

Towards climate services for European cities: Lessons learnt from the Copernicus project Urban SIS

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ABSTRACT

The growing share of Europe's population living in cities makes urban climate change impact assessment and adaptation a critical issue. The urban environment is characterized by its sensitivity to small-scale meteorological, hydrological and environmental processes. These are generally not fully described in climate models, largely because of the models' insufficient spatial resolution. The Urban SIS climate service offers historical and future simulated data downscaled to 1 km × 1 km resolution over selected European metropolitan areas. The downscaled data are subsequently used as input to air quality and hydrological impact models, all made available to users as Essential Climate Variables and Sectoral Impact Indicators through a web portal. This paper presents the Urban SIS climate service and demonstrates its functionality in a case study in Stockholm city, Sweden. Good model performance was attained for intra-city temperature gradients and small-scale precipitation extremes. Less positive results were obtained for large-scale precipitation and hydrology, mainly due to an insufficient domain size in the meteorological and climate modelling, in turn related to the substantial computational requirements. An uncertainty classification approach was developed to aid the interpretation and user application of the data. We hope our lessons learnt will support future efforts in this direction.

Acronyms: ALADIN, Aire Limitée Adaptation Dynamique Développement International; AROME, Applications of Research to Operations at MEscale; C3S, Copernicus Climate Change Service; CANARI, Code for the Analysis Necessary for ARPEGE for its Rejects and its Initialization; CTM, Chemical Transport Model; DDF, Depth-Duration-Frequency; EC-Earth, European Community Earth-System Model; ECLIPSE, Evaluating the CLimate and air quality imPacts of Short-livEd pollutants; ECV, Essential Climate Variable; EMEP MSC-W, Meteorological Synthesizing Centre-West of the European Monitoring and Evaluation Programme; GCM, Global Climate Model; HARMONIE, Hirlam Aladin Regional Mesoscale Operational NWP In Europe; HCLIM, Harmonie CLimate; HIPRAD, High-resolution Precipitation from gauge-adjusted RAdar Data; HRU, Hydrological Response Unit; HYPE, HYdrological Predictions for the Environment; MACC, Monitoring Atmospheric Composition and Climate; MATCH, Multiple-Scale Atmospheric Transport and Chemistry Modelling System; MESAN, MESoskalig ANALys; NSE, Nash-Sutcliffe Efficiency; PM, Particulate Matter; RCM, Regional Climate Model; RCP, Representative Concentration Pathway; RE, Relative Error; RMSE, Root Mean Square Error; SII, Sectoral Impact Indicator; SIS, Sectoral Information System; SMHI, Swedish Meteorological and Hydrological Institute; SURFEX, SURFace EXternalisée; TEB, Town Energy Balance; UERRA, Uncertainties in Ensembles of Regional Re-Analyses; UHI, Urban Heat Island; UK COMEAP, United Kingdom's Committee on the Medical Effects of Air Pollutants; WHO HRAPIE, World Health Organization and its Health Risks of Air Pollution in Europe project

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1. Introduction

Three quarters of the European population live in cities and the urbanization trend is increasing (EC, 2016). The climatic conditions inside urbanized areas determine how the population is exposed to health-related climate variables like temperature, as well as other variables such as humidity, wind speed and air pollution that affect human well-being and comfort. Cities do not only concentrate people, they are also a focus for countries' assets and economic activities, making them vulnerable to extreme climate conditions like heat waves, intense rainfall, storm events and flooding. Improved climate information in urban areas for the two sectors health and infrastructure was the major objective behind the *Copernicus Climate Change Service* (C3S) proof-of-concept project Urban SIS (*Sectoral Information System*), running between 2015 and 2017. Urban SIS developed and evaluated a climate service designed for European cities, offering information at high spatio-temporal resolution in terms of *Essential Climate Variables* (ECVs), as well as user-defined *Sectoral Impact Indicators* (SIIs) tailored for the sectors mentioned above. The development, evaluation and demonstration of Urban SIS were made for three urban areas: Stockholm, Bologna and Amsterdam/Rotterdam. The aim of this article is to openly share the climate service design, the results obtained and the lessons learnt, illustrated by the application in Stockholm.

The gap between the available spatial and temporal scales of climate data and the local city-specific information desired by urban end-users is emphasized in e.g. Cortekar et al. (2016). Baklanov et al. (2018) stress the key role that the meteorological community, in particular the national meteorological and hydrological services, should play with respect to providing integrated urban weather, environment and climate services. It is also important for cities to manage the interactions between different mitigation actions and adaptation pathways (Ürge-Vorsatz et al., 2018), a process that will require information on climate responses of individual cities.

The computational demands of coupled meso-scale models operating on scales that resolve urban structures, i.e. $1\text{ km} \times 1\text{ km}$ or higher spatial resolution, have so far prevented dynamically downscaled urban climate data to be offered in climate services. Specific phenomena like the urban temperature response to urbanized (grey) surfaces, the so-called Urban Heat Island (UHI), has been successfully assessed with simplified meso-scale models like UrbClim (De Ridder et al., 2015), which is used as a basis for the urban climate services provided by VITO in Belgium (<https://www.urban-climate.eu/>). Statistically downscaled urban climate data from RCM output is commercially provided by the climate data factory (<https://theclimatedatafactory.com/>). In Europe, climate services are being developed with the target of delivering the best available user-tailored climate data and information for public and private end-users operating in cities. Examples include My Climate Service (<https://myclimateservices.eu/>), Climate-fit.city (<https://climate-fit.city/>) and AirCloud (<http://www.clara-project.eu/>). The dynamical climate model downscaling used in Urban SIS was designed to solve parts of these gaps for long-term urban planning, but not for handling weather related day-to-day emergencies (although the model concept could be adapted also for this purpose).

Hereafter we describe and discuss our experiences with the Urban SIS concept in four sections:

- general overview of the Urban SIS approach, illustrated with details from the proof-of-concept case study in Stockholm City (Section 2);
- presentation of the results obtained, both in terms of historical model performance and expected future changes (Section 3);
- discussion on the findings and key lessons learnt to help guiding future development in the field (Section 4);
- concluding remarks (Section 5).

A description of the Urban SIS web portal is included in Supplement 1. For further details of the developed systems, their application and validation than what has been possible to include here, we refer to the full documentation from the Urban SIS project available at <http://urbansis.climate.copernicus.eu/> or <http://urbansis.eu/>.

2. The Urban SIS climate service concept: Stockholm City case study

The objective of Urban SIS is to develop, demonstrate and put into production a method to downscale (i.e. provide information on higher resolution) atmospheric Essential Climate Variables (ECVs, as defined by WMO's Global Climate Observing System) and Sectoral Impact Indicators (SIIs) to the urban milieu. Urban SIS delivers this data to consultants, urban engineers, scientists and health experts acting in urban areas, in a format suitable as input to specific/local models or to be used directly for dimensional calculations. Special emphasis is put on generating information useful for assessing, planning and adapting to urban hazards in the form of intense rainfall, heat waves and air pollution. During the development, a close dialogue has been held with stakeholders representing urban planners, different sectors operating in cities and for which climate conditions constitute essential information, as well as experts in urban climate and health effects, to assure that the Urban SIS information is as useful and tailored as possible to end-users.

The downscaling is performed in a system consisting of three numerical models (Fig. 1): the meteorological/climate model HARMONIE-AROME/HCLIM-AROME (executed first), the air quality model MATCH and the hydrological model HYPE (the latter two executed off-line with input from the meteorological/climate model). In total, 26 ECVs and 65 SIIs (see list in Table A.1) are delivered as 15-min (precipitation) or hourly (all ECVs) data over an $110\text{ km} \times 110\text{ km}$ area intended to cover an arbitrary city with surroundings, with a spatial resolution of $1\text{ km} \times 1\text{ km}$.

A fundamental assumption behind the proposed approach is that high-resolution, physically consistent and well verified ECVs provide a distinct added value as compared with alternative sources of data on urban climate change impacts. This added value is critical for justifying the very computationally expensive downscaling system (Fig. 1). Our main premise is that the approach offers a flexibility that is virtually unattainable by more simplified approaches. This flexibility allows for highly specific tailoring of

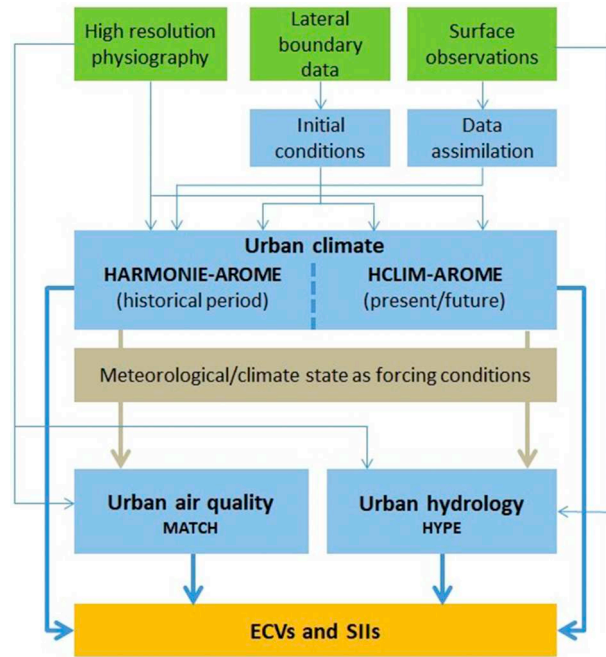


Fig. 1. Simplified flowchart representing the general dynamical downscaling approach applied in Urban SIS.

information or indicators, involving multiple and consistent ECVs, making it possible to meet the needs of different categories of stakeholders (at different levels), as well as taking into account national and regional differences in methods, guidelines and policies. It further simplifies a dynamic evolution of the information provided, where e.g. a key indicator can be made gradually developed and optimized in an iterative collaboration with a stakeholder (see further Section 4).

In Sections 2.1 to 2.4 we compactly describe the Urban SIS concept, including the different components, and how it was applied to Stockholm City in the proof-of-concept case study. Stockholm was selected as it was Europe's first green capital in 2010 and works intensively on lowering its greenhouse gas emissions with a target to be fossil fuel-free by 2040 (Stockholm City, 2018).

2.1. Models and simulations

This section starts with an overview of the simulations performed and the definition of time periods used (Section 2.1.1), followed by descriptions of the models included in the Urban SIS system (Fig. 1) (Sections 2.1.2–2.1.4) and their domains in the Stockholm set-up (Section 2.1.5).

2.1.1. Simulations and time periods

In the Urban SIS climate service, two types of downscaling simulations are performed for three different 5-year periods:

- downscaling of a meteorological reanalysis for a historical 5-year period, used for model evaluation against observations and for application by end-users interested in historical gridded data that are “as close as possible to observations” (this will in the following be termed the *historical simulation*);
- downscaling of an RCM model projection for two 5-year periods representing present (1980–2010) and future (2030–2065) climates, used for assessing future changes at the urban scale (*present and future simulations*).

Due to the very high computational requirements of the $1\text{ km} \times 1\text{ km}$ resolution dynamical downscaling, only simulations of 5-year periods are attainable within the time constraints of this climate service, which requires adequate selection criteria. For the historical simulation the selection is mainly based on the availability of model input data (namely, boundary conditions from the meteorological reanalysis and observations for assimilation and/or validation), as well as end-user requirements and expectations. For the present and future simulations, a selection process is included to identify separately within each 30–35 year window, five representative years that encompass combinations of cold/wet, cold/dry, warm/wet, warm/dry and “normal” seasons. All years in each time period are inter-compared using a range of indices that indicate occurrences of extreme events. For temperature this could encompass days with extreme heat or multi-day heat waves, and for precipitation it could be long- (multi-day) or short-duration (daily to sub-daily) rain events. In order to focus on high temperatures and intense rainfall in line with end-user requirements (Section 2.2), and also because of computational limitations, the selection process in this application is based only on the summer season (May–September), but other seasons or periods may be used if the focus is different. It is important to note, though, that for the

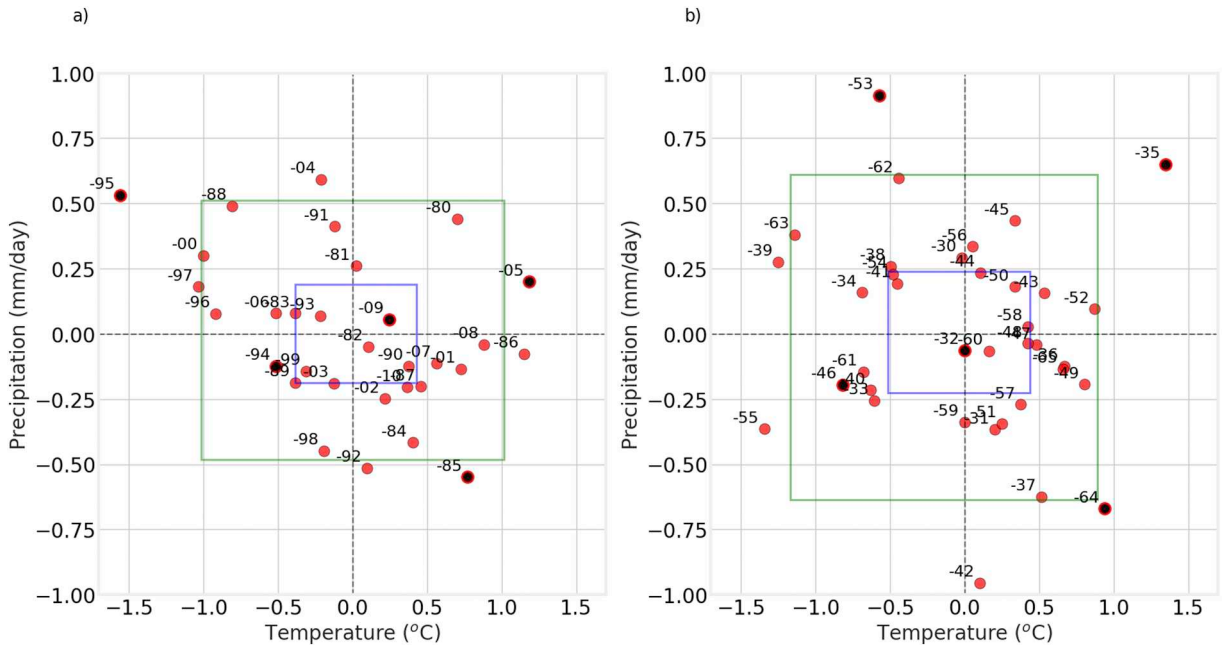


Fig. 2. Scatter plot showing summer (MJJAS) daily mean temperature and precipitation anomalies with respect to the time mean for Stockholm present (a; 1980–2010) and future (b; 2030–2065) periods as simulated by HCLIM-ALARO (Section 2.1.2). Numbers represent respective year and black dots represent selected years. The coloured rectangles represent statistical measures of the spread of the data; the inter-quartile range (blue) and 5th–95th percentile range (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

selected years, full year-round simulations are performed. The selection procedure of representative years is accomplished individually for each city, see further SMHI (2017a).

Fig. 2 illustrates the seasonal characteristics of all and the selected years for the present and future simulations in Stockholm. The dots in the scatter plot quadrants are years signifying combinations of wet/dry (along the y-axis) and warm/cold (along the x-axis) summer seasons (May–September). The data has been de-trended before the anomalies were calculated to avoid unfair comparison between years due to statistical artefacts. From the scatter plots, one may identify years that are particularly anomalous with respect to precipitation and temperature. For example, the year 1995 (–95 in Fig. 2) stands out as being anomalously cold and wet (upper left quadrant in left panel). This gives a first indication of plausible candidates for each of the sought after combinations based on seasonal mean values. To decide which years to select, an additional analysis step is applied whereby plausible candidates are further inter-compared using a set of temperature and precipitation indices that indicate the degree of extremeness. The year which shows the most interesting characteristics for a particular combination (wet/dry/warm/cold) is then selected (black dots in Fig. 2).

2.1.2. Meteorological and climate models

For the dynamical downscaling of the urban climate, two versions of the convection-permitting limited-area numerical weather prediction system HARMONIE are used depending on the type of simulation. For the historical simulation, cycle 40 h1.1 of HARMONIE-AROME is used (Bengtsson et al., 2017). For the present and future simulations, cycle 38 h1 of the climate version, referenced as HCLIM (Lindstedt et al., 2015; Lind et al., 2016), is applied. HCLIM can be used with a number of atmospheric physics packages, including AROME and ALARO (Termonia et al., 2018), and all are coupled to the surface/atmosphere scheme SURFEX (Masson et al., 2013). As part of the latter, the Town Energy Balance (TEB) model (Masson, 2000), which simulates the exchanges between a town and the atmosphere, is of special interest for UrbanSIS. Most of the HCLIM-AROME system used in Urban SIS is identical to the HARMONIE-AROME set-up and differences are mainly in the surface parametrizations. Also, data assimilation is not utilized for climate applications, where only lateral and surface boundaries are updated during time integration after the initialisation.

The total model domain consists of 240×240 horizontal grid points with a grid size of $1 \text{ km} \times 1 \text{ km}$, thus covering $57,600 \text{ km}^2$ centred over the urban area. The model uses 65 vertical levels that extend up to 10 hPa, with the lowest one at approximately 12 m above ground. Additionally, the model computes also values at 2 and 10 m high for some diagnostic variables. The size of the domain is a compromise between accuracy and computational resources available for the data production (see further Section 4). In order to reduce the computations in spectral space while retaining the horizontal grid spacing of 1 km, a cubic grid is used by HARMONIE-AROME. Thus, the shortest resolved wave in spectral space has a wave length of 4 km. For each time-step the horizontal grid is re-projected into a local geographical projection (different for each city) and cut-out to a smaller grid of 110×110 points in order to avoid boundary effects.

High-resolution physiographical data is generated by processing different open-access databases and products: (i) the spatial coverage of land cover types from Urban Atlas 2012 (Copernicus Land Monitoring Services, <http://land.copernicus.eu/local/>

urbanatlas), (ii) building polygons from OpenStreetMap (<https://www.openstreetmap.org>), (iii) building heights from Lidar measurements (Swedish Forest Agency, <http://www.skogsstyrelsen.se/Myndigheten/Om-oss/Opnna-data/>) and (iv) time series of leaf area index (LAI) from the Copernicus Global Land Service (<http://land.copernicus.eu/global/themes/vegetation>). The resulting $\sim 300 \text{ m} \times 300 \text{ m}$ grid-squares are then interpolated by SURFEX to the final model grid at $1 \text{ km} \times 1 \text{ km}$ and combined with the default European ecosystem classification and surface parameters dataset ECOCLIMAP-II (Faroux et al., 2013) where additional information is needed. The urban physiography is kept constant in the future scenarios by HCLIM.

Meteorological lateral boundary conditions for the historical simulation are provided by the UERRA-ALADIN reanalysis (Ridal et al., 2016), which covers the period 1961–2015 and is produced with the ALADIN model combined with SURFEX within the HARMONIE script system. The resolution is $11 \text{ km} \times 11 \text{ km}$ horizontally and 65 levels vertically. A three-dimensional variational data assimilation of conventional observations is employed, including synoptic stations, ships, drifting buoys, aircraft observations and radio soundings. For surface data assimilation, an optimal interpolation method with CANARI (Taillefer, 2002) and SURFEX is used. Only synoptic observations are used to analyse (2-m) temperature, (2-m) relative humidity and snow water equivalent.

For present and future conditions, lateral and surface boundary data are provided in a two-step procedure. Firstly, a simulation by the earth system model EC-Earth (Hazeleger et al., 2012, 2013) at $80 \text{ km} \times 80 \text{ km}$ horizontal resolution is used as forcing data for HCLIM-ALARO with a grid size of $20 \text{ km} \times 20 \text{ km}$. Secondly, the HCLIM-ALARO output is used as lateral boundary conditions for the HCLIM-AROME simulations. Differences between HCLIM-ALARO and HCLIM-AROME are primarily in the parameterization of atmospheric physics, and also HCLIM-ALARO uses here the hydrostatic dynamics while HCLIM-AROME is non-hydrostatic. To be able to prepare also for the high-end climate change situation, preferred by end-users and stakeholders involved in the Urban SIS project, the EC-Earth projection based on the RCP8.5 scenario (Meinshausen et al., 2011) is selected as boundary conditions in the present and future simulations within the Urban SIS project.

2.1.3. Air quality model

The MATCH model system (Robertson et al., 1999; Andersson et al., 2007; Watson et al., 2016; Lacressonnière et al., 2017) is a state-of-the-art off-line chemical transport model (CTM) developed and operated by SMHI. The chemical mechanism and the aerosol module are based on those implemented in EMEP MSC-W model with adaptations on isoprene chemistry and on the volatile secondary organic aerosols (a complete list of references is included in Markakis et al., 2016).

For Urban SIS applications, three-dimensional fields describing the European background concentrations of air pollution and the episodic long-range transport to the different cities are provided by a pan-European application of MATCH. Computational and data-storage restrictions forced us to interpolate both the meteorological (i.e. UERRA-ALADIN and HCLIM-ALARO) and the emission fields to a $0.2^\circ \times 0.2^\circ$ ($\sim 22 \text{ km} \times 22 \text{ km}$) resolution grid. The MATCH air quality $1 \text{ km} \times 1 \text{ km}$ resolution downscaling over the urban domains is performed on a $120 \text{ km} \times 120 \text{ km}$ grid, with a vertical dimension typically extending up to 550 hPa ($\sim 5 \text{ km}$ above surface). The vertical resolution and number of layers are reduced by a factor of two in the air quality model compared to the meteorological model, averaging all meteorological parameters over every two layers starting from the ground and extending throughout the model atmosphere. In the standard MATCH configuration the boundary layer parameters, e.g. the turbulent velocity scale, Monin-Obukhov length and the boundary layer height, are calculated on the basis of the similarity theory. The standard scheme was used in the pan-European application of MATCH. For the urban downscaling to $1 \text{ km} \times 1 \text{ km}$ resolution, the turbulent kinetic energy – available from the output of HARMONIE-AROME and HCLIM-AROME – is instead taken as input variable to determine the scaling parameters and the vertical turbulent mixing coefficient.

In addition to the meteorological forcing, MATCH also needs complementary input data, such as temporally and spatially resolved emissions and boundary concentrations. The MATCH set-up for Urban SIS needs anthropogenic emissions of nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), ammonia (NH_3), particles with aerodynamic diameter smaller than $2.5 \mu\text{m}$ (PM_{2.5}) and particles with aerodynamic diameter between 2.5 and $10 \mu\text{m}$ (PMcoarse). Two different emissions inventories were used for the pan-European application of MATCH: for the historical simulation the emissions were taken from MACC (Kuenen et al., 2014) and for the present and future simulations the ECLIPSE V5a global emissions (Stohl et al., 2015; Klimont et al., 2017) were used. The historical, present and future emissions are presented in Table 1.

Table 1

Emissions over Europe and in the Stockholm urban domain, used as input to the MATCH pan-European simulation and the urban downscaling over Stockholm.

Pollutant	Pan-European (Tg year^{-1})			Stockholm (Gg year^{-1})	
	Historical (MACC)	Present (ECLIPSE)	Future (ECLIPSE)	Historical/present (local 2010)	Future (local 2030)
CO	47	36	27	48	39
NH_3	4.8	4.9	5.0	0.72	0.83
NMVOC	12	11	8.0	7.2	6.0
NO_x	19	17	10	11	9.3
PM ₁₀	6.2	4.7	4.2	5.9	5.0
PM _{2.5}	5.3	3.3	2.9	3.7	3.3
PMcoarse ^a	0.88	1.4	1.4	2.2	1.7
SO_2	9.9	9.9	5.0	2.5	2.6

^a PMcoarse is PM₁₀ minus PM_{2.5}.

2.1.4. Hydrological model

The continuous process-based hydrological model HYPE (Lindström et al., 2010) is employed to model the land surface and sub-surface hydrological processes and derive a set of hydrological variables. It is a semi-distributed model, in which a river basin may be subdivided into multiple sub-basins, which are further subdivided into homogeneous hydrological response units (HRUs) based on combined soil type and land use classes. Model simulation can be performed at a daily or hourly time step and HYPE is used for national flood forecasting and warning at SMHI.

The model has conceptual routines for most of the major land surface and subsurface processes (e.g. snow/ice accumulation and melting, evapotranspiration, surface and macropore flow, soil moisture, discharge generation, groundwater fluctuation, aquifer recharge/discharge, irrigation, abstractions and routing through rivers, lakes and reservoirs) that are controlled by a number of parameters that are often linked to physiography to account for spatial variability. Many of the parameters need to be estimated through calibration against observed basin response, such as discharge. Sub-basin average precipitation and temperature corresponding to the time step of the model simulation are the main forcing data required to run HYPE. To calibrate the model and validate the model performance, discharge data at the outlet locations of one or several sub-basins are required.

HYPE computes the different hydrological variables such as runoff, evapotranspiration, etc. for the HRUs, but provides sub-basin average outputs. It may be, however, useful to have hydrological variables for different land uses within the sub-basins. Furthermore, the sub-basins are normally polygons of irregular shapes. There is, however, a need to provide model simulations on regular grids. Further technical developments were implemented to render the model such capabilities within the Urban SIS framework.

In an Urban SIS application, HYPE is used to provide hydrological information with a spatio-temporal resolution relevant in an urban context. The time step is 1 h and detailed land-use data are retrieved from Urban Atlas 2012. The computational domain for the hydrological modelling of each case study city is, therefore, established based on delineation of a basin that covers the selected city where land use information from Urban Atlas 2012 is available.

Simulating river flow through cities requires that contributions from the entire upstream basin area are taken into account. This upstream area may, however, extend outside both the coverage of Urban Atlas 2012 and the computational domain of the meteorological simulations used as forcing data (Section 2.1.2) in the HYPE model. In this situation, either river discharge is not calculated or other forcing data needs to be applied (see further Section 4). Other local hydrological variables can be estimated as long as the local model can be calibrated using discharge gauging stations at sub-basins that do not drain upstream areas.

The HYPE model setup for Stockholm (Fig. 3) was calibrated and validated using a precipitation data base of hourly gauge-adjusted radar observations (HIPRAD; Berg et al., 2016) and hourly temperatures from the MESAN reanalysis system (Hägmark et al., 2000), which assimilates gauge observations with the operational weather prediction model system of SMHI. The standard split-sampling procedure was employed, in which the model simulation period is split into two non-overlapping periods and the model is calibrated over one of them and validated over the other. Calibration was done for a 3-year period (2012–2014) and the model was validated using data for an independent 3-year period (2009–2011). The Nash-Sutcliffe efficiency measure (NSE; Nash and Sutcliffe, 1970) and the relative percentage volume error (RE) were employed as goodness-of-fit measures to evaluate the model performance.

2.1.5. Model domains

Fig. 3 shows the domains used for setting up the HARMONIE-AROME/HCLIM-AROME and HYPE models for Stockholm city. The MATCH domain extends just outside the 110 km × 110 km inner domain, in which ECVs and SIIs are provided. The historical/present and future emissions data for Stockholm are taken from Gidhagen et al. (2012), where we used the future scenario with a new road bypass west of Stockholm (see Table 1, the two columns to the right). The HYPE model domain was chosen as the drainage area that covers the Stockholm County (Fig. 3). The entire drainage area includes the Lake Mälaren and its upstream drainage area. However, as (i) the drainage area reaches outside of the HARMONIE-AROME/HCLIM-AROME domain and (ii) the lake has two outlets and is regulated, which highly complicates outflow simulation, the lake and its upstream area are excluded from the HYPE domain in this application. The total modelled area (6840 km²) is subdivided into 602 sub-basins, which are in turn further subdivided into homogeneous HRUs (Section 2.1.4).

2.2. Essential Climate Variables (ECVs) and Sectoral Impact Indicators (SIIs)

The ECVs and SIIs presented as Urban SIS output have been selected to follow requirements formulated by end-users and stakeholders participating in two workshops held in Stockholm and Bologna. Through the participation of experts and advanced end-users from project partners, requirements from a broad European community have been identified.

The ECVs constitute the basis for further processing to generate the SIIs. Some of the SIIs are based solely on ECV information, only statistically processed, while other SIIs require complementary data in their generation process (e.g. population data). The complete set of ECVs and SIIs is provided in Table A.1 and in the following we only highlight some SIIs that are conceivably not well known to a wide audience. It should be emphasized that other, and potentially also better, SIIs may well exist but that our selection reflects mainly the needs of the end-users and stakeholders involved as well as to some extent the experiences within the Urban SIS consortium.

Health indicators are calculated from heat wave temperatures and air pollution levels, together with population density data. Relative risks extracted from a European multi-city study (de Donato et al., 2015) are used to describe the effect of high temperatures on mortality. For long-term exposure to annual mean levels of air pollutants, relative risks are based on recommendations from WHO HRAPIE project (WHO, 2013) regarding PM_{2.5} and UK COMEAP (2015) regarding NO₂. In Urban SIS output, health effects due to

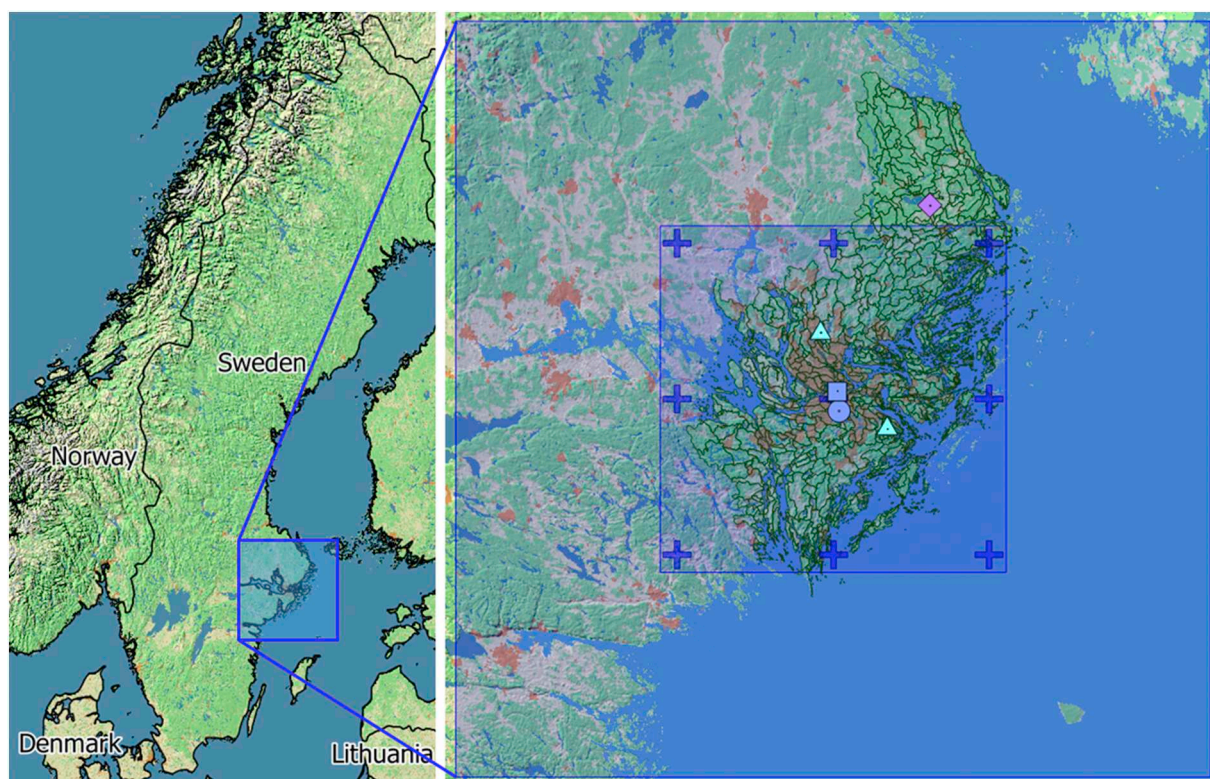


Fig. 3. Outer square in right-hand panel: the 240 km $\times$ 240 km HARMONIE-AROME/HCLIM-AROME domain. Inner square: the 110 km $\times$ 110 km domain in which ECVs and SIIs were calculated. Dark green lines: domain and sub-basin division of the HYPE model. Crosses: location of grid cells in the 3 $\times$ 3 matrix used in the DDF calculations. Observation stations: meteorological (circle and square), air quality (rhomb and square), hydrology (triangle). Orange area (inside the inner square): Stockholm city. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

exposure to PM_{2.5} and NO₂ are separated. However, also the combined effect of simultaneous exposure to both PM_{2.5} and NO₂ is calculated, the latter being lower than the sum of the separated effects due to overlap in the relative risk estimates. Calculations of short-term exposure to ozone (O₃) are based on the WHO HRAPIE recommendation (WHO, 2013) assuming a 0.3% increase (95% confidence interval: 1.4–4.3) per 10 $\mu\text{g m}^{-3}$ increase in SOMO35 (sum of means over 35 ppb applied to daily maximum of 8-hour running averages) for O₃.

Concerning intense rainfall, the Depth-Duration-Frequency (DDF) curve is a compact statistical description of short-duration rainfall extremes that is widely used in engineering design (e.g. Chow, 1964). The DDF curve specifies the rainfall depth associated with a certain duration and frequency, e.g. with a return period of 10 years we will have ≥ 25 mm of rain in 1 h. The approach used in Urban SIS is based on fitting the Gumbel distribution to annual maximum values for different durations between 15 min and 24 h, in order to estimate depths associated with different return periods (e.g. Olsson and Foster, 2014). To produce a long enough time series for meaningful analysis from the 5-year simulation period, time series from nine different grid cells in HARMONIE-AROME or HCLIM-AROME are concatenated into a 45-year time series. This corresponds to the station-year method widely used in extreme value analyses of gauge observations (e.g. Buishand, 1991). The nine cells constitute a 3 $\times$ 3 matrix with 50 km spacing inside the 110 km $\times$ 110 km inner model domain (Fig. 3). At 50 km spacing, the short-duration precipitation extremes are expected to be statistically independent, and thus the time series from the sub-grid may be regarded as different realizations of the same climate (e.g. Olsson et al., 2018). This approach also requires that the entire domain is statistically homogeneous with respect to the short-duration precipitation extremes, which is a reasonable assumption considering their stochastic nature and limited the size of the domain in this context.

2.3. Model validation

Urban SIS includes a three-level validation procedure of the historical simulation to evaluate model performance and form the basis of the uncertainty assessment (Section 2.4).

1. *Visual inspection.* All ECVs, i.e. also the ones not validated against observations, are visually inspected using the Urban SIS web portal (Supplement 1). This is done to identify any obvious artefacts in the data and generally to assess the plausibility and

accuracy of the data using expert judgment.

2. **General validation.** A number of ECVs are used for general validation (see Table A.2). The selection is made based on the availability of consistent observational data. The general validation is performed in terms of inter- and intra-annual variability in standard ECV statistics, which are based on monthly minimum, average and maximum hourly values throughout the 5-year historical period. Additionally, the mean value and standard deviation over the entire period are calculated for both observations and simulations, and the agreement is also quantified by the root mean square error (RMSE).
3. **Tailored validation.** This type of validation is intended for ECVs and SIIs that are particularly expected to benefit from very high-resolution downscaling. During the Urban SIS project, tailored validation focused on different aspects of three key variables:
 - temperature: diurnal cycle, land-use dependence, key SIIs (e.g. number of hot days and frost days);
 - precipitation: short-duration rainfall extremes as represented by DDF statistics (Section 2.2), spatial accumulation patterns;
 - air quality: diurnal cycle, high percentiles of O₃, NO₂ and PM₁₀.

Comparisons between Urban SIS model output and measured data from the Stockholm area were made in a couple of locations, for temperature (six different metrics), precipitation, relative humidity, global radiation, wind speed, air pollution levels (NO₂, O₃, PM₁₀, PM_{2.5}) and river discharge (see Tables A.1 and A.2 in Appendix A). Two stations were selected for validating the meteorological variables; one in the city centre, located on the top of a building, and another more suburban station, located in an open area of an industrial zone (Fig. 3). For the air quality validation, one station located in the city centre, representing the urban background, and a second station ~40 km northeast of the urbanized area, representing the regional background, were used. Validation of discharge was based on observations from two stations, one north and one south of central Stockholm, both representing a rural or mixed rather than a fully urban environment (Fig. 3). To validate intense precipitation and DDF statistics, published statistics from Hernebring (2006) were used, as well as statistics generated from the HIPRAD data base (Section 2.1.4). HIPRAD was also used to validate monthly precipitation over the entire result domain.

2.4. Uncertainty assessment

The results from Urban SIS can, as a consequence of how they are produced and which input data are used, be associated with three quality or uncertainty aspects:

1. downscaling model performance (in the following denoted *model uncertainty*);
2. determination of impact indicators (*indicator uncertainty*);
3. climate scenario uncertainties (*scenario uncertainty*).

Some results are only associated with one uncertainty aspect (e.g. an ECV for the historical period), some with two aspects (e.g. an SII for the historical period or an ECV for the future scenario) and some will be associated with all three aspects (e.g. an SII for the future scenario).

The uncertainty is communicated to the end-user in terms of three levels.

1. **LOW** uncertainty flagged as green colour, indicating that the data is relevant and in agreement with observations or other model data. Message: Go ahead!
2. **MEDIUM** uncertainty flagged as yellow colour, indicating that the results are considered to be useful, but that the user must be aware of certain limitations and/or restrictions. Message: Caution!
3. **HIGH** uncertainty flagged as red colour, indicating results that are only partly useful. The user must be fully aware of the limitations before using this data. Message: Warning!

The classification of *model uncertainty* is based on ECV validation using the historical simulation (Section 2.3), characterizing absolute and relative errors in model output. Table 2 shows the final ECV limits used in Urban SIS, based on all validation performed in the different case studies. Concerning *indicator uncertainty*, any additional data used in the SII calculations (e.g. population) representing current conditions are assumed not to increase the uncertainty of a historical or present simulation. For a future

Table 2

General rules applied for assessing the ECV uncertainty. AE and RE denote absolute and relative error, respectively, and subscripts denote mean (m) and standard deviation (s).

	LOW		MEDIUM		HIGH	
	Mean	Std.dev.	Mean	Std.dev.	Mean	Std.dev.
Temperature	AE _m < 1 °C	RE _s < 10%	1 °C < AE _m < 2 °C	RE _s < 20%	AE _m > 2 °C	RE _s > 20%
Met. ECVs (except T), discharge	RE _m < 10%	RE _s < 20%	10% < RE _m < 20%	RE _s < 30%	RE _m > 20%	RE _s > 30%
Air Quality ECVs	RE _m < 20%	RE _s < 30% ^a	20% < RE _m < 50%	RE _s < 60% ⁽¹⁾	RE _m > 50%	

^a Not applied to PM_{2.5} for which only annual mean values are considered for health effects.

simulation medium uncertainty is assumed, since e.g. population growth and spatial redistribution are not taken into account. For the *scenario uncertainty*, two types of comparisons are made to determine the uncertainty category (more details on the uncertainty classification are given in [SMHI, 2017b](#)):

1. ECV mean values from the GCM and RCM projections used as forcing in Urban SIS ([Section 2.1.2](#)) are compared to the mean values of climate model ensembles, in order to assess the representativeness of the Urban SIS projections;
2. aiming to assess to which degree the downscaling modifies the trends of specific ECVs, the changes between the present and future Urban SIS simulations at $1 \text{ km} \times 1 \text{ km}$ resolution are compared to the corresponding changes in the $20 \text{ km} \times 20 \text{ km}$ projections by the driving RCM.

The final uncertainty score (low, medium or high) of a given ECV or SII corresponds to the maximum uncertainty level of the three evaluation aspects (model, indicator or scenario). Examples of uncertainty assessment in the Stockholm case are given in [Section 3](#).

3. Results

In this section we present selected results from the application of the Urban SIS climate service in Stockholm. The main focus is the validation of the historical simulations by comparison with observations ([Section 3.1](#)) but we also show some examples of estimated future changes ([Section 3.2](#)).

3.1. Validation of historical simulations

[Table 3](#) shows the results from the general validation of the meteorological, air quality and hydrological ECVs. The uncertainty categories are based on the assessment described in [Section 2.4](#). In the following sections, these results are described and interpreted, together with selected results from the tailored validation. The reader is referred to additional validation available in [SMHI \(2017c, d and e\)](#).

3.1.1. Meteorology

The observed monthly mean temperature is accurately reproduced, as shown in [Table 3](#) for two urban stations and as illustrated for station Högdalen in [Fig. 4a](#). Concerning precipitation, even if the general annual cycle with higher amounts in summer and lower in winter, as well as intra-annual variability, is rather well captured, there is a clear underestimation in the historical simulation ([Fig. 4b](#)). The underestimation is most pronounced in winter, especially in 2005/2006, 2011/2012 and 2013/2014 ([Fig. 4b](#)).

The spatial variation of air temperature shown in [Fig. 5](#) (and in general for the entire historical period) has shown to respond to the properties of the urban surface beneath, exhibiting a good representation of the intra-city thermal gradients induced by the combination of densely constructed neighbourhoods, green areas and water bodies. Despite a better agreement with observations in the city, the model performs reasonably well over the rural areas in the outskirts (e.g., for the Norr Malma station the RMSE is 2.32°C and the correlation coefficient is 0.96 over the 5 years), providing a spatially detailed simulation of the UHI (quite evident in [Fig. 5](#)).

Concerning precipitation, the winter dry bias found in central Stockholm ([Fig. 4b](#)) is representative for the whole simulation domain, with somewhat lower bias north of Stockholm city but even higher bias towards the south-west (not shown).

In [Figs. 6, 5-](#) and 10-year DDF curves for Stockholm are shown. The black lines (STATION) represent curves obtained from a municipal rainfall gauge in central Stockholm by [Hernebring \(2006\)](#), conceivably the best available estimate of the truth with respect to DDF statistics in Stockholm. The 5-year (10-year) curve extends from a depth of ~ 12.5 (16) mm in 15 min up to almost 25 (32) mm in 2 h. At duration 15 min, the DDF-values from the historical simulation (HARMONIE) are ~ 70 – 80% of the station values, i.e. clearly underestimated. At 30–45 min, however, the simulated values equal the station values and at 1–2 h they are markedly higher (10–30%). Complementary analyses in terms of visual inspection and spatial correlation (not shown) implies that rainfall fields, especially the high-intensity cores, in HARMONIE-AROME are larger and more coherent (i.e. spatially correlated) than observed fields (HIPRAD) ([SMHI, 2017d](#)), which may to some extent explain the pattern in [Fig. 6](#).

3.1.2. Air quality

The performance of the high resolution ($1 \text{ km} \times 1 \text{ km}$) MATCH model is summarized in [Table 3](#). At Norr Malma, the regional background station, NO_2 and $\text{PM}_{2.5}$ concentrations are reasonably well reproduced while PM_{10} is underestimated and O_3 is overestimated in the historical simulation. At the urban background site, Torkel Knutsson, the MATCH model shows an underestimation of NO_2 and PM_{10} . Average O_3 concentration is consistently overestimated in the high-resolution air quality model, both at the urban background site and at the regional background site. While the model overestimation outside the city largely originates from the pan-European simulation, the overestimation of O_3 at the urban background site is likely exacerbated by the underestimated NO_x in the urban environment (not shown). Previous studies have also indicated that the MATCH model typically overestimates the night-time O_3 production ([Markakis et al., 2016](#)) which contributes to the overestimation of average O_3 concentrations. The diurnal and seasonal variability (standard deviations) was underestimated for all pollutants at both stations ([Table 3](#)). A detailed analysis of monthly mean, maximum and minimum values revealed that the overestimated O_3 level in the city centre was to a large extent caused by the model failing to reproduce the night-time minimum values ([SMHI, 2017c](#)), confirming the findings discussed in [Markakis et al. \(2016\)](#). The simulated maximum O_3 levels, determining the health impact, were however similar to measured levels (not shown).

The distinct underestimation of PM_{10} at Torkel Knutsson is, in part, a consequence of too low PM_{10} in the incoming long-range

Table 3

Results from the general validation of ECV data for the Stockholm area over the 5 historical years: temperature ($^{\circ}\text{C}$), precipitation (P ; mm h^{-1}), relative humidity (RH; %), global radiation (GR; W m^{-2}), wind speed (W ; m s^{-1}), air pollution levels (NO_2 , O_3 , PM_{10} , $\text{PM}_{2.5}$; $\mu\text{g m}^{-3}$) and discharge (Q ; $\text{m}^3 \text{s}^{-1}$). Mean, standard deviation and RMSE have been calculated for hourly time series in observations (OBS) and in the historical simulation (by HARMONIE-AROME; SIM). The resulting uncertainty level in the historical simulation is represented by green (low), yellow (medium) and red (high).

	Mean			Standard deviation			RMSE			Mean			Standard deviation			RMSE		
	OBS	SIM	DIFF	OBS	SIM	DIFF	OBS	SIM	DIFF	OBS	SIM	DIFF	OBS	SIM	DIFF	OBS	SIM	DIFF
Meteorology	Torkel Knutsson (roof top, 20 m, at city centre)																	
T	8.02	7.96	-0.06	8.04	8.18	0.14	1.31	7.41	7.40	-0.01	8.16	8.36	0.21	1.43				
P	0.035	0.049	0.014	0.301	0.420	0.119	0.468	0.069	0.046	-0.023	0.475	0.392	-0.083	0.548				
RH	77.1	73.3	-3.9	18.6	16.1	-2.5	10.4	76.8	77.4	0.7	18.6	16.1	-2.5	9.7				
GR	118	127	9	197	204	6	75	111	126	15	190	203	13	74				
W	3.59	3.25	-0.34	1.66	1.42	-0.24	1.05	3.18	3.31	0.14	1.53	1.52	-0.01	0.88				
Air quality	Torkel Knutsson (urban background city centre)																	
O ₃	51.4	72.8	21.4	21.7	16.9	-4.8	27.0	55.8	66.5	10.7	21.8	18.9	-2.9	20.8				
NO ₂	13.3	7.8	-5.5	11.6	7.3	-4.3	11.5	1.9	1.7	-0.2	7.7	1.6	-6.1	7.6				
PM2.5	6.0	6.1	0.1	6.5	3.8	-2.7	5.8	4.1	4.1	0.0	5.9	3.2	-2.7	5.1				
PM10	14.6	8.7	-5.9	11.6	5.2	-6.5	12.5	9.8	5.1	-4.7	7.5	4.1	-3.5	8.1				
Hydrology	Saxbro																	
	Skällhora																	
Q	2062	385	-1677	1866	577	-1289	2363	1367	457	-910	1157	573	-585	1282				

*Measured precipitation highly uncertain.

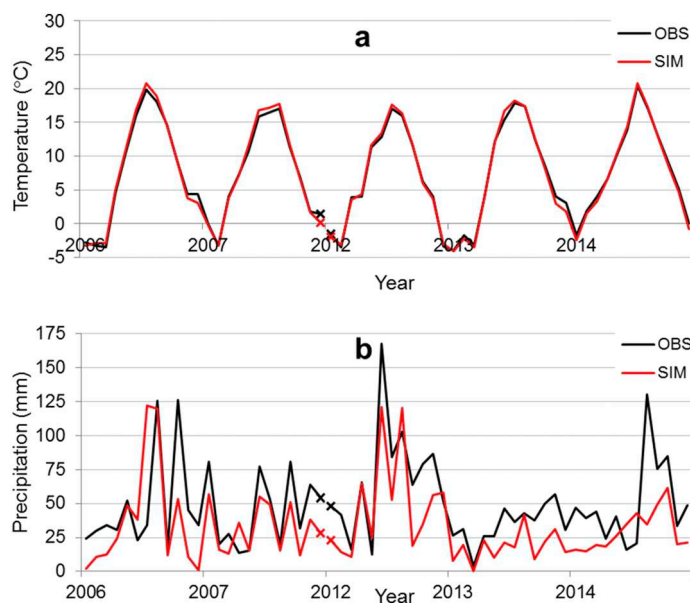


Fig. 4. Monthly mean temperature (a) and precipitation (b) in observations (OBS) and historical simulation (HARMONIE-AROME; SIM) for station Högdalen. Note that there is a gap in the data (shown by crosses) corresponding to the period 2008–2011.

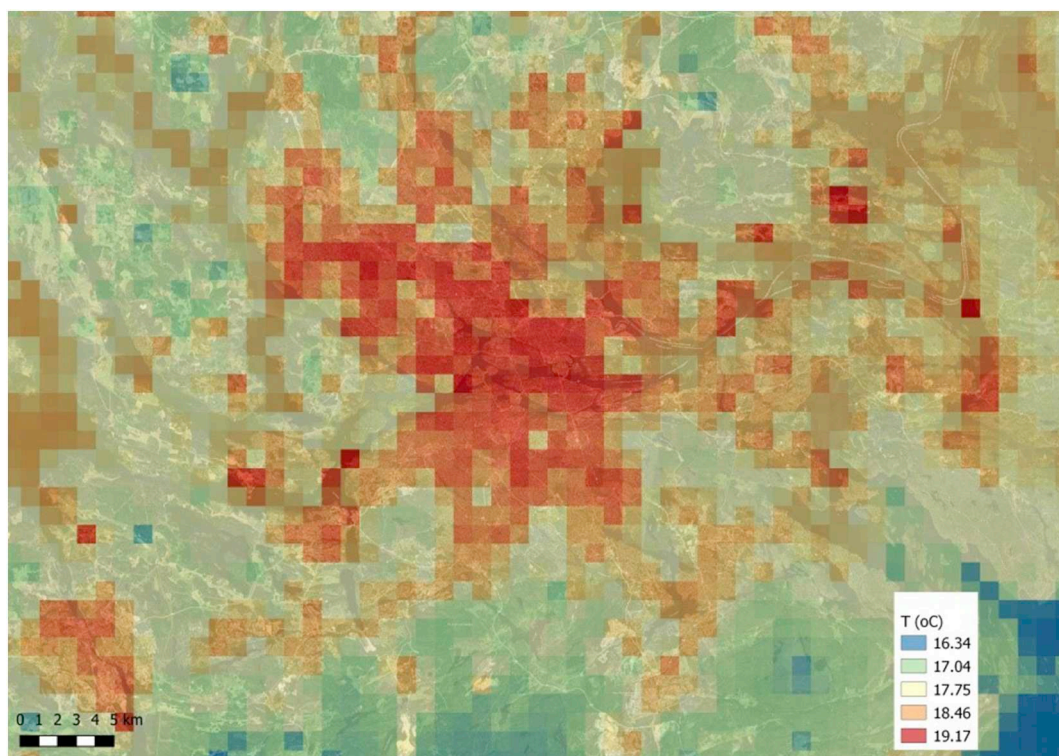


Fig. 5. Mean summer (JJA) temperature in 2014 as simulated by HARMONIE-AROME over Stockholm.

transported air masses (Table 3), following regional-scale models' tendency to underestimate PM₁₀ concentrations (see e.g. Lacressonnière et al., 2017). The underestimation is also related to the underestimated non-exhaust PM₁₀ emissions in the present urban set-up.

The comparison between the modelled and observed average diurnal cycle of NO₂ at the urban background station of Torkel Knutsson, both in winter (January) and summer (July), shown in Fig. 7, reveals that the high resolution MATCH model is in phase with the observed variability; model results are however consistently underestimated, both in the winter and in summer. This points

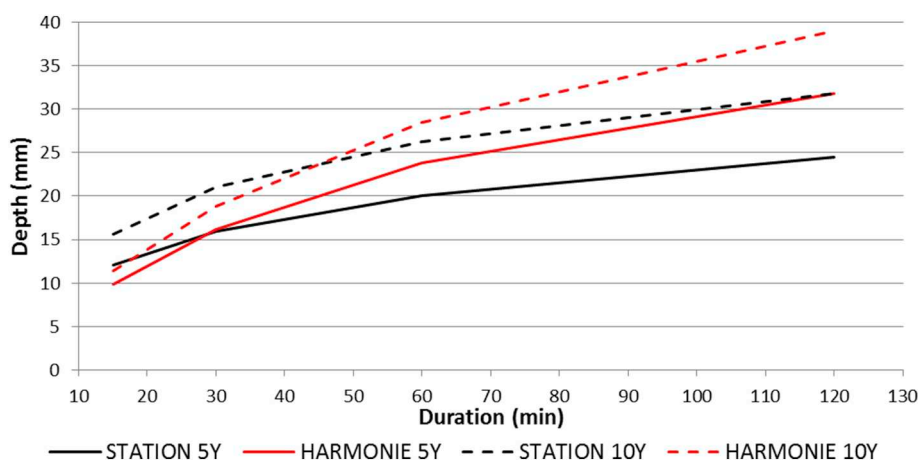


Fig. 6. 5- and 10-year DDF curves for Stockholm obtained from observations in a local station (STATION) and in the historical simulation by HARMONIE-AROME (HARMONIE).

to a likely underestimation of the NO_x emissions in the urban domain. $\text{PM}_{2.5}$ is largely a regional pollutant in the Stockholm area. This explains the relatively modest average diurnal variation of $\text{PM}_{2.5}$ at the urban background site as seen in Fig. 7.

3.1.3. Hydrology

Before validating the historical HYPE simulations, i.e. forced with HARMONIE-AROME, we evaluate the HYPE performance when forced with observed inputs (HIPRAD and MESAN; Section 2.1.4). The average NSE at the five stations used for model calibration and validation in Stockholm during the model calibration period (2012–2014) is 0.74 and the average RE is -4.2% . During the validation period (2009–2011), the values are 0.51 and 4% , respectively. Fig. 8a illustrates the performances attained in terms of discharge time series.

by the validation period at station Saxbro. Overall, we consider the model performance to be quite satisfactory with limited bias and well captured dynamics.

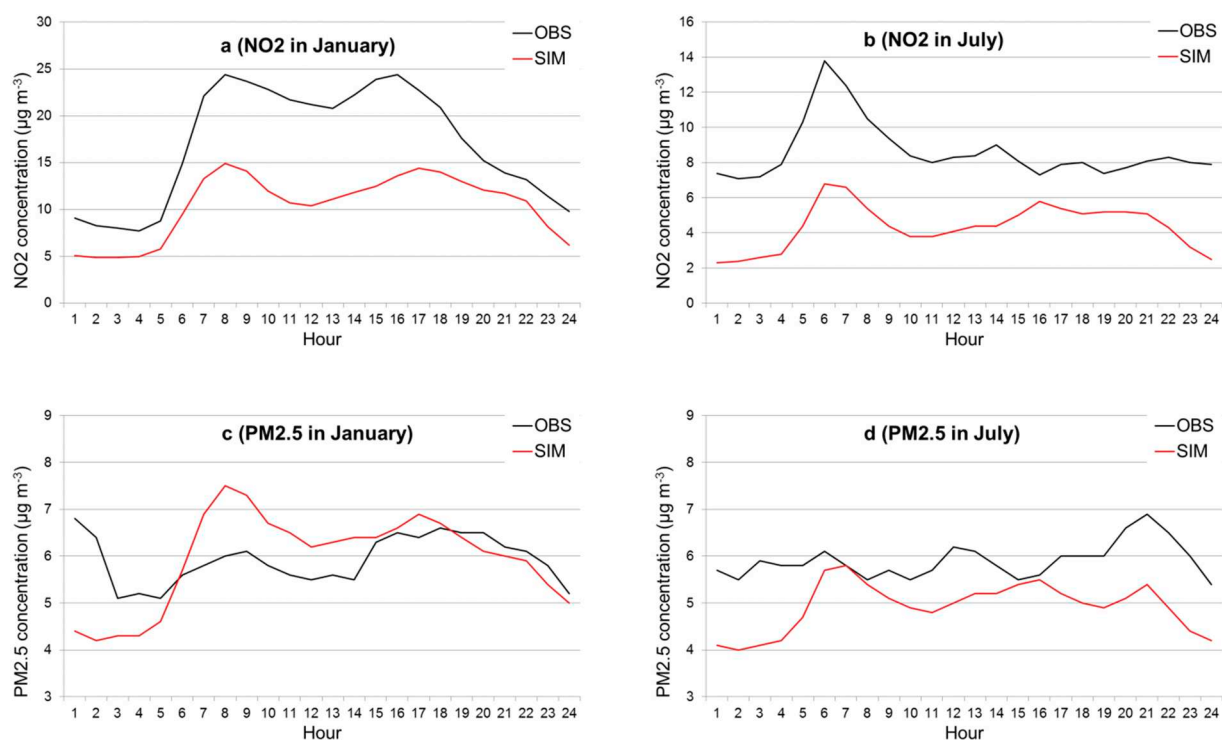


Fig. 7. Monthly-mean diurnal cycle of NO_2 and $\text{PM}_{2.5}$ during wintertime (January) and summertime (July), in observations (OBS) and in the historical simulation (SIM) at Torkel Knutsson urban background station. Data averaged over the five years 2006, 2007, 2012, 2013 and 2014.

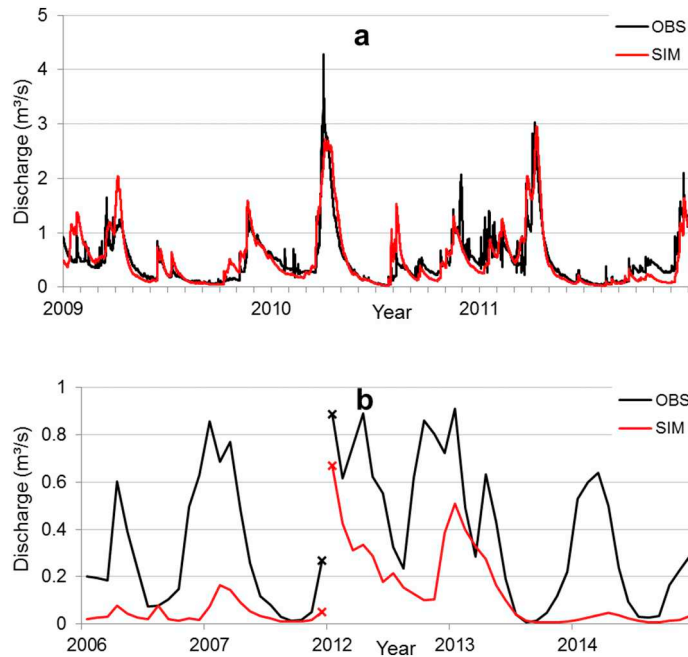


Fig. 8. Observed (OBS) and HYPE-simulated (with observed forcing) (SIM) discharge hydrographs during the validation period in stations Saxbro (a). Monthly mean discharge in observations and historical HYPE simulation (with HARMONIE-AROME forcing) in station Skällnora. Note that there is a gap in the data (shown by crosses) corresponding to the period 2008–2011 (b).

The analysis of the simulations with HARMONIE-AROME reveals that the observed discharge at the two stations is substantially underestimated (Table 3). In terms of monthly mean discharge, only the low-flow periods in summer agree reasonably well. In the months with the highest observed discharge, in late winter and early spring, the simulated discharge is strongly underestimated (Fig. 8b). The reason for the underestimation can be traced back to the strong underestimation of precipitation in HARMONIE-AROME over Stockholm during winter (Fig. 4b). The winter/spring high flows are generated by rainfall or snow melt or a combination, and both rain and snow are underestimated in HARMONIE-AROME. There is some variation between years; in 2012 and 2013 the simulations capture a distinct winter/spring flood peak whereas in the other years there is almost no discharge at all in the winter simulation (Fig. 8b).

3.2. Assessment of present and future simulations

In this section we focus on expected trends in some urban ECVs of special interest and which have shown low to medium uncertainty in the validation (Section 3.1): temperature and air quality ECVs. The hydrological ECVs are omitted as they were highly impacted by the HARMONIE-AROME precipitation bias (Section 3.1.1). The main issue is to find out to which degree the very high-resolution Urban SIS downscaling contributes to a more useful information for urban planners within the health and infrastructure sectors.

Fig. 9 shows 5-year mean temperatures (columns) in the present and future simulations as estimated by the driving RCM HCLIM-ALARO at 20 km × 20 km grid spacing and by the urban downscaling with HCLIM-AROME at 1 km × 1 km resolution (see Section 2.1.2 for more details on model configuration). In addition, the mean values over the full periods simulated by the lower resolution model are also shown (triangles). From this comparison, we conclude that the mean temperature signals in the five years selected in Urban SIS are consistent with the longer periods, with a difference of only 0.2 °C in both climates. A relevant conclusion to retain from the figure is that, according to the computations, the urban atmosphere of Stockholm warms up by 3.2 °C in the future, in both HCLIM-ALARO and

HCLIM-AROME. In addition to this, the latter shows a higher mean temperature in both periods, revealing the effect of the UHI as it is captured by the model at 1 km grid resolution using the TEB town surface scheme and detailed urban physiography data. If we had considered a different land use in the future simulations, a larger variability would be expected also in the difference between HCLIM-ALARO and HCLIM-AROME, at least in locations affected by increased urbanization.

Fig. 10 shows annual and January/July monthly average temperature differences between the future and present climate scenarios (at 1 km × 1 km). The increase of around 4 °C during the summer months clearly demonstrates that heatwaves can be expected to become more frequent and more severe. On average for the three locations an increase of 3.4 °C in mean annual temperature is predicted for the future compared to present climate.

Fig. 11 presents the difference of PM_{2.5} and NO₂ concentration fields over Stockholm conurbation between the present and future simulations. The PM_{2.5} and NO₂ levels are projected to decrease both outside and inside the city. According to the model, NO₂ levels

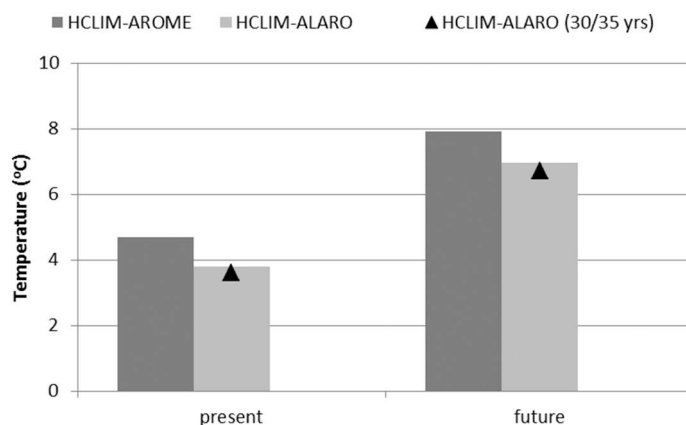


Fig. 9. Mean temperature in Stockholm (at the location of the Högdalen station) in present and future simulations at 20 km × 20 km (HCLIM-ALARO) and 1 km × 1 km (HCLIM-AROME) resolution over the same 5-year period. The triangle indicates the mean values from HCLIM-ALARO over 1980–2010 and 2030–2065 representing, respectively, present and future climates.

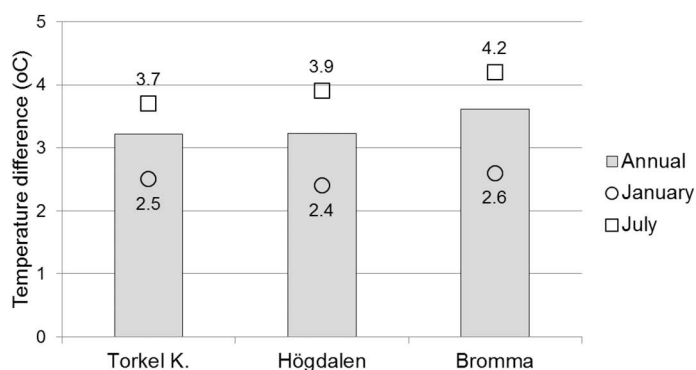


Fig. 10. Difference between future and present simulations in terms of mean annual temperature (bars) and mean January (circles) and July (squares) temperature for three meteorological stations in Stockholm.

will diminish more than PM_{2.5}, with reductions from $1.0 \mu\text{g m}^{-3}$ to over $2.4 \mu\text{g m}^{-3}$ in the city centre. The urban downscaling demonstrates the impact of the local emission reductions indicated in Table 1, with stronger effect for NO₂ for which the long-range contributions are relatively smaller than for PM_{2.5}.

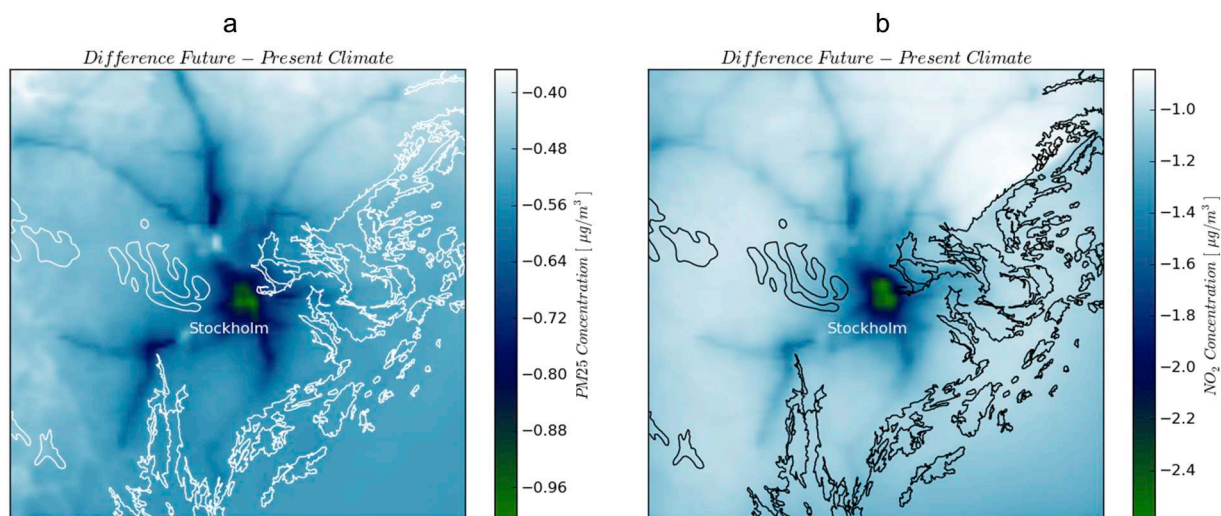


Fig. 11. Fields of concentration differences between present and future simulations over Stockholm for PM_{2.5} (a) and NO₂ (b).

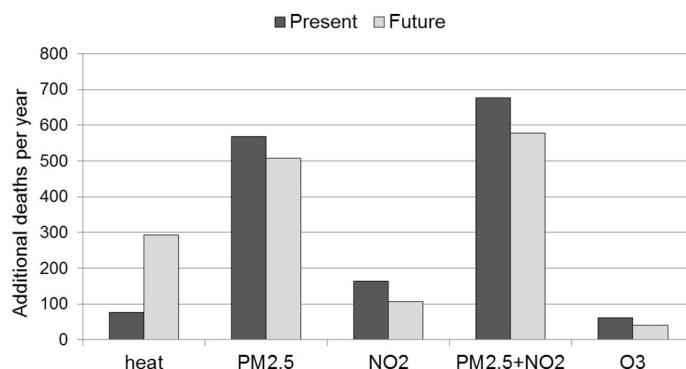


Fig. 12. Expected changes of health impacts in Stockholm due to heat waves and air pollution, as assessed from the present and future simulations in Urban SIS. Population and urban distribution assumed the same from present to the future, only climate and air pollution levels are different.

The comparison of the health impact indicators for air pollution and temperature given by the present and future simulations indicates a positive trend in the air pollution related impacts, while the increased temperatures are expected to have a much stronger negative impact on urban citizens' health (Fig. 12). The results should however be interpreted with caution, as they rely on a number of assumptions that may not be valid in the future, e.g. a constant population without any adaptation to changed temperatures and no urban development. Nevertheless, the results allow a comparison of how different health threats are expected to evolve in the future, highlighting the need for urban planning to account for the trends in both heat and air pollution.

4. Discussion

The Urban SIS web portal, developed in cooperation between web designers, stakeholders and technical and scientific experts, provides the user with easy access to data via thorough meta-data descriptions and tools for visualization and data download. We have found that user needs vary from city to city concerning specific SIIs. Thus a toolbox allowing for calculation of city-specific SIIs should form part of future urban climate services. Another user-specific feedback was that the future urban climate simulations should preferably include expected land-use changes, perhaps as a few alternative scenarios.

With respect to the functionality of the portal, it is hard to provide one solution that fits all. For example, while our solution provides an efficient way of getting an overview of most of the ECVs, SIIs and statistics, advanced users demand functionalities for more complicated analyses and comparisons of the datasets. Within the project we have proposed extensions of the design, e.g. providing several map layers side by side to facilitate comparisons of results, or developing specialised functionalities for some of the variables, such as the possibility to search for specific rain events.

For the dynamical downscaling with a meteorological or climate model, high-resolution land-use data is needed. To this end, national databases freely available online through European services were processed and merged to provide an improved description of the urban physiography. For future applications over a larger number of cities, an automation of this merging process would be useful. One important simplification in Urban SIS is that the urban physiography was kept constant in all simulations. Forthcoming efforts of delivering high resolution urban climate data should combine projections of both climate evolution and urban development, the latter based on the city's master plan, if available.

The computational cost of running a dynamical downscaling of climate-related ECVs over a city is still the bottleneck in delivering a service based on high resolution climate data. In Urban SIS, the simulations with HARMONIE-AROME/HCLIM-AROME and MATCH were carried out on a Linux cluster equipped with Intel Xeon E5-2640v3 processors at 2.6 GHz (<https://www.nsc.liu.se/>). The total CPU cost for the production of the full model output (no queuing time on the supercomputer and subsequent post-processing of SIIs is considered) amounts to 3.05×10^6 CPU-hours, running on 4 (MATCH) to 32 (AROME) compute nodes with 16 cores each. The total amount of data stored on the portal equals 390 GB.

Consequently, a careful year selection was conducted to represent the climatological behaviour of impact indicators during present and future climate. For the estimation of future climate uncertainty, several scenarios and different climate models should be included in a similar procedure. An additional approach for examining urban-scale weather impact could be to downscale certain historical severe events and to examine how these events would be affected by changes in land-use or during future climate scenarios.

The reduced domain size caused spin-up problems for precipitation that were especially severe under strongly forced conditions during winter. A set of sensitivity tests was carried out with HCLIM-AROME for Jan-Feb 1995. During these months most of the precipitation was large-scale non-convective, therefore the precipitation in the downscaling model is expected to be consistent with the forcing model. Fig. 13 shows the results obtained for a range of increasing domain sizes with the aim of assessing the spatial spin-up for precipitation. The model grid spacing here is 3 km, which enables using larger domain sizes and which, according to performed tests (not shown), does not change the nature of the spin-up issue. These results clearly show the underestimation of precipitation over the inflow part of the domain (i.e. extending from the western boundary). The spatial structure and amount of precipitation, analysed over the 144×144 domain, are not converging to the forcing model values for domain sizes smaller than 432×432 grid points (i.e. $\sim 1300 \text{ km} \times 1300 \text{ km}$). This means that the spatial spin-up, i.e. the part of the computational domain from its western

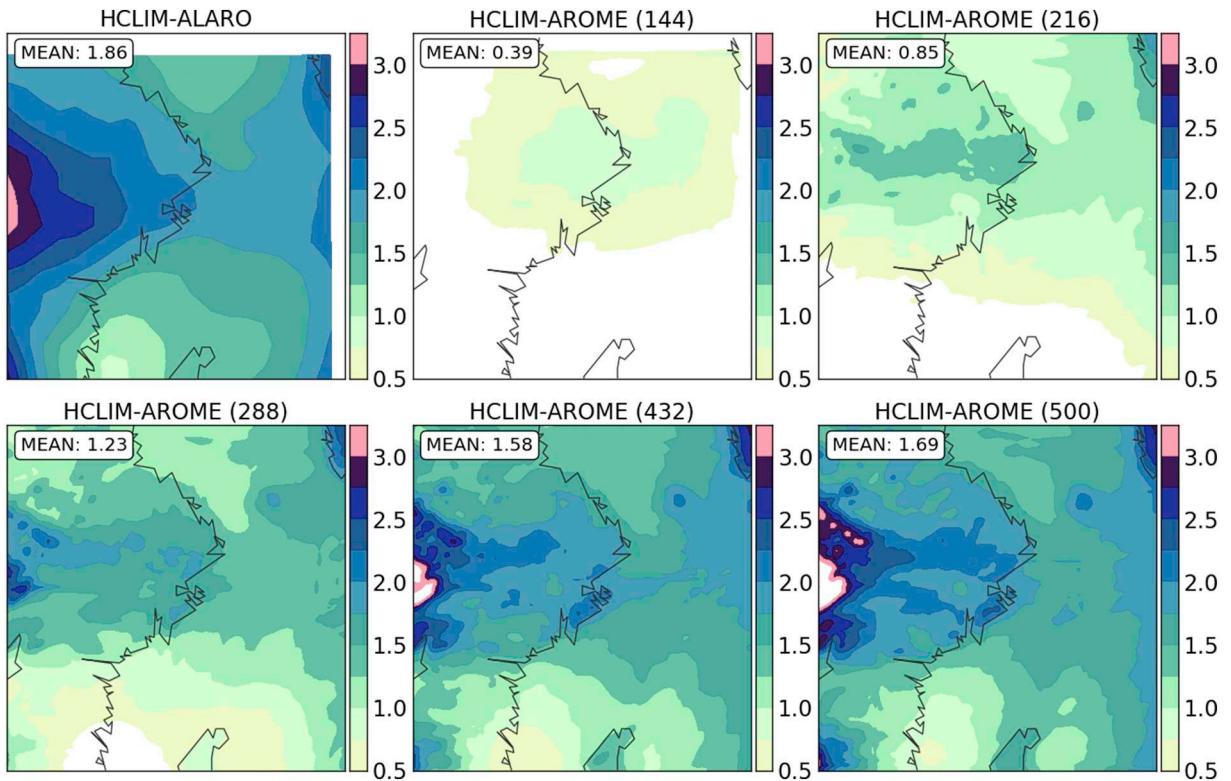


Fig. 13. Results from the sensitivity tests showing the comparison of precipitation (mm/day) averaged over Jan-Feb 1995 from the forcing model (HCLIM-ALARO, 20 km grid spacing) and HCLIM-AROME simulations (3 km grid spacing), with increasing number of grid points in both horizontal directions (indicated in each panel title). All results are shown over the 144×144 grid points domain. The domain average precipitation is given in the top left corner for each simulation.

boundary to the analysed area, is at least 430 km. The main conclusion from this sensitivity analysis is that especially for the spin-up of precipitation in strongly forced weather situations, i.e. with strong winds advecting in through the lateral boundaries, a much larger domain should have been used (if the increased computational cost could have been supported by Urban SIS timeline). Further studies are needed in order to understand and resolve this issue. In this study, the bias had to be addressed by using the precipitation of the regional-scale host model.

As already pointed out, computation time is a major limiting factor in high resolution urban climate/air quality studies. Previous studies on future urban air quality have typically compromised on the grid resolution of the urban domain, decreased the number of years representing a particular period or used simplified methods to represent the urban climate forcing in the high resolution CTM model. Gidhagen et al. (2012) used one-way nested CTMs driven by regional and urban emissions data to study the effect of climate change and emissions changes on the future air quality of Stockholm on a domain with $2 \text{ km} \times 2 \text{ km}$ resolution. For the climate data their study used interpolated meteorology from a coarse-resolution ($50 \text{ km} \times 50 \text{ km}$) RCM. A set of three consecutive years was chosen to represent present and future climate. In Markakis et al. (2016), 10-year windows of historical and future air quality was modelled on a $1 \text{ km} \times 1 \text{ km}$ grid covering Stockholm, again utilizing climate data interpolated from an RCM (here $0.11^\circ \times 0.11^\circ$ resolution). None of these studies did therefore explicitly address changes in urban climate.

In Urban SIS, on the other hand, we specifically use dynamically downscaled urban climate, representing a carefully selected set of climate regimes, to provide a description on how the air pollutants are spatially and temporally distributed over Stockholm. The results are far from perfect but provide important information where conclusions emerging from the comparison between the present and future time slices can be drawn. The meteorological conditions in future climate in combination with the reduced emissions trends, both at European and local level, are associated with reduced levels of all four air pollutants studied in Urban SIS. A future task, specifically requested by end-users, is to repeat the urban downscaling using the same emissions in the future time slice as in the present, thereby isolating the effect of climate change on air pollution levels.

The air quality data obtained for the Stockholm city centre showed good similarity with measurements of PM_{2.5} mean concentrations. Similar findings were obtained by Markakis et al. (2016), using a chain of GCMs and RCMs coupled to a CTM operating over Stockholm. The less accurate simulation of PM₁₀, O₃ and NO₂ emphasize the need to revise the current emission inventories, not only for the cities, but also for entire Europe, assuring an accurate long-range transport and better agreement with the rural stations outside the cities. There is also a need to improve the descriptions of deposition and photo-chemistry reactions close to the surface, to obtain more realistic night-time (low) O₃ concentrations.

The health indicators, reflecting conditions and changes of air pollution and heat waves, are an important basis and motivation for adapting the city in a way that reduces future health-related climate change impacts. However, it is important that the users of the information are well aware of the assumptions behind the health impact indicators provided for a specific city. The meaning and implications of the uncertainty classifications provided with the Urban SIS output must be clear to all users.

Concerning hydrology, the HYPE model proved to perform overall well when calibrated for a 1-h time step, as opposed to the normal 1-day time step. This is encouraging as it provides a substantial added value in the representation of the fast flow response characteristic of urban and peri-urban basins. During the Urban SIS project, further development of the HYPE model towards high-resolution applications has been made, e.g. by providing the option to specify results (e.g. runoff) for each type of land-use (e.g. impervious surfaces) individually.

All HYPE model simulations were heavily influenced by the underestimated precipitation in the HARMONIE-AROME/HCLIM-AROME downscalings, consequently leading to a pronounced underestimation also of discharge. All climate models have more or less precipitation bias, and this is usually handled by some form of bias adjustment (e.g. Yang et al., 2010). This option was considered in Urban SIS but it was finally rejected, because of e.g. the high level of bias found in certain months and sub-regions, making statistical post-processing questionable. Another solution is to use precipitation from the coarser-resolution model that is downscaled (HCLIM-ALARO in our case; Section 2.1.2), which would however not allow fully high-resolution hydrological simulations. The hydrological results underline the need for further development of the downscaling method with respect to precipitation (see also Fig. 13 and associated discussion).

Another aspect of the hydrological simulation is that the basins upstream cities may extend (far) beyond the downscaling domain, as was the case in Stockholm (Section 2.1.4). Also in this situation, meteorological data from the coarser-resolution model need to be used. It is thus important to identify the upstream basin in the beginning of the process.

As argued in Section 2, we consider the flexibility provided by the comprehensive set of high-resolution and physically consistent ECVs a key advantage of the Urban SIS concept. This allowed us to take rather complex end-user requirements into account with a limited effort. For example, after discussion with end-users in Stockholm, the DDF analysis (Section 2.2) was extended to include also a spatial dimension to estimate changes in extreme areal mean rainfall intensity (in standard DDF analysis only local “point-scale” rainfall is considered). The importance of this aspect when studying large urban basins was realized only after the ECVs and SIIs had been selected, and owing to the available ECVs implementation of “spatial DDF analysis” was straight-forward. Similar experiences were made in the other case studies, e.g. related to development of tailored meteorological indicators for future air quality in Bologna, which we believe support the usefulness of the approach.

5. Concluding remarks

The main conclusions drawn from the Urban SIS project may be summarized as follows.

- In some aspects, the urban downscaling managed to describe important small-scale processes and patterns of obvious importance for climate adaptation and urban sustainability. Examples include intra-city temperature gradients and the UHI effect as well as short-duration rainfall extremes and DDF statistics. Also the air quality downscaling reproduced spatial and temporal gradients of importance for urban planning. Considerable bias in absolute levels was however evident, pointing out to the need of improving emission inventories both over the Northern Europe, as well as the cities themselves. Less successful results were obtained also for long-term accumulations of precipitation.
- The substantial computational resources required had a number of negative consequences. The 240 km × 240 km domain proved to be too small to accurately downscale large-scale precipitation, particularly in winter, which greatly affected also the hydrological simulations. Furthermore, as compared with 30-year periods, the 5-year time slices used in the simulations introduce an additional uncertainty in the estimation of long-term climate and its future changes, even with careful selection of the years included.
- Involving a wide range of end-users from the start of the project was important for ensuring well selected and practically applicable ECVs and SIIs. An innovative approach was developed to assist end-users with respect to the uncertainty of the data provided, distinguishing between the uncertainty of the model, indicator and scenario, respectively.

We hope that our experiences from the Urban SIS project, both the positive and the negative ones, presented in this paper will be useful in the design of new efforts in the same direction. All results and documentation may be accessed at <http://urbansis.climate.copernicus.eu/> or <http://urbansis.eu/>. Providing realistic and reliable projections at the very small scales relevant for urban climate change impact assessment remains a key future task that will require continued and substantial resources from now on.

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Declaration of Competing Interest

None.

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Appendix A. List of ECVs and SIIs

Table A.1

Essential Climate Variables (ECVs) produced for Stockholm. ECVs that have not been possible to validate are unclassified. For details on the uncertainty classification, see [Section 2.4](#).

		Scenario uncertainty		
		Historical	Present	Future
Temperature	Air temperature*			
	Urban air temperature*			
	Nature air temperature*			
	Higher layer air temperature* (3 levels)			
Precipitation	Precipitation*			
	Snowfall			
Other meteorological variables	Wind*			
	Relative humidity*			
	Boundary layer height			
	Total Cloud Cover			
	Global radiation*			
	Direct shortwave radiation			
	Diffuse shortwave radiation			
Air quality	O3 concentration*			
	NO2 concentration*			
	PM10 concentration*			
	PM2.5 concentration*			
Hydrology	Discharge*			
	Runoff			
	Surface runoff			
	Evapotranspiration			
	Soil moisture			
	Snow cover			

*Used in model validation.

Table A.2

Sectoral Impact Indicators (SIIs) produced for Stockholm. SIIs that have not been possible to validate are unclassified. For details on the uncertainty classification, see Section 2.4.

			Scenario uncertainty		
			Historical	Present	Future
Health indicators	Air quality	EU limit values: concentrations			
		EU limit values: exposure			
		Mortality, long-term exposure			
		Mortality, short term exposure			
	Heat stress	Number of hot days*			
		Heat wave duration			
		Heat induced mortality			
	Discomfort	Thom Discomfort Index			
		Universal Thermal Climate Index			
		Frequency of tropical nights			
Energy	Energy consumption	Heating degree days			
		Cooling degree days			
	Solar energy	Short-wave solar insolation			
Infrastructure	Flooding	Extreme precipitation*			
		DDF statistics*			
	Green infrastructure	Growing season length			
		Frost days*			
		Ice days			
	Transport infrastructure	Zero-crossings			
Non-sector	Temperature	Daily air temperatures			

*Used in model validation.

Appendix B. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.uclim.2019.100549>.

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