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Urban SIS
D441.3.1 Urban climate ECV and impact indicator data for historical conditions

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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 are carried out for historical and future time periods.

The current deliverable (D441.3.1) addresses specifically the urban climate downscaling over a 5-year time window representing the historical period. Two other reports, D441.3.2 and D441.3.3, complete the work description for past conditions, respectively with the air quality and hydrology components. Sector-related impact indicators are included in each one of the deliverables. Future climate data will be delivered with reports D441.3.4 to D441.3.6.

The downscaling modelling chain consists of three numerical models as depicted in Figure 1: the meteorological/climate model HARMONIE-AROME, the air quality model MATCH and the hydrological model HYPE. For the historical climate, the meteorological boundary and initial conditions are provided by the UERRA-ALADIN reanalysis. Detailed urban physiography description in HARMONIE-AROME aggregates data from ECOCLIMAP-II, Copernicus land services and national databases. Essential Climate Variables (ECVs) and Sectoral Impact Indicators driven by the outputs of the models are available through the data portal.

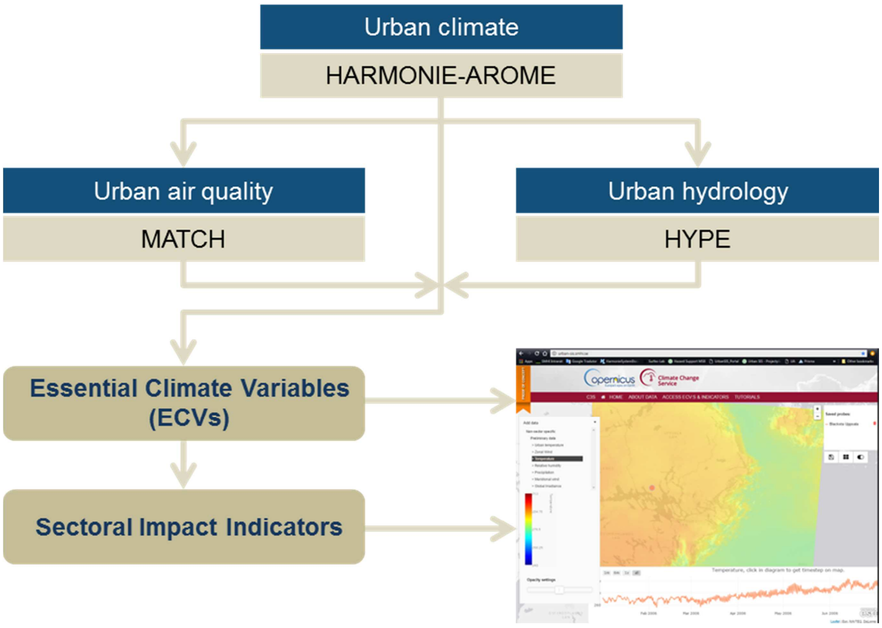


Figure 1 – General flowchart representing the numerical downscaling approach applied in UrbanSIS. More detailed information about each model will be given in the following sections.

This report summarizes relevant information about the main characteristics of the model, specific assumptions, computational domain, and input/output data. More details about the models and the numerical techniques applied can be found in the literature listed at the end of the document. Examples for climate-related ECVs and indicators are also given.

The last section of the report intends to share some experiences from the climate downscaling within UrbanSIS 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. Climate model used for downscaling

For the dynamical downscaling the Numerical weather prediction (NWP) system HARMONIE-AROME cycle 40h1.1 is applied. HARMONIE-AROME is used operationally as the regular cycle with the reference within the HIRLAM consortium, e.g. in the MetCoOp collaboration between Sweden and Norway (Müller et al., 2017), and it is part of the shared ALADIN-HIRLAM system, developed by the 26 countries of both NWP consortia.

Figure 2 shows the flowchart for the dynamical downscaling process. As input, high-resolution physiography data is compiled, lateral boundary data is provided by the UERRA-ALADIN reanalysis (Ridal et al., 2016), and surface observations are retrieved from the ECMWF MARS archive. In the next step the initial states for the atmospheric and surface model are generated, where the previous 6-hour forecast serves as input. Finally, the forecast model is run and produces a 12-hour forecast as output. The latter is used in the post-processing of the ECVs, and also as input to the air quality and the hydrological models.

In the following subsection, we will describe the components of the HARMONIE-AROME system used in UrbanSIS, i.e. the atmospheric initialisation, surface data assimilation and the forecast model.

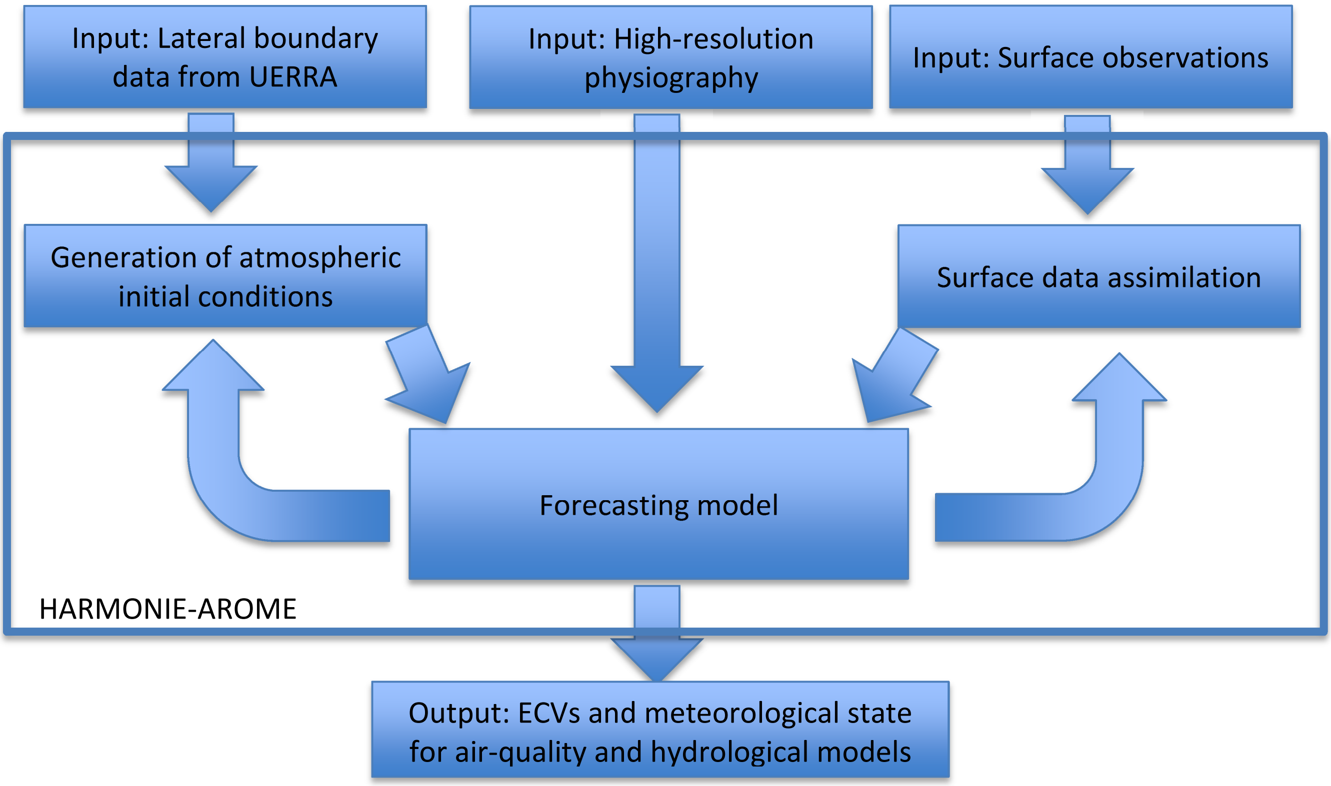


Figure 2 – Flowchart of the dynamical downscaling process.

1.1 Initialization

The atmospheric state for the dynamical downscaling in UrbanSIS is initialized by using the so-called blending feature (Derková and Belluš, 2007) of the shared ALADIN-HIRLAM system. In this approach, the previous 6-hour forecast is combined with the analysis from the UERRA-ALADIN reanalysis (see below in section 2.3) that is also used as the lateral boundary condition. The large-scale state is taken from UERRA-ALADIN reanalysis, while the small-scale state is provided by the previous 6-hour forecast from the HARMONIE-AROME. The blending can be expressed with the following equation:

$$I = G^H + (A^U_{LOW} - G^H_{LOW})_{HIGH}$$

where I stands for the blended initial state, G^H for the high-resolution first guess from HARMONIE-AROME and A^U for the analysis from UERRA-ALADIN. The subscript LOW represents the low-pass filtered fields, while the subscript $HIGH$ is the projection on the full high-resolution.

The employed surface data assimilation scheme (Giard and Bazile, 2000) uses optimal interpolation. Finally, a digital filter initialization is applied (Lynch and Huang, 1992) in order to filter out imbalances in the initial state created with the blending and the surface data assimilation.

1.2 Forecasting model

HARMONIE-AROME is a spectral limited area model aimed for the convection permitting scales (O ~1km), and has been developed to use the full non-hydrostatic equations, since the vertical velocity is large at the resolved scales due to convection and orographic forcing. Within HARMONIE-AROME the model physical parameterizations are based on AROME (Seity et al., 2011). At SMHI, HARMONIE-AROME has been used for operational weather forecasts since 2014.

The main components of the physical parameterizations (radiation, surface, thermodynamic adjustment, cloud-cover, cloud-microphysics, turbulence and shallow convection) can be found in Seity et al. (2011). Specific changes in the forecast model HARMONIE-AROME were developed within the HIRLAM consortium and are described in Bengtsson et al. (2017).

We use the surface model SURFEX version 7.3 (Surface Externalisée, Masson et al. (2013)). One component of special interest for UrbanSIS is the Town Energy Balance model (TEB), specially designed to represent the exchanges between a town and the atmosphere (Masson, 2000). Furthermore, we employ the lake model model FLake (Le Moigne et al., 2016) for lakes and coastal waters. The specific setup of SURFEX in HARMONIE-AROME is described in Bengtsson et al. (2017). The forecast model is run up to the 12-hour forecast.

2. Input to the climate downscaling

2.1 Time period of simulation

The 5-year historical period selected is comprised of the following years: 2006, 2007, 2012, 2013, and 2014. The same period is considered for the 3 use cases. The criteria for the selection were mainly the availability of data needed by the models (namely boundary conditions from UERRA and observations for assimilation and/or validation), and the project´s goal of addressing the end-user requirements and expectations. In particular, this time window responds to a specific request from Bologna end-users to consider more recent conditions, including the year 2012, which was particularly warm in the summer. More information about the time period selection process can be found in report D2.1.

2.2 Computational domains

Three urban areas were defined for Stockholm, Bologna, and Amsterdam/Rotterdam. The respective computational domains are displayed in Figure 3. Each domain consists of 240 x 240 gridpoints with a grid spacing of 1 km, thus covering 57600 km^2. The size of the domain was a compromise given the computational resources available to the data production. Vertically, 65 levels are used. In order to reduce the computations in spectral space while retaining the horizontal grid spacing of 1 km, we used a cubic grid. Thus, the shortest resolved wave in spectral space has a wave length of 4 km. The position of the domain was chosen centrally around the urban areas, taking into account local topography and hydrology.

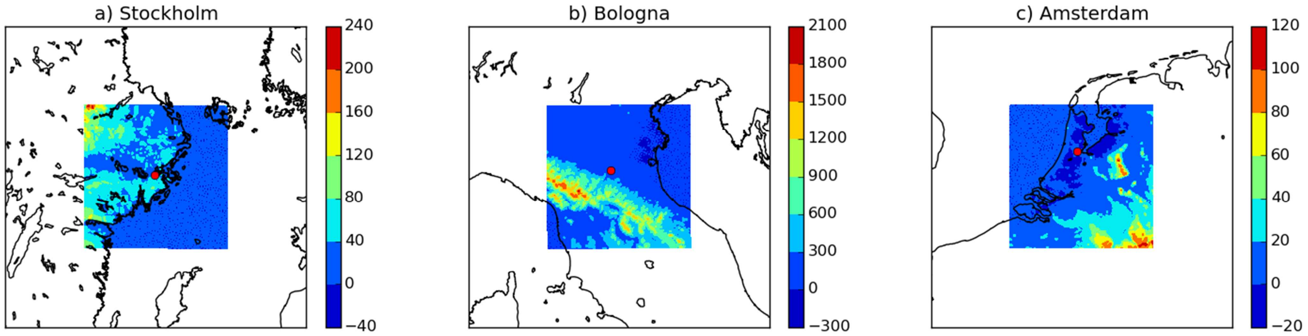


Figure 3 – Topography of the three urban areas in metres for the used computational domain. The red dot marks the respective city.

2.3 Boundary forcing

The meteorological lateral boundary conditions to the dynamical downscaling are provided by reanalysis of the European project UERRA (Uncertainties in Ensembles of Regional Re-Analyses), specifically from the UERRA-ALADIN reanalysis (Ridal et al., 2016). The UERRA-ALADIN reanalysis covers the years from 1961 to 2015 and it is produced with the ALADIN NWP model combined with the surface model SURFEX and the HARMONIE script system. The resolution is 11 km horizontally and 65 levels vertically. A 3-dimensional variational data assimilation is employed. The following observations are assimilated: conventional observations which include synoptic stations, ships, drifting buoys, aircraft observations and radio soundings. For surface data assimilation, an optimal interpolation (OI) method with CANARI (Code for the Analysis Necessary for ARPEGE for its Rejects and its Initialization) and SURFEX (surface externalisée) is used. Only synoptic observations are used to analyse 2 meter temperature (T2m), 2 meter relative humidity (RH2m) and Snow Water Equivalent (SWE).

As SMHI produces the UERRA-reanalysis, the full model state on model levels is available as boundary condition to UrbanSIS. It should be noted that this model level data will not be stored as part of the UERRA project. For the boundary conditions of the 12-hour forecasts for the dynamical downscaling, we employ the UERRA-ALADIN reanalysis and its 5-hour forecast with hourly output.

2.4 Surface description

2.4.1 Land-use description method

Urban morphology, surface materials, vegetation characteristics, and human activity are key drivers of urban climate, generating strong intra-city gradients of temperature, wind, and air pollutants. In HARMONIE-AROME, surface/atmosphere interactions are computed by SURFEX (version 7.3) (Masson et al., 2013), as described in report D2.1.

Major physical processes occurring in urban areas are taken into account in SURFEX, namely, the trapping of longwave and shortwave radiation by the canyon, including the shadowing effect, the anthropogenic sensible heat flux, the interception of rain and snow by roofs and roads, the conduction and storage of heat in buildings walls and roofs or the interaction of the built surfaces with the canyon air through the transfer.

For the description of the surface, SURFEX uses a tile approach that allows accounting for sub-grid heterogeneity, as depicted in Figure 4. Four tiles are defined: ‘Town’ (composed of buildings, roads and other transportation infrastructure, and gardens); ‘Nature’ (which can be further divided into 12 patches encompassing bare soils, rocks, permanent snow, glaciers, natural vegetation and agricultural landscapes); ‘Lake’ (inland waters, including lakes and rivers); and ‘Sea’ (including both sea and ocean).

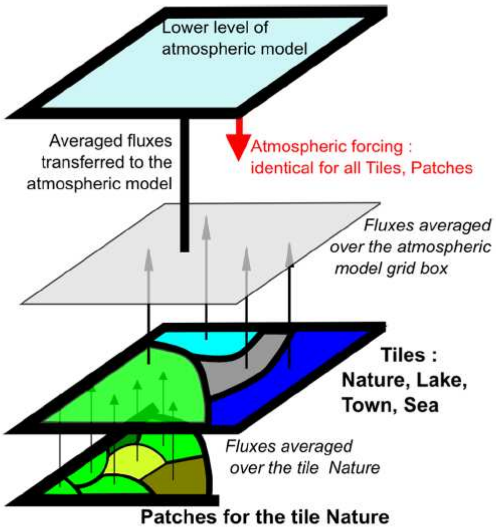


Figure 4 – Scheme representing SURFEX tiling approach and coupling with an atmospheric model (from Masson et al., 2013).

Depending on the type of surface, different modelling schemes are activated in SURFEX, namely the Town Energy Balance (TEB) (Masson et al., 2013) model in urban areas, and the Interaction Soil-Biosphere-Atmosphere (ISBA) land surface model for soil and vegetation. An important consequence of this concept is that sub-grid meteorological parameters are provided by the model for each tile fraction within a grid cell, in addition to the weighted average.

The physiographic characterization of the surface in SURFEX/HARMONIE-AROME is driven by the European, 1 km resolution, land cover database ECOCLIMAP-II (Faroux et al., 2013). This database aggregates information on an ecosystem classification and a coherent set of land surface parameters that are primarily mandatory in meteorological modelling (notably, leaf area index and albedo). Due to the focus of Urban SIS on urban environments, we were particularly interested in the way this dataset represents the spatial gradients of the surface within the city (including the interactions between built-up areas and green-infrastructure) and in the urban/rural interface, and specifically in the case of Stockholm and Amsterdam, how realistically is the interface land/water captured.

As described in deliverable D2.1 we have concluded, as we started with the processing of Stockholm´s land-use, that ECOCLIMAP-II didn´t offer the level of detail we required, namely, in the description of the urban surface, as also of the land/water interface along the Baltic sea coast line and in the lakes that characterize the Swedish landscape. The improvement of the land-use description will be hereafter analysed.

2.4.2 The development of a refined physiography database

Aiming to assure that the land cover data used as input to HARMONIE-AROME over cities are the “best available” we have produced 1x1 km^2 resolution gridded data that provide enhanced surface characteristics to the ECOCLIMAP-II database, which result from a more detailed description of the physical boundaries of each ecosystem type. The selection criterion for the sources was based on the accuracy, resolution, and availability of the information. We have also privileged the use of Copernicus products. This resulted in the selection of the following open-access databases and respective products shown in Table 1.

Table 1 – Surface description data sources used in the construction of the refined physiography database for Stockholm, Bologna and Amsterdam/Rotterdam.

Input data type	Product	Spatial resolution (m)	Source data type	Webpage
European ecosystem classification and surface parameters	ECOCLIMAP II	1000	Various sources: ECOCLIMAP-I, GLC2000, MODIS	https://opensource.cnrm-game-meteo.fr/
Spatial coverage of land cover types	Copernicus Land Monitoring Services: Urban Atlas 2012	100	Satellite data (PROBAV v1.4)	http://land.copernicus.eu/local/urban-atlas
Building polygons	OpenStreetMap	Nd	Various sources	https://www.openstreetmap.org
Leaf area index (LAI) of vegetation	Copernicus Global Land Service	1000	Time-series of satellite data	http://land.copernicus.eu/global/themes/vegetation

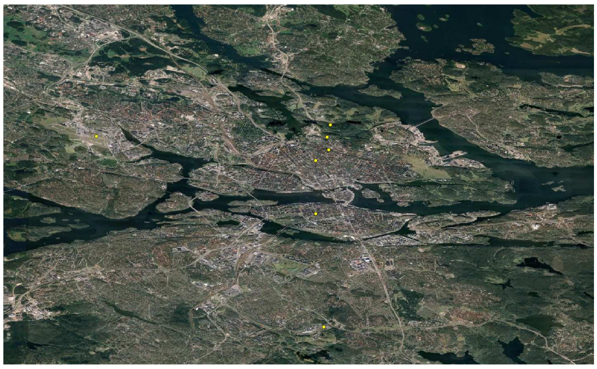
Additionally, for the Stockholm use case we have extracted and aggregated buildings height data available at 12.5 m resolution from lidar measurements. This high resolution dataset is available online free of cost through the Swedish Forest Agency website (http://www.skogsstyrelsen.se/Myndigheten/Om-oss/Oppna-data/). For Bologna and Netherlands domains we have relied on the original ECOCLIMAP-II buildings height data.

Moreover, the methodology for creating the surface gridded data offers the possibility to be replicated for other cities using open-access high-resolution data sources.

The new physiographic data is supplied to HARMONIE-AROME as gridded data files (latitude, longitude, parameter value) with an average spatial resolution of 300x300 m^2. These are then interpolated by SURFEX to the final model grid (1 km^2 resolution) and combined with the default ECOCLIMAP-II database where needed.

2.4.3 Quality analysis of the new surface data

Figure 5 shows, as an example for Stockholm, the capacity of the new refined physiography to accommodate different fractions of water in each grid cell, which enables it to capture the interface land/water significantly better.



Default ECOCLIMAP-II: New refined physiography:

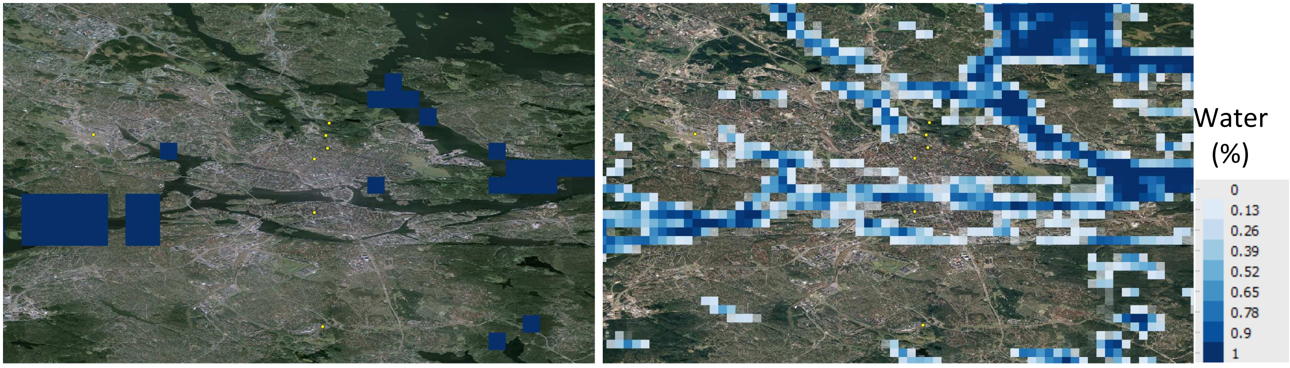


Figure 5 – Example of how the new physiography treats the interface land/water over Stockholm. The colour pattern represents the fraction of water in the default ECOCLIMAP-II database (left) and the new refined physiography (right). The yellow dots represent the location of meteorological masts in the region.

Another clear example of the capability of the new product to show very fine details in the surface characteristics is given in Figure 6 for Bologna. Here the intra-city gradients of building density are much clear in the refined grid. Also vegetation fraction, both in the city and outskirts, is plotted with much finer detail.

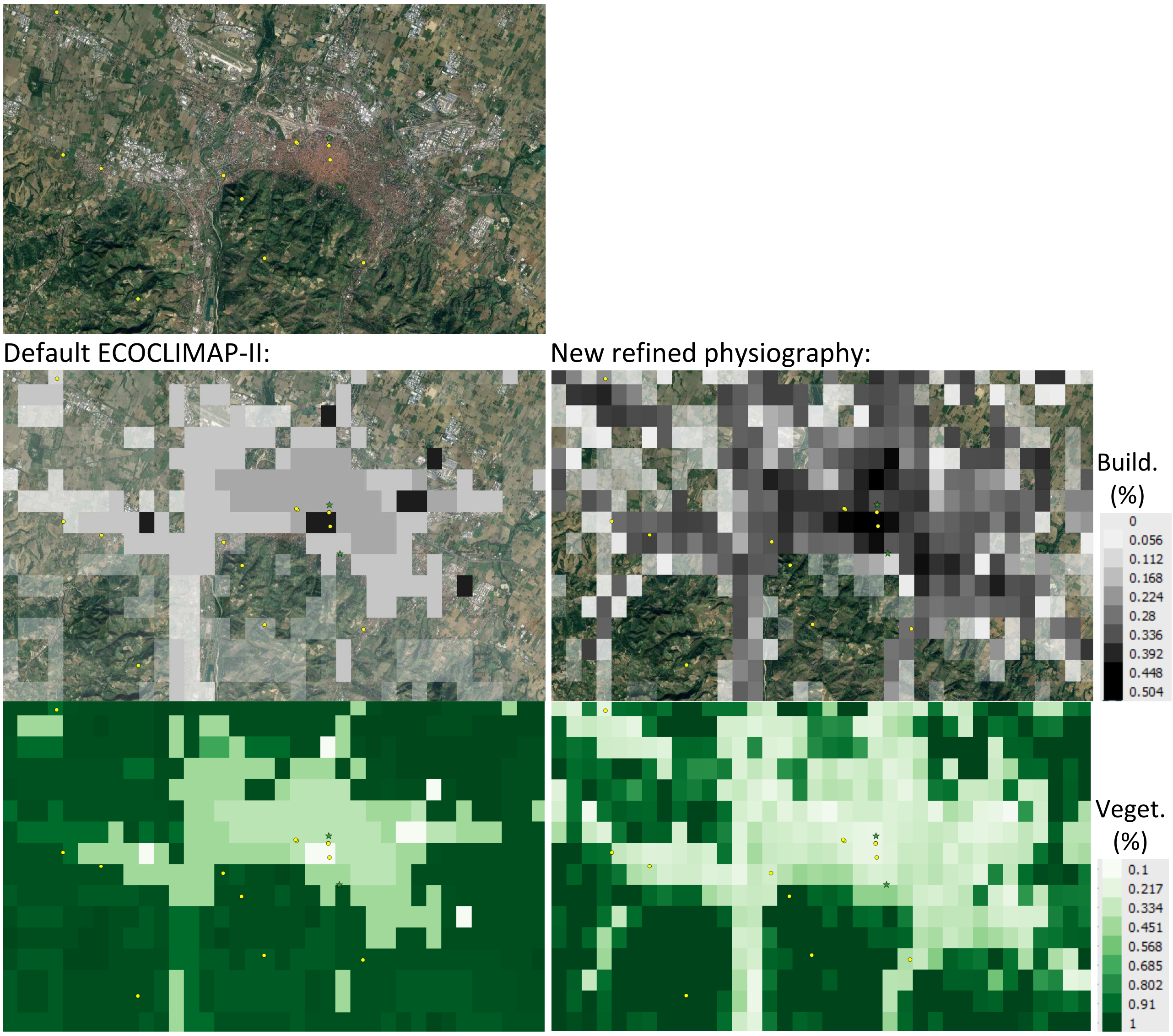


Figure 6 – Example of how the new physiography treats the interface between built-up areas and vegetation over Bologna. The grey and green colour pallets represent, respectively, the fractions of buildings and vegetation in the default ECOCLIMAP-II database (left) and the new refined physiography (right). The yellow dots represent the location of meteorological masts in the region and the green stars the two largest urban parks in Bologna.

2.5 Observations

For the surface data assimilation, we use near-surface temperature, relative humidity and snow water equivalent observations from SYNOP- and airport (METAR) stations. All observations were retrieved from the ECMWF MARS archive. The number of available stations is 20 for the Stockholm domain, 10 for the Bologna domain, and 29 for the Amsterdam/Rotterdam domain.

3. Post-processing of model output

3.1 Transformation of gridded time series to NetCDF

The gridded time series data 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).

Since some parameters in HARMONIE-AROME are accumulated, in each timestep the grid for the preceding timestep is subtracted in order to obtain the non-accumulated values. Further, for some parameters the unit is converted and thus the gridded data is scaled by a given factor.

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 climate ECVs

The statistical post-processing of meteorological variables is made using the same methods and software as for the hydrology and air quality related 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 meteorological 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 combination of parameter and statistical operators are not shown in the final results, since they are not meaningful. One such combination is yearly minimum of precipitation.

3.3 Calculation of climate 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 climate data

4.1 Climate ECVs

Table 2 lists the climate related ECVs defined in agreement with the requirements detailed in deliverable D4.2.

Table 2 – List of climate related ECVs. The spatial resolution is 1x1 km^2 over the entire modelling domain (110x110 km^2) and the temporal resolution is 1 hour, except for precipitation that equals 15 min.

ECV name	Unit
Air temperature (at 2 m above ground)	°C
Air temperature in the 'town' tile	°C
Air temperature in the 'nature' tile	°C
Air temperature at layer 1 (aprox. 12 m above ground)	°C
Air temperature at layer 2 (aprox. 38 m above ground)	°C
Air temperature at layer 3 (aprox. 50 m above ground)	°C
Precipitation	mm
Snowfall	mm
Relative humidity	%
Wind speed (at 2 m above ground)	$m\ s^{-1}$
Wind speed at layer 1 (aprox. 12 m above ground)	$m\ s^{-1}$
Wind speed at layer 2 (aprox. 38 m above ground)	$m\ s^{-1}$
Wind speed at layer 3 (aprox. 50 m above ground)	$m\ s^{-1}$
Gustiness	$m\ s^{-1}$
Friction velocity	$m\ s^{-1}$
Boundary layer height	m
Global radiation	$w\ m^{-2}$
Direct shortwave radiation	$w\ m^{-2}$
Diffuse shortwave radiation	$w\ m^{-2}$

As an example, Figure 7 presents a print screen of the type of information that an end-user can access on the UrbanSIS portal for a typical meteorological ECV. Further information on the use of the portal can be found in deliverable D4.4.

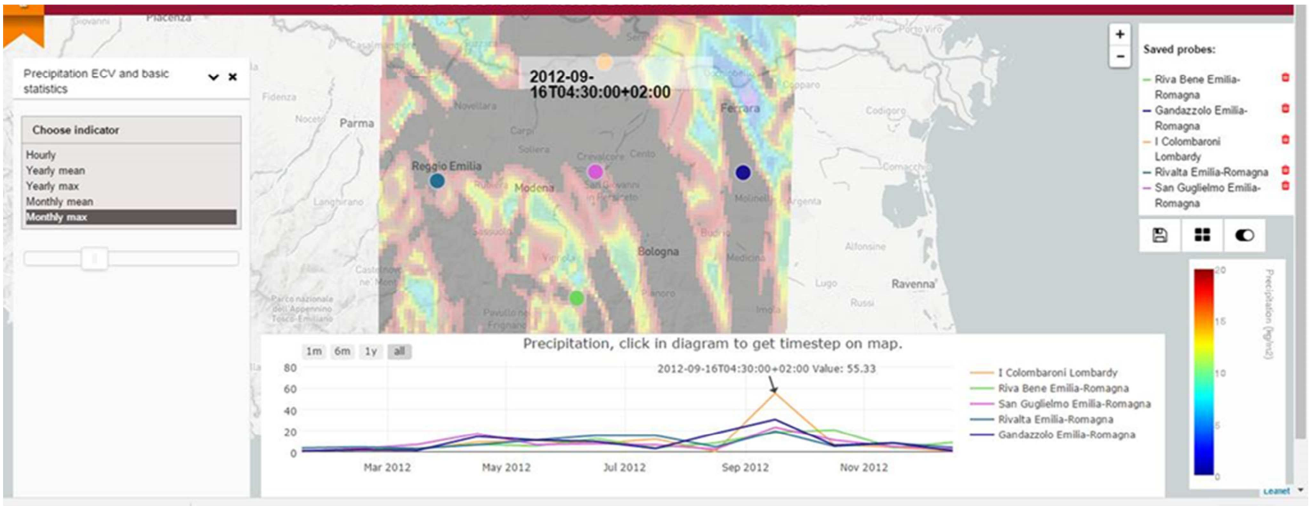


Figure 7 – Example of visualization of an ECV on the data portal. The figure shows monthly maximum of precipitation over Bologna as a 2-dimensional contour map and as time-series for three selected locations.

4.2 Climate impact indicators

Table 3 lists the indicators that are climate specific. These are described in detail in report D4.3.

Table 3 – List of climate related indicators.

Sector	Indicator		Aggregation	Unit	Threshold
Health	Heat stress	Hot days (degree days > 75th percentile)	yearly	°C day	
		Heat wave duration	yearly	days	97.5th and 81th percentiles
		Annual heat related deaths	yearly	deaths year^{-1}	75th percentile at position of an official weather station
		Annual heat related deaths per 100,000 inhabitants	yearly	deaths year^{-1} 100,000 inhab^{-1}	75th percentile at position of an official weather station
	Discomfort	Thom discomfort index	yearly		
		Universal Thermal Climate Index (UTCI)	yearly		
		Tropical Nights	yearly		
Energy	Energy consumption	Heating degree days	yearly	°C day	17
		Cooling degree days	yearly	°C day	20
		Degree days	yearly	°C day	
	Solar energy	Shortwave solar insolation	Average monthly values for modelling period	MJ m^{-2} month^{-1}	
Infra-structure	Soil	Soil temperature	monthly	°C	
	Green infrastructure	Leaf on date	yearly	day of year	
		Leaf off date	yearly	day of year	
		Growing season length	yearly	days	
		Growing degree days	monthly	°C days	10° C
		Senescence degree days	monthly	°C days	10° C
		Drought duration	yearly	days	20th percentile
	Transport infrastructure	Frost days	yearly	days	
		Ice days	yearly	days	
		Zero-crossings (number of days on both sides of 0 °C)	yearly	days	
Non-sector specific	Temperature	Daily max air temperature	daily	°C	
		Daily min air temperature	daily	°C	
		Daily mean air temperature	daily	°C	
		Yearly maximum of daily temperature range	yearly	°C	

As an example of the 2-dimensional plotting of an impact indicator, Figure 8 shows the Growth Season Length over Stockholm for the 5-years historical period. The map provides a very detailed understanding of the spatial variability of this parameter across the domain, with obvious interest for the agriculture and forestry sectors.

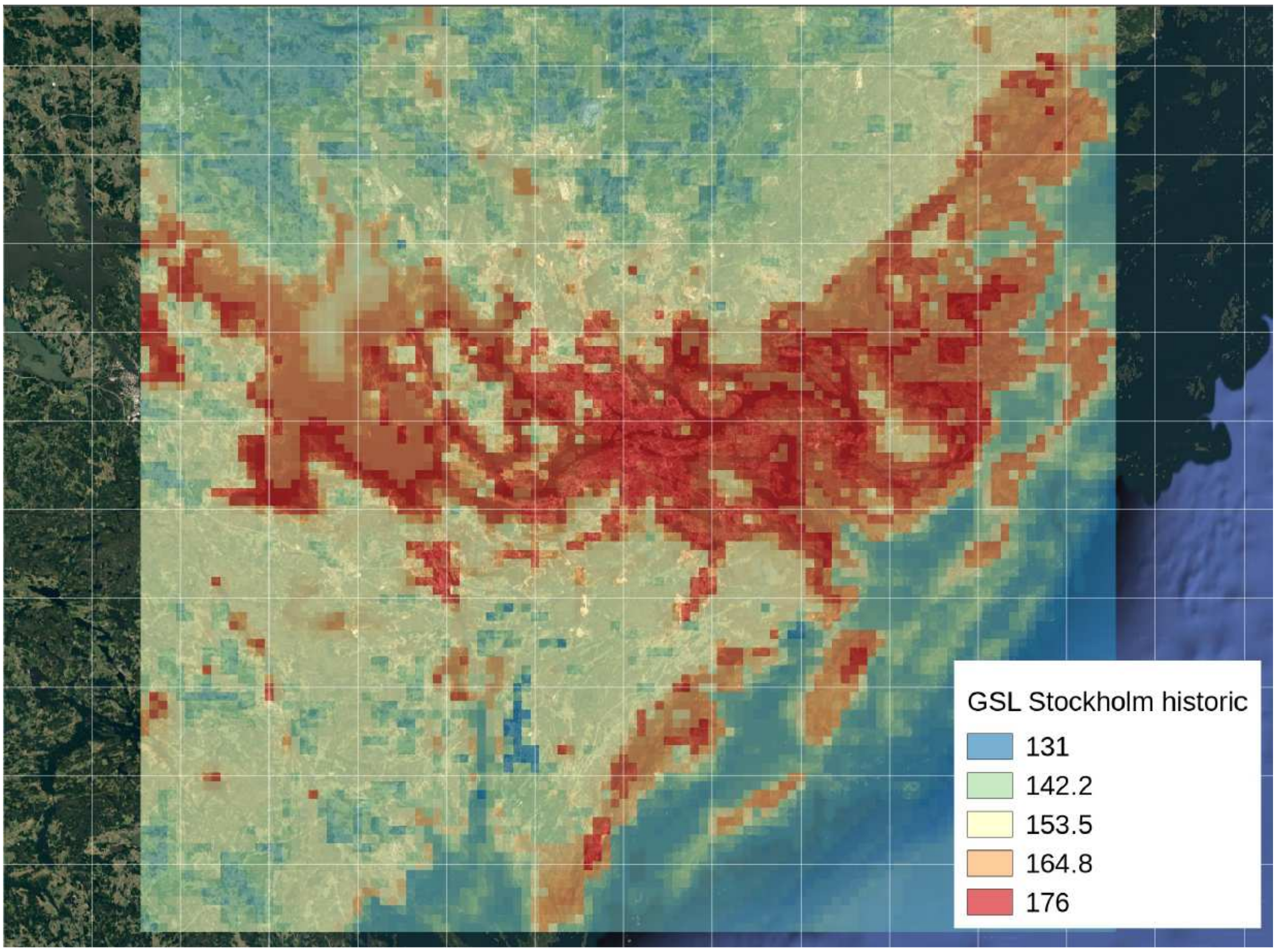


Figure 8 – Example of an impact indicator output, showing the Growth Season Length (GSL) over the Stockholm area for the historical period. Unit: days.

5. Experiences from the climate downscaling

For the dynamical downscaling the required computational resources are considerable. For one month of data we needed, when running on 16 compute nodes with 32 processors each, 32 hours of wall-clock time on a Linux cluster with Intel Xeon E5-2640v3 processors at 2.6 GHz. This sums up to ~$3x10^6$ CPU-hours for the 5 years over the 3 cities. In this estimate, no time in the supercomputer's queue was included. The resulting data amounts to 303 Gigabyte per month and per city, while the amount of data stored on the portal equals 100 Gigabyte per month.

The production runs with HARMONIE-AROME were quite stable with approximately 2 incidents per model year. Incidents would normally result from problems with boundary files or missing observations. In these cases, either the missing file was reloaded or replaced manually.

We used a cubic grid with a relatively small domain in order to reduce the computational costs. While the cubic grid yielded comparable results as the conventional linear grid, the domain size created problems with the spin-up of precipitation in strongly forced weather situations, i.e. with strong winds advecting in through the lateral boundaries. For these cases and the related precipitation, a larger domain would have been beneficial. Since the used surface model version 7.3 of SURFEX in HARMONIE-AROME has only a short memory in the surface, we needed to include surface data assimilation. The next version of SURFEX will include a more realistic description of the surface processes, reducing the need for surface data assimilation.

It should be noted that the lateral boundary data from the UERRA-ALADIN reanalysis is only currently available, as SMHI has stored the full-model state on model levels. For future dynamical downscaling, it is important that this data is going to be archived and made available. The large data amounts pose a problem for the archiving and the data's fate has not been decided.

High resolution physiography data was compiled and provided as an upgrade to ECOCLIMAP II. The surface refinement methodology can be replicated for other cities using open-access high-resolution data sources. As described in current report (see section 2.4) there was a substantial improvement on the representation of the interface land/water and the intra-city gradients (e.g., urban parks). Preliminary evaluation of model results reveals good agreement against meteorological observations, both in city and outskirts. Moreover, HARMONIE-AROME has shown to respond to urban surface features and their characteristic fingerprint, namely, the Urban Heat Island (UHI) and the Park Cool Island (PCI) effects.

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