each of the time slots. These criteria are described in deliverable D441.3.4, which includes a combination of climate possibilities inside the domain between hot/cold and wet/dry years. This combination may smooth the averaged curves when compared to the historical period (as e.g. in Figure 9 and Figure 10).

Inside the domain it was estimated an emission reduction of NO_2 and PM2.5 of 18 % and 25 %, respectively, which is reflected in the concentrations averages of the future period, for the two types of air quality stations. These assumptions are noticeable in the lower values of the air pollutants concentration in the future scenarios at both locations. For NO_2 the relative decrease is lower at the more polluted urban background site compared to the regional background site, where clear decreases in NO_2 concentrations are evident for the average day, month and hour. For PM2.5 a prominent decrease can be observed, both in absolute and in relative terms at both locations. The anomalous PM2.5 concentration during the historical period in June and on Monday through Wednesday is likely the result of numerical instabilities in the calculation of some chemical species that was noticed after the completion of the historical simulation. These instabilities occasionally create unreasonably high values during a few hours. These values can be several times greater than the normal concentrations and although they only appear during a limited fraction of the modelled period they may obviously impact also long-term mean values.

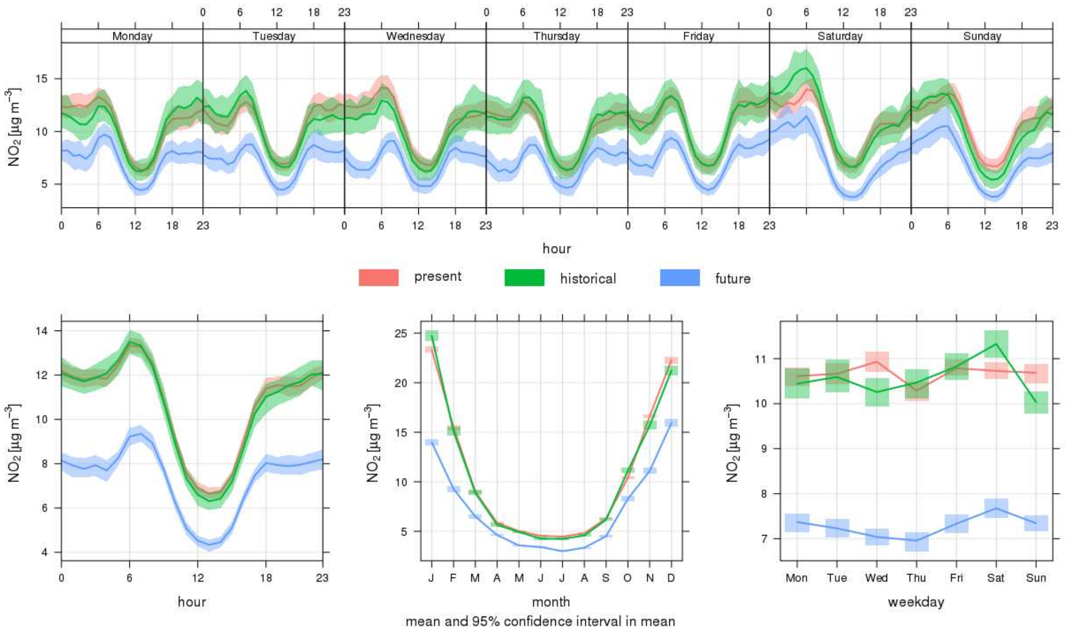

Figure 7 – NO2 concentrations mean time series averaged (and theirs 95 % confidence levels in shade) according to the hour of the day, days of the week, months, and hourly by day of the week over San Pietro Capofiume, Bologna.

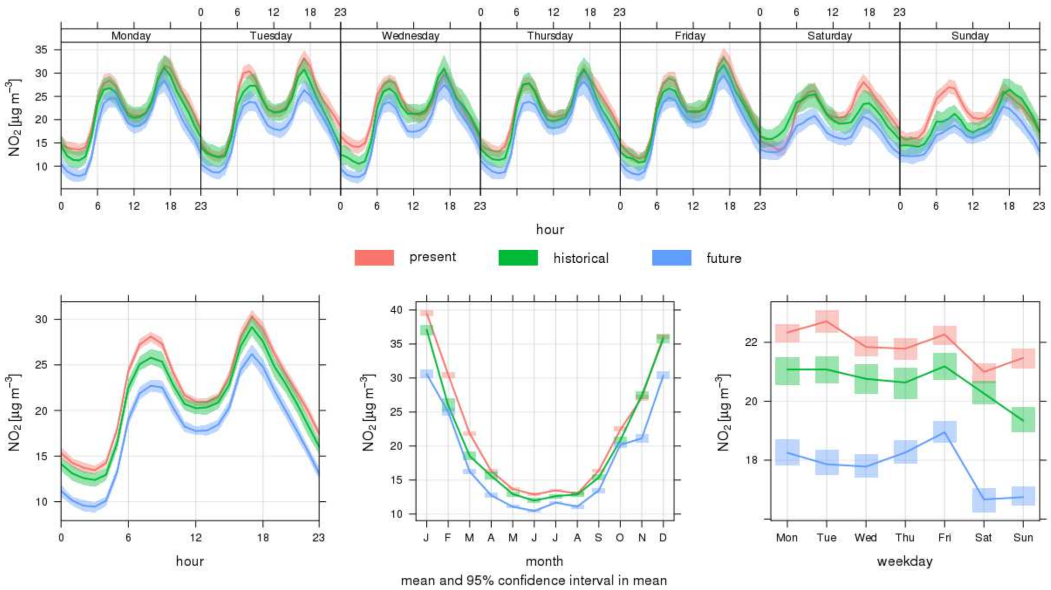

Figure 8 – NO2 concentrations mean time series averaged (and theirs 95 % confidence levels in shade) according to the hour of the day, days of the week, months, and hourly by day of the week over Giardini Margherita, Bologna.

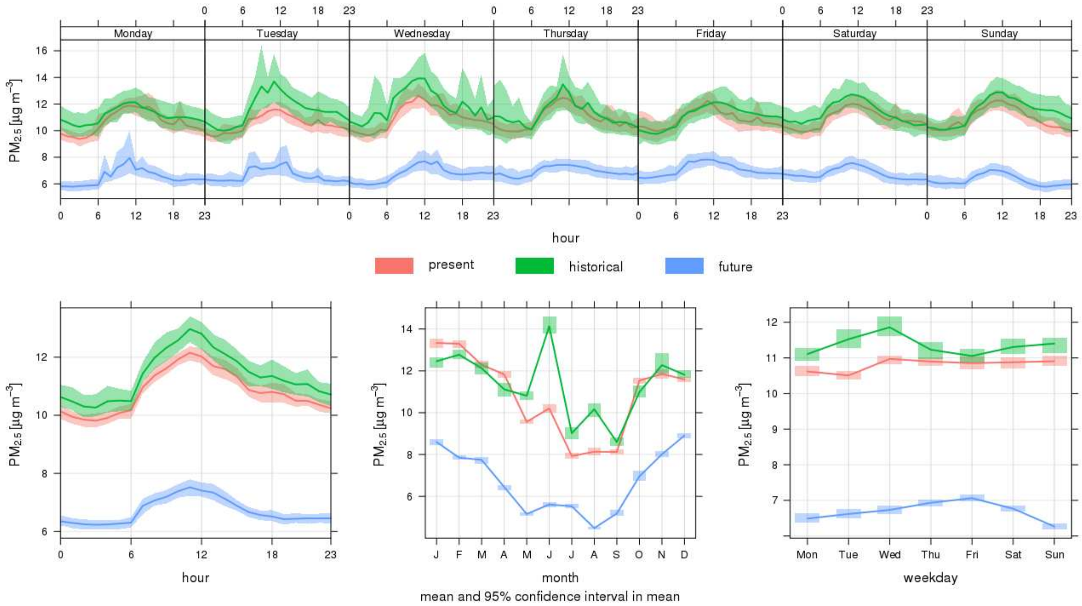

Figure 9 – PM2.5 concentrations mean time series averaged (and theirs 95 % confidence levels in shade) according to the hour of the day, days of the week, months, and hourly by day of the week over San Pietro Capofiume, Bologna.

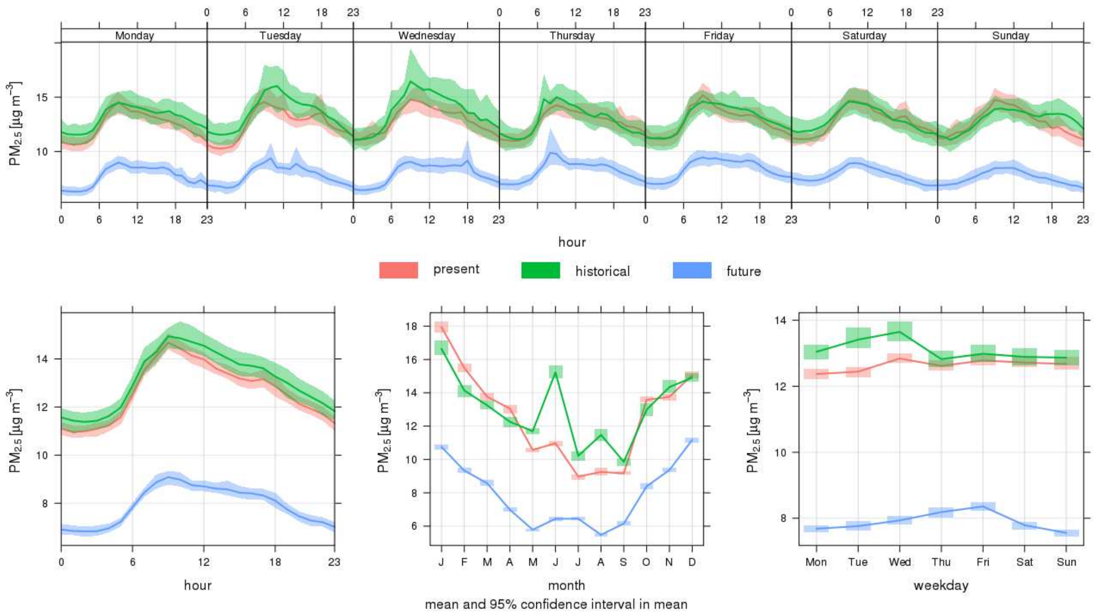

Figure 10 – PM2.5 concentrations mean time series averaged (and theirs 95 % confidence levels in shade) according to the hour of the day, days of the week, months, and hourly by day of the week over Giardini Margherita, Bologna.

Figure 11 to Figure 16 depict the spatial variation of NO_2 and PM2.5 concentration in the Bologna domain for the three periods, as printscreens from the project portal. Five-year averages extracted for the same stations as in Figure 7 to Figure 10 (orange and pink circles) are also shown.

For NO_2 the 5-year mean concentrations are very similar during the present climate as in the historical period. One notable difference is the very low NO_2 concentrations seen in present climate along and close to the Po river. These low concentrations are likely not correct and were introduced during a post-processing step going from averages over the lowest model layer to concentrations valid at 3 meters above ground; these technical problems are also visible in Figure 13. The large impact of the major highway connecting cities in the Po-valley is still clearly seen and the improvement in NO_2 concentrations from present to future climate with its 18% lower NO_2 emissions in the domain is rather modest along this string of high-emission grid cells. Further away from the major emissions, i.e. in the northern part or the domain, are NO_2 concentrations expected to go down following the general decrease of NO_2 levels across Europe.

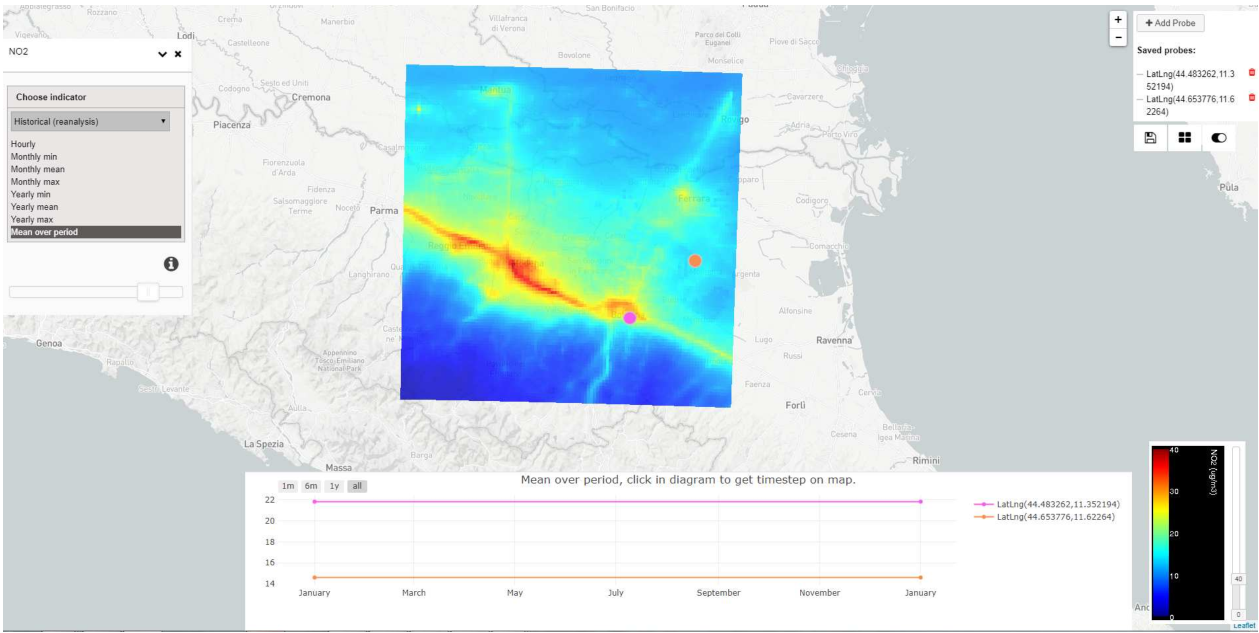

Figure 11 – Average NO2 concentration over the historical period in Bologna. The time series refers to Giardini Margherita (pink) and San Pietro Capofiume (orange). Concentration from 0 (blue) to 40 µg/m^3 (red).

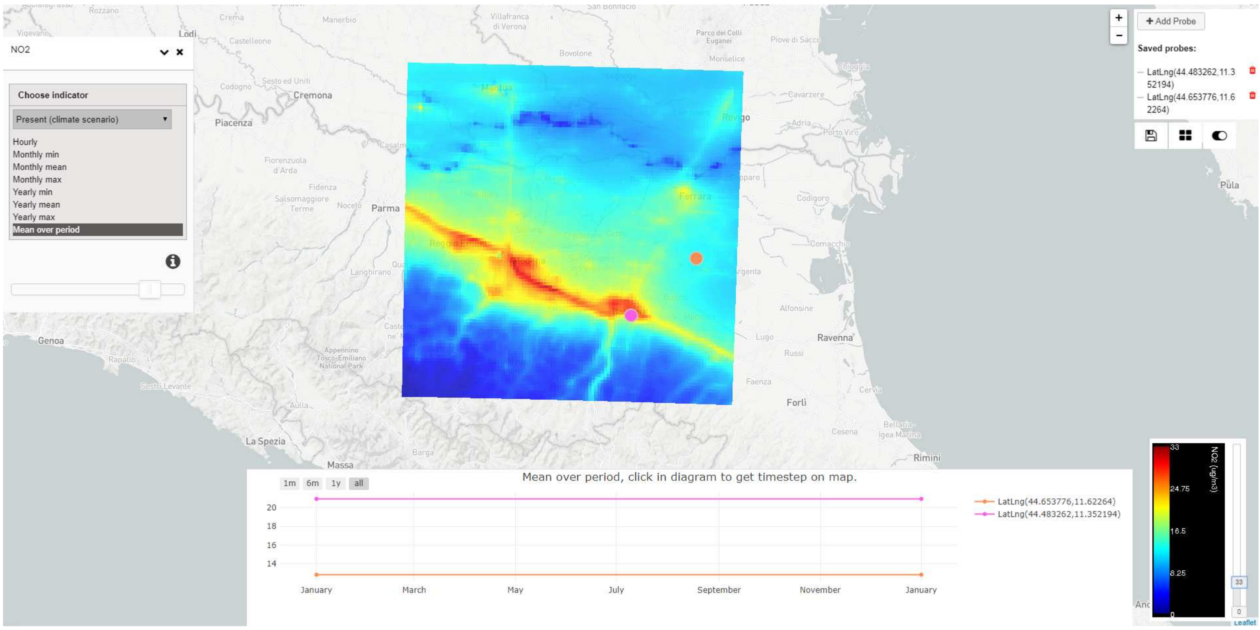

Figure 12 – Average NO2 concentration over the present climate period in Bologna. The time series refers to Giardini Margherita (pink) and San Pietro Capofiume (orange). Concentration from 0 (blue) to 33 μg/m^3 (red).

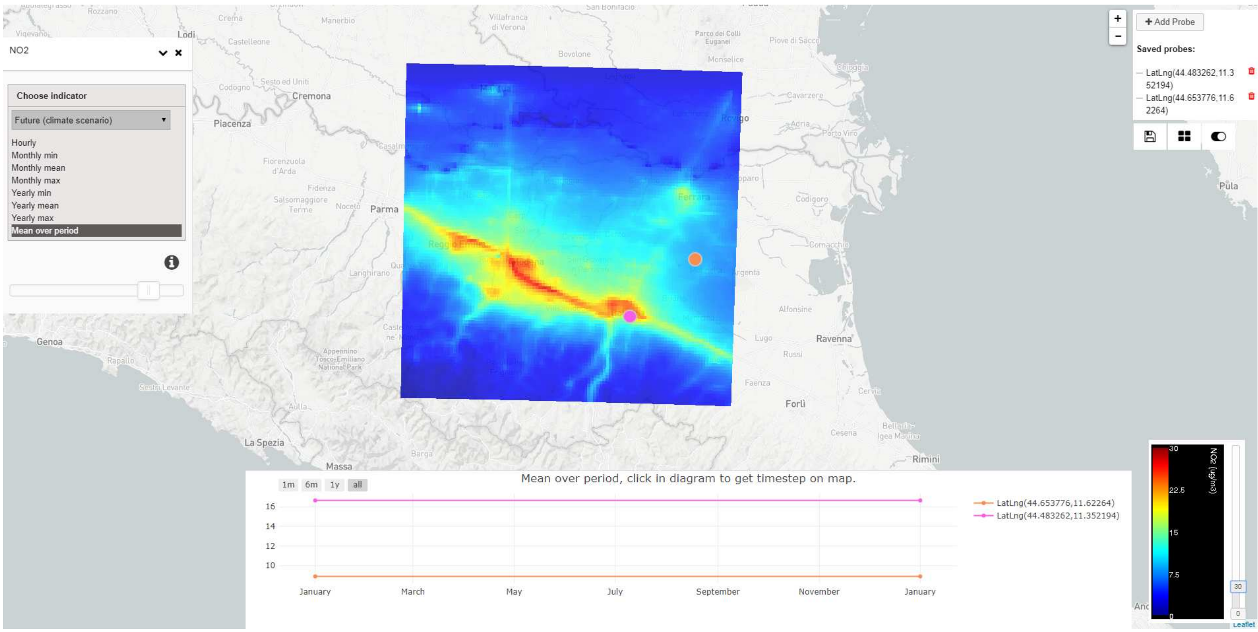

Figure 13 – Average NO2 concentration over the future climate period in Bologna. The time series refers to Giardini Margherita (pink) and San Pietro Capofiume (orange). Concentration from 0 (blue) to 30 μg/m^3 (red).

For PM2.5 there are relatively larger differences in our modelling of the historical period and the present climate. This is especially true in a large area around Modena where PM2.5 concentrations are considerably higher in the historical period than in the present climate simulations. This was an unexpected feature which is not yet fully understood. PM2.5 concentrations are expected to decrease in the future. This is visible throughout the modelling domain.

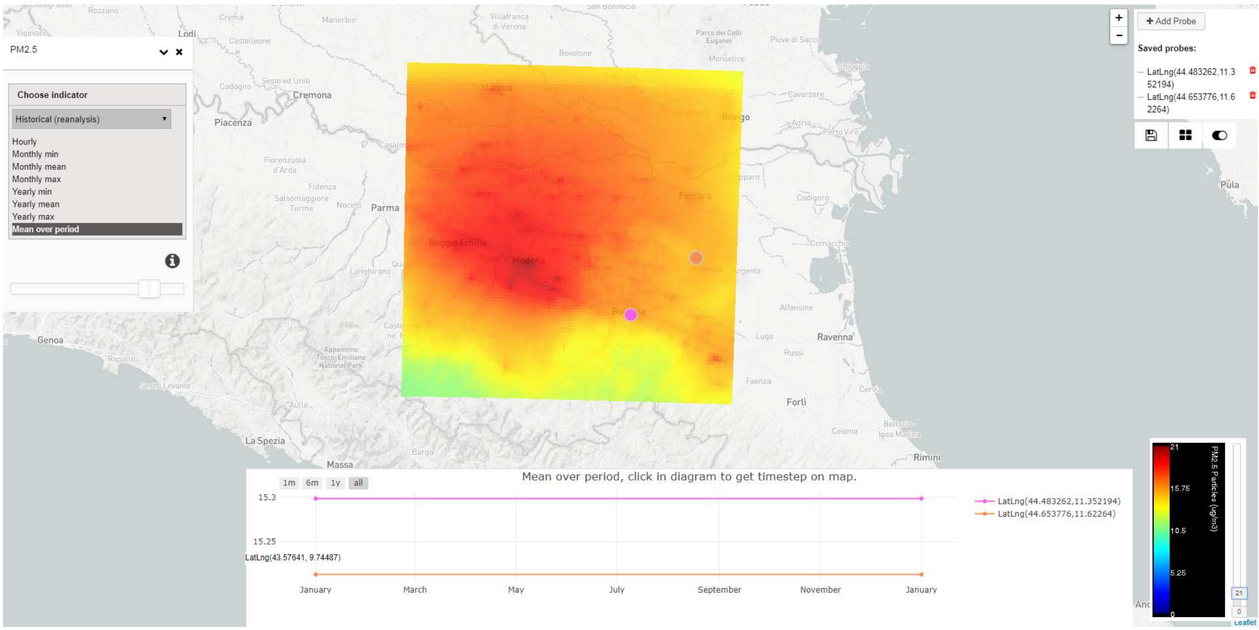

Figure 14 – Average PM2.5 concentration over the historical period in Bologna. The time series refers to Giardini Margherita (pink) and San Pietro Capofiume (orange). Concentration from 0 (blue) to 21 µg/m^3 (red).

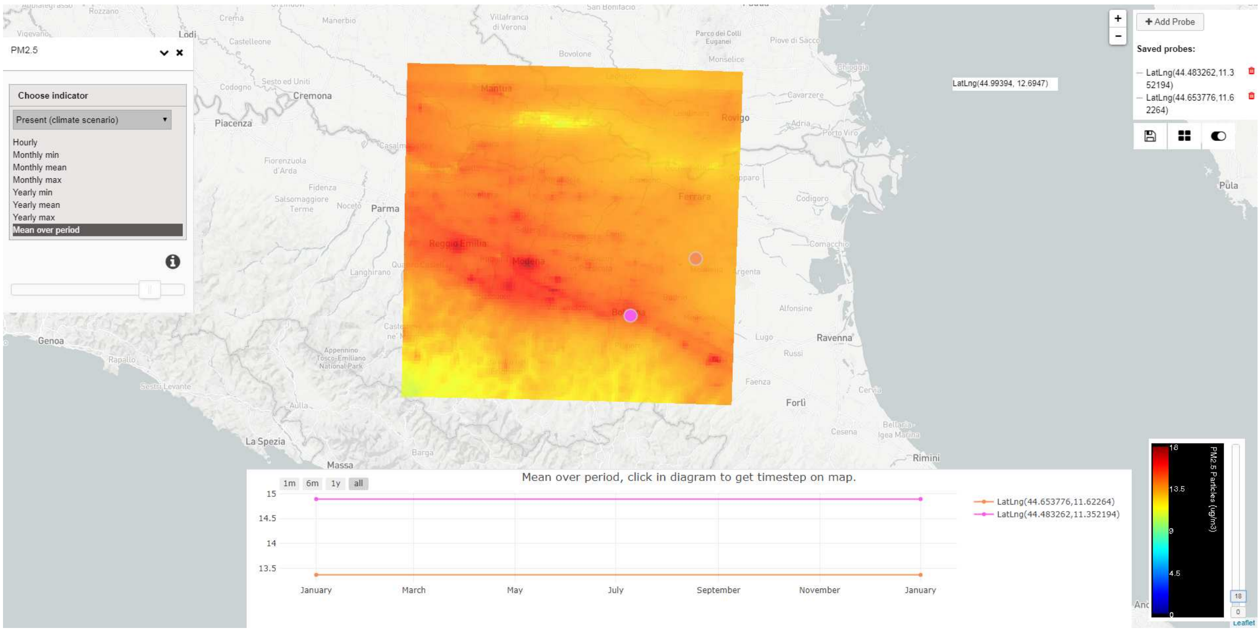

Figure 15 – Average PM2.5 concentration over the present climate period in Bologna. The time series refers to Giardini Margherita (pink) and San Pietro Capofiume (orange). Concentration from 0 (blue) to 18 μg/m^3 (red).

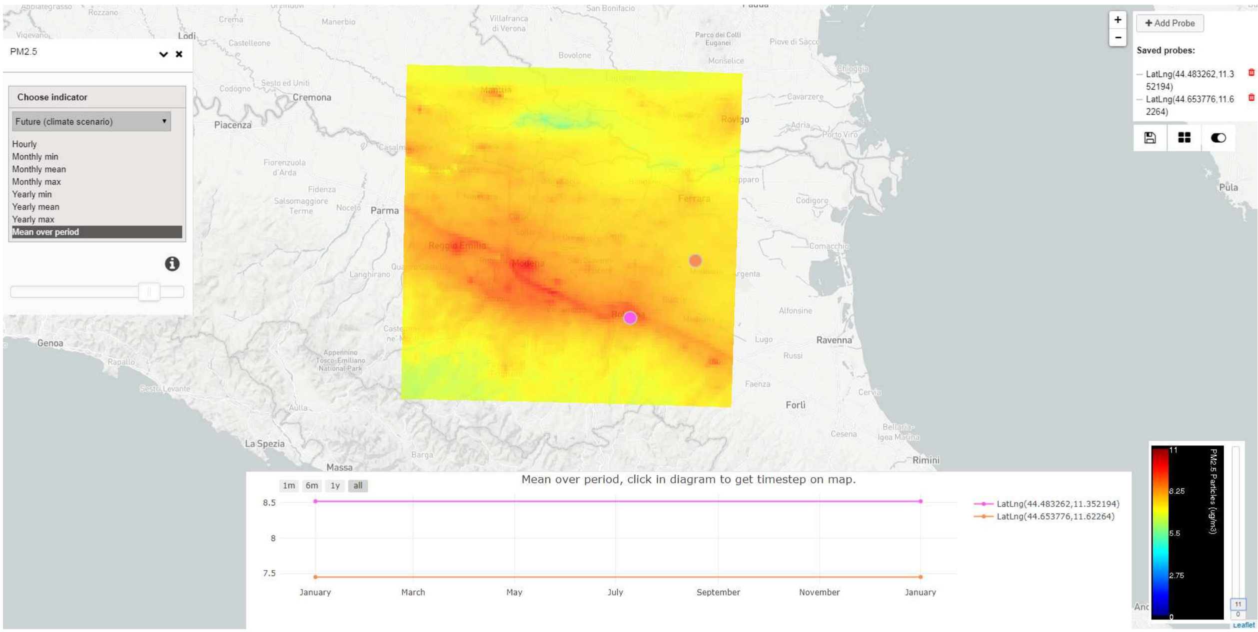

Figure 16 – Average PM2.5 concentration over the future climate period in Bologna. The time series refers to Giardini Margherita (pink) and San Pietro Capofiume (orange). Concentration from 0 (blue) to 11 μg/m^3 (red).

6. Experiences from the urban air quality downscaling of climate scenarios

The urban air quality downscaling was the last major model simulation in a chain of model runs. Before completing these simulations it was also necessary to collate, verify and reformat an array of input data (emissions estimates and high-resolution land-use classification). Finally, we faced the challenge of reading meteorological data from HCLIM-AROME and make use of the turbulent parameters calculated by the climate model, which is not the normal mode of operation of the air quality model MATCH. We clearly underestimated the extent and time requirements in all these endeavors and we did not foresee the implications in doing developments in our air quality model simultaneously as the high-resolution meteorology was being generated.

The consequence of these choices is that there is room for further developments and fine tuning of the results. Areas we know could be treated in more detail, with likely improvements in the model results include: making better use of the local information regarding the emissions (more detailed treatment of large point sources, and the utilization of local temporal profiles of the emissions, where such data exist) and fine tuning of our methods to use the high-resolution surface classification and the boundary layer parameters provided by HCLIM-AROME.

A 1-year air quality downscaling took approximately 152 hours on 64 cores (i.e. ~9 700 CPU-hours). Ignoring the duplicate simulations performed for testing and development etc., the air quality data presented in the current report thus represents the results of 3×5×9 700 =145 500 CPU-hours of calculation on a high-performance Linux-cluster for each climate scenario (in total around 291 000 CPU-hours for the climate runs). As the air quality downscalings were so time-consuming we were forced to operate the model on a relatively small domain, and small number of vertical levels, although we had emission data for a larger domain for most cities. Running high-resolution simulations on a high-resolution domain would probably improve the quality of the results.

A 1-year simulation on the pan-European domain, needed to provide boundary data for the urban downscalings, took ~30 hours to complete on 64 cores. The modelling domain covered an area of 172×200 cells, but as the advection time step could be kept at 300 s (instead of 20 s as in the case of the urban downscaling) these simulations were reasonably efficient. The pan-European simulations lacked wind-blown dust from Sahara or other arid lands. This is likely not a problem for the long-term averages but will undoubtedly result in severe underestimations of some dust episodes.

Aiming to carry out climate change impact studies on the air quality indicators, two additional sets of MATCH-pan-E runs would be needed to produce chemical boundary conditions to the urban domains: (I) air pollutants concentrations derived only with meteorological fields in different climate conditions, and (II) historical runs with historical ECLIPSE emissions, or other comparable set of emission estimations. With these group of runs it would be possible to determine the influence of the meteorology and the emissions conditions on the air pollutants concentrations derived in each historical and scenario simulation.

For sake of consistency, the underlying assumptions on the estimations of the urban emissions should be as close as possible to the ones driving the MATCH-pan-E air concentration fields, since they are imposed as boundary values in the MATCH-local applications. In case of further downscaling procedures of the MATCH-local 1 km x 1 km model results (with Computational fluid dynamics models or statistical modelling), it should be kept in mind the possible discrepancies that may arise from the different assumptions made in the emission inventories used.

A plethora of combinations between the meteorology derived from climate scenarios, emissions on pan-European and local inventories is possible. Setting the goals for the local applications, and the assumptions made, is of high importance both for further use of the data resulting from MATCH-local, at 1 km x 1 km, and for the analysis of the obtained results.

An additional collection of lessons learned and recommendations for users and for production is given in report D441.2.3 on “Recommendations of input for operational production”.

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